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Indoor environmental quality related risk factors with energy-efficient retrofitting of housing: A literature review

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ABSTRACT

There are indications that energy-retrofitted buildings can create risks for indoor environmental quality (IEQ) and therefore for health and comfort of occupants. A review was conducted to identify and verify those risks, within three themes: building envelope, heating, ventilating and air conditioning (HVAC)-systems, and occupants. Publications from the last five years in major peer-reviewed journals from different fields (energy, buildings, indoor air, social sciences) were found by using a variety of keywords (health effects, occupant behaviours, energy-efficient retrofitting, etc.). For the building envelope, retrofitted buildings tend to be air-tighter and more thermally insulated. Hence, humidity problems, build-up of pollutants, and overheating may occur. Installing HVAC-systems and issues within (ducts, filters, maintenance, noise) may also compromise IEQ. Although relationships are difficult to establish, evidence shows that certain retrofits increase the risk of health problems, particularly for airways, skin, and eyes. Despite the installation of energy-retrofitting technologies, not all buildings lower their energy consumption. This is partly due to occupants (behaviours, preferences, needs, awareness) and partly due to technical issues. The studies reviewed, mainly focused on the performance gaps of energy-retrofitted homes and on energy-saving measures. “Comfort” and “health” tend to be disregarded, with both being seldom measured and only assessed by simulation. Occupant behaviours, preferences, and needs are understudied and need to be incorporated into the research and development of retrofitting measures. More interdisciplinary approaches are needed, in which buildings & HVAC-systems, occupants, health and comfort, and IEQ are investigated as interacting elements and based on an integrated approach.

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1. Introduction

Generally, people spend more than 60% of their time at home [1] and the rest of their time at work, at school and/or commuting, resulting roughly in 90% of their time or more indoors. In most buildings, the indoor environment to which people are exposed can cause negative health effects. Energy efficiency improvements as well as consequences of climate change can increase these effects [2].

To achieve low carbon emission buildings by 2050, at European and national levels, stringent targets for the necessary energy transition have been set [3]. In the Netherlands, the energy transition has mainly focused on the renovation and refurbishment of the current housing stock, particularly that of social housing. Residential buildings, with about 30% of the total Dutch final energy consumption, play the main role in the realization of these targets. As of 2020, all new housing should be energy neutral, while the current housing stock should be so by 2050. As a result, the Dutch government has agreed to make more than 300,000 existing homes more energy-efficient every year. The majority of the residential buildings that should be energy-neutral by 2050 already have been built. This is because the demolition and the yearly new construction rate is less than 1% [4]. The energy transition in the residential sector is therefore mainly to be realized by renovating existing houses, by using a combination of building-related energy efficiency measures (e.g. insulation, mechanical ventilation), renewable energy systems (e.g. heat pumps, district heating, solar panels), and their related distribution systems (e.g. low temperature heating, smart grids) [5].

The first steps for reducing energy consumption started in response to the energy crisis of the 1970s. Then, improved thermal insulation and increased air tightness of the building envelope led to dampness and mould problems, and ‘bad’ indoor air quality (IAQ) [6]. A pan-European study led by the World Health Organization (WHO) showed that occupants of approximately 25% of the European social housing dwellings were exposed to increased (i.e.

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30-50%) health risks associated with exposure to indoor moulds [1]. Several researchers provided evidence about the association between indoor mould and adverse health effects for occupants, specifically children [6]. Additionally, many studies on social housing all over the world have shown that living in social housing is often associated with negative health effects, with high prevalence of respiratory problems and links with living conditions (e.g. poor thermal comfort, pollution due to cigarette smoking, presence of pests) [7].

It is well-known that a 'bad' indoor environmental quality (IEQ) (including IAQ, thermal, acoustical, and lighting quality) can affect the health and comfort of occupants. IEQ is determined by the outdoor environment (for example location, soil and traffic), the occupants and their activities (e.g. cleaning, cooking, maintenance, laundry, showering), other non-human occupants (pets, pests), and the dwelling and its systems (construction and furnishing materials, furniture, ventilation, heating, lighting, etc.) [8, 9].

Although the main purpose of retrofitting houses is to become more energy-efficient and consume less energy, in practice, for the occupants (whether homeowners or renters) improving the indoor environment is a more interesting incentive. In a Swedish study on perceptions of benefits and barriers of energy renovation among homeowners, it was found that energy cost reduction may not be the determining factor in deciding to undertake the renovation; rather improving the indoor environment is more likely to be the reason [10].

