2 Existing Knowledge About Occupant Behavior and Energy Consumption

Introductory note

Chapter 2 provides an overview of a literature study of the existing knowledge on energy consumption from the urban to the user scale, energy performance modelling methods, the energy performance gap, and insights to determinants of heating energy and electricity consumption.

This review first helped to set up a reference point for the reasons to actual occupant behavior, how perception, lifestyle, norms, rules lead to various actions at home (Figure 1). Secondly, through this study, a framework for the relationship between occupant behavior and energy consumption was created (Figure 2), based on the determinants of behavior, i.e. occupant characteristics (educational, economic, social), dwelling characteristics (envelope, systems, lighting and appliances…). This literature study set the context and also the first steps of this research. The determinants found through this review (Table 2) gave input to the content and structure of the questions of the survey designed for the OTB dataset.

The paper below was written by Bedir. The co-authors commented on the drafts and gave advise on the structure, and the content of the paper. The co-authors have given their permission to include the paper in the thesis. The review of determinants of energy consumption was first published as:

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TOC

§ 2.1 A Review of Research on Energy Efficiency in Buildings

Housing more than half of global population in 2013, cities account for about two-thirds of primary energy demand, and 70% of total energy-related carbon dioxide (CO2) emissions (IEA, 2013). The energy and carbon footprint of cities will increase with urbanization and the growing economic activity of citizens. This puts cities at the heart of the sustainable energy transition. Efforts aimed at fostering sustainable urban energy paths, a vision for meeting demand for end-use energy services in cities while at the same time significantly reducing primary energy use and its environmental impacts, are crucial to meet energy ambitions. Improvement in the rural areas is also important, since buildings in rural areas might have greater potential to be sustainable. However, the current trends of urbanization attract more attention to cities, zero-energy buildings (ZEBs) and near-zero energy buildings (nZEBs) remain as the niche fields of development more for rural areas. The scope of this review is the urban, in relation to the focus of this thesis.

Urban planning and buildings, mobility and transportation, low-carbon/efficient energy supply and smart energy networks are the main fields of research and development. Attention is growing for the concept of 'prosumers' i.e. active citizens taking initiative in issues of energy, environment and sustainability.

§ 2.1.1 Urban planning and buildings

Achieving the goal of limiting global temperature rise to 2 C degrees would require an estimated 77% reduction in total CO2 emissions in the building sector by 2050, compared to today's level. If no action is taken to improve energy efficiency in the buildings sector, the energy demand is expected to rise by 50% by 2050 (EC, 2012). This increase is driven by rapid growth in the number of households, residential and services floor area, higher ownership rates for existing electricity-consuming devices and increasing demand for new products. However, this growth could be limited to just over 10% by implementing several energy efficient installations in dwellings including high-performance windows, optimal levels of insulation, reflective surfaces, sealants, heat pumps, solar thermal heating, co-generation, energy efficient appliances and equipment, efficient cook stoves and solid-state lighting (SSL), among others. Another important first step in improving the energy efficiency of the global building stock is to establish and enforce stringent building codes that include minimum energy performance for new and refurbished buildings.

Though no one-size-fits-all solution exists to ensure energy and environmental sustainability, compact and dense urban development is a structural assumption towards energy use reduction. For instance, compact urban form and density create the premises for reduced demand for mobility and for greater efficiency of energy use in buildings. Urban form that incorporates mixed-use and public-transport oriented developments, as well as size, density, maturity, economy and the local policy-making capacities of urban areas will heavily influence the appropriate choices of policies and technologies for sustainability.

Improved building envelopes in all regions allow for the downsizing of heating and cooling equipment, and for a significant reduction in energy use. Tougher regulations are needed to reduce the electricity demand for lighting, appliances and cooling. Efficient district heating systems benefit from thermal energy storage coupled with waste heat and renewables, offering increased systems efficiency and flexibility. While low or zero energy buildings (nZEB) are well applicable in rural areas; they are still a niche field of implementation in urban areas. High densities, limited on-site renewable potential and cultural heritage conventions are some of the reported reasons that constrain the potential for broader implementation of nZEB's in cities.

Energy renovation of existing buildings is as important as the advanced implementations for new buildings, especially in highly urbanized areas, and where population is not expected to grow more in future. In these contexts, reducing building energy demand through renovation can facilitate electricity export, avoid grid infrastructure investments, unlock biomass to substitute fossil fuels in transport and enable deployment of new technologies such as low temperature district heating and cooling systems. Reduced energy demand also brings together important energy security benefits. Building renovation could be supported by more advanced building technologies and intelligent energy management systems that empower consumers and encourage behavior change.

The speed of urbanization is an opportunity to the transition towards low-carbon/low-energy urban energy systems, new buildings, retrofits of existing buildings and new transport infrastructure to service the growing urban population. The greater density of urban areas leads to infrastructure investments like public transport, cycling, district heating and cooling, and utilization of excess heat. This tempers the additional costs to achieve lower energy consumption levels in urban areas compared with rural areas. Advanced building and laboratory programs striving for zero-energy buildings need to continue.

TOC

§ 2.1.2 Energy efficient supply

Renewable energy sources located in urban areas can make an important contribution to meeting the energy needs of cities while at the same time increasing energy resilience and retaining economic value within communities. Among renewable energy sources that can be deployed in urban areas, rooftop solar photovoltaic (PV), solid waste (SW), and sewage and wastewater gas are already cost-effective today and can play a relevant role in covering the electricity, heating and cooling needs of cities. Though the potentials from SW, sewage, and wastewater gas are not large, these energy resources can provide relevant cost savings for waste and water treatment services. Rooftop solar PV can make a significant contribution to meeting electricity demand in cities. The technical potential for rooftop solar PV could provide up to 32% of urban electricity demand and 17% of global total electricity demand by 2050. The solar PV potential is larger in small cities, due to the lower density (ECEEE, 2016).

Currently, space heating and cooling together with water heating are estimated to account for nearly 60% of global energy consumption in buildings (IEA, 2016). They therefore represent the largest opportunity to reduce buildings energy consumption, to improve energy security and reduce CO2 emissions. Meanwhile, cooling demand is growing rapidly in countries with highly carbon-intensive electricity systems. A systems approach, where equipment upgrades are coordinated in particular with improved building envelopes, is crucial to achieving higher energy efficiencies and a low-carbon heating and cooling supply. The use of electric resistance heaters in existing buildings is promoted to be avoided, and eventually be prevented for new installations and equipment replacements. Instead, heat pumps, solar thermal and co-generation for space heating and cooling as well as hot water are prioritized (ECEEE, 2016).

In regions that are highly dependent on traditional biomass, energy use in buildings represents as much as 80% of total final energy use (IEA, 2016). In these regions, a major initiative seems to be needed to promote modern biomass equipment that can reduce air pollution and improve human health, while allowing more of the scarce resource to be used in central systems. The priority for countries with hot climates seems to be highly reflective external surfaces to reduce the need for cooling, and the development and wide adoption of high-performance cost-effective air conditioners. The implementation of minimum efficiency standards helps to improve energy efficiency and control the growth in electricity demand from this end-use. This will be particularly beneficial in reducing peak loads, which often coincide with demand for space cooling.

Cities can decrease the carbon footprint of their thermal demand by reusing excess heat from industrial plants located in the proximity of urban areas. The cost-effectiveness of using industrial excess heat (IEH) in cities depends on local conditions such as the existence of thermal distribution networks and the quality of the heat source among others. Systems integration of distributed energy services in cities can allow accelerated penetration of distributed energy sources and renewable sources, increasing the resilience and security of energy systems. In a global scenario characterized by a high build-up of renewables and distributed generation (DG), smarter urban energy infrastructure is an important prerequisite, providing additional non-climate benefits. The monitoring and control potential from ICT is incorporated into urban grid planning.

Lighting has significant potential for energy efficiency improvements through the application of more efficient technologies, better matching of lighting intensity to need, and continued emphasis on technical and behavioral solutions that turn off or reduce lighting levels when no longer needed. With better use of natural lighting and adoption of highly efficient lamp technologies, buildings energy consumption for lighting is reduced by 40% in 2050 compared to current levels (IEA, 2016). Variable controls and sensors are added to the existing lighting systems via retrofit programs.

