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Introduction

Due to pandemics (i.e. Covid-19), climate change, dwindling of natural resources and economic crises, creating resilient buildings is of high importance. Resilient buildings are needed as people spend more than 60% of their time at home (Bonnefoy 2004) and most of the rest of their time at work, at school or commuting, resulting in lives spent 90% indoors. The indoor environments that occupants are exposed to in dwellings can have detrimental effects on health, and resilience measures can exacerbate these effects (Bluyssen 2014).

To improve the resilience of the current stock, most buildings need to be retrofitted. One strategy to create more resilient buildings is to prepare them for the energy transition. The European Union, by 2050, is expected to have a majority of low-carbon buildings with energy transition measures (Rijksoverheid 2019). In the Netherlands, the existing housing stock, particularly social and residential homes, is being renovated and refurbished. These buildings currently consume around a third of the country's energy. By 2050, the current stock should be energy-neutral and all newly built homes should have been so since 2020 (CBS 2019).

Because demolition rates are lower than 1%, the 2050 target buildings already largely exist. Therefore, a resilient stock will be achieved through a three-step renovation strategy. First, with energy-efficient adaptations (i.e. double glazing, mechanical ventilation and insulation). Second, with renewable energy systems (i.e. heat pumps, solar panels and infrared heating), and third, with distributing methods involving, for instance, smart grids and low-temperature heating (Itard and Meijer 2008).

Energy resilience started as a reaction to the 1970s oil crisis, driving improvements in air-tightness and thermal insulation, alterations that often increase humidity problems, moulds and poor indoor air quality (IAQ) (Adan and Samson 2011). Currently, occupants of one-fifth of European social housing suffer from health risks because of indoor mould exposure

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(Bonnefoy 2004). Worldwide, social housing has been reported to increase the risks for respiratory health problems due to substandard thermal conditions and high levels of indoor air pollutants (Patino and Siegel 2018).

Indoor environmental quality (IEQ), including air, thermal, acoustical and visual qualities, can affect the health and comfort of the residents. Several factors determine the level of the IEQ: outdoor elements, such as the soil or cars, the occupants and their activities, the building's materials (construction, furnishings, finishes) and the types of systems (heating, ventilation, etc.) (Bluyssen 2015, 2019).

Resilient home programmes often focus on reducing carbon footprints with energy efficiency. However, for the resident, improving the comfort of the indoor environment is a more relatable motivation, as was concluded in a study where homeowners saw the need to improve the indoor environment as the deciding factor in renovating their homes, rather than the decrease of energy costs (Azizi et al. 2019).

Counterintuitively, evidence suggests that resilience measures can degrade the IEQ, leading to health problems (Bone et al. 2010, Richardson and Eick 2006), while the intended energy savings tend to be seldom achieved. This phenomenon is called the 'performance gap' (Ioannou and Itard 2017, Majcen et al. 2016). Research shows that for effective resilient renovations, both the residents' and the buildings' characteristics ought to be considered (van den Brom 2020).

This chapter presents a summary of the risk factors that are known to affect health and comfort in the existing housing stock related to energy-efficient retrofitting for better energy management and the reduction of greenhouse gas emissions (Ortiz et al. 2020).

Building envelope

Increasing airtightness and improving the thermal insulation of the building envelope are fundamental strategies for reducing energy use in buildings. Air leakages and heat loss in buildings increase consumption (Pan 2010); therefore, renovation programmes focus on increasing thermal insulation, often causing increases in condensation, moisture and build-up of pollutants, because of the reduced ventilation and overheating. These problems can be exacerbated if the mechanical ventilation system is poorly designed, installed, maintained or used.

Condensation and dampness

Internal condensation caused by thermal bridging, moisture excess (Vinha et al. 2018) or 'dampness' (Bornehag et al. 2004) can moisten the materials and surfaces, degrading them and encouraging mould growth (Havinga and Schellen 2019). Internal condensation can also increase thermal transmittance across surfaces (Ibrahim et al. 2019), requiring more energy to heat the spaces where moist materials are present.