However, there are indications that homes that have been renovated with the aforementioned weatherization measures tend to worsen the IEQ and tend to lead to ill-health [11, 12], and tend to not lead to the expected energy consumption (energy performance gap). The expected energy performances are not achieved (on average 30% less than expected), leading to governmental targets not being reached, and hence energy bills and therefore pay-back times turn higher than expected [13, 14]. Recent studies performed by den Brom [15] showed that the effectiveness of the energy-efficient renovations depends both on occupants and on building (and systems) characteristics. While municipalities, area health services, housing associations and tenant associations are warning for possible health problems arising from low energy renovation concepts; housing associations and individual owners are wondering which measures are robust to occupant behaviour and achieve the expected energy, financial and comfort performances. The European Commission's policy report of 2016 suggested that a poor understanding of and a lack of data on IEQ in energy retrofitted homes, may jeopardize occupants' health and comfort [16].

The underlying article presents the results of a literature review on the risk factors that are known to affect health and comfort in the existing housing stock in relation to energy-efficient retrofitting and construction. Literature from major peer-reviewed journals (e.g. Indoor Air, Building and Environment, Indoor and Built Environment, Energy Build., Energy research & Social Science, Building Research & Information) in the past 5 years were searched using key words such as energy-efficient retrofitting, occupant behaviour, health effects, social housing, etc. to identify and verify possible IEQ-related risks, along three main themes: the building envelope, the heating, ventilating and air conditioning (HVAC)-systems (and interfaces), and the occupants.

2. Building envelope

Controlling airtightness in combination with thermal insulation of the building envelope and its windows, have been regarded as key measures to achieve energy reductions in buildings. This is because more than half of carbon emissions in the residential sectors are attributed to space heating. Thus, buildings that enable air leaking and/or heat loss, tend to spend more in heating [17].With weatherization and renovation programs that tend to highly focus on reducing permeability and increasing thermal insulation with the end goal of saving energy, some risk factors can appear in the health of the occupants. Applying internal thermal insulation and increasing building airtightness may result in: internal and surface condensation, moisture excess or dampness, build-up of pollutants due to reduced ventilation, radon problems, and overheating. These IEQ-issues are particularly true if the mechanical ventilation system is not properly designed, installed, maintained, or used (see Section 3).

2.1. Condensation and dampness

Internal condensation caused by thermal bridging, moisture excess [18], or 'dampness' (index resulting from: mould spots, damp stains, water damage, window condensation and mould odour) (because of reduced vapour diffusion [19]), can result in 'wet' materials and surfaces and consequently to mould growth [20].

Almost a decade ago, it was reported that in the Netherlands fungal problems occur in about 15% of the dwellings. In Belgium in social housing, it was reported to be 20%, in Germany around 30%, and in the UK from 20% to 25% [6]. In a recent study among students in the Netherlands, 24% reported visible mould growth [21]. A recent literature review on mould in indoor environments in France [22], showed that visible mould is estimated to be present in between 14% and 20% of dwellings, mainly in old dwellings that do not follow thermal and ventilation regulations and that suffer from fuel poverty and overcrowding.

Another effect of condensation in constructions is that the thermal transmittance increases with increased water content [23]. Therefore, more energy is needed to heat up that indoor environment where the construction materials are wet. For thermal performance of thermal insulation (resistance) it is therefore important to keep the construction and insulation materials dry, which can also prevent moulds from growing.

Fungi and moulds grow in the presence of three elements, water, carbon, and nitrogen. They tend to find such conditions in construction materials such as wood, textiles, natural fibres, glues, and paints. Other materials, like metals, concrete, and plastics, although not providing the right nutrients, if they are not cleaned, they can become breeding grounds for fungi as the dirt on the surface provides the nutrients. As fungi grow, they will release spores into the air, especially when the environmental conditions change and the fungi feels "under threat" [24].

Dampness at home has been associated with airway, nose and skin symptoms among children in Sweden [19], in Texas [25], and adults in China [26]. Moisture damage was associated with systemic inflammation in children in Finland [27], and window condensation in winter (as well as recent indoor painting and living in a wooden house) with increased risk of respiratory symptoms and allergies for young Japanese school children [28]. Visible mould was associated with new-onset wheezing in children in New Zealand [29].

Human health is not affected by water excess itself, yet dampness can create a scope of issues in the environment that cause health problems. Dampness can increase moulds and house dust mite levels, which in their turn can cause allergic reactions and problems in the respiratory tracts, skin, eyes, as well as increased prevalence of asthma [30]. Most of the health-related problems caused by dampness are related to the indoor air, and therefore tend to affect health through their inhalation, although they can also occur through the skin [31].

House dust mites need an environment of above 70% relative humidity for perfect breeding conditions, as their composition is of 75% water by weight, and need to maintain such ratio in order to survive. Humans can have allergic reaction to secretions and dry body parts of the mites. Field studies have suggested that humidity levels of below 50% will significantly reduce house dust mite reproduction; in addition to that, specialized vacuum cleaning is required, and hot washing of upholstery, carpeting, mattresses, pillows, etc., are all breeding grounds for the mites [32].