In many countries, appliances and other electrical equipment represent the fastest-growing end-use for energy in buildings. Some improvements have been realized, but additional effort is required to address stand-by energy use. Innovative, low-cost sensors and controls for appliances and electronic equipment could reduce peak loads on average by about 15%. Cooking is currently one of the largest end-uses in the residential sub-sector, accounting for nearly one-quarter of global residential energy consumption and about 20% of total buildings energy use (IEA, 2016). Common medium- and long-term targets for implementing building codes and minimum energy performance standards for lighting, appliances, heating and cooling equipment seem to require immediate action.

§ 2.1.3 Smart energy networks

Smart urban energy networks can leverage the combined potential of DG and integrated urban energy grids to provide increased flexibility to the main energy system. Smart, ICT-enabled distributed energy resources (including energy storage) within urban smart energy networks are claimed to provide a range of technical services, allowing grid operators to better plan and operate main power systems and, in turn,

TOC

increase the hosting capacity for renewable and decentralized energy technologies at lower cost. Integrating power, heat and fuel networks is claimed to increase the utilization of the system, reduce total costs and offer the national electricity system greater flexibility (ECEEE, 2016). For instance, a district heating network can link power and heat production and consumption locally, providing operational flexibility to accommodate periods of excess or scarce variable renewable generation in the national grid. Overall, the greater flexibility provided by such urban power-to-heat systems can not only balance variable renewable generation in the main system but also provide local balancing and other system services to support the integration of distributed energy sources. By enabling a more distributed system where energy is produced and consumed locally, smarter integrated urban energy grids can reduce the need for investments in the main energy infrastructure. More broadly, they can also enhance energy security through greater redundancy and resilience to external shocks.

Innovative management models for effective system integration at the urban level are interesting. New models such as micro-grids or the various existing models that turn consumers into producers and "prosumers", enable a wide range of benefits at the local level, including reduced environmental impact, reduced energy cost for urban communities, increased energy access and greater security of supply.

§ 2.1.4 Energy technology and innovation

Energy technology and innovation is central to meeting climate mitigation goals while also supporting economic and energy security objectives. Continued dependence on fossil fuels and recent trends such as unexpected energy market fluctuations reinforce the role of countries, individually and collectively, to stimulate targeted action to ensure that resources are optimally aligned to accelerate progress.

The buildings sector uses a wide array of technologies including the building envelope and its insulation, space heating and cooling systems, water heating, lighting, appliances and consumer products, and business equipment. Broader deployment of district heating, heat pumps and solar heating helps to transition the energy supply away from fossil fuels and direct electric heating. In cities with district heating, it seems it may be more cost effective to pursue only moderate building energy efficiency improvements together with investments in low-carbon district heat supply with lower temperatures and peak demand.

Primary strategies and technologies needed for efficient building include high-performance envelopes optimized to harvest passive solar energy and daylight, combined with advanced windows, optimal insulation and proper sealing, along with reflective surfaces in hot climates. With buildings in some countries lasting well over 100 years and expensive to retrofit, urgent action is needed to ensure that high-performance building envelopes rapidly gain market share and quickly become the standard for all new construction globally. More than 40% of the savings expected in heating and cooling energy demand under a low-carbon scenario can be directly attributable to improvements in the building envelope (ECEEE, 2016). Lower heating and cooling requirements will also allow downsizing of the equipment needed to reach a desired indoor temperature.

Among energy end uses, heating and cooling systems offer substantial potential for energy efficiency. The energy sector accounted for around two-thirds of global CO2 emissions in 2012, highlighting the benefits of clean energy technologies that are essential for de-carbonization. Wind and PV power have the potential to provide 22% of reduction in annual electricity sector emissions in 2050; to fully exploit the performance improvements achieved through technology (ECEEE, 2015).

In 2015, clean energy technologies continued their advancement as mainstream energy solutions in 2015. The threshold of one million electric cars was crossed in 2015, with an overall annual sales growth rate of 70%. Renewable power generation grew by an estimated 5% in 2015 and now accounts for around 23% of total electricity generation globally. Energy efficiency improvements continued at a steady pace, with buildings and appliances improving at a faster rate than other end uses. Despite a notable scale-up of production capacity over 2014-2015; advanced biofuels are not on track to meet 2DS targets. Global solar heat deployment has slowed in recent years due to challenging economics, insufficient support and non-economic barriers. Broader integration of sustainable energy into policy and market frameworks is needed, as well as strategic planning in all energy end-use sectors. In the transport sector, improved land-use, infrastructure and integrated territorial planning are important for curtailing energy demand. Necessary further effort is emphasized for technological advancements in district energy, car technology, and lighting (IEA, 2016).

§ 2.1.5 Prosumers

The European Commission recognizes the importance of putting citizens at the core of the energy transformation, but citizens still do not have their rights set up on the EU

TOC

level. In order for the EU Energy Union to work, individuals and communities should no longer be treated only as passive consumers of established energy companies, but also as potential energy producers, or 'prosumers', particularly through self-generation of renewable energy, storage, and energy conservation, and participation in demand response (Clientearth, Greenpeace, 2016).

However, prosumers now currently face a number of obstacles due to the lack of a dedicated legal framework in the EU, and their situation varies from state to state. Not only do prosumers contribute to the energy transition, they themselves benefit from reduced energy bills as well.

§ 2.2 Determinants of Energy Consumption and Occupant Behavior

The human being shapes the physical environment around itself and in response; the physical environment that he deformed begins to change it. Currently, this mutual interaction has been leading to environmental depletion and energy resource decay in broad terms. On the other hand, the measures proposed for reducing energy consumption have to meet the demands for the optimum livable environment for the inhabitant. Nevertheless, in most cases, these two goals cannot be achieved at the same time, either because of the design of building systems and components, or resulting from the behavior of the occupant. The aim of this section is to develop an understanding of the relation between occupant behavior, indoor comfort and energy consumption in dwellings, based on previous research. Literature on the subject matter is analyzed in order to derive out the following: what the actual behavior of an occupant is, how it occurs, and what they mean in terms of comfort, health and energy consumption; as well as to produce a framework for evaluating the relationship.

Considered literature focuses on the relationship between occupant behavior and energy performance/consumption or occupant behavior and comfort/health. Few studies make assessments of actual occupant behavior from both energy consumption and comfort/ health respects. This kind of research is mainly within the context of a specific dwelling type (single family dwellings-multifamily dwellings/apartments), condition of the dwelling (renovation/new built or old/new), the energy conservation approach ('energy efficient'/conventional), or from a project framework. Besides, when the occupant behavior is considered, it is either a typical activity domain (heating, cooling, ventilation...) or an activity scenario (studying, eating, cooking....).

Reviewed literature is classified according to the parameters related to the occupant behavior (Figure 1). In the literature reviewed, the common method used is post occupancy evaluation. Data about actual behavior of occupants are collected mainly through interviews, questionnaires and diaries; and in some of the cases through measurements like photography, micro switches and observation. Data about indoor air quality, thermal comfort and energy performance is collected also through field measurements and evaluated with simulation and/or statistical analysis.

§ 2.2.1 Actual behavior of the occupant

Planned behavior is a consequence of behavioral intentions. These intentions result from attitudes, norms, and perception. Underneath behavior lie beliefs of behavior, norms and control. In Giddens's structuration theory, the analysis of environmental behavior focuses principally on the behavioral or social practices in which human agents participate. Discursive and practical consciousness affects behavior through lifestyle; rules and resources affect behavior through provision systems (in Spaargaren et al. 2000).

As actual behavior influences indoor air quality and energy consumption in dwellings, existing or resulting indoor air quality influence behavior through perception (Figure 2). For example, ventilation behavior (Engvall et al. 2004) is strongly correlated with indoor air quality through perception. The occupant (re)acts depending on how he perceives fresh/ stuffy air, dry/humid air, cooking odors and other strong odors. At this point it should be emphasized that adaptation is also involved in perception. Occupants adapt to the changing indoor air quality levels in every 15 minutes. Besides, adaptation raises the acceptability to indoor pollutants when the pollutant source is human behavior (like smoking), whereas building originated pollutants are less acceptable. Also, cross adaptation is observed when among many sources of pollution; acceptability changes according to the change of concentration of the main pollutant that the occupant is exposed to (Gunnarsen et al. 1992).