Most dampness problems are related to the indoor air and present risks to the respiratory and the dermal system (Baughman and Arens 1996). A damp home may cause airways, nose and skin symptoms in the occupants (Bornehag et al. 2004, Sun and Sundell 2013, Zhang et al. 2019). Systemic inflammation, wheezing, respiratory symptoms and allergies are associated with dampness, window condensation and visible mould (Mustonen et al. 2016, Shorter et al. 2018, Takaoka et al. 2016). High humidity by itself is not detrimental to human health, but it can cause a range of environmental problems that do impact health. Dampness can stimulate the reproduction of fungi, and domestic house dust mites, both of which can increase asthma prevalence, allergic reactions and respiratory tract, skin or eye problems (Peat et al. 1998). Relative humidities of below 50% can decrease the reproduction of dust mites, while frequent vacuum-cleaning and other hygienic measures (mattress, pillow and upholstery hot-washing) may also help to control them (McDonald and Tovey 1992).

Another effect of high humidity is that it encourages fungi and moulds. These need three elements to thrive: water, carbon and nitrogen. Wood, textiles, natural fibres, glues and dusty surfaces may provide those conditions. When environmental conditions change, spores are released by the fungi as survival mechanisms (Pasanen et al. 1991). About 15% of Dutch buildings have mould problems (Bluyssen et al. 2016), which is more common in old buildings that do not comply with thermal and ventilation regulations.

Low humidity can lead to skin and eye conditions: the prevalence of atopic dermatitis is higher in dryer conditions (Sato et al. 2003). Exposing individuals for one hour to environments where the RH was less than 40% increased their eye discomfort (Abusharha and Pearce 2013). In offices, associations were found between low RHs of 5% to 30% and the prevalence of complaints related to stuffy air, air dryness and ocular irritation (Wolkoff 2018). A low RH also affects a person's airways and dries the mucus membranes in the nose and upper airways. This dryness can cause epithelial damage, reduce mucociliary clearance, making the person more vulnerable to infection by airborne viruses (Memarzadeh 2012).

Relative humidity can be controlled by the use of HVAC systems or with dehumidifiers. However, longer periods of low humidity may not inhibit fungal growth (Wu and Wong 2020). Rather, the materials' moisture retention properties are more likely to determine fungal growth (Adan 1994). Thus, even with low relative humidity, moulds may still grow. Other mould control measures can be waterproofing materials, cleaning or disinfecting surfaces, and larger measures, like removing or replacing the affected materials.

Build-up of pollutants

Increased airtightness can cause the build-up of pollutants emitted indoors by several sources, including occupants, their activities, building, furniture and fittings materials, and chemical products used, particularly for cleaning. These can cause respiratory and dermal symptoms, but headaches and lethargy may also occur. Rhinitis was found in 33% of Dutch students and was associated with the presence of new particle board furniture in the bedroom (Bluyssen et al. 2016), while opening the bedroom's windows at least once a week seemed to reduce the prevalence of rhinitis (Bluyssen et al. 2016).

Indoor chemistry can also have detrimental effects on the health of occupants (Venn et al. 2003, Weschler 2011). Insulating materials installed to reduce energy expenditure emit pollutants that can build up when the building is airtight (Marlow 2012). In France, energy-efficient buildings had higher concentrations of terpenes and hexaldehyde, compared to conventional buildings (Derbez et al. 2018). Similarly, benzene, toluene, ethylbenzene, xylene and radon exist in higher concentrations in multifamily buildings with energy retrofits (Du et al. 2019).

Radon

Radon is a radioactive gas that occurs in nature and has been linked to lung cancer (WHO 2009a). Studies indicate that certain energy-retrofitting measures are associated with higher levels of radon indoors. In the UK, it was found that double-glazed windows, wall insulation and loft insulation in homes were associated with higher levels of radon indoors, compared to homes without them (Symonds et al. 2019). Energy-retrofitted homes in Germany had twice the radon levels as homes without energy retrofits (Meyer 2019). Other studies concluded that materials like granite and other stones used in older houses may increase radon levels, while over-pressurized ventilation systems may decrease radon levels (Collignan et al. 2016). In crawl spaces, ventilation can also decrease radon when it is emitted by construction materials, rather than by the soil or foundations (Francisco et al. 2020).

Overheating

Improving thermal insulation is a popular energy retrofit measure. Poor insulation can cause thermal dissatisfaction during the winter and higher energy consumption. However, greater insulation may improve winter temperatures but can cause overheating during the summer (Tink et al. 2018). Retrofitted dwellings complying with energy-efficiency requirements have higher probabilities of overheating (Bernstein et al. 2008, Buysse et al. 2010, Garssen et al. 2005, Kovats and Hajat 2008, Sharifi et al. 2019). Night ventilation and shading can reduce overheating; however, climate change may increase overheating, further raising the demand for cooling (Tink et al. 2018). Health effects associated with overheating are dehydration, cardiac conditions and increased mortality, and tend to be more prevalent in vulnerable people (Kovats and Hajat 2008).

