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Effects of energy-efficient renovation concepts on occupant behaviour and hence building performance

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Abstract. Dwellings and systems are becoming ever more complex. In achieving high energy performances, the interaction among user, building and systems plays an increasingly crucial role. We studied this interaction in 16 recently renovated low-energy dwellings, to advance the field in terms of methods, and to derive pointers for improved renovation concepts. We used sensors to monitor the indoor environment. And we further developed a method that uses questionnaires, diaries and a so-called 'walk through the house' interview technique to gain insights into occupant behaviour and the reasons for the occupants' behaviours. The results show that the observed behaviour was almost always a normal response to the situation, but often not the behaviour that was expected when designing the renovation concept. A major reason for this was the occupants' efforts to reduce discomfort, which was often the result of the renovation solution itself (for example draught, noise or a warm bedroom). So, we found that behaviour was often a quite normal reaction to the renovation solution. We conclude that the resulting underperformances of renovation concepts are caused by technology centred design. We posit that this can be improved by testing renovation concepts in real world situations.

1. Introduction

Dwellings and systems are becoming increasingly complex. In order to achieve high building performances, the interaction between occupants, building, systems, and environment plays an increasingly crucial role. Renovation concepts are often not tailored to occupants, their preferences are unknown, and there is still little knowledge about the interaction between occupants and renovation concepts. Despite past experience with energy-efficient concepts, few renovation concepts have been monitored in detail. There are indications, however, that indoor environmental quality and comfort are far from always good [1] and that occupants sometimes turn off installation components (such as ventilation) to reduce noise pollution, see for example [2]. The literature also frequently indicates that targeted energy performance is not achieved, even in renovation projects (e.g. [3, 4, 5]). This is also known as the performance gap: On average, energy efficient dwellings consume more energy than expected and energy-inefficient dwellings consume less energy than expected. This automatically results in a gap between the predicted and actual energy saving after renovation. Van den Brom [6] named this “the energy saving gap” and refers to many studies that indicate that on average the actual energy saving after renovations is lower than expected. This will result in a failure to meet national energy targets, higher than expected energy bills and longer payback periods for energy-saving measures.

Although the influence of occupant behaviour on the building performance is undisputed, not much is known about the interaction between behaviour and dwellings, while understanding this is crucial to realize high-performing houses. Hong [7] show that highly energy-efficient buildings, NOM (zero-to-the-meter) homes and passive houses have the potential to have very low CO_2 emissions and a positive impact on comfort, satisfaction and productivity, but "only if the buildings are used as designed." An example from practice where efforts are made to do this, is in Zero-On-Meter contracts. In these contracts, the performance of the house is clearly approached in a one-sided way by obliging the occupants to commit to a maximum setpoint temperature and shower time [8] or sometimes even maximizing the setpoint temperature and/or maximizing the amount of hot water available [8].

Wolff [10] however gives another example that shows that observed behaviour can deviate in practice from the theoretical assumed behaviour: they find an increased ventilation rate in retrofitted buildings and new buildings for temperature regulation: “Opening the windows is sometimes the only option to quickly reduce the room temperature, because of the higher inner surface temperature in renovated buildings”.

Research into the interaction between residents and dwellings is still relatively new and the sparse results are not reflected back to the designers of buildings and systems [11]. In this paper we describe a study on the user-building and user-system interaction in recently renovated low-energy dwellings. Our aims are two-fold: to advance the field in terms of methods, and to derive pointers for improved renovation concepts. We not only looked at the interaction itself, but also at the reasons that residents have for their behaviour. We compared this behaviour with the behaviour expected from the residents in the design of the systems. The research questions of this study are:

- What behaviour do we see in houses that affects the energy consumption of the house for heating and ventilation?
- To what extent does this behaviour deviate from the behaviour as designed, and why?
- And how could you improve the interaction between residents and dwellings?

With the results of this research, it is possible to develop improved renovation concepts, which take into account the interaction between system and user and with which system and user together will perform better.

2. Method

To study the interaction among user, buildings and systems, we visited 16 recently renovated low-energy dwellings. Most visits were done in the first (winter) months of 2021. We used a combination of monitoring via sensors and gathering information from questionnaires and interviews. In the following paragraphs we describe the different methods we used to gather all data (*2.1*) and give a short description of the dwellings and households in the study (*2.2*).