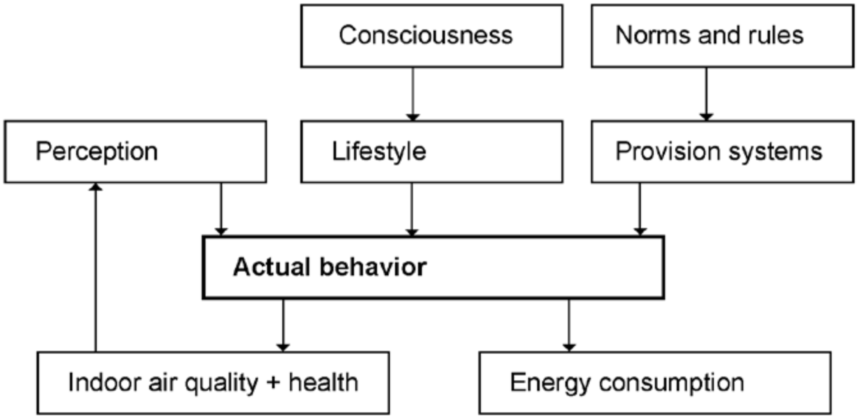

FIGURE 2.1 Framework of causes and impact of actual occupant behavior and energy consumption (interpreted from literature review)

§ 2.2.2 Relation between occupant behavior – energy consumption and Health

Analyzing energy consumption of a dwelling has building related and occupant behavior related aspects. The occupant influences energy performance through its daily activities like studying, watching TV, washing up etc.; through internal heat gain generated from metabolic rate; and through reactions to the changes in the indoor environment (Tanimoto et al. 2008). Since indoor air quality and indoor comfort level have health consequences, health could also be an indicator to evaluate indoor air quality and energy consumption. It is important to build and sustain low energy buildings that are also healthy. In some cases, energy efficient measures and interventions modestly improve some aspects of physical health of occupants in dwellings (Fisk, 2000; Wilson et. al., 2014; Willand et. al., 2015), while in many cases, this cannot be managed (Roulet et.al., 2006).

Energy technologies and occupant behavior have been treated separately in the domains of indoor environment, energy engineering, and social fields (Moezzi and Lutzenhiser, 2010). In literature, occupant behavior in dwellings is analyzed by specific daily activities, most of which are, in fact, interrelated in terms of the output patterns such as heating and electricity use, cooling and ventilation etc. Relation between occupant behavior, energy consumption and health is bilateral: Either the occupant behavior affects them and/or they affect occupant behavior.

§ 2.2.2.1 Occupant characteristics

A Household characteristics (Social)

Size and composition of a household has an influence on occupant behavior (Fleury et al. 2001; Liddament, 2001; Ndiaye and Gabriel, 2010; Yohannis et al., 2008; Genjo et al., 2005; Bartiaux and Gram-Hanssen, 2005; Rooijers et al., 2003; ECN, 2009), and especially in terms of electricity consumption by the use household appliances and lighting (Papakostas et al. 1997; Al-Mumin et al. 2003; Tyler et al. 1990). Household size (Vringer, 2005; Biesiot & Noorman, 1999) together with poor ventilation, volume of the house and heating system has a significant impact on NO2 concentration, as well as energy consumption. Increase in NO2 concentration may lead to health problems like asthma and allergen illnesses (Zota et al. 2005).

Some studies claim that occupant's lifestyle has strong effects in energy consumption and should be changed through education for energy conservation (Groot-Marcus et al. 2006), whereas some others show that differences in lifestyle do not have much effect on space heating energy behavior (such as Emery et al. 2006). Occupant's age is an important predictor of both heating energy and electricity consumption at home (Brasche et al. 2005; Liao & Chang, 2002; Linden et al., 2006; Yohannis et al., 2008; O'Doherty et al., 2008; Baker and Rylatt, 2008).

Habits are also major elements of behavior; the motivation to achieve a goal within a context and with cues create habits. Repeating the habit strengthens it, and then, even when the original motivation is not there, habits will still be triggered by the contextual cues. Most of everyday behaviors are claimed to be led by habits, especially using technologically advanced devices and systems. At home, research shows higher probability that occupants will act upon habits; because at home behavior with cues do not require cognitive effort (Maréchal, 2010; Pierce, et. al., 2010; Martinez, 2011; Ortiz, et. al., 2017). Habits allow the individual to achieve goals in a quick and effective way that requires minimal thought (Maréchal, 2009). In other words, the stronger the habits are the weaker the influence of knowledge and attitude on behavior (Verplanken et al. 1994). For example, clothing habit is a means for the occupants of the dwelling to maintain their own energy balance with indoor climatic conditions, and the extent to which they rely on physiologic responses to maintain that energy balance determines the magnitude of their thermal discomfort and attendant dissatisfaction. Indoor thermal conditions influence body heat balance which leads to thermal discomfort feeling through physiological strain and this process results in behavioral thermoregulation (clothing) (Morgan et al. 2003; Baker and Rylatt, 2008; ODYSSEE, 2008). In naturally ventilated buildings, clothing behavior of the occupants is more related with outdoor temperature than mechanically ventilated buildings (De Carli et al. 2007).

A Educational characteristics

The increase in education level of the occupant (Mansouri et al., 1996) may result in awareness about energy consumption and environment, hence reducing energy consumption. Motivation is another important determinant of electricity consumption (Vringer & Blok, 2007; Linden et al., 2006), and could be created through educational and economic measures. In a study in Finland, economic reasons provided the motivation for households to save energy: the occupants were eager to save energy by changing their lighting appliances, sealing windows, lowering room temperature and reducing hot water consumption. Further, households wished to get advice on use of electricity, space heating, ventilation and use of water. Half of the users began to turn down lights in the rooms not occupied, 29% reduced water use, 27% change clothing habits (Haakana et al. 1997).

In Denmark, eco accounts were used to provide information (Jensen, 2003) for tenants; after one year, heating energy consumption was reduced by 9% and electricity consumption by 22%. Product information about energy conservation also affects behavior but relies on the actual willingness of the user to initiate or change specific behavior patterns (Wiese et al. 2004). Provided feedback and general information about energy consumption to the occupants have strong influence on occupant behavior. For example, in many cases occupants do not know that ventilation demands are only met at the highest speed level of the exhaust fan, and they do not operate it correctly. This results in poor indoor air quality (Ginkel et al. 2003, Liddament, 2001). Feedback should not be handled alone; factors such as the conditions of housing, personal contact with a trustworthy advisor when needed, and support from utilities and government which can provide the technical, training and social infrastructure are important to make learning and change possible (Darby, 2000). Satisfaction of the occupant and education about using the energy efficient features, good performance of a passive house, and about cleaning and maintenance requirements are important behavioral aspects. Lastly, occupant involvement in design stage is crucial for achieving intended energy performance levels (Blum et al. 1989).

B Economical characteristics

Economics treat attitudes, beliefs, values and the like as mere preferences, and tastes are exogenous to economic models. Economic psychology provides psychological and financial influence in combined and contrasting means (Brandon et al. 1999). Psychological influence could be observed in owner occupied houses where energy consumption level is less compared to the similar conventional (Schneiders et al., 2006). Financial influence could be used by supplying energy consumption feedback to users (Haakana et al. 1997). Design Context Booklet, the report of Task VIII conducted in IEA-SHC program, states the economical determinants of user behavior as ownership (as well as O'Doherty et al. 2008 and Leth-Petersen and Togeby, 2001), income level (as well as in Vringer, 2005; Biesiot and Norman, 1999), savings, employment situation or general; subsidy and advancement, tax reduction, energy (as well as Linden et al. 2006), building and appliances costs (as well as Lohnert et al., 1989).

§ 2.2.2.2 Building characteristics

In this study, the components of a dwelling that have impact on occupant behavior directly or indirectly are categorized as site & climate, building envelope, mass composition, mechanical system and lighting and appliances.

A Site and climate

Outdoor air temperature, horizontal global irradiance, wind velocity and wind direction have an impact on user behavior in terms window opening (Erhorn, 1988; Feustel et al. 1985). Users tend to open windows less depending at night and temperature below 12 C degrees and when the wind velocity is greater than 3 m/s whereas horizontal global irradiance has a minor impact on user behavior in correlation with outdoor temperature. The use of windows is linearly correlated with the outside temperature for temperatures between -10 C degrees and 25 C degrees and inversed correlated with wind velocities. When it is raining or snowing, windows are less often used (Hainard et al. 1986). In mild climates, residents' behavior during the summer season and whether the residents opened windows/doors or operated air conditioners is very different (Iwashita et al. 1997). Next to the weather characteristics, the quality of the outdoor environment; air pollution (odour) and noise (Van Dongen et al. 1990) are important factors. People shut the windows when the outside noise level is between 60 and 65 dB(A) and take more serious precautions like sound insulation, changing spatial organization, when it is noisier than 65 dB(A) (Lambert et al. 1984). On the corridor side of the apartments the windows or vent-lights were opened maximum half an hour on average and on the balcony side maximum 1.4 hour when nobody was at home.