Moulds can produce microbial volatile organic compounds (recognized as mould odour) and mycotoxins. However, not all moulds can cause negative health effects and not all of them produce toxic chemicals that the occupants can inhale or be exposed to [6]. As an example, the Cladosporium mould does not produce any significant toxins, while the Stachybotrys, a toxic black mould, does.

Although many complaints have been made on 'mouldy' homes or indoor dampness, and these have been associated with several health effects, no strong, consistent relationships have been found with quantitative microbial measurements [33, 34]. It is suggested by Lorentzen et al. [33] that chloroanisoles (microbial volatiles) contribute to health effects by evoking odour which induces stress-related and inflammatory symptoms and is enhanced by the belief of exposure being hazardous. While Järvi et al. [35] suggested to take microbial measurements from building material samples (specifically including actinomycetes), Mendell et al. [34] suggested to measure building moisture (i.e. the moisture in walls, the "water activity"), as an indicator of moisture-related health risks.

It is currently recommended to control mould growth by increasing the operation time of air conditioning systems or dehumidifiers. However, a study on the growth of indoor mould under different water conditions, showed that extended dry periods each day does not necessarily contribute to a long delay in growth (at least of the common indoor mould, Cladosporium Cladosporioides) [36]. In fact, it has been known for some time that the material constituents and moisture retention characteristics of a product determine the risk of microbial growth [37]. This indicates that even with a low relative humidity, mould growth can still occur. Other measures than ventilation are required to control mould growth: from protecting materials from becoming wet, to simply cleaning or disinfecting a surface or product, to removing parts of 'infected' material, to completely breaking down constructions with severe mould damage.

2.2. Build-up of pollutants

Indoor air pollutants, such as VOCs and fine or ultrafine particles, caused by emissions from activities, building and furnishing materials, cleaning products or other chemicals, and people, have all been associated with airway, nose and skin symptoms as well as headaches and tiredness [8]. Even perceived dryness (perceived dry air), suggested to be caused by pollutants or dust in the air, has been associated with children's allergies [38]. In a Dutch study performed on student homes in three technical universities in the Netherlands in 2016, 396 students answered a questionnaire about their health, comfort, other personal variables, and housing conditions [21]. It was found that 33% of respondents suffered from rhinitis, which after adjustment, was concluded to be positively related to having family history of rhinitis and having less than one-year old particle board furniture in the bedroom. However, the condition was negatively related to people who worked out frequently, and to those who did not have pets. Finally, opening the windows in the bedroom at least once a week was also associated with reduced risk of suffering from rhinitis [21]. Therefore, biological and chemical pollutants were associated with having rhinitis, as well as physical health and ventilation.

The indoor chemistry of the dwelling can have a negative impact on the health of the occupants when sealing the home for energy reductions [39, 40]. Next to unwanted emissions of the insulation products applied [41], indoor pollutants can become more prevalent in an airtight home. For example, the comparison of indoor air quality of energy-efficient dwellings to conventional buildings in France, showed higher concentrations of terpenes and hexaldehyde, possibly related to wood or wood-based products and human activities [42]. In a study on the effects of energy retrofits on the IAQ of multifamily buildings in Finland and Lithuania, an increase in the chemicals benzene, toluene, ethylbenzene and xylene (BTEX) and in radon concentrations was found in the Lithuanian cases while mechanical ventilation in the Finnish buildings was associated with lower formaldehyde concentrations [43].

2.3. Radon problem

Radon has been associated with lung cancer and is considered to be the second main cause of this disease after smoking [44]. Radon is a radioactive gas that occurs in nature (e.g. released by soil, stone-like materials), but also in buildings (e.g. released by soil into the house or by construction materials).

In a study on the association of indoor radon concentrations and energy efficiency measures that increased the airtightness of more than 470,000 UK homes, it was found that homes with double glazing had higher indoor radon levels than homes without it, as did those with loft insulation and wall insulation [45]. Also, in Germany it was seen that houses with energy efficient refurbishments had nearly twice as much radon as the non-refurbished houses [46]. In France, it was concluded that radon levels are associated primarily with construction materials (especially granite and other stones) foundation type, and concentrations are higher in older houses [47], The results also showed that this increase can be avoided by installing ventilation systems with overpressure. Other measures are ground covers at the foundation level and sealed sump pumps to prevent the radon gas leaking into the living area of the house [48]. Ventilation of the crawl space, when present, is also recommended. However, in the case the source of radon is not the soil, but the construction material, the last measure will have no effect.

