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ARTICLE

A study on occupants' behaviour, satisfaction, and experiences in a zero-energy renovation social housing project in the Netherlands

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Abstract
This research intended to understand the effect of renovation solutions on occupants' behaviour, and the effects of the behaviour on the indoor environmental quality of the buildings. The investigation is based on the findings from a short, in-depth monitoring campaign in four apartments in the Netherlands. The results showed that the households studied have different preferences for comfort, as well as ways to interact with the building. The small range of options provided by the systems created some level of dissatisfaction in three out of the four households studied regarding temperature (control), air quality, or noise produced by mechanical ventilation system. The monitoring results confirmed that the apartments were within a good range of thermal comfort, however the residents complained about lack of control over the indoor environment. Furthermore, high CO_2 levels were found in three of the four apartments, especially at night. In these homes, the residents kept the ventilation setting on the lowest due to the noise produced by it, or due to lack of knowledge on the functioning of the system. In addition to the lack of control and lack of knowledge, the residents reported a lack of feedback from the Heating Ventilation and Air Conditioning systems to know whether they are working correctly. These results emphasize the need of user-centric design, and the need for people to be able to control their environment. Systems design should consider the actual needs and preferences of the occupants, while interfaces should be designed to provide timely and accurate feedback to the user.

Keywords Social housing · Indoor environment · Building performance · Occupants' behaviour · Building monitoring

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1 Introduction

In the European Union, there is currently a significant focus on energy efficient renovations to achieve energy transition objectives (European Commission, 2019; European Commission, 2020). An increasing number of projects target low and zero-energy renovations (e.g. Ferreira Silva et al., 2019; van der Grijp et al., 2019; Dartevelle et al., 2021). These projects aim at decreasing energy consumption and transitioning towards a gas-free economy, while at the same time providing more comfortable and healthy homes to the residents. However, to ensure the energy efficiency or energy neutrality in such homes, heating, ventilation and air conditioning (HVAC) systems and their controls are becoming more complex, less intuitive and in many cases, they contradict the old-fashion ways of controlling the indoor environment of buildings (Revell & Stanton, 2017; Tweed et al., 2015). Therefore, occupants and their behaviour are taking even more importance in the design and performance of buildings (e.g. Bakaloglou & Charlier, 2021; Breadsell & Morrison, 2020; Glad et al., 2024; Sarran et al., 2023).

In the Netherlands, a large share of rental properties is owned by housing associations, which may facilitate energy neutral renovation but also come with specific challenges (Itard & Mejer, 2008). In rental housing, the (future) occupants of the dwellings are often not involved or well informed during the renovation process, and thus, their actual needs and preferences are not considered in the selection and design of the systems (Guerra-Santin et al., 2021a, 2021b; Keyanfar et al., 2024; Ortiz et al., 2020; Sunikka-Blank et al., 2018). Furthermore, for the calculation of the energy performance (and thus, also for the design of the buildings' HVAC systems), an average household is considered and therefore, assumptions are made about the behaviour of the occupants (Cuerda et al., 2020). Previous research has shown that these assumptions contribute greatly to the performance gap (Cuerda et al., 2020; Majcen et al., 2015). For this reason, numerous studies have been dedicated to understand the impact of occupants on buildings' energy efficiency (e.g. Carpino et al., 2017; Palani et al., 2023). Consequently, within the construction industry, endeavours are made to render buildings more resistant to user influence (Boerstra et al., 2015; Hellwig et al., 2020; Loengbudnark et al., 2023; van Beek et al., 2023, 2024). This may involve automation and reducing user control options, such as windows that cannot be opened or ventilation systems that are non-adjustable. Nevertheless, past experiences have demonstrated that reducing user control can, not only lead to increased user dissatisfaction, but can also adversely affect both energy efficiency and the indoor environment quality (Wolff, 2017).

In the same line of thought, there is a common understanding that there is a right way to use a building. For example, Hong et al. (2017) concluded that energy efficient homes can potentially have very low CO_2 emissions and provide the right indoor environment to occupants *if the buildings are used as designed*. Similarly, Hauge et al. (2011) concluded that occupants' complains may be a *result of inappropriate use*. Design specifications and instructions from installers and manufactures are usually considered to be the right way to operate a building (Spiekman et al., 2022). A large amount of research has thus been conducted in the field on changing energy-related behaviour (Abrahamse et al., 2007; Erell et al., 2018; Gyberg & Palm, 2009; Palmer et al., 2012; Pothitou et al., 2016) as well as using feedback and information to steer towards the correct use of building systems (Chatzigeorgiou & Andreou, 2021; Hargreaves et al., 2010; Jain et al., 2012; Podgornik et al., 2016). However, as design assumptions seldom consider the (individual) needs and preferences of the occupants (Guerra-Santin et al., 2021a, 2021b; Keyanfar et al., 2024;

Ortiz et al., 2020; Sunikka-Blank et al., 2018), we often see occupants struggling to achieve comfort in their own homes (Peffer et al., 2011; Revell & Stanton, 2017; Tweed et al., 2015), even if they are operating the building correctly. This situation is aggravated in renovated dwellings, where occupants must deal with new systems, for example with a low temperature heating system (Revell & Stanton, 2017; Tweed et al., 2015).

As countries make substantial efforts towards the energy transition by tackling their existing building stock, more knowledge is needed on the effect of such renovations on the comfort and adapted behaviour of the occupants of the building, as well as on the effects of occupants' behaviour on building performance. This knowledge can be used subsequently to improve renovation concepts in a way that can be both energy efficient and user-centric.

In this paper we study a zero-energy renovation social housing project in the Netherlands. The Dutch zero-on-the-meter approach (Nul-op-de-meter), is used by the industry and housing associations in the Netherlands. The approach is based on a balance between annual energy demand and generation, which is also in line with the Energy Performance of Building Directly. The annual balance is appropriate for temperate countries, otherwise the energy targets would be difficult to reach, given the large differences between summer and winter on energy production and demand. The general characteristics of the Dutch zero-on-the-meter approach are outlined in (Guerra-Santin et al., 2018).

With this investigation, we intend to determine and understand the effect of renovation solutions (such as low temperature heating, high insulation, and heat-recovery ventilation) on occupants' behaviour. Furthermore, we investigate how their behaviour and use of systems might affect the occupants' comfort, the indoor environmental quality of the building, which consequently will also influence the energy performance of the building. Thus, the research is divided in three phases: 1) what are the occupants' behaviours in the renovation project? 2) what are the causes for such behaviour?, and 3) what are the consequences of the behaviour for building performance?

The paper is organised as follows: Sect. 2 discusses the state of the art of recently renovated homes. Section 3 presents the methodology of the study. Section 4 focuses on the results, showing the results per household, since we do not intend to compare occupants' behaviour or the performance of the dwellings. Three sections are shown per household: indoor environmental quality and occupants' behaviour, drivers for behaviour, and occupants satisfaction with the renovation. Furthermore, the four households are then characterised into different profiles. Sections 5 and 6 deal with discussion and conclusions, focusing on recommendations for practitioners and target groups.

2 State of the art

In the available literature on the actual performance in energy efficient homes (from energy label B to zero-net performance), the most common renovation measures were prefab façade and roof elements, extra insulation in roofs, ground floor, and walls, high performance glazing, and photovoltaics, while some projects also included heat-recovery ventilation systems, heat pumps and low temperature heating systems (e.g. De Jong & Borger, 2018; De Jong, 2019; Ferreira Silva et al., 2019; van der Grijp et al., 2020; Dartevelle et al., 2021; Guerra-Santin et al., 2021a, 2021b). In most of the available literature, two main trends are seen to investigate the performance of low energy buildings. In the first trend, mostly seen in Dutch industry reports (i.e. grey literature) the actual indoor environmental quality (IEQ) (such as temperature, CO_2 concentration, noise levels, presence of draughts, etc.), was often not measured. Instead, the focus was on occupants' satisfaction and their opinions on the IEQ of the buildings. Given the strict rules for social housing renovation in the Netherlands (70% of the residents most agree with the renovation), it is not strange to see this focus. Thus, in these reports, there is a lack of investigation on the relationship between residents' subjective answers (i.e. satisfaction with the renovation, thermal comfort), and the actual performance of homes (indoor parameters, energy use). Satisfaction in residential buildings has been usually studied in relation to physical comfort (temperature, light, indoor climate, noise) (Xu et al., 2023), although other contextual attributes can also be studied, such as the characteristics of the neighbourhood (Wegener & Schmidt, 2024).

On the other hand, in the scientific international literature, we see more examples of studies in which both, building performance and occupants' behaviour are studied. However, in these studies there is a lack of consideration of social and individual practices that affect behaviour, as well as the specific circumstances of the occupants (Breadsell & Morrison, 2020; Guerra-Santin et al., 2024; Keyanfar et al., 2024). These contextual factors are important because they will affect the interaction of the occupants with the building's technology. In the following sections, we focus on these two main focuses on building renovation.

2.1 Thermal comfort, air quality and acoustic quality in renovated homes

A direct, sought after, consequence of low energy and energy neutral projects is the improvement of indoor environmental quality. These homes are provided with an improved (airtight) building envelope that decreases the energy demand for heating and cooling. However, more airtight envelopes can also contribute to poor indoor air quality if the correct ventilation system is not provided, or if it is misused, not properly commissioned or maintained (Ortiz et al., 2020). According to Ortiz et al. (2020) these conditions can affect the health and comfort of occupants, for example build-up of pollutants, and overheating, mould growth, lack of control, thermal comfort stress, and noise produced by heating and ventilation systems. For example, in a few studies, where renovation measures were only related to an upgraded building envelope and addition of PV panels (thus, not with a new ventilation system), reported that a percentage of residents were less satisfied with indoor comfort (Borsboom et al., 2016; Jacobs et al., 2015), both in terms of thermal environment (including air dryness) and air quality (Jacobs et al., 2015). Heat recovery ventilation in very airtight buildings can, if used correctly, provide the needed about of fresh air. However, it has been seen that residents still feel the need to open windows for fresh air (Gram-Hanssen, 2010; Hauge, 2013; Rudge, 2012), even when the indoor air quality is satisfactory.