TOC

Fear for burglary plays a role here, but also fear for escaping of pets (Van Dongen, 1990).

B Building envelope

Basic natural ventilation is through the cracks in building envelope (Van Dongen, 1990). Air tightness of the wall and material choice for infill, insulation and cladding are also influencing. Thus, construction quality and maintenance are crucial. Reducing the air tightness of the envelope may cause an impaired air quality perception and may lead to health-related consequences (Stymne et al. 1994; Singh, 1996; Engvall et al. 2005). This is a proof of the necessity for further studies to figure out occupant reaction to the change in indoor air quality conditions. However, a profound review about airborne particles in the indoor environment reveals that existing scientific evidence does not necessarily prove that indoor air quality has direct health consequences (Schneiders et al. 2003).

C Mass composition

Occupants use natural ventilation less when volumes of rooms are smaller; windows are less oriented to sun and more oriented to the prevailing wind direction (Van Dongen, 1990). Windows that are fixed on the bottom of the frame and that open inwards are more often open than other types of windows (Wouters et al. 1986). Upper wings of windows are open twice more often than the lower ones that are opening outwards. If the window in open stand cannot be fixed at several positions through a grip, it is possible that the window will never be used (Van Dongen, 2004).

Type of dwelling and floor area are important determinants of occupants' energy consuming behavior at home (Linden et al, 2006; Yohannis et al., 2008; O'Doherty et al., 2008; Bartiaux and Gram-Hanssen, 2003; Vringer et al., 2007; Baker and Rylatt, 2008; ODYSSEE, 2008; Fuks and Salazar, 2008; Rooijers et al., 2003; ECN, 2009)

The location of the dwelling (Yohannis et al., 2008; O'Doherty et al., 2008) is another important parameter and the age of the dwelling (O'Doherty et al., 2008; Vringer et al., 2007) also appears to have a significant impact on electricity consumption. Lastly, the number of rooms (Baker and Rylatt, 2008; ECN, 2009) and bedrooms (Baker and Rylatt, 2008) also emerge as significant predictors of electricity consumption.

D Mechanical systems

The type of heating system plays a role. In dwellings with central heating windows are less often open than in other dwellings (Wouters et al. 1986). In addition, several studies focus on the effect of the type of thermostat control on energy use. Households with programmable thermostats are claimed to set the thermostat temperature at a lower level when nobody is at home or during night time. Nevius and Pigg (2000) found that presence of thermostat has a minimal effect on energy use, and temperature settings do not significantly differ between dwellings with programmable and manual thermostats. Shipworth et al. (2010) research showed that households with thermostats set the mean temperature slightly lower than those without thermostat. Lutzenhiser (1992) proved that households with manual thermostats consume less energy in comparison to households with programmable thermostats. The other parameters are heating system type and appliances (Haas et al., 1998; Leth-Petersen and Togeby, 2001; Papakostas and Sotiropoulos, 1997).

Closely related with heating system, ventilation system is important both in terms of occupant use and indoor air quality effects (Liddament and Orme, 1998; Iwashita and Akasaka, 1997; Erhorn, 1988). Ventilation rate should be as low as possible for energy conservation. On the other hand, to sustain indoor air quality it should be at a certain level which may conflict with energy conservation target. This relation is open to the impact of occupant behavior (Dubrul, 1988; Soldaat et al., 2007). Behavior is related with ventilation system type: Natural and/or mechanical ventilation use differ depending on household size, dwelling age, single/multifamily (Stymne et al. 1994). When a household includes elderly and children, mechanical ventilation is less used. Grills are preferred more than windows for natural ventilation (Van Dongen, 1990). However, air temperature fluctuations may cause feeling of draught in rooms, largest temperature fluctuations appear in mechanical exhaust ventilation system, and the minor changes are measured with balanced ventilation systems (Melikov et al., 1997).

Besides thermal comfort, health aspects are means for ventilation behavior: Higher ventilation reduces the prevalence of air borne infectious diseases. Ventilation rates below 10 Ls-1 per person are associated with a significantly higher prevalence of one or more health or perceived air quality outcomes. Increases in ventilation rates above 10 Ls-1 per person, up to approximately 20 Ls-1 per person, are associated with a significant decrease in the prevalence of Sick Building Syndrome (SBS) symptoms or with improvements in perceived air quality (Wouters et al. 1986). Poor ventilation in longer periods would lead to fungi growth in bathrooms, but there is no clear relationship stated between ventilation and dust mite allergies (Ginkel et al. 2003). Ginkel et al. further state that number showers, together with age of the ventilation system has a direct relationship with the mold growth in bathrooms (Ginkel et al.

TOC

2005). However, Seppanen (2001) puts forward respiratory allergies and asthma as health consequences of poor ventilation system use. On average, the prevalence of SBS symptoms is higher in mechanically ventilated buildings than in naturally ventilated buildings. Better hygiene, building commissioning, operation and maintenance of air handling systems may be particularly important for reducing the negative effects of HVAC systems.

Römer indicates that together with the introduction of balanced ventilation to houses, as energy consumption decreased around 15-20%, health risk is elevated mainly due to the change in tap water temperature, relative humidity, dust and air exchange rate (Römer, 2001). Lembrechts et al. (1996) point out that seldom use of the mechanical ventilation system in full capacity result in radon increase in Dutch dwellings, in addition to the decrease in air tightness levels and building material use change. Dirty filters/heat recovery cores/HRV (Heat Recovery Ventilation) cabinets, substandard ventilation and unbalanced supply and exhaust air flows create health problems in dwellings (CMHC, 1999).

Satisfaction and comfort level with respect to heating and ventilation system performance is another important factor in ventilation and indoor air quality. If the air inlets do not fit with the aesthetical preferences of the occupants, they may remove them. Noise from ventilation system also plays a main role (Van Dongen, 2004). In a field study about HRV use, it is found out that; cooking, noise from outside, smoking, shower and cooling are the mentioned behaviors not to use HRV, so additional exhaust ventilation is required. Occupants have complaints about perceived air quality and dust around filters, nevertheless feel control over the HRV system and satisfied (Macintosh et al. 2005). Most failures leading to discomfort and dissatisfaction are observed owing to bad manufacturing of components, improper selection and installations of components, bad system flow balancing, and inadequate commissioning, too high sound emission at supply and extract terminals and sound transmission, excessive window airing by occupants and general poor acceptability (Dorer et al. 1998).

E Lighting and appliances

Lighting behavior in a dwelling depends on the type and characteristics of the dwelling, the type and duration of activities performed there, and the lighting habits of the members. Variations and behavioral factors about lighting and appliances among households can also be explained, in part, by the demographic composition of an area or country and its institutional setting (Bartlett, 1993). Several studies are conducted to measure how different household appliances are used (Papakostas et al. 1997; Al-Mumin et al. 2003; Tyler et al. 1990) and it could be stated that use of household appliances is also directly and mostly related with culture and habits. Appliance control behavior is clearly different according to occupant characteristics and thermal comfort level (Vine et al. 1989).

Appliance ownership and size are proved to be significant predictors of electricity consumption. The appliance index of Cramer et al. (1985) included number, frequency of use, location in dwelling, published efficiency, and estimated seasonality factor. Appliance index combined with the air conditioning index explained the variance in electricity consumption by 51%. Cramer's research further included electricity price, income, education, ethnic background, occupation, age, thermal comfort, conservation, environmentalism, and energy knowledge scales were able to explain 34%, and the combined model of appliance, air conditioning indexes and household characteristics was able to explain 58% of the variance in summer electricity consumption. The appliance index of Tiwari (2000), on the other hand, was based on ownership of appliances and their power data. Tiwari's work also included household and dwelling characteristics, i.e. dwelling age, type, and location, number of rooms, household size and age, income and electricity tariff.