HVAC systems and operation

Heating and ventilation systems, combined with insulation upgrades, are popular retrofitting measures. These systems can be balanced ventilation, demand-controlled ventilation, air-water heat pumps and ground source heat pumps. Although helping to reduce energy consumption and improving the occupants' comfort, these systems may pose certain IEQ-related risks.

'Bad' air quality

Mechanical ventilation can both improve and worsen IAQ (Du et al. 2019, Lajoie et al. 2015), due to poor maintenance or design; and health problems can result from the HVAC-system pollution (Bluyssen et al. 2003, Coelho et al. 2005, Mendell et al. 2003, Mendell et al. 2006, Sonne et al. 2016, Withers 2019). Different health effects can result from different components of ventilation systems, ranging from annoyance with smells, nose, eye and skin allergies, to asthma (Carrer et al. 2015). One study found that bad odours can result from air filters or from leftover oil from the production of the ducts. Humidifiers, if poorly installed and maintained, can encourage the growth of microorganisms, while heating and cooling coils with the presence of stagnant or condensed water in their drains can also emit pollutants (Bluyssen et al. 2003). Dirty dripping pans, dirty filters or blocked ducts can encourage biological pollutants in the mechanical system, leading to irritation of mucous membranes and other symptoms in the airways (Coelho et al. 2005, Mendell et al. 2003, Withers 2019).

Noise from systems

Noise from ventilators, airflow in ducts and pumps are a common nuisance for occupants, to the degree that people may shut them off to reduce the noise. Low but constant sound levels can affect concentration, sleep and stress levels (Babisch 2002). Certain systems with overnight fans, a setting to save energy, have been reported to be a nuisance (Sweetnam et al. 2019), while systems with silent modes tend to spend more energy (Ochs et al. 2017). Constant and prolonged stressors cause annoyance: a symptom of chronic stress resulting from the frequent secretion of cortisol without coping behaviours. Chronic stress weakens the immune system, leading to anxiety, depression, heart disease, fatigue, allergies and asthma (McClellan and Hamilton 2010). Dutch standards propose a 30dB threshold, which is the acceptability limit but it does not consider individual sensitivity (WHO 2009b).

Thermal discomfort

Energy retrofits can not only save energy but also improve thermal comfort. However, occupants may be more thermally satisfied in traditional buildings with natural ventilation than in retrofitted buildings with air conditioning (Schnieders and Hermelink 2006, Martínez-Molina et al. 2016).

Thermal comfort tends to be studied theoretically, from simulations, PMVs or the adaptive comfort theory, rather than from surveys and measurements. Studies that used surveys and measurements concluded that perceived thermal comfort is better than the theoretical one in residential buildings and nearly zero-energy buildings, proposing that there is a knowledge gap between current theoretic comfort approaches and actual perceived thermal comfort (Ioannou and Itard 2017, Ioannou et al. 2018, Piasecki et al. 2019). Very few post-occupancy evaluations are reported in the literature concerning air velocity and draught perceptions. Most studies calculate PMV without considering the perception of occupants (Nguyen et al. 2019). Occupants blocking inlets to avoid draught have been reported in China and Denmark (del Carmen Bocanegra-Yanez et al. 2017).

Operation

Energy retrofits in buildings tend to use automated systems operated by sensors (temperature, CO2, infrared, light). Thus, they are arguably more precise for optimizing the performance of thermostats, heating, ventilation or shades. However, occupants need to control their environment and tend to bypass the settings (de Dear et al. 2013, Hong et al. 2017). The perception of control has effects on stress levels and health, through psycho-neuro immunological processes linking environmental stimuli to emotions and stress (Cohen et al. 2013, Ortiz et al. 2017, Zachariae 2009). A feeling of control in automated environments can be offered with feedback (Li et al. 2017). Studies show that thermal satisfaction can be increased by 60% and energy use reduced by 20% with such a feedback system (Winkler et al. 2016). Energy use reductions can be achieved by giving occupants more frequent feedback, with more detail of data in the feedback (Froehlich 2009).