Furthermore, in building envelope renovations, overheating seems to be a common problem, especially in bedrooms. Previous studies show that from 10 to 44% of the residents complain about overheating (De Jong & Borger, 2018; Jacobs et al., 2015). Active cooling and an air heat pump can help to reduce overheating complaints (De Jong, 2019; Jacobs et al., 2015), but not all low energy and neutral homes are provided with them. In this regard, the role of the specific occupants' preferences for thermal comfort is usually neglected. Previous research has shown that thermal comfort differs according to gender, age, background and health condition (Glad et al., 2024; Hagejärd et al., 2021; Hansen et al., 2019; Ortiz et al., 2020).

According to Bonnefoy et al (2003), based on data collected from over 600 residents in 259 dwellings, noise annoyance is one of the most common problems affecting occupants' health and well-being. The found statistically significant evidence of the links between self-perceived health status and perception of noise problems. Noise from traffic and other outdoor activities are usual sources of dissatisfaction in older less-insulated dwellings, while in renovated homes, residents experience less noise from outside (Jacobs et al., 2015), but more noise from neighbours (De Jong, 2019), and from the ventilation system and heat pumps (Borsboom et al., 2016; De Jong, 2019). Noise from heat recovery ventilation systems has been a known source of acoustic discomfort among residents of new and renovated dwellings for more than a decade. Consequently, residents are more likely to set the ventilation system on the lowest level or have it totally off (Jacobs et al., 2015; Ortiz & Bluyssen, 2022; Santin, 2011), increasing the risk of poor air quality and moisture problems.

2.2 Ease of use, control and understanding

Improving the energy performance and indoor environmental quality require the installation of new HVAC systems, new building interfaces, and building elements. Therefore, users have to get used to interact in a different way with the building and its systems. In many cases, they do not understand how the systems work, especially if they were not involved in the design process or not enough information was provided about the new installations (Sunikka-Blank et al., 2018). For example, changes towards low temperature heating systems poses a change on how people interact with the system to obtain the desired indoor temperature, since systems react slower to thermostat settings. In building with such systems, users complain about the slow responsiveness of the system (Borsboom et al., 2016), or their lack of control to adjust the temperature (De Jong, 2019). Previous studies have concluded that perceived control influences users' satisfaction (Hagejärd et al., 2021; Henning, 2020).

Interfaces can also be challenging for some users, since the feedback they provide to the users is not always intuitive, and there seems to be a lack of awareness of the need for a proper induction to the residents (Glad et al., 2024). In the same example as above, residents in homes with low temperature systems often complain of the lack of radiant heat, that apart from providing thermal comfort, is a way in which people determine whether the heating is working (De Jong, 2019; Jacobs et al., 2015).

In renovated projects, it is often found that information related to the functioning and use of the all-electric systems is too complex for residents (Borsboom et al., 2016; De Jong, 2019), or not properly developed for the target group (Brunsgaard et al., 2012). Residents ignore or are overwhelmed by the much too complex information, which leads to misuse and causes complaints. Lack of understanding on how heat recovery ventilation systems work has been also reported in previous studies (De Jong, 2019; Jacobs et al., 2015). In other instances, residents have reported to operate the systems in a different manner than expected due to a misalignment between their needs and preferences, and the conditions to operate the system. For example, Brunsgaard et al. (2012) reported occupants prioritising safety and convenience over the instructions given to provide night-ventilation to avoid overheating.

3 Methodology

3.1 The case study

The case study consists of a zero-on-the-meter social housing renovated project in the Netherlands. The building is located in a community (< 10,000 inhabitants) part of the metropolitan area of Rotterdam and The Hague. The Netherlands has a moderate oceanic climate, with mild winters and cool summers. Precipitation is common during the year. Winters' mean temperatures oscillate around 3 °C and summer mean temperatures oscillate around 17 °C. The building studied is a porch apartment building from the years 1950s renovated in the period 2017–2018. There are 12 apartments in the building. Each unit has a living area of around 50 m^2, and consist of a living room, kitchen, two bedrooms, toilet, and separate shower with access from the kitchen (see Fig. 1 floor plan).The renovation consisted of a façade renovation with insulation and prefabricated elements, new double-glazing windows, renovated balconies (separated from the main body of the building to decrease thermal bridges), heat recovery ventilation system, all-electric low temperature ground source heat pump system (shared among three units) for heating, cooling, and domestic hot water with a buffer tank (per unit), and solar photovoltaic panels. Showers, toilets, and kitchens were also renovated, but the new kitchens did not include an extraction hood. The renovation included new building-user interfaces:

- The old high temperature heating system with radiators was upgraded to a low temperature system with convectors. The convectors have a 'boost' function providing warm/cool air at a higher speed, for when the residents want to heat or cool the spaces faster. The convectors cannot be shut down or turned lower or higher by the residents.
- The old thermostat was replaced with a manual thermostat that can be adjusted from 18 to 24 °C.

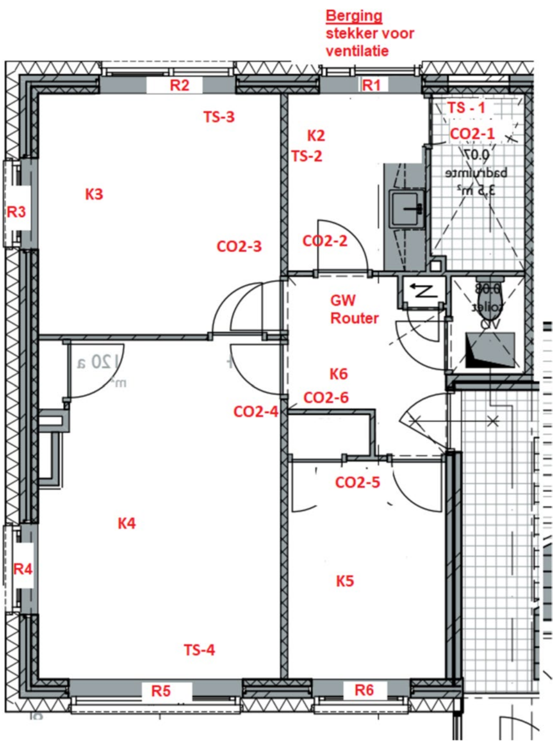


Fig. 1 Floor plan and sensors' locations (K = Temperature, RH; TS = temperature sensor in convector; CO_2 = CO_2 sensor)

- The heat recovery ventilation system includes outlets in kitchen, shower and toilet and inlets in the living room and bedrooms. The control panel allows the resident to select one in four modes: low setting, normal setting, high setting, and boost setting with a timer of 10, 20, or 30 min.
- The domestic hot water system includes a boost function for extra hot water. This is located in an installation closet in the balcony.

3.2 Data collection

For the study, four apartments were monitored in detail, based on the willingness of the residents to participate in the study. The study was designed to obtain rich and in-depth information about the occupants and their behaviour. The thus, given the need for engagement of the residents in the intensive data gathering for the study, it was important to be welcomed into the residents' homes to carry out the study.

The monitoring schedules were based on the availability of the households, and thus data collection was not carried out in the same period. The subject of the study was not to compare the behaviour of the households, or their energy consumption, which are dependent on weather conditions, household composition, building orientation and more. Rather, it was to identify underlying reasons for behaviour, and for this it is advantageous that the data are diverse.

The monitoring campaign consisted of quantitative and qualitative data collection methods. A set of sensors was installed in each apartment and removed after at least three weeks of data collection. The set included sensors for room temperature, relative humidity (RH) and CO_2 that were placed in the living room, both bedrooms, kitchen, bathroom, and hallway (only in the 3rd and the 4th household). A surface temperature sensor was located on each convector to determine whether they were on or off. Table 1 shows the sensors specifications. Sensors' locations are shown in Fig. 1.

The following Table 2 shows the monitoring dates and the composition of the households. All apartments have the same orientation, with the living room facing south and the kitchens facing north.

Households 1, 2 and 3 lived in the same apartments before the renovation, while household 4 moved only after the renovation from her parents' home. The residents were not relocated during the renovation. Table 1 shows that the household characteristics of the occupants of the apartments are different and could be considered to belong to different user profiles. Standards to evaluate indoor environment do not make distinctions among their needs, thus we assess the building performance in the same way for all the households.

Table 1 Sensors' specifications

Type	Measurement range	Typical accuracy
Temperature	-40 °C to + 85 °C	±0.2 °C at + 5 °C to + 60 °C ±0.5 °C at − 20 °C to + 85 °C
Humidity	0 – 100%RH	+/2%RH at 20–80%RH +/3%RH at 10–90%RH +/3.5%RH at 0–100%RH
CO_2	0–5000 ppm	±(50 ppm + 3%) after calibration

Table 2 Household characteristics and monitoring dates per apartment

Household	Type	Age range	Occupation	Monitoring period	Location of apartment
1	Single woman and 4 cats	Mid-fifties	Full-time employed, retail management	10–22 December	Ground floor, east wall
2	Single man	Mid-thirties	Full-time employed*, fitness trainer	19 Feb–01 March	2nd floor, inner apartment
3	Couple with 2 children	Mid and late thirties	Father full-time employed, warehouse; mother homemaker	12 March–15 April	Ground floor, inner apartment
4	Single woman and 3 cats	Mid-twenties	Full-time employed, care sector	27 May–08 June	3rd floor, west wall

(*) working at home during the pandemic

Qualitative data collection consisted of: 1) a questionnaire about habits in a normal weekday and a weekend, e.g. presence in each room, setting of heating and ventilation system, frequency of taking showers; 2) residents' diaries for a maximum of two weeks focusing on opening windows and doors, as well as operating convectors and changes on the ventilation setting and thermostat; 3) a reflection booklet regarding their comfort preferences at a few moments chosen by themselves; 4) one walkthrough interview per household focused on the systems' use, knowledge about the systems, maintenance of the ventilation system (cleaning valves and filters), and the reasons for their behaviour; and 5) a phone call with questions related to satisfaction and environmental attitudes.

There were three contact moments with the residents. In the first session the sensors were installed, and the residents were given a diary and a reflection booklet to fill in. In this session, the residents were explained the purpose of the research and their data rights. At the end of the session, they were asked to sign the consent form. Two weeks after, the walkthrough interview was carried out. Last, the phone call interview was carried out to limit the face-to-face contact with the residents. The sensors were picked up after the phone call at the most convenient time for the residents.

The project plan was reviewed and approved by the ethical boards of the Eindhoven and Delft Universities of Technology, ensuring the rights of the participants, and the privacy of the data analysis, handling, and storage. All participants signed consent forms were the purpose of the study, as well as their data rights were explicitly explained.