In addition, number of household appliances (Yohannis et al., 2008; O'Doherty et al., 2008; Genjo et al., 2005; Mansouri et al., 1996; Bartiaux and Gram-Hanssen, 2003; Vringer et al., 2007; Saidur, 2007; Baker and Rylatt, 2008; ODYSSEE, 2008; Parti and Parti, 1980; Fuks and Salazar, 2008), number and type of lighting appliances (Vringer et al. 2007), labels of appliances (Mansouri et al., 1996) were found as crucial factors of electrical energy consumption in dwellings.

§ 2.2.2.3 Determinants of behavior and energy consumption: A framework

Occupant behavior is influenced by (1) occupant's educational and economical background and household characteristics, (2) dwelling's outdoor environment and climate characteristics, envelope and mass composition, mechanical systems installed, and lighting and appliances used in the house. Behavior is either a reflection of the occupant's inherited and developed personal characteristics or a reaction to the perception of the indoor comfort conditions created. Dwelling's architectural characteristics, service systems and outdoor environment affect occupant behavior in terms of their contribution to the indoor comfort conditions. Therefore, in order to understand the occupant behavior with respect to indoor comfort and energy performance of the house, these relations must be analyzed in correlation (Figure 1). However, in the literature revised, there is little research that covers these aspects in correlation but rather, approaching from one aspect.

Guerra Santin et al. conducted research on the occupant behavior and heating energy consumption using OTB dataset (2010), and revealed that the determinants of heating energy consumption are household size, age of the respondent, ownership of the house and income, the number of heated bedrooms and thermostat settings.

Perception of comfort is an important part of occupant behavior and adaptation to indoor comfort might have a considerable impact on energy consumption. Ioannour and Itard (2015) explain the three forms of adaptation: psychological adaptation, i.e. a person's thermal expectations based on his past experiences and habits (Humphreys and Hancock, 2007; Shove, 2004; Holmes and Hacker, 2007) physiological adaptation to a thermal environment over a period of time; and behavioral adaptation, i.e. modifications or actions of an individual that changes in the heat and mass fluxes governing the body's thermal balance (Brager and de Dear, 1998). Adaptations are interrelated and affect one another, besides modifications are grouped as personal (Holmes and Hacker, 2007; Fiala and Lomas, 2001; Baker and Standeven, 1996), technological or environmental adjustments (ASHRAE, 2004).

In literature, systematic studies are missing covering both occupant and dwelling related aspects; research generally focuses on energy consumption or indoor comfort/ health. It should be emphasized that long term measurement covering both winter and summer behavior in relation to energy performance and comfort, and validation is needed. Occupant and building characteristics that are covered in literature are categorized in Table 1 and Figure 2.

Moreover, it is important to realize if behavior should be modified or the technology should be adapted to achieve reduced energy consumption levels and how. Practical information is necessary for the actors in building process about the design of systems and equipment to better adapt the systems to user behavior. In addition, more information for legislation especially about air tightness and ventilation rate standards is needed. In some studies, the abovementioned characteristics were able to explain as much as 75% of the variance in electricity consumption. More research on the voltage of appliances, the use of battery charged appliances and stand-by/on-off function use seems lacking in existing body of literature.

TOC

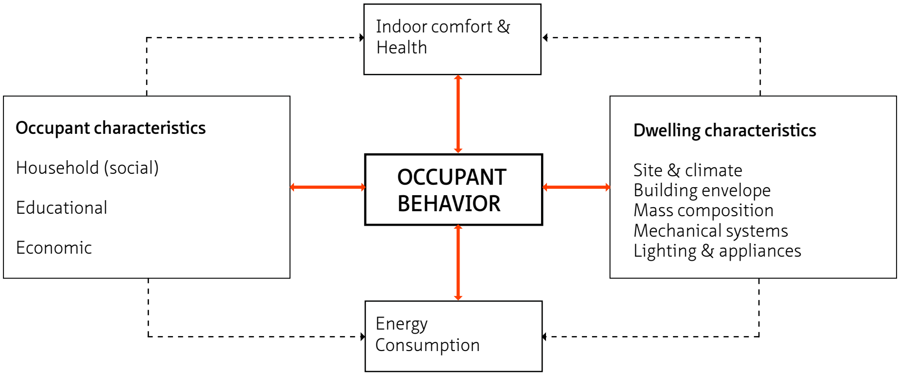

FIGURE 2.2 Framework for evaluation of occupant behavior in relation to indoor comfort and health, and energy consumption (interpreted from literature review)

Occupant characteristics			Building Characteristics				
Household	**Educational**	**Economic**	**Site & Climate**	**Building envelope**	**Mass composition**	**Mechanical systems**	**Lighting & appliances**
Age	Awareness	Ownership	Irradiance	Air tightness	Floor height	Heating	Lighting
Occupation	Knowledge	Energy use	Wind	Material use	Window design	Ventilation	Appliances
Culture	Realization	Income level	Noise	Insulation	Design elements	Hot water	
Lifestyle	Attitude		Odor				
Hobbies	Motivation						
Habits	Sensitivity						
Health							

TABLE 2.1 Characteristics affecting occupant behavior (interpreted from literature review)

§ 2.3 Energy Performance Gap

There is significant evidence to suggest that buildings do not perform as expected when they are completed as was expected when they were being designed (such as Bordass et. al., 2001; Bordass, 2004; Demanuele, et. al., 2010). The difference between expected and actual performance is known as the energy performance gap (Menezes et al. 2012). Energy performance gap means that products and systems developed for energy efficiency do not meet expected levels. In addition, differences in occupant behavior is responsible for part of energy performance gap. This is a serious threat for negotiating energy conservation with policymakers, with sectoral actors, consumers/users, ... Furthermore, in terms of the developing technologies and experiments, if this gap exists to such an extend today, it might be too difficult to catch up with later on, reducing the possibilities of implementing new technologies in future in more radical occupancy and user patterns, and climate conditions. Therefore, it's important to identify the source(s) of energy performance gap and bridge them.

Findings from studies such as PROBE (Post Occupancy Review of Buildings and their Engineering) which assessed 23 'exemplar designs' in the Building Services Journal between 1995 and 2002, revealed that actual energy consumption in buildings is often twice as much as predicted (Designing Buildings (last view: 2017)). More recent studies (Zero Carbon Hub; Carbon Trust (last view 2016); Carbon Buzz, 2011; Turner and Frankel, 2008; Menezes et al. 2012) have suggested that in-use energy consumption can 2 to 10 times higher than compliance calculations carried out during the design stage. Leeds Metropolitan's monitoring research on 700 dwellings show a significant gap between the energy use expected before construction and the actual, once the house is occupied. Thermal bridges on the building envelope, but also between adjacent dwellings have the largest share in this discrepancy (Wingfield et al., 2011).

§ 2.3.1 Uncertainties

The energy performance gap is mainly due to uncertainties (Ramallo-González, 2013). As early as 1978, Gero and Dudnik presented a methodology to solve the problem of designing subsystems (HVAC) subjected to uncertain demands. After that, several studies looked into the uncertainties that are present in building design, including measurement errors, lack of information, and a poor or only partial understanding of the driving forces and mechanisms (Lomas and Eppel, 1992; Hopfe, 2009, and Rabl and Rialhe, 1992; Turner and Frankel, 2008; Wang et. al., 2011; Lee and Chen, 2008; Saporito et. al., 2001 found in Ioannou and Itard, 2015). Uncertainties a limit on the reliability of the output of the model (Hamby et al., 1994; Helton et al., 2006; Saltelli et al., 2000). The uncertainties in building design/construction are categorized in three different groups: environmental, workmanship, and occupant behavior.

Uncertainties on climate data concern the consideration of climate change in weather data and the use of synthetic weather data files. Regarding the former, long life span of buildings makes them likely to operate with climates that might change due to global warming. De Wilde and Coley (2012) proved the importance of designing buildings

TOC

that are resilient to extreme weather conditions. Regarding the latter, the uncertainties in weather data may cause great variations (0.5% - 57%) in energy demand calculations (Wang et al., 2012; Eames et al., 2011; Soebarto and Williamson, 2001; Dell'isola and Kirk, 2003).

As early as 1994, Pettersen researched the uncertainties regarding workmanship and occupant behavior in energy performance calculations. He showed that the total energy use follows a normal distribution with a standard deviation of around 7.6% considering the uncertainties due to occupant behavior, and of around 4.0% considering those by building characteristics. Following research showed that lack of information on the building's envelope and installations might have a share in the discrepancies between theoretical and actual energy use, as low as 30% and as high as 100% in some cases (Soebarto and Williamson, 2001; Dell'isola and Kirk, 2003; Majcen et. al., 2013; Majcen et. al., 2013; Guerra Santin and Itard, 2012; Yudelson, 2010).