2.1. Description of the test methods

During the study 6 test methods were used in every house: technical inventory, intake questionnaire, monitoring with sensors, reflection booklet, flyers, and ‘Walk through the house’.

2.1.1. Technical inventory, questionnaire and sensors. The study started with a technical inventory, in which technical information about the houses was collected, like floorplans, types of systems, year of construction, etc. Photos were taken of the layout and devices in each room.

The intake questionnaire was done by phone, to reduce the time of contact between the researchers and the residents during the Corona pandemic. Together with the technical information, this data was mainly background information about the household and house.

All dwellings were equipped with a space temperature sensor, a CO_2-sensor and a relative humidity sensor in all rooms. These collected data during 3 weeks. In addition, a temperature sensor was placed on all radiators, to measure whether the radiator was turned on or off. A power sensor was placed on the mechanical ventilation, to give an indication of the air flow of the system (low, middle, high). The setpoint temperature of the heating system was measured, if possible. And the data of all smart meters was collected. All sensors had a measurement time step of 10 minutes or shorter and could be read remotely. This data was used to get an objective idea of the situation in the dwellings: which rooms were heated, how warm they got, did the rooms cool down quickly or not, what was the indoor air quality (in terms of CO_2-level), etc.

2.1.2. Reflection booklet and flyers. The residents were asked to fill in the reflection booklets and flyers during at least 4 days in de monitoring period. The booklets contained questions on the perception of their comfort at that moment, their clothing level and their wishes, related to the activities just before that moment.

The flyers were placed by all windows, all radiators, at the cooker hood, the switch of the mechanical ventilation system and the thermostat in the living room. The participants were asked to fill these in at any time they were operating a device. Specifically they listed the time of the action, the type of action and the reasons behind the action. For instance, on the window-related flyer in a bedroom an entry might be: 22:43u – open – to cool down the bedroom to prepare for sleep. Or on a flyer of the mechanical ventilation switch: 7:23h – turn to level 3 (highest level) – to remove moisture during shower.

Each flyer had a list of about 10 numbered reasons for actions dedicated to the specific device printed on it, so people could quickly note the number of the reason (or reasons) behind the action. They could of course add additional reasons to the list. The flyers typically served for the residents to become more conscious about their actions, so they could more easily reflect on these during the interview (‘Walk through the house’).

2.1.3. ‘Walk through the house’. The final test method that was used was the ‘Walk through the house’, which was done during the final visit. During this interview, the researcher asked various questions about satisfaction, health, sustainability and the mental model of the energy systems in the house. Furthermore, the researcher and the residents walked through the house together, and followed the course of the residents' day (e.g. starting in the bedroom, via the bathroom to the kitchen, etc.) and discussed what the residents did during the day and how they interacted with their house and how they experienced their environment.

2.2. Description of the houses and households in the study

The participants in the study were 16 households in 6 different cities in the Netherlands. Characteristics of the households, houses and the energy saving measures in the homes after renovation are shown in table 1.

Table 1. Characteristics of the households, houses and the energy saving measures in the 16 homes after renovation.

Type of dwelling	Apartment	x	x	x	x												
	Single family house					x	x	x	x	x	x	x	x	x	x	x	x
Year of construction	<1945													x	x	x	x
	1946-1980	x	x	x	x	x	x	x	x		x		x				
	>1980									x		x					
Household	Number of adults	2	1	2	1	1	1	1	1	2	1	2	2	1	2	2	2
	Number of children	2				1				2	1	2	1	1		1	
Insulation	Good									x	x	x	x	x	x	x	x
	Very good (passive house level)	x	x	x	x												
	Thermally compartmented[a]					x	x	x	x								
Heating system[b]	Heat pump/Hybrid heat pump	x	x	x	x	x	x	x	x	x			x				
	Boiler										x	x		x	x	x	x
Mechanical ventilation system	Balanced with heat recovery	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	CO_2-sensor in central exhaust canal					x		x						x	x	x	x
	Central and decentral CO_2-sensors[c]									x	x	x	x				

[a] Thermally compartmented: downstairs very good insulation, upstairs basic insulation.

[b] One house had underfloor heating in the living room and radiators in the bedrooms. The others had radiators and/or convectors, occasionally supplemented by infrared panels in the bathroom or bedroom.