3.3 Analysis methods

A mixed methods methodology was used in this research, based on Guerra-Santin et al. (2016). Figure 1 shows the research framework. Qualitative data is intended to complement quantitative data to enlighten the reasons for the users to use in determined manner the systems or the different elements of their homes. To answer RQ1- What are the behaviours followed by occupants in the renovated homes? (left of the Fig. 1), the self-reported data obtained from the diaries completed by the occupants regarding user-building interaction (opening doors and windows and use of HVAC system) has been aggregated through visual representation with the quantitative data from the monitoring period (indoor temperature, relative humidity and CO_2 concentration) and temperature measured at the nearby weather station. The interactions with the building were chosen based on findings from previous studies, where they were found to be statistically correlated to energy consumption and indoor comfort (Guerra-Santin & Silvester, 2017; Van den Brom, 2020; Guerra-Santin et al., 2017). Descriptive statistics and visual methods were used to assess the indoor environmental quality of the apartments, based on current regulations and standards (ASHRAE, 2020) shown in Table 3. This step was important to determine whether discomfort is a consequence of poor indoor climate, or personal preferences.

To develop the figures, a week data was selected per apartment, based on the availability of self-reporting data (diaries). Indoor temperatures, relative humidity, CO_2 concentration obtained from the sensors were plotted next to the external temperature from a nearby weather station, and the surface temperature of the convectors measured with individual sensors. Self-reporting data on building operation (opening of windows and doors, HVAC operation) obtained from the diaries were manually added to the figures. A figure was created per room, although only relevant figures are shown for briefness.

To answer RQ2—What are the causes for the behaviour (right side of Fig. 2), we used the information obtained from the four walkthrough interviews, where the residents were

Table 3 Acceptable indoor parameters ranges in the standards (ASHRAE, 2020)

Building category	Temperature winter	Temperature summer	Relative humidity [%]	CO_2 above external levels [ppm]
Category A: Exceptional building	21.0–23.0	23.5–25.5	30–50	< 350 (~ 750)
Category B: New and renovated buildings	20.0–24.0	23.0–26.0	25–60	350–500 (~ 750–900)
Category C: Existing buildings	19.0–25.0	22.0–27.0	20–70	500–800 (~ 900–1200)

asked specifically about their use of the system and asked to describe two moments in their daily lives: a moment in the morning and a moment in the evening. The interviews were analysed to determine the reasons for the occupants to use the systems and elements on the way they do. Based on previous research (Guerra-Santin et al., 2024), we considered: 1) **habits** based on common knowledge or pre-renovation use of home, 2) **needs** related to their current daily activities, 3) **information and understanding** of the systems, 4) thermal comfort and fresh air **preferences**, and 5) other **drivers** such as background, (health) condition and attitudes towards the environment. This information was used to determine the causes for the measured and reported behaviour.

Last, to answer RQ3—What are the consequences for building performance (bottom of Fig. 2), we looked into how the behaviour and the reasons for behaviour reported in RQ1 and RQ2 affected the IEQ of the apartments. A summary of these consequences is provided per studied dwelling. The results from RQ2 and RQ3 are presented in narrative from and summarised per household in tables.

3.4 Users' profiles

Current occupants' behaviour research is being endeavour to the development of occupants' profiles (e.g. Braulio-Gonzalo et al., 2021; Ortiz & Bluyssen, 2022; Ortiz et al., 2022). Developing occupants' profiles is not within the purposes of this research, since we aim to create deeper understanding on the effect of building renovation on occupants' behaviour and satisfaction. However, in order to provide recommendations to improve the performance of renovated buildings, the characteristics and needs of the users should be considered when discussing the lessons learned. Therefore, the resulting behaviours and occupants' needs and characteristics are presented in relation to occupants' profiles.

Occupants' or users' profiles have different uses and are generated in different ways. Occupants' profiles are often generated from energy data, indoor parameters sensors, and time-use surveys. The intention of these types of profiles are to be used as input in building simulation programs and tend to focus on obtaining occupancy profiles (when

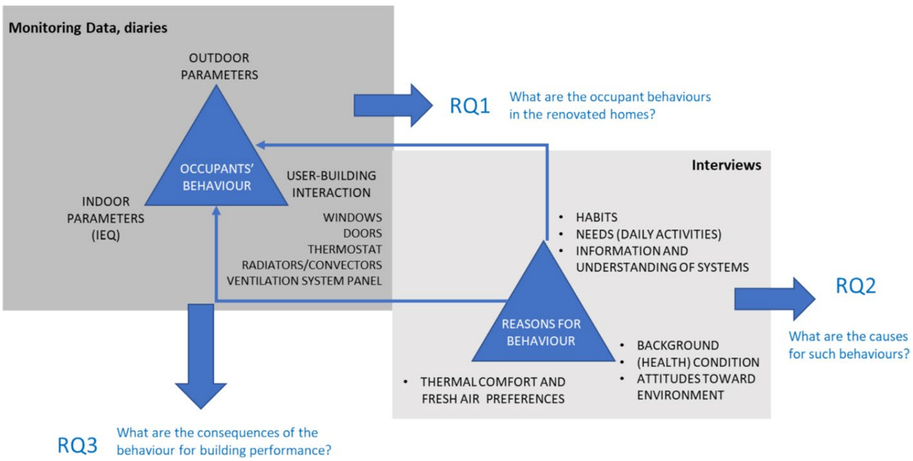


Fig. 2 Research framework

people are at home), electricity profiles (when people consume electricity), window opening profiles (when people open windows) and so on.

Another type of occupants' or users' profiles, also called archetypes are developed with the objective of differentiating between different types of households (sometimes also office workers) by taking into account their characteristics and drivers for behaviour. The profiles we consider for this research are more in line with the archetype style and take into account household characteristics (such as age, gender and household composition), as well as background and preferences.

4 Results

In this section, the results are shown per monitored apartment. Table 4 shows the statistics for each room and apartment. First, a quantitative analysis of the indoor conditions in the apartments are presented. In this analysis, the quantitative data is further explained with the self-reported behaviour of the occupants in the diaries and questionnaires. Afterwards, the behaviour reported by the occupants during the walkthrough interviews are presented for the different systems in the home. A summary per household is presented explaining the consequences of the behaviour on building performance. Last, the resulting occupants' profiles are presented and discussed.

Table 4 Descriptive statistics of monitored rooms

		Temperature (°C)	RH (%)	CO2 (ppm)	Convector (°C)
HH3	Kitchen	21.8 (0.8)	50.4 (7.4)	1339 (351)	23.3 (1.3)
	Bedroom1	22.2 (0.5)	48 (5.0)	1658 (567)	23.3 (2.5)
	Bedroom2	21.4 (0.7)	47.5 (6.8)	1095 (308)	21.3 (1.5)
	Living room	21.9 (0.9)	47.2 (6.1)	1343 (410)	22.4 (1.9)
	outdoor	7.9 (4.1)	–	–	–
HH2	Kitchen	20.7 (1.2)	42.6 (4.3)	612 (146)	19 (2.3)
	Bedroom1	22.9 (1.4)	39.2 (2.9)	712 (301)	19.3 (1.0)
	Bedroom2	23.8 (1.2)	39.5 (2.3)	600 (163)	18.9 (1.0)
	Living room	19.5 (1.5)	45.3 (4.6)	489 (79)	18.5 (1.5)
	outdoor	9.7 (4.4)	–	–	–
HH1	Kitchen	21.1 (0.5)	40.7 (4.7)	636 (187)	22.1 (0.8)
	Bedroom1	20.6 (0.4)	42.9 (5.8)	865 (291)	22.7 (1.4)
	Bedroom2	20 (0.4)	44.2 (4.7)	649 (208)	21.7 (1.3)
	Living room	20.2 (0.4)	45.3 (4.7)	655 (219)	21.4 (1.0)
	outdoor	6.0(3.2)	–	–	–
HH4	Kitchen	22.4 (1.5)	47.6 (6.3)	648 (166)	22.0 (1.4)
	Bedroom1	22.7 (1.5)	49.0 (5.2)	806 (557)	21.5 (1.6)
	Bedroom2	22.5 (1.6)	46.7 (5.3)	524 (262)	–
	Living room	22.5 (1.5)	47.5 (6.8)	569 (184)	20.6 (2.2)
	outdoor	16.3 (5.0)			

4.1 Single middle-aged woman (hh1)

This apartment was monitored during a cold period (December 2020 – January 2021) when temperatures decreased to close to zero.

4.1.1 HH1 Indoor environmental quality and building operation.

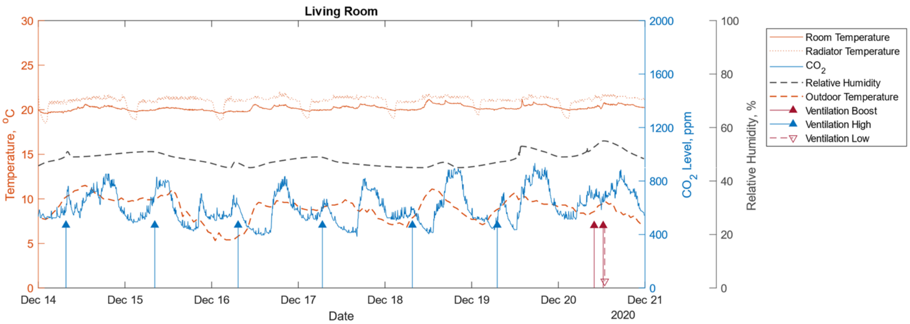
The occupants' behaviour studied was related to the use of the heating and ventilation systems, and the opening of doors and windows. The resident of this apartment filled in the diaries for the use of ventilation system, window opening in the bedroom, and backyard door opening in the living room.

Figure 3 presents the indoor conditions (temperature, RH, CO_2 level) and outdoor temperature for a selected week in the living room, main bedroom, and kitchen. The second bedroom is usually noy used by the resident. According to the diary, the resident only opens the door of the backyard during the winter to let the cats in an out, thus she closes the door immediately. Figure 3c shows that opening the door (green dotted lines) for such a short time does not affect neither the indoor temperature, nor the CO_2 level. The Fig. 3b shows the instances in which the resident opened the window at night in the bedroom (see 19 December). A sharp decrease on CO_2 when the windows are opened, followed by an increase when it is closed is observed. Although the moment when the ventilation is turned higher coincides with the decrease on CO_2 level, this is actually the consequence of the resident leaving the bedroom in the morning and turning on the ventilation higher during showering. Figure 3c further confirms that the resident always uses the boost setting on the ventilation during showering times in the morning, which coincides with peaks on RH (due to the showering) and CO_2 (due to the presence) in the kitchen. Furthermore, the figure shows a very steady temperature in all rooms (around 20 °C). The analysis shows that the apartment is within an acceptable temperature range (19 to 22 °C). The monitoring period covered a period with exterior temperatures fluctuating between 5 and 12 °C.