Hopfe and Hensen (2011) proved that the uncertainty in the value used for infiltration is the factor that is likely to have the largest influence on cooling and heating demands. Another study performed by de Wilde and Wei Tian (2009), compared the impact of most of the uncertainties affecting building energy calculations taking into account climate change. In addition to infiltration value, they introduced factors including uncertainties in weather, U-Value of windows, and other variables related with occupants' behavior (equipment and lighting). Uncertainties could be due to the underestimation of the role of, and the variance in occupant behavior, also proving that occupants have a substantial influence on energy use (Blight and Coley, 2012; Richardson et. al., 2008; Soebarto and Williamson, 2001; Yudelson, 2010; Clevenger and Haymaker, 2006).

§ 2.3.2 Sources of energy performance gap

De Wilde and Jones (2014) make a summary of the sources of energy performance gap under five titles during four phases of building: actual occupant behavior; weather conditions; workmanship/installation errors; systems' control settings and modelling issues:

1 In design stage, issues of communication among the different actors within the team can be a root cause for the later performance gap issues (Newsham, et al. 2009), where the design itself might constitute an initial issue, incorporating inefficient systems, missing construction details, or lack simplicity and buildability. At this stage, it is hard to predict the future occupancy and user patterns. Energy saving technologies

planned in the design stage might not meet the manufacturer's energy performance specifications and are subject to degradation over time, which lead to a performance gap once the building is operational (Newsham et al. 2012). Predictions made on energy performance might not account for all energy uses in buildings, unregulated sources of energy consumption such as small power loads, server rooms, external lighting, and so on. Appropriate tools and models, or adequate training of the analyst might be lacking in calculating the building energy performance. Any calculation at this stage includes a degree of uncertainty. Building energy performance modelling and uncertainty analysis are fields that still need further development (Reddy and Panjaporn, 2007; Ryan and Sanquist, 2012).

2. During a building's construction process, other factors might also contribute to the energy performance gap (Bell et al. 2010). Implementing the defined insulation and airtightness levels are challenging, construction defects might be hidden from view inspection, thermal bridges might occur.
3. Building commissioning is a difficult process, when a full performance testing might not be possible due to budget and time constraints (Bunn and Way, 2010).
4. During post occupancy phase, one issue is that actual building use and real weather conditions might not match the assumptions made during the design process. Thermostat control and the Building Energy Management System (BEMS) might not fit the design intentions, might be used quite differently by occupants. Furthermore, metering itself might come with uncertainties (NMN, 2012) especially capturing contextual factors such as weather data and occupant behavior. Measurement/monitoring can often have issues of calibration, accuracy, missing data, which causes an energy performance as well.

§ 2.3.3 Energy Performance Gap in Dwellings

Majcen et al.'s (2013) article about understanding the reasons to the discrepancies between theoretical and actual gas consumption is based on a regression analysis on the Energy Label and CBS (Central Office for Statistics), coupled by housing register (WoONruimtereregister), municipal records (Gemeentelijke Basisadministratie), employment dataset (Social Statistisch Bestand Banen), and the WoON survey. The analysis revealed that variables such as floor area, ownership type, salary and the value of the house, which predicted a high degree of change in actual gas consumption, were not significant (ownership, salary, value) or had a minor impact on theoretical consumption (floor area). Besides, the installation system predictors showed that there was more overestimation in less energy-efficient systems. These are most likely a consequence of occupant behavior influencing actual energy use. In her sensitivity analysis, average indoor temperature was found to have a large influence on the theoretical gas consumption together with the ventilation rate. The number of occupants together with internal heat load have a more limited impact on theoretical gas consumption.

Research by Ioannou and Itard (2015) on the influence of building characteristics and occupant behavior on heating energy consumption utilize a Monte Carlo sensitivity analysis based on the results of energy performance simulation. A single residential housing unit in the Netherlands was selected for this. The analyses were conducted using the technical and physical properties of the building, which are the thermal conductivity of the walls, floor and roof, window U and g values, orientation, window frame conductivity and indoor openings. The simulations were carried out with the variations of: multi-zone and single-zone versions of the building, two different grades of insulation, three different types of HVAC services, and the occupant behavioral characteristics focusing on the heating period in the Netherlands (thermostat level, ventilation behavior, metabolic rate, clothing and presence which in simulation terms is the heat emitted by people). The predictor parameters were chosen in such a way that they cover all of the parameters mentioned above. The thermally efficient and thermally inefficient reference building were first simulated with predictor variables: walls, roof and floor conductivity, window glazing U and g values, window frame thickness, building orientation, and then with the additional occupant behavior related parameters of ventilation, thermostatic level and the heat emitted due to the presence of the occupant.

The technique of sensitivity analysis was used to assess the thermal response of buildings and their energy consumption (Lomas and Eppel, 1992). The findings were articulated on the basis of the simulation results of physical characteristics alone and when combined with occupant behavior; compared the themally efficient building with the thermally inefficient one; the different heating systems; and the comfort index. This research revealed that when behavioral parameters were not taken into account, the most critical parameters were the window U-value, window g value and wall conductivity in the thermally efficient building, and in the thermally inefficient building the orientation of the building replaced the window U-value.

Ioannou and Itard (2015) found the predominance of behavioral parameters on energy performance (thermostat setting and ventilation flowrate), meaning they reduce the explanatory power of the physical parameters considerably. For both the thermally efficient and inefficient model, specifically the thermostat setting was the parameter that dominated the effect on the heating consumption, and the physical parameters had a very small impact. For most of the simulation model configurations and different heating systems, the proportion of variance in the heating that was explained by the parameters used in the study (higher than 70%, and in some cases reached 98%, except the thermally inefficient building with behavioral parameters and floor heating as the heating system).

Majcen et al.'s (2015) second (more in-depth) study on theoretical and actual heating energy consumption focused on a survey conducted in a subset of Amsterdam dwellings that had an official energy label, which provided a deeper understanding of the performance gap. Upon evaluating descriptive results of several statistical tests, several regression analyses were performed on different subsamples. They proved once more that occupant behavior has a large effect on heating consumption, in particular where it accounts for almost half of the variance. Also in theoretical consumption and in the difference between the theoretical and actual consumption (DBTA) occupant behavior accounted for over 7.5 and 9.1% of variance, which is still remarkable. The research found significant differences in the separate analysis of under and over predictions of heating energy consumption. Water saving shower head and programmable thermostat are the two factors that seem to effect DBTA in under-predictions but these two were not significant with regard to theoretical gas use. Some presence variables (morning and midday) were significant predictors, but were also difficult to interpret, since the results were conflicting (positive predictive power for morning and negative for midday presence).

Majcen et al. (2015) found that occupant behavior explained the most variance in actual gas use, and comfort relevant for only the DBTA. They proved that actual gas use could be predicted with a higher correlation of household and behavioral variables with, which was detected in household composition, the ability to pay energy bills, presence at home, set point temperature and efficiency of behavior. Presence and indoor temperature were found to be two very important parameters in determining real gas use of a dwelling. Midday presence related to a decreased DBTA, which could mean that households who spend more time at home somehow matched conditions assumed by the theoretical calculations better. On the other hand, occupants who spent more time at home during the night tended to have an increased DBTA. It also seemed that people who were not often sleeping elsewhere tended to have a larger DBTA. Conversely, the ones that often slept elsewhere had a smaller DBTA.

Current concerns and future work regarding energy performance gap

Most work on the performance gap is based on deterministic predictions and measurements. Work at Plymouth University has piloted a probabilistic approach, contrary to several other works which follow more deterministic methods (Field, 2005;

TOC

de Wilde, et al. 2013). De Wilde makes a summary of the current concerns and future work regarding energy performance gap, as follows:

1. There are different types of energy performance gap that vary over time and with context. The models used for energy performance simulation of buildings are sensitive to input parameters. The accurate representation of the building in these models depend on the correct modelling of the sensitive parameters (Lam et. al., 2008; Lam and Hui, 1996; Rabl and Rialhe, 1992, Ioannou and Itard, 2015).
2. Need for further monitoring: In spite of the advancement in measurements and monitoring in building energy consumption field, the resolution of data necessary to clearly understand the main causes of energy performance gap is still rather low.
3. Actors and responsibilities of a building's energy performance: The responsibility for the energy performance gap has not been shared by different actors in the design, construction and post occupancy stages of building, hence the actors and their responsibilities are unclear to bridge the performance gap.
4. Most research into the energy performance gap focusses on non-domestic buildings; hence the uncertainties for dwelling sector remain unclear. Determining the exact U-values of walls is very important. Considering that dwellings' vintage might influence the amount of information that can be gathered on building characteristics, a faster and more reliable method is needed for the determination of the U-values of the building envelope (Ioannou and Itard, 2015; Majcen et. al., 2013).