2.4. Overheating

Fuel poverty and poorly insulated homes have led to many complaints about thermal comfort in homes during the colder winter periods. In a recent study in student homes in the Netherlands, 41% of the 396 students reported it to be too cold in the winter, while 30% complained about having stuffy air [21]. Therefore, improving the thermal insulation of homes in the energy-efficient retrofitting is welcomed. However, improving thermal insulation to reduce energy consumption during the winter raises concerns about potential summertime overheating [49]. While overheating occurs in various dwellings, the new or refurbished dwellings that comply with energy efficiency regulations appear to be at a higher risk of overheating [50–54]. Measures such as (night) ventilation and shading have shown to reduce overheating [49], but might not be enough. Climate change might increase this risk and might increase the cooling demand in the summer period. Overheating in houses is associated with a higher risk of heart problems, dehydration, and with increased mortality, especially in the vulnerable populations (elderly, infants, and immunocompromised people) [53].

3. HVAC- systems and its interfaces

In the past years, particularly in the social housing sector, several types of heating and ventilation systems (usually in combination with thermal insulation) have been improved or newly-installed for retrofitting [5]. Some of the measures installed or improved involve balanced ventilation and demand-controlled ventilation systems, air-water heat pumps and ground source heat pumps. However, each of these components may evoke IEQ-related risks.

3.1. Bad' air quality

From the previous review on the risks of increasing the airtightness for reduction of energy loss, it is clear that ventilation is important in preventing the build-up of certain pollutants in the home. Whether an increase in ventilation will also prevent mould growth in construction materials and on surfaces, depends on the way the thermal insulation has been added, and on whether the 'infected' building parts have been well-treated or removed.

In the past decades, many studies have shown that mechanical ventilation can both improve e.g. [43, 55] and deteriorate the air quality, the latter being due to poor maintenance or wrong design [56–61]. Bad IAQ has been associated with many diseases and disorders [8]. A review of the literature showed that different systems can cause different health effects, from odour annoyance to symptoms in nose, eyes and skin to severe allergies and asthma symptoms [62]. HVAC-systems and their components can pollute the supply air and can therefore cause health problems and discomfort [9].

In the European Airless project, it was concluded that [56]:

3- Both new and used air filters can pollute the air; in particular causing bad odours.
3- Ducts with oil residuals can be a source of smell; as can ducts with dust/debris accumulated during construction at the work site and/or during operation.
3- Badly installed and/or maintained air humidifiers can pollute the air. In particular micro-organisms play an important role in this polluting effect.
3- Pollution caused by heating and cooling coils is in general negligible, except when condensed or stagnant water is present in the drain pan of the cooling coil. Heat pumps do not have an effect on air quality.
3- With the exception of rotating heat exchangers, heat recovery systems are not a source of pollution because of their closed nature. Rotating heat exchangers can transport pollutants from the supply to the return side when in use.

Poor system maintenance can generate biological proliferation, which may be the reason of increased negative effects in the respiratory tract amongst occupiers [59]. Other maintenance issues that can lead to risks of mucous membrane symptoms, can be the failure to clean cooling coils or dripping pans [61]. General poor ventilation system maintenance, dirty filters, and blocked ducts or vents has also been related to higher prevalence of acute health symptoms [57].

Recommendations for design and maintenance of HVAC-systems and its components, to prevent a 'bad' quality of the air supply can be found in [9].

3.2. Noise from systems

Noise from heating and ventilation systems is an important risk factor. Some of the more common noise sources in homes are from ventilators of the mechanical ventilation, from airflow in ducts, and from pumps. There has been evidence that people shut down the systems that are producing these noises, due to the annoyance that they cause.

High levels of noise can cause hearing loss, but at relatively low environmental sound levels, negative effects of noise can also occur, especially when certain activities such as concentration, relaxation or sleep are disturbed [63]. Annoyance is an important aspect in the anti-stress mechanism. With prolonged stress (chronic stress), anti-stress hormones such as cortisol are increased and a chronic imbalance in the hormones released during stress can occur. This imbalance can contribute to changes in carbohydrate and fat metabolism, it can lead to anxiety, depression, heart disease, fatigue, allergies and asthma [64].

It is therefore important to make appropriate design decisions for both the systems and the environment in which these systems are installed, to prevent these types of noise being created. For mechanical ventilation systems, the design and maintenance rules are pretty well-established [9], but both the installer and the occupant are often not aware. However, these well-established rules (in the Netherlands 30 dB (A)) are just at the limit of acceptability and do not account for individual sensitivity [65].

For low-temperature air-air or air-water heating pumps, which are generally systems running also during the night (to make use of low electricity tariffs and/or because heat pumps are most efficient when running continuously), night time fan activity has been reported as a burden [66]. Many heat pumps are equipped with a silent mode, but this mode works at the expense of its efficiency [67], and there is ongoing research on reducing the noise levels (e.g. [68]).

3.3. Thermal discomfort

Thermal discomfort can occur from feeling too cold or too warm or from experiencing draught.