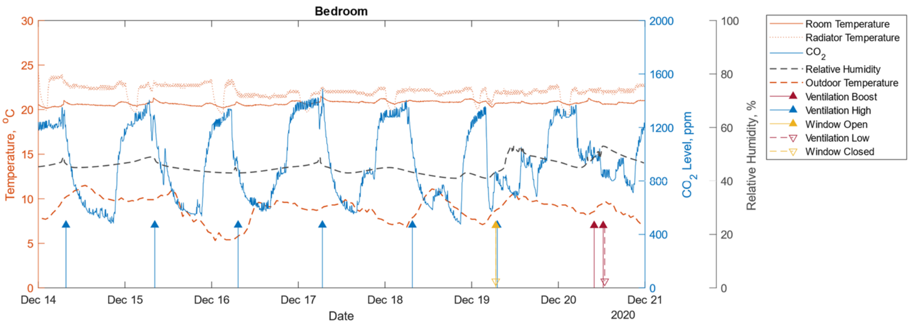
Figure 3 also shows the CO_2 concentration in the rooms. Higher levels are seen in the living room in the evening when the resident is at home, in comparison to nights and afternoons. However, the CO_2 in the living room is always well below 1000 ppm. In the bedroom, much higher levels are seen in the night, which can reach up to 1500 ppm. This is caused by the resident closing the bedroom door at night and by the low ventilation setting throughout the day (except boost mode during showering, cooking, or cleaning). According to the standards, the CO_2 concentration in this home is outside the recommended ranges ($<$750 ppm for exceptional buildings, and $<$900 ppm for renovated building).

4.1.2 HH1 Reasons for behaviour

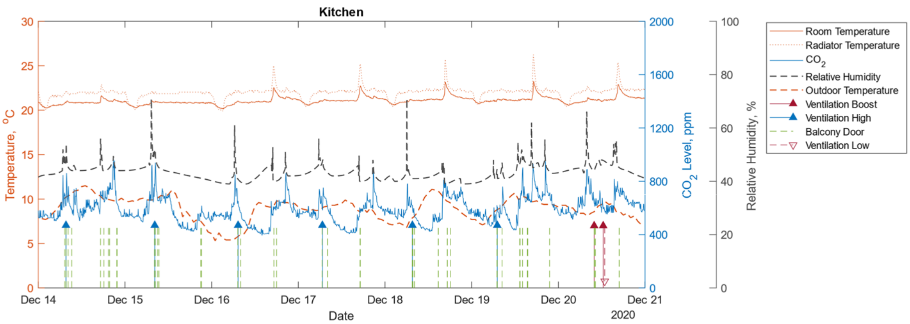
The resident keeps the ventilation system on position 1 most of the day, both in winter and in summer, because of the flow-generated noise of the ventilation system. She knows that it should be set at 2, so she makes a deliberate choice because she thinks that the noise may be bothering her cats. However, she is herself bothered by the sound at night. As instructed by the system supplier, she switches the boost option (position 3) with a timer of 10 min while she takes a shower every morning, and while cooking if there is a lot of steam. She never visits the ventilation box outside the apartment because she does not feel comfortable



a Household 1 (14-20 December) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. – Living room



b Household 1 (14-20 December) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. - Bedroom



c Household 1 (14-20 December) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. - Kitchen

Fig. 3 **a** Household 1 (14–20 December) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems—Living room. **b** Household 1 (14–20 December) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems—Bedroom. **c** Household 1 (14–20 December) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems—Kitchen

with its technical appearance. She does not feel well informed regarding how to clean the filters and the ventilation valves.

The resident controls the heating system manually through the thermostat. She sets the thermostat at 20–21 °C as suggested by the supplier. The resident is very energy conscious and likes to keep the temperature low (20–21 °C), both for her own physical preference and because she wants to save energy (mostly for environmental reasons). She experiences the bedroom as nearly always too warm, especially during her sleep. She is dissatisfied with the inability to regulate this to a lower temperature. For this reason, the resident purposefully uses windows to regulate the temperature. Furthermore, she perceives the heating system as very slow, so she does not adjust the thermostat and keeps windows closed. She reported to not use the convectors to provide a higher temperature. At the beginning, she tried the speed-up function but could not feel any difference. To increase her comfort, she adapts her clothing. She is also dissatisfied with the inability of the heating system to temporarily provide a higher temperature when she minds her grandchildren once a week.

4.1.3 HH1 occupant's satisfaction

The resident reported to be very satisfied with her renovated home. She finds the temperature and air quality during the day very comfortable, and she has not experienced mould or moisture problems, which were very common before the renovation. Furthermore, she is also satisfied with the sound level in her place, no suffering herself from too much noise, but she worries about her cats.

The resident suffers regularly from headaches when she wakes up. She attributes this to the high temperature in her bedroom, but she does not know if it is true. She also reported to not very satisfied with the interaction with her home and the control over the temperature and the indoor climate.

Table 5 summarised the behaviour of the resident for the different systems and user-interface, the reason for the behaviour and the (possible) consequences for the indoor environmental quality (IEQ) and energy performance of the dwelling.

4.2 Single young man (hh2)

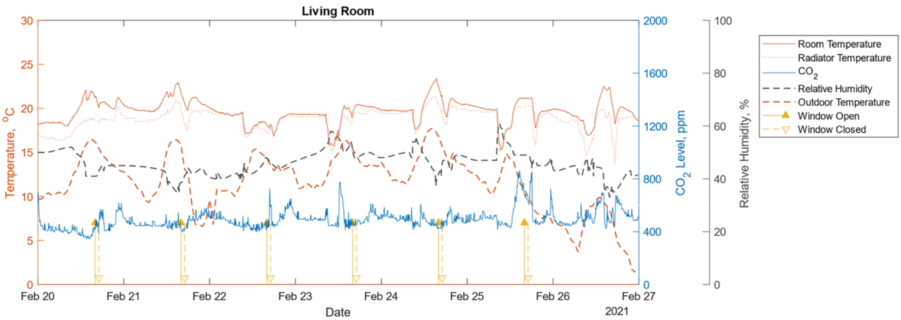
The measured period was from 19/02/2021 to 28/02/2021 when outside temperature was very warm for this period of the year (daily maximum temperature was around 20 °C). Thus, the behaviour of this household reflects more closely the transition towards warmer outdoor temperatures (i.e., winter to spring).

4.2.1 HH2 Indoor environmental quality and behaviour

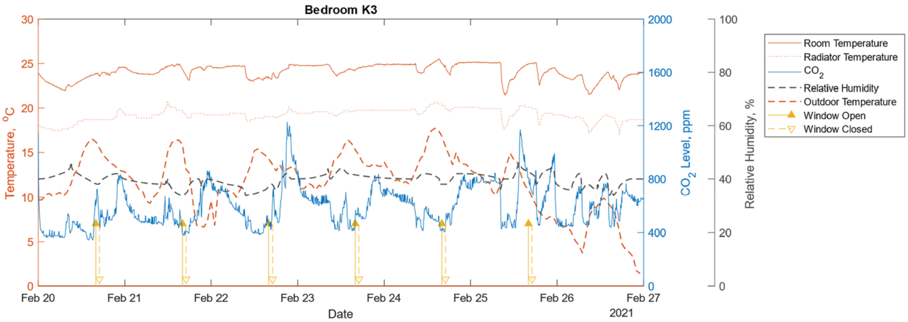
Figure 4 shows the indoor temperature, CO_2 and RH, and external temperature for full week Friday to Thursday) and showing occupants' interaction with systems. The temperature fluctuates a lot in the rooms. The living room (Fig. 4a) and the kitchen (Fig. 4c) had a median temperature of around 20 °C, but it decreased to 17 °C during nights and mornings. The temperature seems to be higher in the midday, at the time that the resident works out. The temperature of the main bedroom (Fig. 4b) seems quite warm, the median being around 23 °C, but the resident reported to have covered the sensor with clothing. The actual room temperature is shown by the sensor located in the convector, which is closed to the temperature recorded in the living room. The temperature fluctuations are caused by the frequent use of windows to ventilate, and due to the low temperature setting in the thermostat (the heating system is not providing heat in this period). According to the diary, the resident opens the windows in the living room and the balcony door in the kitchen at least 2 or 3 times per day (see yellow arrows), around midday and in the evening, when he works out and cooks. Temperature decreases are seen in the living room in the morning and in the afternoon-evening, which coincide with some of the data gathered in the diaries, However,

Table 5 Summary of household behaviour, reason for behaviour and possible consequences on performance

	Heating	Ventilation	Windows and doors	Control
Behaviour	20–21 °C No interaction with convectors Adjustment of clothing	Lowest stand (1) Boost or higher level when cooking or showering	Window open in winter in bedroom. Bedroom door closed	Dissatisfied with system control and speed: not able to heat or cool rooms if needed
Reason	Environmentally aware Was instructed to keep it on this range after the renovation	System too noisy for cats, and she can hear it at night	Prefers lower temperature in the bedroom For fresh air	She prefers to sleep in cooler room. Grandchildren visit and she would like living room to be warmer
Consequences for IEQ and energy performance	Bedroom is too warm for sleeping	CO_2 concentration in the bedroom is higher than recommended Lower energy use for ventilation due to low setting Infrequent cleaning might increase energy use	Opening window for cooling the bedroom improves IAQ The heating consumption might increase	She has tried to use an extra heating system. This could increase energy use



a Household 2 (20-26 February) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. – Living room



b Household 2 (20-26 February) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. - Bedroom

c Household 2 (20-26 February) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. - Kitchen

Fig. 4 **a** Household 2 (20–26 February) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems—Living room. **b** Household 2 (20–26 February) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems—Bedroom. **c** Household 2 (20–26 February) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems—Kitchen

we can see some instances in which the temperature decreases without a report on opening the window or door. This is however probably due to missing data in the diary.

Figure 4 also shows that the CO_2 concentration in the apartment is maintained most of the time, under 800 ppm, close to the recommendations for indoor air quality (see Table 2). The CO_2 levels are generally low in all rooms given the frequent opening of windows and the adequate use of the ventilation system. In the main bedroom there were some periods when the CO_2 level was higher than 1200 ppm but not very often.