[c] The central CO_2-sensor is in the hall, in addition every room has a decentral CO_2-sensor.

3. Results

We analysed the results for behaviour related to ventilation and heating separately. In these analyses, we compared the observed behaviour against the theoretical behaviour that is assumed in the Dutch energy labelling scheme for existing buildings. This scheme is determined according to the Dutch Energy Performance Standard (NTA8800), which complies with the European Energy Performance of Buildings Directive (EPBD). The theoretical behaviour we used in the comparison is given in table 2.

Table 2. Theoretical behaviour used in the analyses, based on the behaviour assumptions in the Dutch Energy Performance Standard (NTA8800)

Theoretical ventilation behaviour	• If there is a balanced mechanical ventilation system (which there is in all 16 dwellings in our study), this system is assumed to be set on the lowest level when the residents are not at home, on the middle level when residents are at home and on the highest level when the residents use the shower and during cooking (if there is no cooker hood). • If there is CO_2-control, the system is assumed to be set on automatic control. • There is assumed to be no extra ventilation via windows or air vents in windows, except for short periods of for instance 15 minutes.
Theoretical heating behaviour	• Living rooms and kitchens are heated to 20ºC. Bedrooms, guestrooms and study rooms are most of the time unheated (or heated to a much lower temperature). • In the whole house a night setback to 16ºC is used each night. Except for heat pumps, where no night setback is assumed for good functioning.

3.1. *Ventilation behaviour: theory versus practice*

Of the 16 households, the ventilation behaviour of only 3 households was as described above in table 2.

In the study 6 out of the 16 dwellings had a ventilation system without automatic CO_2 control. In 5 of these 6 houses, the system was usually on the lowest ventilation setting even though people were present. The residents reported the following reasons for this: Two residents said that the system otherwise made too much noise. Two said that this low level resulted in a good enough air quality. This, however, was not reflected in the CO_2 measurements that often rose above 1200 ppm. And one said that the system was not working and therefore increasing the ventilation level made no sense. This however was not true: the system actually was working.

In many houses the residents used additional ventilation by opening windows or ventilation grids, especially in bedrooms: in 6 out of the 12 houses that had mechanical ventilation in the bedrooms, windows were often open at night. These residents reported the following reasons for this extra ventilation: to cool the bedroom before sleeping, to remove dust more quickly than the mechanical ventilation system can do it, to supply extra fresh air, because the installation professional had said so, because the resident can't sleep well due to heat and wakes up with a headache, because the ventilation system gives no feedback and therefore the resident doesn't trust that the system provides enough fresh air. The residents who kept their bedroom windows closed during the winter, reported the following reasons: Some trusted the ventilation system, some said they had been told that this way the system would perform optimally and they wanted to comply with this, and one resident had studied the system thoroughly and was capable of tuning it in detail and make it function properly without additional ventilation.

In 10 houses the ventilation system had some form of CO_2-control. In 1 house the resident had turned off the CO_2-control and put the mechanical ventilation manually on the middle level (level 2 out of 3). Her reason was that he had good experiences with this. Some residents turned off the automatic CO_2-control when the system showed an orange or red light (which occurred when the CO_2-level increased above a certain threshold) and set the mechanical ventilation in the highest level manually for a period of time. In the 8 houses with a CO_2-control in the bedroom, 5 residents ventilated additionally by opening windows. In these bedrooms the air quality was good (CO_2-levels below 1200 ppm). However in the 3 houses where no additional ventilation was present, the CO_2-levels were too high in one or more bedrooms, despite the CO_2-control. We found the following possible causes for this: in 1 house the mechanical ventilation system was disabled partly (see below), in another house the CO_2-sensor in one of the bedrooms was possibly tuned to a too high level to reduce the sound of the ventilator. And in the 3rd house there were often 5 people staying in the house, which might be too much for the maximum capacity of the ventilation system.

In 4 houses the residents had partly disabled the mechanical ventilation system: One resident had installed a switch in the corridor with which she could turn off the entire mechanical ventilation system. She did this every night and sometimes during the day. The reason she reported was serious draught and noise from the mechanical ventilation. Another resident had completely switched off the decentralised control in the rooms, which meant that there was no mechanical supply or exhaust in the bedrooms. Here too, the reason was serious draught. In the third house, the mechanical supply system was completely switched off in the winter and only the exhaust system was used, disabling the heat recovery system. Again, this was due to draught problems caused by the temperature of the air being blown in being too low. In the last house, the plug was pulled out of the ventilation system in the event of frost. The reason reported was the too low temperature of the supply air in combination with the location of the air inlet.