Occupants

Activities and preferences

Performance gaps describe the differences between the predicted and the actual energy consumption, before and after the installation of the retrofitting measures. Such gaps tend to be caused by the behaviours of occupants and their interactions with the interfaces of the systems (Greening et al. 2000).

Researchers propose that to have stable and lasting energy reductions, human behaviours have to be included in the design of retrofitting measures, their interfaces and feedback types (Scott et al. 2012). Renovation initiatives fail to do this, leading to performance gaps and dissatisfaction with IEQ, discomfort and health problems (Bunker et al. 2020, Hammink et al. 2019, Santangelo and Tondelli 2017, Wierzbicka et al. 2018).

Behaviours can also reduce certain health risks. A study showed that health benefits in a retrofitted building were negligible, while comfort was improved; yet, occupant health was significantly improved with cleaning habits (dust, moulds) and enhanced safety measures (Willand et al. 2019). Other studies show that occupants usually do not understand how to operate ventilation systems, and when they perceive stuffy air, they tend to open windows rather than increase the ventilation (Avro-Tros Radar 2019, Itard et al. 2016), a phenomenon caused by a lack of knowledge of the operation of the systems.

Behaviours are difficult to study since they are influenced by multiple factors (environment, personal, psychosocial, physiological). Researchers have studied them by profiling occupants into behavioural types. These profiles can be based on quantitative factors (i.e. room usage, heating times, income, dwelling type, cleaning schedules, window opening and heating schedules) (Bedir and Kara 2017, Pereira and Ramos 2019, Pereira et al. 2018, Sun and Hong 2017) or qualitative factors (needs, preferences or emotions) (Langevin et al. 2015, O'Brien and Gunay 2014, Ortiz 2019, von Grabe 2016, Zou et al. 2018). Behavioural profiling is valuable for creating resilient buildings as retrofits can be customized to the occupant profile, a strategy that can reduce energy consumption and increase comfort and health.

Awareness

Occupant actions have consequences on the IEQ of the dwelling, but occupants are often unaware of them. Behaviours result from personal, environmental and social factors, and the way an occupant understands the concepts of energy and comfort will influence their actions. Therefore, creating healthy, comfortable and resilient buildings needs to be done in conjunction with occupants' perceptions, and understandings of the contexts they live in (D'Oca et al. 2017).

Awareness of energy costs can lead to behavioural changes, especially of control-related behaviours. If an occupant notices cost reductions from adopting energy-efficient products, their focus on controlling that product may increase, leading to more usage and higher energy consumption despite the efficiency of the technology. This phenomenon is called the rebound effect (Santarius and Soland 2018). Since energy costs and behaviours are tightly related, research has looked for strategies to change occupants' behaviours, so that they use less energy. These strategies normally focus on campaigns aiming at increasing awareness and persuading occupants to change their behaviours. These methods tend to be unsuccessful since people normally don't change their behaviour based simply on new information (Verbeek and Slob 2006).

Energy-efficiency-driven resilience is achieved by developing energy-efficient technologies; nevertheless, it should be recognized that occupant actions are not always aligned with the development of the technologies leading to increased energy use through actions like changing settings, turning technologies off or misusing the technologies (Scott et al. 2012). Such behaviours not only lead to increased energy consumption but may also worsen the IEQ, reducing comfort and health.

Synthesis and recommendations

The reviewed literature demonstrates that savings-related energy-efficiency measures in retrofit projects may come at the expense of the health and comfort of the building occupants.

Few studies have assessed the impacts of retrofitting measures on the occupants' comfort and health, even though evidence exists that the retrofits can encourage mould issues, pollutant build-up, lower perceived control by occupants and thermal comfort problems, including feelings of excessive cold, heat, draft, noise nuisance and a variety of health and respiratory problems.

Mechanical ventilation systems, heat recovery systems and heat pumps may perform poorly because of poor maintenance or design and development of the systems, but also from mis-operation of the systems by the residents, because of poor interface design, user training or feedback systems.

Homes are places where people spend most of their time and must be 'fit for purpose', providing adequately comfortable and healthy environments to their users via the fabric, systems and services of the building. Resilient homes should provide such benefits while having low carbon footprints. This, theoretically, should be done through the energy-efficient and clean performance of the comfort-providing technologies, and the provision of usable, accessible and effective passive building elements such as opening windows. All of these systems only work well when used well.