4.2.2 HH2 reasons for behaviour

The resident keeps the ventilation system in position 2 (default setting by supplier). During and after showering, he sometimes switches the ventilation system to position 3 for about half an hour as suggested by the supplier, but he also opens the window in the living room at the same time. Before the renovation, he opened the door to the balcony during showering and often when he woke up at night.

During cooking time, he always opens the door to the balcony for half an hour. He opens windows to ensure grease goes outside directly, since he thinks that the extraction valve in the kitchen gets greasy from time to time (he cleans it regularly) and prefers to open the balcony door because he does not believe that the system can remove all cooking residue (grease). While cleaning/vacuuming, he always opens the window and closes it after the cleaning is done. He believes that by opening the window, the dust goes away faster. The resident is allergic to dust and says that the house is dusty every day, so he opens the window to get rid of dust faster. Due to the allergies, he has the habit to open the balcony door when wakes up at night. Furthermore, the resident works out at home every day. During workout, he gets warm and feels the air getting stuffy, so he keeps the window(s) and the balcony door widely open during these activities.

The resident states that he cleans the filter of the ventilation system every quarter and the ventilation valves from time to time. Sometimes he cannot hear the noise from the ventilation system, especially in the living room and the sleeping room, so he then thinks the ventilation system is not working (properly).

The resident controls the heating system manually through the thermostat. He generally sets the thermostat at 18 °C to save energy. If he feels cold, he turns it to 19 °C. He puts on socks when he feels the floor is too cold and so he does not have to turn up the heating. He never adjusts the convectors, including the speed-up function because he has noticed that he cannot control the room temperature through the convectors.

4.2.3 HH2 occupant's satisfaction

The resident is generally satisfied with the performance of his home. The resident reported that the temperature in winter is generally comfortable, while during the hottest days in summer, the apartment did not overheat too much. He had a maximum of 29 °C while other houses in town (and his house before the renovation) were at 34 °C. There are also no problems with mould or moisture.

However, the air quality is an issue of some sort of dissatisfaction. He feels that the air is always too dry, especially during nights. Some people who visited his place also had the same complaint. In addition, he reports that the place gets dust on surfaces very easily. He cleaned in the morning and there would already be a thin layer of dust around noon.

The resident is also not satisfied regarding the control of the systems (score 6 out of 10) because the use of the convector's control panel is not clear for him. Sometimes when he presses the speed-up button, there is no indication light or the lights are blinking, so he thinks the control panel is broken. Another point regarding the control is that he cannot manually change the heating/cooling mode by himself. Furthermore, it is not clear for him whether the ventilation system works properly, and he lacks feedback from the system regarding the current setting.

Table 6 summarised the behaviour of the resident for the different systems and user-interface, the reason for the behaviour and the (possible) consequences for the indoor environmental quality (IEQ) and energy performance of the dwelling.

4.3 Two-parents household with two children (hh3)

The apartment of household 3 was monitored from March 12 to April 15. During this period, the minimum external temperature varied from -1 to 8 degrees, while the maximum outdoor temperature varied from 7 to 23 degrees. The warmest period was from March 29 to April 1st, with a minimum external temperature of 2 to 8 degrees and a maximum outdoor temperature of 18 to 23 degrees. Thus, the behaviour of this household reflects the transition towards warmer outdoor temperatures (i.e., winter to spring).

4.3.1 HH3 Indoor environmental quality

Figures 5 and 6 show the indoor conditions and external temperature for two selected weeks with different outdoor temperatures. These weeks were selected to determine differences in indoor parameters ad behaviour in a colder and warmer week. The figures show that the living room and bedroom temperature is constantly at around 22 °C (although the residents reported to set the thermostat to 24 °C, the maximum allowed by the display). The room temperature in the living room peaks few times during the day (red circles in figure), except for the two warmer days in week 3 (29th March to 4th April) when external temperature exceeded 22 °C. This is an indication of the residents using the extra electric heater. The analysis shows that the apartment tends to be most of the time in the 20 to 23 degrees range. The apartment reaches 24 °C only 7% of the time. This would indicate that a room temperature of 24 °C cannot be achieved only with the use of the heating system.

Higher than recommended levels of CO_2 were observed in all rooms, indicating a low ventilation rate (blue line in Figs. 5 and 6). The high CO_2 levels are also caused by the high occupancy of the apartment (2 adults and 2 children). CO_2 levels usually exceed 2000 pm in the living room during the evenings, and 2500 ppm in the bedroom during the night.

4.3.2 HH3 occupants' behaviour and control

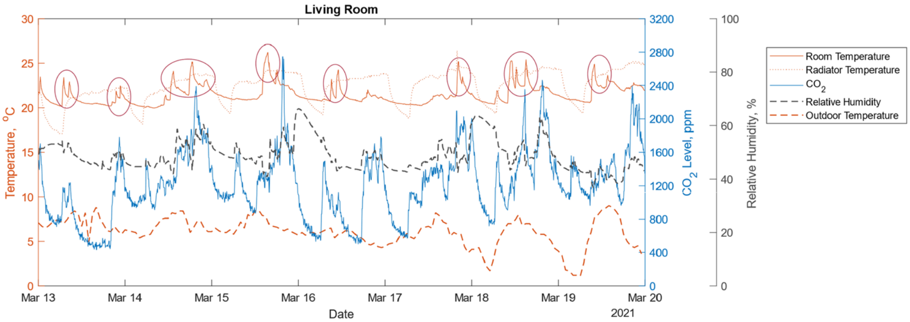
The residents did not fill in the diaries, however, based on the interview, it has been determined that they seldom interact with the systems (they only use the boost option of the ventilation). They also reported to only open windows during the weekend whilst cleaning.

The residents keep the ventilation system in position 1 and switch the system to the boost position (position 3) with the timer for 10 min during showering, cooking, and smoking (a water pipe). The residents are bothered by the noise produced by the ventilation system; therefore, they keep it at the lowest setting. They reported the noise to be unpleasantly audible when they sleep. They mostly rely on natural ventilation.

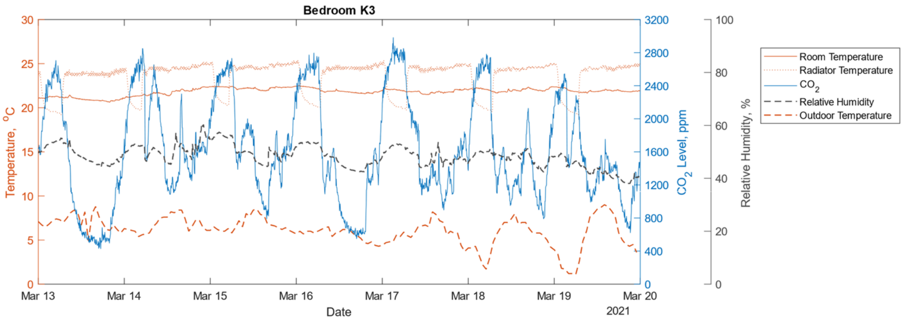
The resident identifies whether the system is working by setting the ventilation to boost every morning to shower and when cooking. If it does not become louder, the resident identifies that the system is broken. The mother is aware that the ventilation valves need to be cleaned, but she was not aware that the ventilation filters needed to be cleaned too.

Table 6 Household 2 Summary of household behaviour, reason for behaviour and possible consequences on performance

	Heating	Ventilation	Windows and doors	Control
Behaviour	Thermostat set up to 18–19 °C No use of convectors	Always on setting 2 (standard) and use of boost during showers	Ventilating via windows and balcony door Opening the door to the balcony at night	Not satisfied with systems control
Reason	Low setting to save energy Lack of clarity on the use of convectors	Need to have good air quality due to allergies	Bedrooms much warmer than living room and kitchen Activities (workout)	Not satisfied with feedback from systems and lack of manual settings
Consequences for IEQ and energy performance	Lower energy use than expected due to low setpoint (if windows are closed)	Low CO_2 concentration	Increase of energy use Comfortable indoor temperature for occupant	N/a



a Household 3 (13-19 March) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. Week 1 – Living room.



b Household 3 (13-19 March) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. Week 1 - Bedroom

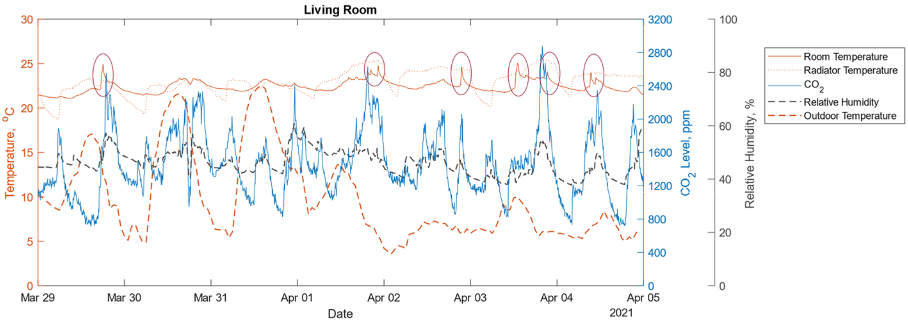
Fig. 5 **a** Household 3 (13–19 March) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. Week 1—Living room. **b** Household 3 (13–19 March) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. Week 1—Bedroom

In any case, she would not do it because it is in the installation box outside the house, to which only her husband has access.

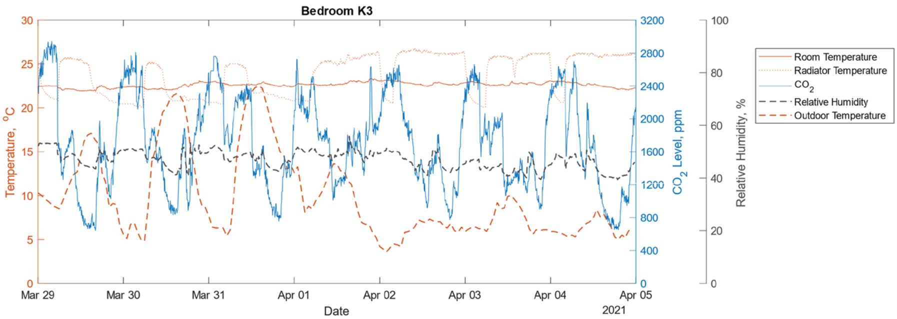
The residents control the heating system manually through the thermostat, which is set on 24 °C (maximum temperature setting of the thermostat). The mother sets the thermostat to the maximum since she always feels too cold, and she worries that the children feel cold too. However, even when they keep the system on a high setting, she does not feel warm enough after getting up and after showering, thus they have two electric heaters that they use several times during the day. She also turns the extra heating on before going to bed. Each time she turns them on for 15 min. They do not use the controls in the convectors, since they think the convectors are broken. Due to the temperature not being reached (the system only reaches 22.5 °C in winter), the resident has concluded that the system does not work properly.