3.2. Heating behaviour: theory versus practice

Of the 16 households, the heating behaviour of only 4 households was as described in Table 2 and was consistent with the behaviour assumed in the Dutch Energy Performance Standard.

Concerning the night reduction, the behaviour is reasonably in line with the theoretical behaviour described in table 2: In 2 of the 10 houses with a heat pump the residents applied a night setback of about 3 degrees, in the rest we see no or hardly any night reduction. The residents of homes with boiler all lower the thermostat at night, some more than others.

However, we saw that in many homes, bedrooms or work rooms are heated during the day and at night (11 of the 16). This is partly because of Corona: people are increasingly working or studying at home. In 5 of the 16 dwellings, no bedrooms or workrooms are heated. In the 4 very well insulated dwellings, however, the bedrooms were all heated, but not because the residents wanted this: the heating in these bedrooms could not be regulated separately from the living room, and bedrooms were sometimes warmer than the living room, even when nobody was present. Here we see that although there is a deviation from the theoretical behaviour, it is not caused by the behaviour of the residents but by the technical characteristics of the system.

Many residents found the lack of flexibility in heating their homes undesirable. This did not only apply to residents of the very well insulated homes. In the very well insulated houses many residents indicated that they preferred the bedroom to be cooler and that the only way to get the bedroom cooler in winter was to open the window. But residents of other houses also indicated that the bedroom had become much warmer after the renovation and that they therefore liked to open their windows. Residents of houses with a heat pump, however, did not always do so because this system reacts slowly: the experience was that if the temperature dropped too much, it could take a long time before the room warmed up again. This meant that control was also limited for these residents.

Also in the less insulated floor of the houses with thermal zoning, in 2 of the 4 houses one or more of the bedrooms were heated, while the idea of the concept is that, in principle, the rooms on the first floor are not heated.

3.3. Satisfaction

During the study we asked the residents about their satisfaction with the systems in their house. It is good to start with the finding that many people are happy with the renovation: In almost all houses, it was much more comfortable after the renovation and the energy consumption was much lower than before. However, there were also things that people were less satisfied about. Here are the most striking findings:

Three out of four of the interviewed residents of the very well insulated houses think that the system gives too little feedback on whether and how well the ventilation is working, the fourth is hardly aware that the system is there. There are no problems with draughts. One resident suffers from headaches and associates this with too little fresh air. Two residents think the system makes too much noise (and therefore have it on the low setting).

The residents of the 4 houses with the decentralised ventilation system are divided in their enthusiasm. They are all bothered by the noise of the local fans or the central system and they all experience draughts from the air blowing in from the stairwell. One resident was able to adjust the system in detail to his own wishes, although this did not solve all the discomfort. Two residents have partially turned off the system to reduce their discomfort. The fourth resident likes the idea that the system regulates the air quality on its own, but notes that the system does not do this properly.

In general, the residents of the 4 houses with a CO_2 control based mechanical ventilation system with a CO_2 sensor in the exhaust duct were satisfied with the ventilation system. One resident was dissatisfied: the supply air temperature was far too low for him and he therefore switched the supply system off in winter. Another resident also suffered from cold air, but only when it was freezing outside. His solution was to pull the plug. He is otherwise satisfied, although he did not like the large ducts in his home because they come at the expense of cupboard space. The other two residents are mostly satisfied.

The residents of the 4 houses with thermal zoning are generally satisfied with the air quality in their homes and do not suffer from draughts. Related to the heating system (heat pumps), two residents in these houses reported that there is a big temperature difference between upstairs and downstairs, one resident stated the ground floor feels cold, one resident reported that it doesn’t get warm enough downstairs and it takes a long time to heat up the house and three residents find that the heat pump makes too much noise.