Too warm/too cold

Thermal discomfort in older residential buildings has been for a long time an area of concern and it is generally assumed that energy efficient renovations also help in the improvement of thermal comfort. This was shown for instance in Schnieders and Hermelink [69]. However, from a literature study in energy efficiency and thermal comfort in historical buildings [70], it was shown that occupants report greater satisfaction in warm weather with thermal sensations in traditional buildings with natural ventilation than in modernized buildings with air conditioning. Noticeably there is very little literature on perceived thermal sensation in the cold season in cold/moderate climates in energy efficient buildings, and even less for renovated buildings. Most papers relate to warm climates, summer situation and newly built dwellings. Additionally, in many papers claiming a thermal comfort analysis, this thermal comfort is just a theoretical one, resulting from simulation software using either PMV (predicted mean vote) or adaptive comfort theory, and not the result of a survey or measurements.

In Piasecki, Fedorczak-Cisak, Furtak and Biskupski [71] the thermal comfort in one NZEB (nearly zero energy building) office building was analysed through a survey and measurements, leading to the observation that the perceived thermal comfort was better than the theoretical one. Similar results were also mentioned for residential buildings in Ioannou and Itard [13] and Ioannou, Itard and Agarwal [72], stressing a possible knowledge gap between current theories and actual perceived thermal comfort in residential buildings.

In Berge, Thomsen and Mathisen [74] an analysis of the thermal comfort in 62 passive houses in Norway is presented. Because of a very limited heating system in the past, relying only on fresh air heating leading to complaints such as bathrooms being too cold and bedrooms too warm, the systems have been adapted and most Norwegian passive houses are equipped with floor heating in the bathroom, radiator heating in the living room, and a mechanical ventilation with heat recovery and electrical heat coil for peak heating. Considering the thermal comfort in summer, approximately 50% of occupants considered the living room to have an acceptable temperature while it was too warm for the other 50%. This was worse in the bedroom. Almost all occupants were satisfied with the balance ventilation system in the living room, but much less in the bedroom. As for the heating, most occupants were satisfied with the living room, but not with the bedroom, in which no additional heating possibility was present and the temperature of which seems difficult to control.

When it comes to low temperature water systems for space heating, which are generally used in combinations with air-water or ground source-water heat pumps or with low temperature geothermic applications (see for instance [73]), here too, no scientific literature on perceived comfort is present.

Draught from air inlets

Whole house ventilation tends to produce more complaints, as opposed to personalized ventilation systems with outdoor air into the breathing zone, as shown in Kaczmarczyk, Melikov, Bolashikov, Nikolaev and Fanger [75]. This is often related to the turbulences produced by mechanical ventilation systems. Although it is well known from ventilation standards that air velocity and direction (and therefore the quality and/or setting of the valves) are of main importance for preventing draughts, almost no post-occupancy evaluations are reported in scientific literature. In most studies the PMV is calculated, but the perception of the occupant is not studied. Nguyen, McGuinness and Dai [76] is an example of a very recent detailed study, but without any occupant perception. Finally, in another study cold draughts and occupants blocking the main air inlets to avoid draught are reported as problems in both China and Denmark [77].

3.4. No or lack of control

The quest for energy efficiency and carbon reduction for retrofits and the transition sometimes makes use of more automation systems in the buildings. It is argued that automation systems, operating with building sensors, will control and optimize the use of comfort-providing installations. Sensors monitoring the indoor and outdoor air temperature are being used in most homes to control the heating system and respond to the requested thermostat settings of the occupant. But more recently, CO_2 or (other chemical)-controlled ventilation systems are introduced to control ventilation, as well as infra-red sensors to detect occupants' presence and/or daylight sensors to control blinds. However, as is shown in the next section, these tend to be by-passed by the behaviour of the occupant as such systems do not always satisfy what the occupant demands [78] or they simply do not work properly. Therefore, occupants tend to have the feeling that automated systems work erratically, with lights shutting off when the occupant is there, automated blinds drawing when it is dark, etc., which leads to feelings of lack of control and being controlled by the building [79].

Having the ability to control or the perception of being able to control the environment and surroundings, has been shown to reduce effects of stress, and increase overall health. This is a process that tends to be studied in psychoneuroimmunology (PNI) studies, however, as of the writing of this article, no PNI studies exist in dwellings [80–82].

A number of studies have shown that personalized feedback can be successful to satisfy personal comfort levels while reducing energy consumption. One study designed a personalized HVAC-control system, integrating environmental data from sensors, and physiological and behavioural data from humans, gathered through wearable devices and smartphones. Although this study was limited to thermal comfort, it found that thermal preferences of occupants, were successfully predicted and maintained [83].