4.3.3 HH3 occupants' satisfaction

The mother is not satisfied with her apartment in general (4 out of 7). She complains about their thermal comfort and lack of space, especially regarding the bedroom for their two children and the kitchen. The main complaint regarding the performance of



a Household 3 (29 March – 03 April) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. Week 3 – Living room.



b Household 3 (29 March – 03 April) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. Week 3 - Bedroom

Fig. 6 **a** Household 3 (29 March–03 April) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. Week 3—Living room. **b** Household 3 (29 March–03 April) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. Week 3—Bedroom

their home is that the heating is not enough for them. They always feel very cold. On the other hand, the residents are satisfied with the air quality. For them, the air is fresh enough. They also do not have complains about draught. However, they experience high humidity after showering. The resident also complains about too much dust in their home.

Table 7 summarised the behaviour of the resident for the different systems and user-interface, the reason for the behaviour and the (possible) consequences for the indoor environmental quality (IEQ) and energy performance of the dwelling.

4.4 Single young woman (hh4)

The monitoring period of this dwelling was from May 27th to June 8th, 2021. The daily minimum temperature varied from 5 to 16 °C, and the maximum from 14 to 26 °C. The warmest days were June 1st to June 4th (maximum temperature above 25 °C). Thus, the behaviour of this household concern slightly warm seasons.

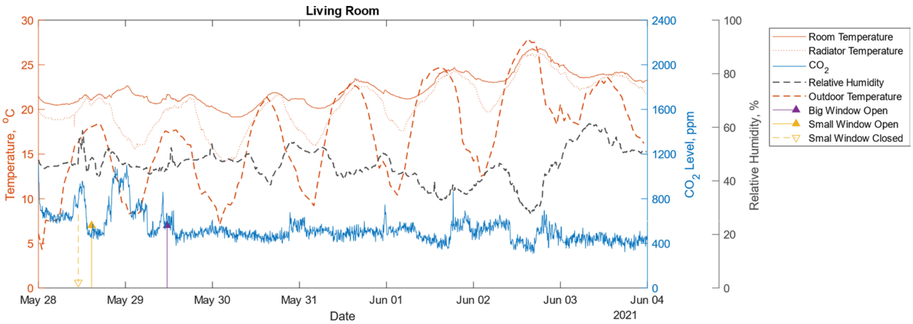
Table 7 Household 3 Summary of household behaviour, reason for behaviour and possible consequences on performance

	Heating	Ventilation	Windows and doors	Control
Behaviour	Thermostat set up to 24 °C No use of convectors Use of extra electrical heating	Always on setting 1 and use of boost during showers, cooking, and smoking	Cross ventilation while cleaning once per week	They think that the heating system does not work
Reason	Too cold most of the time. The system does not heat to 24 °C, as stated by thermostat	Too much noise from the system	Habit Satisfied with air quality provided by the system	22 °C not enough for this household
Consequences for IEQ and energy performance	Higher energy use	Very high CO_2 levels and high humidity after showers	High CO_2 levels	N/a

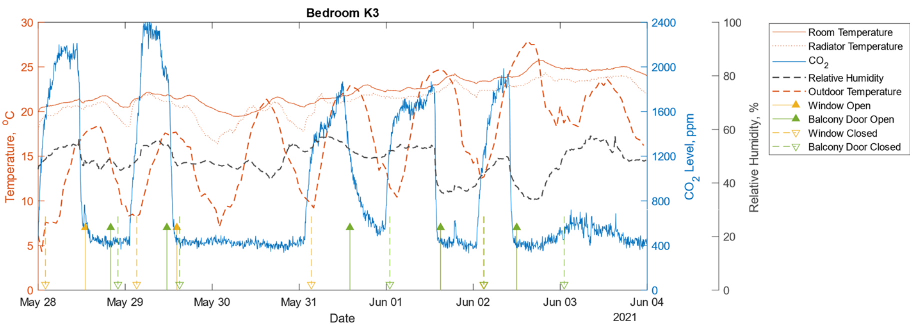
4.4.1 HH4 indoor environmental quality and behaviour

Figure 7 shows the indoor conditions and external temperature for the selected week. The resident reported her behaviour regarding opening windows in the bedroom, living room (small and large window) and the balcony door. The indoor temperature in the apartment is very similar in all rooms. The median temperature is around 22.5 degrees. The temperature is maintained between 19 and 27 °C, with only a few outliers in the kitchen. The data also show that the living room and bedroom temperature fluctuated according to the outdoor temperature, and that the convectors are off (convectors temperature is lower than air temperature, since the sensors are closer to the open window). For these figures, it is apparent that the indoor temperature is very similar to outdoor temperatures on warm days (1–4 June), while on colder days, the lowest indoor temperature is around 20 degrees.

The windows are opened several times during the day when the resident is at home (yellow and green arrows). Changes in the indoor temperature at these moments are visible, for example a slight increase is see in warmer days in the bedroom. The effect of opening and closing the window in the bedroom on the CO_2 level is visible in Fig. 7b. The resident recorded the times when she closed the window at night and opened it in the morning. She reported to close the window at night to avoid the noise from the traffic in the street. The



a Household 4 (28 May – 03 June) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. – Living room



b Household 4 (28 May – 03 June) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems. – Bedroom

Fig. 7 **a** Household 4 (28 May–03 June) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems—Living room. **b** Household 4 (28 May–03 June) Indoor Temperature, CO_2 and RH, and external temperature for full week, showing occupants' interaction with systems—Bedroom

CO_2 values in the bedroom are very high at night in the main bedroom (> 2000 ppm) during the colder days (28th and 29th May), exceeding, during the night, the recommended levels. This can be explained also by the fact that windows (and doors) are closed at night, while the mechanical ventilation is on level 1. In the warmer days, the CO_2 is lower during the night, because the windows (and doors) were kept open most of the time. Very low CO_2 levels at night in the figure (May 30th, June 3rd, and 4th) were caused by the resident not being at home.

4.4.2 HH4 reasons for behaviour

The resident keeps the ventilation setting in 1. She occasionally turns on mechanical ventilation after showering or cooking in the 'boost' position. She is not familiar with heat recovery ventilation; mechanical ventilation is mainly seen as an extraction system. Thus, she ventilates through windows and (balcony) door, which are almost always open during summer days, and very often in winter days. Interior doors are also almost always open, for passage and for ventilation. The feeling of fresh outside air is important for her, since 'she is an outdoor person'. The fact that heat is lost as a result is not a relevant issue for this resident since she almost never has the thermostat 'on'.

The ventilation valves are cleaned regularly (approx. annually) by a family member. However, the filters in the installation cabinet are not cleaned, although the occupant knows about their existence.

The resident reported not interacting with the thermostat (apart from a few weeks in the winter), since she rarely feels cold. In the winter she sets the thermostat up to 20–22 degrees for a short time. The rest of the time she sets the thermostat 'off' (below 18 degrees). For the resident, it is important to keep the right temperature for the cats (one of the cats is elderly), thus for extra heating, the convector fan is sometimes switched on. Furthermore, the temperature is controlled by opening and closing windows. If the resident or visitors are cold, a blanket is first used, even if visitors ask to turn the heating higher.

4.4.3 HH4 occupant's satisfaction

The resident is very satisfied with the house. The resident moved after the renovation, so she may have fewer or different expectations than other residents. The resident indicates that she experiences good control of the temperature and ventilation. The resident is happy with the ventilation system and the other renovation measures. The resident uses the system at her own discretion and experiences (partly because of this) few issues. However, the resident indicates that the ventilation system does not work properly in the bathroom, and that the system does not discharge enough air in the kitchen.

Table 8 summarised the behaviour of the resident for the different systems and user-interface, the reason for the behaviour and the (possible) consequences for the indoor environmental quality (IEQ) and energy performance of the dwelling.

4.5 Household profiles

Table 9 shows a summary of the main households' characteristics, preferences and attitudes towards technology, intentions, and satisfaction with the different aspects of the building that influence occupants' behaviour (Guerra-Santin et al., 2024). Based on these

Table 8 Household 4 Summary of household behaviour, reason for behaviour and possible consequences on performance

	Heating	Ventilation	Windows and doors	Control
Behaviour	Thermostat set up to 20–22 °C for a short time. Rest of the time off (below 18 °C) Use of fan function in convectors Makes use of clothing to feel warmer	Always on setting 1 and use of boost during showers	Ventilating via windows and balcony door during the day Windows closed at night	Not issues with systems control
Reason	Prefers cool and fresh environments but heats up for the cats Guest must use blankets too	Unaware that system also provides fresh air	She likes to have fresh air Closed windows only when noise from traffic in the street	Not much interaction with systems Moved to the apartment after the renovation
Consequences for IEQ and energy performance	Lower energy use than expected due to low setpoint	High CO_2 concentration at night when windows are closed	No increase of energy use in the winter Thermal comfort improved	

Table 9 Household profiles

	Hh1	Hh2	Hh3	Hh4
Composition	Single	Single	Family of 4	Single
Socio-economic level	Social housing	Social housing	Social housing	Social housing
Gender	Female	Male	Female-Male	Female
Age	Middle age	Young	Middle-age and children	Young
Pets	3 cats	N/a	N/a	2 cats
Health condition	Good health	Good health Allergies	Good health	Good health
Origin	Native	Native	Not native	Native
Preference thermal comfort and fresh air	Cool environments	Fresh air	Warm environment	Fresh air
Technology	Lack of technology knowledge Follows instructions	Good technology knowledge / Investigates	Lack of technology knowledge	Lack of technology knowledge
Maintenance	No maintenance done	Maintenance done	No maintenance done	Maintenance done by others
Control	Lack of control Lack of trust	Lack of control Lack of trust	Lack of feedback Lack of trust	No issues reported
Attitudes/intentions	Energy conscious Care for others (pets, grandchild)	Care for own health	Care for own comfort	Care for own comfort Care for others (pets)
Satisfaction	IEQ Noise from HVAC Control ☹	Temperature Air quality ☹ Control ☹	Temperature ☹ Air quality Noise HVAC☹	IEQ Noise from outside ☹ Control
Profile	1bx	1ax	2bx	1by

results, households are categorised into different profiles according to three main factors described below.