§ 2.4 Modelling User Behavior: A Review of Methodologies

Research on the influence of occupant behavior on the energy performance of dwellings tends to follow one of two methodological approaches: deductive or inductive. The deductive approach deals with the relationship at a macro level, considering household characteristics, income, rent, and energy consumption data garnered through a survey and establishing correlative and regressive statistical models to explain the relationships among these factors. In contrast, the inductive approach is based on actual occupancy patterns, including the operation of heating and ventilation systems, lighting, and appliances, and utilizes a bottom-up model that includes simulations of probabilities and considers presence as a precondition of behavior. The data-collection methods used in the inductive approach are mostly daily records and monitoring, while the data-processing techniques are generally more related to components, such as Monte Carlo (MC), Markov chain, S-curve, and probabilistic methods. These models suggest a greater influence of occupant behavior on the energy performance of dwellings (Figure 3) (for further reading, see Bedir, et al., 2011).

TOC

Chapter 3 of this thesis follows the inductive methodological approach, focusing on the heating energy demand of dwellings that originates from occupant behavior, namely the heating energy required to sustain indoor comfort levels and the internal heat gain that results from presence and intermediate activities. The core principle of the inductive approach is the presence of the occupant as the determining element of energy consumption, causing internal heat gain and the probability to act. As Mahdavi (2011) explained, internal heat gain is the passive effect of occupancy, so the model first deals with presence, which generates an indoor resultant temperature. Next, the model addresses the required heating energy demand and the internal heat gain from the occupant's behavioral patterns; this is the active effect of the occupant's presence and is more representative of the occupant's influence on the energy performance of the dwelling. This research evaluates the influence and weight of these patterns on heating energy demand and creates a model of the relationship between occupant behavior and heating energy demand based on this evaluation.

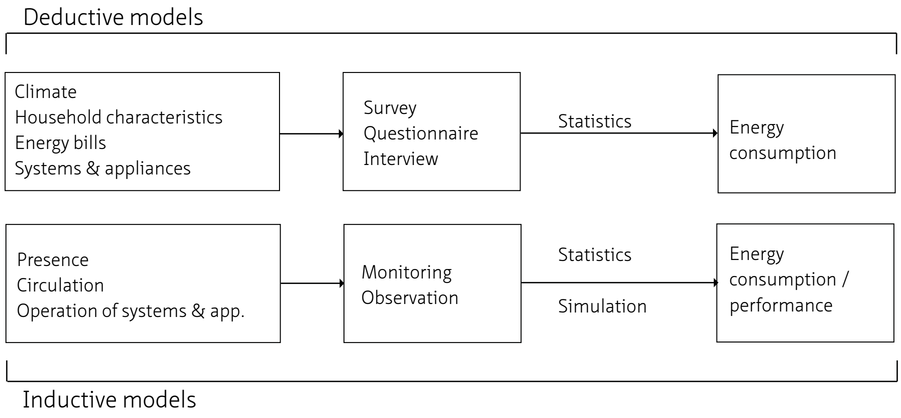

FIGURE 2.3 The inductive and deductive models of occupant behavior-energy consumption relationship

Chapter 3 presents a Sensitivity Analysis (SA) of the influence of occupant behavior on the energy performance of dwellings. The aims of the study were to determine occupant behavior patterns quantitatively and reveal the robustness level of energy consumption in dwellings with respect to occupant behavior. Unlike in the existing research, in this study, presence is not assumed to be a precondition for behavior; instead, the occupant is assumed to have both an active and a passive influence on energy consumption. The passive influence results from the default settings of control mechanisms, which affect energy consumption even when the occupant is not present; active influence results from the occupant being present in a space, changing the systems and devices according to his or her needs, and the internal heat gain resulting from his or her presence.

The literature review presented a number of methods for modeling and analyzing the influence of occupant behavior on the energy performance of dwellings. Since the objective of this research considers the robustness of behavior, the research methodology is based on an SA (see Hamby, 1994; Helton, et al., 2006; Saltelli, et al., 2000). Sensitivity analysis is the study of how the variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variation. A mathematical model is defined by a series of equations, input factors, parameters, and variables aimed to characterize the process being investigated. Input is subject to many sources of uncertainty including errors of measurement, absence of information and poor or partial understanding of the driving forces and mechanisms. This imposes a limit on our confidence in the response or output of the model. SA is used to increase the confidence in the model and its predictions, by providing an understanding of how the model response variables respond to changes in the inputs. There are several ways of carrying out SAs, the most common of which is based on sampling. "A sampling-based SA is one in which the model is executed repeatedly for combinations of values sampled from the distribution (assumed known) of the input factors" (Saltelli, 2000). A number of sampling-based strategies are available, including random, importance, and Latin hypercube sampling. Chapter 3 of this thesis uses the latter.

There are many examples of the use of SA in building thermal modeling (Bedir, et al., 2011; Corson, 1992; Fürbringer and Roulet, 1999; Harputlugil, et al., 2011; Lam and Hui, 1996; Macdonald, 2004; Spitler, et al., 1989; Westphal and Lamberts, 2005). For energy-sensitivity simulation models, a set of input parameters and their values are defined and applied to a building model, and the simulated energy consumption of the model is used as a base for comparison to determine the extent to which output (here measured in terms of heating energy demand per year) changes as a result of particular increments of input values (Corson, 1992; Harputlugil, et al., 2011). The results show which parameters can be classified as "sensitive" or "robust." Sensitive parameters are those that cause effective changes in the outputs when changes are made to their values; in contrast, a change to robust parameters causes a negligible change in the outputs (Harputlugil, et al., 2011).

Hamby (1994); Hansen (2007); and Saltelli, et al. (2000) discussed the various classifications of SAs, including local SAs and global SAs. According to the definitions put forward by Hansen (2007), a local analysis follows a one-at-a-time approach, is less

TOC

complex, has a sensitivity ranking that is dependent on the reference building, and has parameters that are assumed to be independent. In contrast, a global analysis requires random sampling, has a large degree of complexity, has a sensitivity ranking that is less dependent on the reference building, and provides information about possible correlations (interdependencies) between parameters. Chapter 3 of this thesis uses a global SA.

§ 2.5 A Review of Behavioral Patterns

Lutzenhiser (1993), in his cultural model, proposes to look at household types for studying energy consumption. Raaij and Verhallen (1983) and Tyler and Schipper (1990) investigate energy consumption from a lifestyle point of view, and consider lifestyle as patterns of activities. Groot et al. (2008) and Paauw et al. (2009) combine this consideration with household characteristics. Another common approach to lifestyle is about values, motivations, needs and attitudes (Gladhart, 1986; Ajzen, 1991; Assael et al., 1995; Poortinga et al., 2005; Vringer and Blok, 2007). A series of energy studies adopt Bourdieu's concept of lifestyle on energy consumption (found in Holm Pedersen et al, 1997; Kuehn et al, 1998), and therefore focus on social classes. Lastly, Gram-Hanssen's (2004; 2010) and Shove's (2003) works imply that lifestyle could be used only partially to understand routines and to explain energy consumption. They propose to look at routines and habits, as well as household and building characteristics.

Routines and habits may oppose the cognitive and financial drive and dominate other rational alternatives (Heijs et al, 2006); therefore, they could indeed become alternative predictors of electricity consumption (van Raaij and Verhallen, 1983). In addition, because electricity consumption seems to depend far less on the physical characteristics of a house, than space and water heating (Wright, 2008), routines of electrical appliance use might provide us with more articulated insight into household and user behavior. This could be important for research and policies which focus on influencing individuals and households to consume less energy.