Another study focused on the type of feedback to be given to the occupant, in order to improve the quality of the comfort provision. Through 40 weeks, users across three buildings rated different types of feedback, and the outcomes showed that user satisfaction with thermal conditions can be increased up to 60%, while reducing 20% of energy use, when using a voting feedback system, as compared to a non-voting system. Furthermore, it was found that a 'drifting control strategy' of feedback can increase energy savings up to almost 40%, while maintaining a stable thermal satisfaction [84]. One study also found that as data shown to occupants becomes more precise, energy use can be reduced by an average of 10% to 15%, only by showing more detailed and frequent data in the feedback [85].

Unfortunately, most studies so far have focused on the reduction of energy consumption in relation to thermal comfort. There is clearly a need for studies on the type of sensors used to control those systems and the effect on IEQ. There is a need to design systems along with the behavioural patterns, motivations, and (health and comfort) needs of the building occupant. Especially, the actions and control measures that affect health have not been understood well. However, it is proposed that, different types of occupant, with different mental models will need specific types of feedback, depending of what is meaningful for them to see in terms of energy use and comfort. Yet, it can be concluded that the feedback needs to show environmental data, comfort, and health data, while being easy to access, personalized in terms of details shown, and frequency.

4. Occupants

Another important risk factor in houses is the occupant. Their activities, preferences and needs, and the interactions they have with the building and its systems to adapt/change the indoor conditions to their needs, are possible risk factors for IEQ, and possible associated with health effects.

4.1. Activities

The activities an occupant performs, also named occupant behaviour, have been shown to contribute to the energy performance gap [15].

A large part of the issues between predicted and actual energy consumption of energy retrofitted buildings is due to the human building interaction component, especially, how the occupants (mis)use the control systems of the comfort-providing appliances, by certain activities, such as radiator control (thermostat operation), window opening, light switching, shade control. Several studies have compared these activities with measurable and monitored factors (illuminance level, CO_2 concentrations, temperatures), some contextual variables (time of the day, week, season) and personal (gender, age, position of person) [86–93] or less common variables such as use of other electric appliances, electric equipment, and domestic water use [94].

Most studies typically conclude that occupants are at fault of performance gaps, and that occupant behaviour has to be accounted for to reduce gaps and save more energy. However, most renovation initiatives, at least in Europe, tend to fail to consider occupant behaviour equally to the energy efficiency process and therefore fail to consider occupant behaviour as a risk to IEQ and consequently to their health [95]. Building technology and the occupant interact with each other and therefore affect not only energy consumption but also health [96]. It is important to consider the interrelationship and interactions of building design, indoor environmental quality, and the occupant [97].

Willand et al. [98] investigated the link between practices and health in homes with low carbon retrofits. Qualitative data was gathered to understand occupants' behaviours practices, and their experiences about their home and health. The study assessed variables from behaviours, health, energy use, and temperature readings over the winter. It is suggested that small retrofits may provide improved comfort. Specifically, it was proposed that health behaviours mainly revolved around accessibility, safety, and mould control. The health benefits in retrofits were, however, minimal and not statistically significant [98]. Subjective opinions of the participants regarding benefits of the retrofits were focused on their physiological, social, and mental health, but occupants did not report changes in cardiovascular, respiratory, or pain symptoms, after retrofits.

Wierzbicka et al. [99] proposed that occupant activities create changes that can affect both positively and negatively the environment, and ultimately health. Therefore, it was concluded that architectural interventions might change behaviours into healthier ones [100]. A final study addressing health, behaviours, and retrofits was performed by Bunker et al. [101], in which they claimed that to produce positive health effect in dwellings, one must first focus on the interactions with the building, then the technical and physical points of interaction need to be fixed, so as to improve the context of behaviours, and finally, focus on behavioural change for healthy behaviours can be done.

4.2. Preferences and needs

Various environmental factors trigger physical and psychological changes in the human body. The environment is a collection of positive and negative stimuli, and people respond to them by behaving in certain ways, in order to adapt to the environment, and eventually reduce stress (consciously and unconsciously). The individual does not react to the environment as such, rather, they react to their perception and the meaning they give to it and to the stimuli. Usually, such behavioural responses are driven by the person's needs, preferences, or desires. Humans are sentient and cognizant beings, with needs, attitudes and emotions, combined with tools offered by their environment, they are active makers and changers of comfort (and health), depending on their needs [81].

Technological changes in the home and energy efficient improvements, have the potential of changing the residents' preferences. These changes can result in consuming both more and less energy [102]. This has been identified as the cause of the "rebound effect". Preferences can change when new technologies alter the cost-benefit ratio of a particular behaviour. If an efficient technology is installed, the behaviour of using it may be expected to cost less money, less energy, and hence may trigger less feelings of guilt, and eventually be more accepted by the person, and thus encourage more frequent usage [103]. Similarly, social norms may be changed with new energy efficient technologies, as the user may feel or expect higher social acceptance if they increase the use of such type of technologies [104].