Indoor environment preferences. The main difference between occupants in this regard is the preference for cooler temperatures and fresh air (via opening windows), especially in bedrooms for sleeping time.

- Profile 1—Fresh, cooler environment, native, single—lower temperature settings, more natural ventilation
- Profile 2—warmer environment, not native, family—higher temperature settings, little natural ventilation

Technology savviness. The distinction between the households in this parameter is their approach towards technology. Households may have good knowledge of technology or might be interested on it. These people are curious about how things work and tend to experiment with interfaces and settings. On the other hand, other households might have lower knowledge and interest in technology. They either do as they are told (for example keep the heating on ventilation on an advised setting), or they might do the things their own way (for example opening windows instead of using the mechanical ventilation system).

- Profile a—higher technology interest/knowledge—proper use of ventilation.
- Profile b—lower technology interest/knowledge—not proper use of ventilation.

Trust in systems. Another factor influencing behaviour that can be used to develop user profiles is their trust in the technology. In this case study, previous issues with fault in the system shortly after the delivery of the apartments, and lack of feedback from the systems (they did not know when the ventilation or convectors were working) caused some households to mistrust the HVAC systems.

- Profile x—mistrust in the HVAC systems—misuse of HVAC systems.
- Profile y—trust in the HVAC systems—proper use of HVAC systems.

The final profiles are shown on the bottom of Table 7. Household demographics are not considered in these profiles, given the similarity among them (lower socio-economic level, single households, fully employed, and good health condition). Household 3 has different characteristics than the others, but the consequences of this might be reflected in the preferences for indoor environment.

5 Discussion

The monitoring campaign allowed us to determine the behaviours of the occupants, the reasons for it, and the consequences terms of IEQ. Previous research has pointed at the importance of conducting user-centric building performance monitoring (Vischer, 2008). Similar results to those observed in other studies were found.

The participants reported satisfaction with the indoor climate of their home, similarly to the residents of similar low energy and zero energy projects (Borsboom et al., 2016; De Jong & Borger, 2018; Ferreira Silva et al., 2017; Jacobs et al., 2015; Sarran et al., 2023; Van der Grijp et al., 2019). However, two households reported less satisfaction with indoor climate in comparison to a previous situation, in regard to the temperature of the dwelling (hh1, hh3). Similar findings were reported by Borsboom et al. (2016) and Jacobs et al. (2015). The reason for the dissatisfaction with the indoor climate was related to the lack of temperature control, either to cool down or heat up specific spaces (i.e., the bedroom), to heat faster (and thus to be able to open windows for example while cleaning), and to being unable to heat to a higher temperature. Similar complaints were seen in a project with (low temperature) floor heating by De Jong (2019), where less than half of the residents agree with the statement that the temperature in the home cannot be properly adjusted in winter, and by Borsboom et al. (2016), where residents in an all-electric (low temperature) project experience slowness on the respond of the heating system. In a study in Danish retrofitted social housing, residents complained about overheating in the summer, mentioning a sense of helplessness at sleeping times due to the inability to lower bedroom temperatures (Sarran et al., 2023). Furthermore, in our study, residents reported to not be very satisfied with the temperature control, claiming that the temperature cannot be properly adjusted (hh1, hh3), and that the heating system reacts too slowly in winter (hh1). Similar findings were reported by Borsboom et al. (2016), Sarran et al. (2023), and De Jong (2019). In the study by Sarran et al. (2023), the lack of control over indoor temperatures was found in a larger degree on dwellings retrofitted with (low temperature) floor heating. They found that only 38–50% of the residents of retrofitted homes in their study reported to have enough knowledge to operate the heating system, against 65% residents claiming the same in non-retrofitted homes. In a study on Nearly Zero Energy Buildings in the Netherlands, Sweden and France, Van der Grijp et al. (2019) also concluded that residents found temperatures too high and lack of control over the floor heating system. A study by Brown (2016) in LEED certified buildings in Toronto also found that residents complain about uneven heat distribution and discomfort in shoulder seasons. Problems with overheating, in particular in very low energy dwellings (such as Passivhaus) and in bedrooms, have been widely documented in the literature (Baborska-Narozny et al., 2017; Dartevelle et al., 2021; Glad et al., 2024; Jang et al., 2022; Tink et al., 2018).

Air dryness and dust were sources of concern for the residents in the case study, who reported dissatisfaction and lack of trust on the ventilation system (hh1, hh2, hh4). Dust was a complaint mentioned by hh2 and hh4. Similar complaints related to air dryness and dust were reported in previous studies (De Jong, 2019; Jacobs et al., 2015; Sarran et al., 2023), where 5–25% of the residents suffer from physical complaints that they thought were caused by the indoor air and air dryness. However, some of these previously reported projects seem to not have been provided with new mechanical ventilation system. While our case study did provide a new ventilation system, it was in most of the cases not properly used, probably having the same consequences as not having upgraded the system at all. In this study households 1, 3 and 4 also kept the ventilation on the lowest setting, as it was found in studies by Jacobs et al. (2015) and Borsboom et al. (2016). The main reason given for a low ventilation setting was the flow-generated noise from the ventilation system. Similar findings were seen in the study by Borsboom et al. (2016), the projects surveyed by De Jong (2019), and by Sarran et al., 2023. In their investigation in residential high-rise buildings in Toronto, Brown (2016) found that a large percentage (62%) of the participants, in their study on 165 households, had criticism about the ventilation system. The main complaint was the noise caused by the system, which was backed up by measurements taken on-site. Issues with noise from ventilation systems have been also widely documented in the literature (Gupta & Kapsali, 2016; Mlecnik, 2013; Pretlove & Kade, 2016). In other studies, cold air from the ventilation system, as well as draft have been reported, but neither were an issue in our case study.

As a consequence of noise of lack of control in the ventilation system, several researchers have reported actions taken by the residents that can lead consequences to their health or to the energy efficiency of the building (Ferreira Silva et al., 2019). For example, residents have been found to obstruct diffusers or turn unit off either timely or permanently (Brown, 2016; Sarran et al., 2023).

Complaints about the user friendliness of the ventilation system, specifically about the lack of feedback, was also reported by all households, similar to the study by Jacobs et al. (2015), De Jong (2019), and Sarran et al., 2023. Furthermore, the residents reported not to know when the ventilation systems are working properly, and to have difficulties understanding how the systems work. Similar findings were reported by De Jong (2019), Sarran et al. (2023), and van der Grijp et al. (2019), Morgan et al., 2024, and Brown (2016). In the study by Sarran et al. (, 25–40% of residents of retrofitted homes found it difficult to obtain fresh air from the ventilation system. In their study, residents of homes with more manual control were more satisfied with the systems. The study by van der Grijp et al. (2019) across Europe also brought similar results regarding lack of information on how the systems are designed and should be used. In the study by Brown (2016), other complaints about the ventilation system were made in relation to the difficulty in changing filters, or the lack of knowledge on its operation and functioning. Poor user friendliness has also been widely reported in the literature (Glad, 2012; Hauge et al., 2011; Mlecnik et al., 2012), as well as the influence of understanding on how things work and control over their own environment, on residents satisfaction and wellbeing (Hauge et al., 2011; Leaman & Bordass, 2007). Lack of instructions has been also documented as a reason for operational problems (Kleiven, 2007 in Hauge et al., 2011).

While many of the sources for dissatisfaction of the occupants with the building are related to technical matters such as lack of control or feedback, and the noise coming for the ventilation system, many of the reasons for behaviour are related to households' specific needs and requirements. The in-depth diaries and interviews with the residents allowed us to understand better the differences in comfort, and understanding and interactions with the systems. Many of these differences can be attributed to needs related to their current daily activities, household characteristics that cannot be changed, attitudes, or due to individual preferences for comfort. For example, we found that households have different preferences for indoor temperatures and "air freshness". The habit (and desire) of opening windows at night was observed in three of the households in this study, either to adjust the room temperature, or to provide fresh air. Furthermore, the residents expressed their wish to have a lower indoor temperature in the bedroom, which was not possible to achieve due to the functioning of the heating system. Opening windows at night during the winter to adjust room temperature has been reported in previous studies (Berge et al., 2017; Guerra-Santin et al., 2016). For example, Berge et al. (2017) investigated a multi-family passive house building in Norway through a questionnaire survey to understand comfort in air-heated dwellings. They found that different temperatures are preferred in various rooms within a dwelling, and low satisfaction with thermal conditions in bedrooms, where an additional source of heat was not provided. They pointed at the limitations of commonly applied heating and ventilation strategies. This highlights the need for user-centric design and the importance of occupants' profiles. In this case study, we found that we could categorise the households based on three different parameters unrelated to household size or composition: indoor environment preferences, technology savviness, and trust in the HVAC systems.

The first aspect, **indoor environment preferences** affect not only the temperature settings, but also the opening of windows, doors, and vents (when available). Dutch households have shown in previous studies to have a preference towards cooler and fresher sleeping environments; thus, windows or vents are often open during the nights in bedrooms, even during the colder months (Guerra-Santin, 2024). On the contrary, some households have a preference for warmer indoor environments. For example, households with a foreign background or that have lived abroad for a while, or older households with poor health condition tend to prefer higher indoor temperatures and tend to ventilate less in the winter (Guerra-Santin & Silvester, 2017). Previous research has shown that households living in social housing apartments are more likely to be or foreign origin, have poorer health conditions, or have disabilities (Guerra-Santin et al., 2017). Therefore, the differing preference of this target group should be considered in the design of social housing in the Netherlands.

The second aspect is **technology savviness**. This might refer to the existing technology knowledge and skills of the household, as well as their interest and willingness to learn and to understand the technology. For example, Sarran et al. (2023) found that the likelihood that occupants remember instructions given or proactively seeking more information, depend on interest and technology knowledge. Although this might be linked to the type of education followed by the occupants, the type of studies or the level of studies completed might not be a direct indicator for it. In this case study, we found a household with interest in understanding the systems and initiative to investigate how they work and to fiddle with them. In renovated homes, new technologies are installed that might work differently to previous technologies. Thus, how people understand these technologies, or alternatively said, how people are induced to the new technologies, will greatly affect the behaviour of the occupants.