§ 2.5.1 Heating behavioral patterns

According to an empirical study by ECN and IVAM (2001), an energy intensive lifestyle in an energy efficient dwelling can lead to higher energy consumption than an energy extensive lifestyle in a less energy efficient dwelling. If we are able to understand determinants and behavioral patterns related to energy consumption clearer, we might be able to develop advise for energy consumption to be further reduced. The goal would be to ascertain how occupant behavior interacts with the influence of building regulations on energy consumption of dwellings.

Energy use for space heating depends on the heat gains and losses of a dwelling, which are determined by its technical and architectural characteristics on the one hand and by the behavior of the residents on the other (Papakostas & Sotiropoulos, 1997). Guerra Santin (2009) proved that 42% of the variation in the energy consumed in the Dutch dwellings for heating space and water could be explained by type of dwelling, type of HVAC system, and insulation level. An additional 4.2% could be explained by household characteristics and occupant behavior.

User profiles and their behavioral patterns related to energy consumption for space heating have been defined with household characteristics such as household composition, income, age, education, and household size (Groot et al., 2008; Paauw et al., 2009; Assimakopoulos, 1992; Vringer, 2007); lifestyle (Raaij & Verhallen., 1983a; Groot et al., 2008; Paauw et al., 2009; Assimakopoulos, 1992); and cognitive variables such as values, motivations, needs, and attitudes (Assael, 1995; Ajzen, 1991; Vringer, 2007; Poortinga et al, 2005). In addition, Hens discusses habitual behavior and rebound effect in relation to energy consumption, extensively (Hens, 2010). As early as 1983, Raaij and Verhallen found that 5% of the variation in energy consumption could be explained by energy-related attitudes that could be categorized under price, environment, energy concern, health concern, and personal comfort.

In a study by TNO-ECN (2006) five groups of households were studied on the basis of consumption: Single inhabitant, couple, single-parent, family, and seniors. Four profiles were built: convenience/ease (comfort is of priority, saving money, energy or the environment is not a consideration), conscious (comfort is of priority, while environment and cost consideration appears), cost (awareness of energy costs, and saving money), climate/environment (concern for the environment).

Poortinga et al. (2005) found that seniors, singles and low-income households were less willing to apply energy-saving measures at home. Vringer (2007) researched the influence of values, motivation and perception of climate change on the energy

TOC

consumption of Dutch households. He grouped the households according to household size, age, income, and education. He didn't find any significant differences in the energy consumption of groups of households with different values and motivations.

Groot et al. (2008) and Paauw et al. (2009) worked with five groups of households in the Netherlands, which were studied on the basis of household composition: singles, couples, single-parents, families and seniors (>60). Four profiles were built according to the responses to questions about potential reasons to energy consumption in relation to income, environmental concern and personal comfort: 'convenience/ ease' (comfort/ important, no interest/ saving energy, money or the environment), 'conscious' (comfort/ important, some environmental and cost awareness), 'costs' (energy costs and saving money/ important) and 'climate/environment' (environment/important).

Raaij & Verhallen (1983) defined five patterns of energy behavior in relation to heating and ventilation habits: conservers, spenders, cool, warm, and average. They found significant differences according to the age and educational level, while ascertaining no differences for income and employment. Another output was that the inhabitants' lifestyle(s) influences energy-related attitudes and behavior. Family size and composition, besides presence at home, had a direct effect on behavior and energy consumption.

Guerra Santin's (2010) work takes account only of behavior defined as the use of heating and ventilation systems and other home amenities. Previous studies have already revealed a relationship between energy consumption and occupant behavior (Branco et al., 2004; Linden et al., 2006; Haas et al., 1998, Groot et al., 2008; Leth Petersen & Togeby, 2001; Andersen et al., 2009; Papakostas and Satiropoulos, 2007).

Relationships between energy consumption and household (Andersen et al., 2009; Sardianou, 2008; Schweiker and Shukuya, 2009; Lenzen et al., 2006; Liao and Chang, 2002; Biesiot and Noorman, 1999) and building characteristics (Andersen et al., 2009; Sardianou, 2008; Hirst & Goeltz, 1985; Caldera et al., 2008; Tiberiu et al., 2008; Olofsson et al., 2009; Sonderegger, 1977-78) have also been found in other research.

§ 2.5.2 Electrical appliance use patterns

Energy savings in households can be achieved by changing residents' behavior and/ or attitudes. Behavioral changes are planned to be achieved through campaigns,

TOC

awareness, and information (Verbeek and Slob, 2006; Wilhite, 2008; Dahlbom, 2009; Barbu et. al., 2013). Ouyang and Hokao (2009) showed that an average of 14% energy savings could be achieved by merely improving occupants' behavior. Wood and Newborough (2003) reported energy savings of more than 10% (20% in some of the groups) in households included in their study. Similarly, Darby (2014) reported reduced consumption by up to 20% in cases where improved feedback was used. More research on user patterns and profiles at home could help a great deal, to prove both the assumed behavior change and guide to improve the information feedback strategies.

Abreu et al. (2012) adopted a pattern recognition method to identify user profiles of electricity consumption. The study explained that approximately 80% of household electricity use results from the persistent daily routines and patterns of consumption or baselines, typical of specific weather and daily conditions. The applicable "profiles" for this population were unoccupied baseline, hot working days, temperate working days, cold working days, and cold weekend days. Widen et al. (2009) produced load profiles over 5 existing time use data sets, collected in Sweden in 1996, 2006 and 2007. The results showed that household behavior patterns regarding cooking, washing, lighting, TV, PC and audio use were able to be modeled using time use data of electricity consumption. Electricity consumption was closely related to occupancy, and grouping of appliances according to specific activities could be a good way to cluster/model consumption.

Coleman et al. (2012) monitored 14 households in the UK and included between March 2008 and August 2009. They found that usage patterns varied widely between households, in both size and make-up, the average (mean) household electricity consumption from ICE (information, communication and entertainment) appliances equated to around 23% of average whole house electricity consumption (median 18%). Of this, standby power modes accounted for 11.5 kWh, which was around 30% of ICE appliances consumption and around 7% of average whole house electricity consumption. O'Doherty et al. (2008) analyzed the determinants of domestic electrical appliance ownership in the Irish housing stock. Their survey conducted in 2001 and 2002 on 40 000 houses revealed that newer and more expensive houses had more appliances, but also more energy saving appliances (ESA). Lutzenheiser's theoretical study (1993) proposed a new cultural model, which built itself on "recognizable lifestyles or cultural forms". For instance, in the US, these were classified under typology such as: retired working class couples, middle aged couples, low income rural families, suburban executive families, and young urban families.

TOC

§ 2.6 Conclusion

Aspects of urban sprawl, over-consumption of energy and release of CO2 emissions, use of natural resources, excessive use of fossil fuels, and waste production make evident the growing share of the building sector in energy consumption and environmental depletion. Especially for the last 4 decades, improving energy efficiency in all sectors has been a major concern in the European context.

Improving energy efficiency of buildings requires a holistic approach, the close collaboration of several professions, and the consideration of the occupancy period. What we know for sure is that there are large variances between the calculated energy performance and the actual energy consumption of dwellings in energy efficient housing. This energy performance gap could be caused by several reasons, such as unexpected occupant behavior, lack of comprehensive data of the whole building process, calculation drawbacks, the construction defects/mistakes in building construction.

This research is focused on the relationship between occupant behavior and energy consumption in dwellings. It is interested in contributing to the problem areas regarding occupant behavior, which are about (1) collecting more detailed data on the determinants and actual occupant behavior, (2) bringing together cross-sectional and longitudinal methods of analyzing occupant behavior, (3) identifying the determinants, patterns, and profiles of behavior, so that occupant behavior could be represented more articulately in the building design, energy performance simulation, sensivity analysis, and energy consumption calculation processes. This way energy efficiency calculations, and policies, consequently the energy efficiency of dwellings could be improved.

This research contributes to literature in the following areas: (1) applying sensitivity analysis in a large sample size of households/dwellings, (2) combining inductive and deductive methodologies, where cross-sectional data on the determinants and the actual behavior, as well as energy consumption figures in larger household/dwelling samples is brought together with longitudinal data on occupant behavior, (3) revealing behavioral patterns and profiles of electricity consumption, (4) revealing behavioral patterns and profiles of heating energy consumption. This research will help to understand the occupant related factors of energy consumption in dwellings, which will contribute to the better design of products, systems, dwellings, and achieving more advanced regulations.

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