Behaviours are the result of a response to environmental stimuli, guided by an emotional response (distress) [105]. There is no such thing as the average occupant behaviour, rather household energy consumption practices that may greatly vary due to a number of factors, including, social-economic, cultural, household composition and occupant practices resulting from the affordances, the interfaces and performance levels of home indoor environment and energy systems.

To understand occupants' behaviour better, researchers have also tried to create patterns of different kinds of activities, and create profiles that relate to quantitative household or dwelling characteristics (cleaning, room use, space heating times, income, education level, type of house, etc.), for including different occupant variables to simulation, in order to give more margins of results and smaller performance gaps [106, 107]. More recently, global and qualitative variables have been studied, such as ease of control, layout, freedom of movement of the occupant, occupant knowledge about energy or technology, or different usability factors [108–111], as well as understanding of energy, energy use, and meaning of comfort.

A popular profiling method among researchers is time use data (TUD). TUD has been used for profiling schedules in several countries (UK, USA, France, Spain, Denmark, etc.). Based on this type of data, researchers typically develop occupant profiles, by using varying time spans of data collection, and the results profiles tend to be used for both simulations and predictions [112–116]. Time use has also been used to create clusters of energy consuming activities (cooking, laundry and television), rather than creating schedule patterns. Such studies propose that interventions based on those usage patterns may be more efficient to save energy [117, 118].

Questionnaires also have used to find profiles or patterns and to eventually create simulation models or to propose retrofitting strategies depending on the occupancy profile [119–122]. Typical questions asked concern the occupants heating hours, set points, while sometimes they also have to self-report building characteristics, or appliance usage, sociodemographic variables, and psychological constructs (i.e. norms, attitudes, control, emotions).

Pereira et al (2018) and Pereira & Ramos (2019) in Portugal, used environmental data from sensors and journal data to understand motivations behind certain actions such as closing shutters or opening windows [123, 124]. A more recent approach for occupant data collection that has been proposed is the mobile-internet based data gathering which involves tracking individuals via their mobile devices. Pang et al. [125] claim that such approach is more accurate and can help improve predictions of energy consumption and thus reduce performance gaps.

In his doctoral thesis, Ortiz (2019) applied a mixed methods approach to develop archetypes that contained variables pertaining to comfort-related energy-consuming behaviours [126]. The variables used pertained to psychological constructs (attitudes, emotions, habits, needs, locus of control, unconscious meanings of comfort and of energy use) and several building-related variables (actual energy, building characteristics, IEQ monitoring). Based on a mixed methods analysis, five archetypes or profiles were found: Restrained conventionals, Incautious realists, Positive savers, Sensitive Wasters, and Vulnerable pessimists [126].

The archetypes and the results suggest that although occupants can be unique, it is possible to group them into behavioural types, in terms of comfort and energy. Each of the archetypes reflects different characteristics, and buildings should be designed accordingly, so as to reduce energy consumption while maintaining comfort.

All of these studies were, however, focused on the understanding of energy-use related behaviour of occupants, in order to explain the performance gap. None was focused on the explanation of preferences and needs in relation to IEQ, health or comfort. Recent studies on school children of primary schools showed that it is also possible to cluster children into different groups of children with different needs and preferences towards IEQ [127].

4.3. Awareness

A lack of awareness of behavioural repercussions is also an important factor to consider. According to several behavioural theories (theory of planned behaviour, theory of interpersonal behaviour, social cognitive theory), it is proposed that human behaviours are interplays of environmental, personal, and social factors. For example, how an occupant understands energy, control, or comfort will influence their actions and the environment. Therefore, it is important to understand human perception from a behavioural point of view, by understanding their knowledge of the context surrounding them [128].

Awareness of the reduction of the costs may trigger changes in perceived and actual control. If the user perceives a lower cost of usage in newly installed energy efficient technologies, the *per-*

ceived control may increase, which can trigger increased frequency of the behaviour. Energy efficient technologies may increase the occupant's *awareness* that environmental impacts can be reduced. Such awareness can increase the internal control and self-efficacy beliefs, which can also cause and increase in usage of the new product [129].

From such studies, it can be seen that energy and behaviours tend to be closely connected. Therefore, research, especially in the social sciences, has targeted to find ways to change occupant behaviours towards more energy-efficient ones, and seldom towards better IEQ or health. Creating campaigns for occupants to gain more awareness, so as to try to persuade them to change their attitudes, habits and behaviours into more energy-efficient ones. However, it has been shown that such approaches fall short, as the average person will not change their behaviours because of information given to them, while attitudes need more than one technique to be changed [130].

Energy-efficiency measures tend to focus on increasing energy performance of the technologies through their efficiency. However, according to Scott et al. [131], the focus should rather be on the interaction between human and technologies, through the behaviours. It should be acknowledged that behaviours are not always in line with design or engineering intentions and that they lead to unexpected interactions like rejection of the technologies (shutting off), misusing (using more frequently or differently than expected), or hacking (changing settings) [131]. All of these new behaviours can lead to unintended worsening of the IEQ, and ultimately ill-health.