Only the residents of 3 of the 10 houses with a heat pump were satisfied with their heating system. In general, the radiant heat is missed. One resident wanted a higher temperature in the house than the heat pump could provide. At times in some houses the temperature barely could get above 20°C and the thermostat could be set to a maximum of 22,5°C, which is too cold for some. Several residents were dissatisfied with the control of the heating: the temperature could not be regulated and adjusted to their wishes. The residents would also like more differentiation of the temperature: both over the day (colder in the morning, warmer in the evening), and over the house (living room warmer, bedroom colder).

However, it was not possible to arrange this. A resident has school-age children who want to study in a warm bedroom during the day and sleep in a cool bedroom at night. Therefore, the windows are open at night. In the morning, the heat pump does not have enough capacity to warm up the bedrooms quickly and the children are stuck in the cold for the first few hours. Residents were bothered by the lack of feedback from the system: when is the system on and how long does it take for the room to warm up?

Residents of the 6 houses with a boiler were mostly satisfied with their heating system. The complaints were mainly related to the ventilation system: 5 out of 6 residents suffer from too cold air and/or draught through the ventilation system.

3.4. Air quality

We monitored the CO_2-level, as a measure of indoor air quality, in all the rooms in the houses. In 8 of the 16 dwellings, the measured CO_2-level in the bedrooms and workrooms was regularly above 1200 ppm. In the other 8 homes, the measured CO_2-level in the bedrooms and workrooms was generally below 1200 ppm. All homes with low CO_2-levels in the bedroom had windows open. In contrast, the windows in rooms with regularly high CO_2-levels were closed at those times. The mechanical ventilation system was unable to realise good air quality there. There were various reasons for this: In some dwellings, the ventilation system was set on the lowest level. In one house, 5 people were often present at night and it is possible that the mechanical ventilation system was not geared to this. In 2 houses the ventilation system was switched off partially or completely. And in the last house the amount of decentral ventilation was manually reduced to lower the noise level of the local fan.

4. Discussion and conclusion

As we have seen in in the results of the study, residents often behave different than is assumed in the assessment of the energy label or by the designers of the systems. We see that this is often due to comfort issues and issues residents have with the control over their home. Residents try to avoid draught and noise. From the findings we conclude that the behaviour we observed in the homes is normal, i.e. a normal reaction to the situation in the home. Even if the behaviour does not correspond to what theoretically would be the best behaviour, the reaction is normal. Unfortunately, this normal behaviour with the systems in the houses does not always lead to the most energy-efficient situation or to a situation with good indoor air quality. The findings have shown that it is not so much the behaviour of the residents that causes this, but that the design of the system plays an important role in bringing about this behaviour. For example, it is logical for people to set the ventilation system on the low setting if it would otherwise make too much noise. It is also logical that people will open a window if they notice that their air quality is not good, for example because they get a headache.

The results show part of the issues arise from a lack of feedback or inaccurate feedback from the system. This means that good feedback from the system would also help: as we have seen in the study, without feedback residents do not know whether the system is working properly and whether turning the system to a higher setting helps. In addition, feedback must be clear: people must understand what it means and feedback should guide residents in the actions they can take. The observed disconnect between the current feedback and the residents' interpretations of it leads us to argue that not enough knowledge on the latter has been used in the design process. In order to design effective feedback, it is necessary to test it thoroughly with your target group.

We often hear that good user instructions are important to solve behaviour induced problems. Explaining to residents how the system works and what behaviour promotes good functioning certainly does not hurt. However, we emphasise that it is normal behaviour if people react to discomfort, for example noise nuisance, and therefore act in a different way than assumed in the instruction. In that case, better instruction does not help, but a better design without discomfort does. A good and simple manual may also help. However, ideally a manual should not be necessary. Manuals are not read, get lost and are often missing.

How to achieve well-used systems?
From the results and discussion, we concluded the following sequential strategy to achieve well-used systems:

Step 1 is good design. A good design is a design that has been tested in practice with a diversity of residents. This prevents as much as possible unexpected (but normal) behaviour due to discomfort and allows you to anticipate this by adjusting the design.

Step 2 is support through feedback. Again, well designed feedback is always tested on a diverse group of residents. Feedback does not only indicate the status, but also provides action perspectives: based on the feedback, a resident knows what his options are and what he can do to adapt the situation to his wishes.

Step 3 is a good user instruction and manual that fits the installed system solution and is also well tested in practice. A good instruction and manual can help, but is really only step 3 and not step 1 or the only step.

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