The third aspect is related to the **trust in the HVAC systems**. The three households that had lived in the building before the renovation had trust issues toward the new installations, claiming that they did not work (for example due lack of feedback from the systems themselves), and supporting this claim based on misfunctioning issues with the systems on early days after the delivery of their homes. In renovated homes, this is an aspect that is highly influenced by the expectations of the users, as well as by the communication process followed during renovation activities, and as follow up after the renovation has been completed. Previous research has shown similar experiences of residents of renovated homes, when there was lack of communication between the housing association and the tenants during or after the renovation, and when expectations (for example based on demo houses) were not met (Guerra-Santin et al., 2022).

5.1 Research limitations

Qualitative data was collected in different manners: a walkthrough interview, phone questionnaire survey, building operation diaries (use of heating system, ventilation system, and doors and windows), and a reflection booklet regarding comfort. The resident of household 4 provided all the information requested. The resident of household 2 did not return the reflection booklet, while the resident of household 1 returned the reflection booked but she felt bored by it since her activities and comfort are usually quite regular. The residents of household 3 did not return neither the reflection booklet nor the building operation diaries. The hectic lifestyle of the respondent of this household (a mother with two young children) did not allow her to spend too much time on participating in these activities. Thus, we were not able to collect all data from all sources. However, the methodology is design in a way that data from different sources can be used simultaneously or alternatively, which comes from the indication (from previous research projects) that not all data collection methods suit all participants. For example, building operation diaries cannot be taken literarily, since participants might forget or make mistakes. However, based on the measured data, we are able to determine when the users filled in the diaries wrongly, or when and why the missed information.

Therefore, it should be noted that these methods of data collection should be used carefully. In this research, we only used these methods to understand the behaviour of the residents, and the reasons for the behaviour. We would advise against using these qualitative data directly for, for example, building simulations. However, these limitations do not affect the results of this study since we are exploring the reasons for occupants' behaviours. With this study, we do not intend to generalise results, nor use the findings for building simulations or modelling.

Given the sample size of this study, and its focus on social housing, we have focused only on one type of building (porch apartments), and on one type of socio-economic level. While building systems might not variate much from building to building, since the similar technologies are used (low temperature heating, heat-recovery ventilation) also in privately own housing, the household typologies presented in this study might be mostly prevalent social housing. Thus, the findings and recommendations for these types of households might be specific to this target group and further research is necessary to understand the behaviour of households of different socio-economic levels.

6 Conclusions

In this research, we investigated the actual behaviour or residents of Zero-on-the-meter renovated social housing apartments in the Netherlands, the reasons for their behaviour and the consequences on IEQ performance. A discussion on the energy performance is presented in Guerra-Santin et al. (2022). In this section we present the conclusions, and we give some recommendations for practice.

In this building, a technical solution was sought that could provide the right amount of comfort for the average user, minimising the use of energy. For this, the thermostat provided has a very small range of temperature variation, which in the display seems to be from 18 to 24 °C degrees. However, based on the monitoring data, it seems that the system is not designed to reach 24 °C but only 22 °C, as evidenced by household 3 where the thermostat was continuously set at 24 °C, but the indoor temperature was at a steady 22 °C degrees. Convectors were provided to give the users a temperature boost, but 3 out of 4 residents think that it is either not enough, or that they do not work properly. The results showed different thermal comfort preferences in the studied household. Three households preferred a cooler temperature (hh1, hh2, hh4) and reported to keep the temperature in the lowest setting (18 °C) almost all the time. Furthermore, one of these households complaint about overheating of the bedroom during the winter. On the other hand, one household (hh3) complaints that the apartment is too cold for them all the time and use electrical heaters as boosters. However, according to the monitoring data, the temperatures in all apartments are most of the time within ranges considered as comfortable and healthy, although some overheating is seen in the bedrooms during the winter (hh1). More extreme winter and spring temperatures in hh2 and hh4 are due to the residents opening freely the windows to get fresh air.

The ventilation system provided has three modes, 1- a low setting for unoccupied periods, 2—the standard setting for occupied periods, and the boost setting for showering and cooking periods. The results show that, even though the residents were instructed on keeping the setting in level 2, three out of four households keep the ventilation on setting 1. For two households, the main reason is the noise produced by it (hh1 and hh3) and for one household is due lack of awareness that the ventilation system also provides fresh air (hh4). Furthermore, the residents from hh1 and hh2 have the impression that the ventilation system does not work properly. The results also showed that windows are open in the winter and in the early spring, both for obtaining fresh air (hh2 and hh4), to ventilate while cleaning (hh3) and to cool down the indoor spaces such as bedrooms (hh1).

The four households studied have different preferences for comfort, as well as habits and daily activities. The small range of options provided by the systems created some level of dissatisfaction in three out of the four households studied. The dissatisfaction was with at least one aspect of the home: temperature or temperature control, air quality (RH), and noise produced by the mechanical ventilation system. The satisfied resident moved in into the building after renovation, thus it might be that the dissatisfied residents were promised too much before the renovation and therefore had higher expectations. However, the residents reported to be satisfied with the renovation of their home.

The behaviour of people was in all cases caused by a specific need or preference of the users, such as providing care for pets and guests, caring for own's health, thermal comfort, and acoustic preferences. In many instances, the factors that influenced the behaviour and experiences are not directly system-related but caused by the needs related to their current daily activities of the residents.

However, in all households there were instances in which the residents did not understand the system, did not receive the right (or any) feedback from the systems, or had lack of trust in the systems due to previous malfunctioning. For example, the residents reported to turn on and off the ventilation system just to know if it was working, since the noise produced is the only feedback received from it. These results emphasize the need of people to be able to control their environment and to modify the conditions according to their needs, for example to be able to cool their bedrooms. The consequences of 'unexpected' occupants' behaviour (setting the mechanical ventilation system on the lowest setting, instead of the recommended setting) can be seen clearly in the IEQ of the homes but could also have consequences for the energy performance of the building.

The most important findings in this study are summarised below. As mentioned before, these findings are in line with those found in previous monitoring studies and are therefore important aspects to consider in buildings with low temperature heating and heat-recovery ventilation.

- The ventilation system does not give enough feedback to the residents, who do not always know if it is working properly. This causes mistrust in the system and occupants relying on natural ventilation for fresh air.
- The flow-generated noise from the mechanical ventilation system causes occupants to choose the lowest setting possible. This causes high CO_2 concentrations, especially at night in the bedrooms.
- The low temperature heating does not provide high enough temperatures for some residents.
- The lack of flexibility in the temperature control of heating system do not allow the residents to adjust the temperature over the day (colder in the morning, warmer in the evening), or over the house (living room warmer, bedroom colder). This causes that opening windows become the only way to regulate the temperature.

- The low temperature heating systems takes time to heat back the home after a period of opening windows. This causes that windows are not open even when occupants know that air quality is bad, or rooms are too warm.

Thus, we can conclude that occupants' behaviour depends on both the preferences and needs of the residents, as well as on the characteristics of the dwellings and their systems, and the understanding that the users have about the systems. These findings highlight the importance of user-centerness and participatory approaches in the design of buildings and their user-building interfaces. Systems design should consider the actual needs and preferences of the occupants, while interfaces should be designed to provide timely and accurate feedback to the user. Furthermore, a good induction to the residents after the delivery of the building, support during the first months, and good operation manuals could potentially improve the efficient use of the buildings, and therefore also the satisfaction and comfort of their residents. More detailed recommendations are given in the following sections.

6.1 Recommendations for practice

Based on the findings outline before, the following recommendations are given to designers and installers:

- Provide options for occupants to achieve their desired comfort. Building users should be able to choose temperature settings, amount of fresh air, etc. to match with their thermal comfort preferences, lifestyle and needs (Berge et al., 2017). More 'tailored' designs have proved to facilitate acceptance of thermal comfort fluctuations among residents (Hitchings, 2022; Murtagh et al., 2022).
- Give occupants the opportunity to keep control of their home, even in the presence of automated systems. Control can be given back to occupants through well-designed feedback interfaces and by designs facilitating more active roles of the users (Van der Grijp et al., 2019).
- Design and test user manuals and guidelines in suitable media, and provide the support when needed (Brown, 2016; Morgan et al., 2024).
- Occupants need more information and feedback from the system, especially in new systems which workings might seem 'against' common knowledge and old habits and practices. Lack of information or understanding on the functioning of systems provoke occupants to intervene with automated systems, thus they need better information and better instructions on how the newly installed systems function, and how to use them.
- Providing the residents with more intuitive interfaces suitable to different types of users can make them feel in control of their environment (Morgan et al., 2024).
- Reduce noise from the ventilation system through proper design, installation and insulation. A noisy ventilation system does not only produce acoustic discomfort, for example at nighttime, but as a consequence of the noise, occupants will, in most cases, try to adjust, or lower the ventilation system, creating both moisture and air quality problems.
- Make post-occupancy evaluations (POE) and building monitoring in renovated buildings a common practice. The advantages of POE have been widely studied, since they can provide valuable information to improve building performance and to inform future projects (Durosaiye et al., 2019; Guerra-Santin & Tweed, 2015).

The following recommendations are given for housing associations involved in renovation projects:

- Improve the communication process before, during and after the renovation. Considering the actual needs and preferences of residents in the selection of the technologies in social housing might not be feasible due to costs and up-scalability. However, residents' participation during the design renovation process is important to manage expectations, both from the residents as well as from the housing associations. What exactly will be modified? what changes are expected in terms of indoor conditions or building operation? and what should not be expected from the renovation? are important information to be discussed with the residents. Research has shown that both demonstrators showcasing the technologies, as well as good communication with residents can be key in their successful deployment (Morgan et al., 2024). Communication is the basis for trust, which is also consider a key aspect in the retrofit process (Morgan et al., 2024).
- After the renovation, the residents need to get used to their new home (Hauge et al., 2011). New systems and interfaces, that sometimes are too different from traditional technologies will be installed. Therefore, residents need to be provided information about the technologies installed in their home (Brown, 2016; Pretlove & Kade, 2016; van der Grijp et al., 2019), either with a good induction to their renovated home by a qualified person (Berge et al., 2017; Hauge et al., 2011), well developed (and tested) guidelines and manuals (on suitable media), and well-organised customer support for HVAC systems (who do they call if there is a problem?) (Brown, 2016). Further research is still needed to determine the most suitable and effective way to provide feedback to different types of users (e.g. older people, younger people), in different types of housing and living situations (e.g. social housing), and for different types of building systems and interfaces.

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Declarations

Conflict of 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.

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