The link between occupant behaviours and how they use such systems, and their health effects of the relationship between the two tends to be overlooked in research.

Moreover, energy renovation data tends to be disarticulated: knowledge is limited as to how to design energy-consuming technologies so that they support and satisfy the residents' preferences and needs efficiently while regulated for levels of health and comfort indoors (Bluyssen 2020). Appropriate and organized information on the type of retrofitting measures, their costs and performance is lacking, incomplete and even contradictory. As a result, both private and government knowledge sources are unreliable on this topic, being based on little or no solid research on such impacts. Governments are motivated to reduce energy use to underpin policies on the energy transition. Companies are not motivated to threaten profits by advertising or even researching unwanted impacts. Installers are interested in doing an agreed job for an agreed price and making money on the transaction, rather than in the wider societal impacts of the work. Additionally, installers tend to have only enough knowledge about the technologies to do the job they are paid for (Sonne et al. 2016). For example, in the HVAC industry, coordinated communication between operation and design is poor. This is due to a fractured supply chain, where maintenance is conducted by third parties who are separate entities from both the original developer and the installer of the systems. This leads to poor feedback channels and information on actual system performance and user experience being communicated back to product designers and producers, impeding the development of improved designs.

Fail-proof and fool-proof building services and control systems can only be developed in cooperation with the occupants. This is because using such systems in practice requires a two-way interaction between the human and the technical aspects of the system in use. It is therefore important to understand the qualitative and quantitative human responses and interactions at play, to better understand how occupants perceive comfort, their behaviours, awareness, control, needs, perceptions and attitudes, to design for them. The building and systems factors, quality, usability or affordances are elements that must be understood to design genuinely low-energy, comfortable and healthy systems (Nembrini and Lalanne 2017, Ortiz and Bluyssen 2019). Knowledge of how each component fits into and contributes in a system is necessary and can be understood through routine and comprehensive analyses of product performance in use.

Specifically, it is important to understand and include the occupants' preferences and needs, their profiles, habits, health and comfort status to appropriate technologies, matched to those needs. The positive and negative stressors and stimuli, such as noise from fans and ducts, resulting from any indoor environmental technology can affect behaviours, and should be explicitly profiled in product specifications (Ajzen 2012, Bluyssen 2020). Achieving such a holistic understanding requires interdisciplinary, mixed-methods, research on the interactions between occupants and their environment, with expertise from a wide range of sciences like energy, ethnographic, indoor environmental and design sciences. A better understanding of real scenarios, from the development of systems to occupation of buildings, will enhance the knowledge of the factors influencing energy efficiency, health, comfort and IEQ and how to improve them, to create resilient dwellings.

The following steps are the foundations deducted from this review necessary to create resilient, yet healthy and comfortable buildings:

- *Participatory Research and Development phase:* building systems, installations, feedback and control systems, and standards should be developed following the needs of the occupants they are destined for, to ensure customization thereof, to improve personal comfort and energy use.
- *Customized systems and feedback:* occupants should be given the level of personal control that they prefer over the building systems, to control the indoor environment as they prefer, all while providing comfort in an energy-efficient way. Appropriate feedback on energy consumption and comfort levels, as understood by the specific occupants should also be provided.
- *Ventilation:* natural ventilation should be encouraged when possible, while ventilation rates should control pollution sources, pollutants and other chemicals to avoid health problems. Appropriate and frequent maintenance of the systems and the filters should be implemented.
- *Humidity:* inspections for water leakage in roofs, pipes and system components should be conducted regularly to avoid moulds and other pollutants.
- *Dust:* cleaning and vacuuming frequently to avoid the accumulation of dust and other pollutants and allergens. It should be ensured that cleaning products do not contain harmful chemicals or pollutants. Inaccessible ducts should be avoided.
- *Thermal comfort:* temperature indoors should allow seasonality to increase resilience, while individual thermal comfort and control options should be provided if possible.
- *Include the occupants:* conduct regular assessment of the comfort perceptions of the building occupants and the energy consumption, to discover possible issues promptly.

To cope with ever more extreme climates, the global building stock will have to be improved and retrofitted. The time and money are running out to fall short in this exercise. To ensure that the right decisions are made, and acted upon a better understanding of the human impacts of the bringing together of people and technologies, on the health, comfort and well-being of populations, and, in turn, the resilience of societies around the world. Real-world research is needed to achieve this, not just simulation studies.

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