Finally, studies propose that there is a tendency of occupants not to understand how ventilation systems work, and therefore they don't know when to adjust ventilation rates. Occupants have often difficulties to correctly operate HVAC-systems or even shut them down because of experienced nuisance [132, 133]. Perception of stuffy air tends to be coped with by opening windows, rather than increasing mechanical ventilation.

5. Synthesis and recommendations

From the literature review can be concluded that most studies on energy-efficient retrofitted houses, so far, focused on their energy efficiency and gap between predicted and actual energy consumptions. Energy-efficient retrofitting is focused on energy reducing measures and to some extent thermal comfort. Although few studies have been carried out on energy-efficient retrofitted houses focused on IEQ and possible health effects, there are indications that the retrofit can lead to complaints about mould growth, built-up of pollutants (including radon), lack of control, thermal comfort stress (people feel too cold, or too warm, draught), noise annoyance from heating and ventilation installations, and a whole range of health problems. Underperformance of mechanical ventilation and heat recovery systems and air source heat pumps has been found to result from inadequate commissioning and maintenance procedures and poor occupant control due to complex control interfaces.

Homes are environments that should offer health and comfort to the occupant, through the services and systems of the buildings. In energy-efficient retrofitted homes, the provision of health and comfort needs to be done while maintaining a "low" energy consumption, through the performance of the building and its systems. However, these retrofits are rarely performed by accounting for the preferences and needs of the occupants and the influence of the occupant behaviours [134].

Research into occupant behaviour tends to fail to propose a connection between behaviours and health effects. With energy retrofit studies, the focus tends to be on comparisons of thermal comfort or energy consumption changes, yet, study about the impact of retrofits on health are rare. Only few studies have been performed on the effects of behaviour or retrofits on health. In addition, these tend to focus on particular populations (children or the elderly).

Additionally, the information about energy renovation is very fragmented. There is little knowledge how to design both the building and the energy technologies in a home as such that it interacts with occupant preferences, capabilities and needs in an energy-efficient way, and creates a healthy indoor environment at the same time [135]. Which measures to take, their prices and benefits, their operational performances: the sources of information are diverse, incomplete and contradictory. Neither governmental sources nor private sources can be trusted: the government has interest in realizing the energy transition, producers in selling their products and installers in making the realization with profits as high as possible. Numerous studies in the past (e.g. [60]) have pointed out the lack of knowledge of many installers concerning new technologies. A general problem in the HVAC-sector, although often mentioned in reports and literature [136] is the lack of feedback mechanisms between the operational aspects of HVAC-systems and their design: because of the fragmented supply chain, maintenance is generally carried out by other companies than the ones who have designed the system, therefore very little feed-back on actual performances and user experience is fed back to design companies and producers, inhibiting this way the possibilities to improve the designs.

The design process of control systems and building infrastructure needs to be done in conjunction with the occupants, as the interactions have two actors: the human and the building (including its systems). On the human side, it has been proposed to understand in a qualitative and quantitative manner their comfort perceptions, emotions, behaviours, awareness, as well as control levels, attitudes towards energy, needs, and habits, while on the building & systems side elements such as usability, quality, affordances, layout, have to be considered [137, 138]. As the building systems- environment-occupant are so closely interrelated, especially in the indoor environment, every action, behaviour, or habit exercised by the individual will influence the environment, and the environment will in its turn influence the action and the behaviour of the person.

It is, therefore, necessary to understand the components better through an integrated analysis of: (a) occupants' preferences and needs, their *profiles*, e.g. their intentions (locus of control, emotions, attitudes, social factors); their habits (frequency of past behaviours to achieve the same goals); their health and comfort status; (b) but also the indoor environment they are exposed to: the positive and negative stressors to influence their behaviour and other effects, the *patterns of stressors*, also named facilitating factors (appliances, environmental features, affordances) [135, 139].

This requires interdisciplinary studies in which the *interactions* between occupants' behaviour, preferences and needs towards energy and comfort, their health and comfort, the energy-efficient systems and the indoor home environment are studied, integrating and synthesizing knowledge from indoor-environmental sciences, energy sciences and behavioural sciences and design sciences. Learning from real-world case studies, from design to early occupation will contribute to understanding the drivers of energy efficiency, IEQ and health in homes and how it can be addressed in energy-efficient dwellings.

Declaration of Competing Interest

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

CRediT authorship contribution statement

Marco Ortiz: Writing - original draft, Conceptualization, Methodology, Investigation, Writing - review & editing. **Laure Itard:** Writing - original draft, Conceptualization, Methodology, Investigation. **Philomena M. Bluyssen:** Writing - original draft, Conceptualization, Methodology, Investigation, Supervision, Writing - review & editing.

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