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Low-Energy Retrofitted Homes from their Occupants' Perspectives: Indoor Environmental Quality and Satisfaction with Heating and Mechanical Ventilation Systems

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ABSTRACT

This study aims at obtaining feedback from occupants of low-energy retrofitted houses concerning the indoor environmental quality (IEQ) and the building systems in their homes. A questionnaire study was carried out in a social housing complex consisting of 2007 single-family houses, of which 1305 were retrofitted between 2014 and 2019. The different retrofitted houses were equipped with two types of heating systems, as well as balanced mechanical ventilation with two inlet locations. The questionnaire was sent to both retrofitted and non-retrofitted houses, and focused on four aspects: (1) thermal comfort and indoor air quality, (2) perception of the usability of the heating and ventilation systems, (3) adaptive actions in case of discomfort, and (4) interest in obtaining information about IEQ and building systems.

The results show a large improvement in satisfaction with IEQ in the retrofitted houses compared to the non-retrofitted houses, apart from overheating in summer and drier air. The type of heating and mechanical ventilation does not show a significant influence on the occupants' adaptive actions in case of thermal discomfort, but occupants of retrofitted houses air out less frequently in winter. Occupants express a lack of sufficient knowledge about heating and ventilation systems in retrofitted houses. Floor heating is seen as more difficult to control than radiators. Mechanical ventilation with inlets placed on the top part of the walls generates more noise and draft issues than when the inlets are placed on the floor under the radiators. Finally, occupants of retrofitted houses are largely interested in receiving information on IEQ, energy use and systems' status. This study highlights the need for more communication and guidance regarding the operation of technical installations in private homes. The usability and transparency of these systems should be major attention points in future residential retrofit projects.

INTRODUCTION

Reducing the carbon footprint of the built environment is a necessity in order to achieve national and European CO_2 emission targets. While newbuilts have to comply with increasingly strict energy consumption requirements, retrofit of older buildings has been identified by the European commission as a priority (European Commission 2019). Besides the large energy savings that can be achieved, comprehensive retrofit has potential to improve greatly the indoor environmental quality (IEQ) and reduce health issues (Noris et al. 2013). In order to guarantee both efficient energy use and satisfactory IEQ, retrofitted dwellings are increasingly equipped with modern building services such as mechanical ventilation with heat recovery and floor heating. These systems come with new interfaces, often imply changes of practices (Korsnes, Berker, and Woods 2018), and require that occupants go through a learning process (Behar and Chiu 2013; van der Grijp et al. 2019).

Several post-occupancy studies, both quantitative and qualitative, were carried out in new and retrofitted low-energy dwellings. Most of them showed that occupants experienced improved indoor environmental quality (Knudsen and Kragh 2019; Mlecnik 2013; Thomsen et al. 2016). However, the building services were found to be the main source of occupant dissatisfaction. Comfort issues were frequently observed due to installation and operation failures of

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building services (Knudsen, Thomsen, and Mørck 2013; Mlecnik 2013), which highlighted a lack of systematic commissioning (Berry et al. 2014; Knudsen and Kragh 2019). Information and training on their operation were also found to be lacking (Behar and Chiu 2013; Hauge, Thomsen, and Berker 2011), which led to a certain mistrust towards automation and a low perceived control on the indoor environment (van der Grijp et al. 2019; Hauge et al. 2011).

The present study aims at providing an updated picture of recently retrofitted dwellings seen from their occupants' point of view, with a specific focus on usability of heating and mechanical ventilation systems. As retrofit efforts intensify in Europe, is the building industry able to provide retrofitted homes that are comfortable, healthy, and that occupants are able to operate in an energy-efficient way? A survey was carried out in January 2019 among 2007 houses in the Copenhagen area, in Denmark. Occupants were asked to rate their satisfaction with indoor environmental quality and the building services as well as to report on their adaptive actions and rate their interest in diverse proposals.

METHODS

Case buildings

A questionnaire survey was distributed in a large social housing area in the Greater Copenhagen Area in Denmark. 2007 houses were involved in the study. A large energy retrofit plan was ongoing in this area since 2014 and was carried out in four consecutive phases, each affecting a given area and with a slightly different scope. At the time of the studies, the first three phases of the retrofit were finished, giving three different retrofitted house types: A, B and C. The last phase of the retrofit was to be conducted until 2022; the remaining non-retrofitted houses correspond to type D. While type A houses were row houses on two levels, the other three house types were single-storey, semi-detached L-shaped houses with nearly identical geometries. A description of the four house types and of the characteristics of their envelope and building systems is shown on Table 1.

Table 1. Description of the Four House Types

General properties	Type A	Type B	Type C	Type D
Geometry	Row houses	Semi-detached	Semi-detached	Semi-detached
Area (m^2)	106	93 or 108	93 or 108	93 or 108
Construction date	1965	1965	1965	1965
Retrofit end date	2014-2015	2016-2018	2017-2018	Not retrofitted
Renovation extent	**Type A**	**Type B**	**Type C**	**Type D**
Rebuilding of upper floor	X			
Roof	Replaced		Insulated	
Replacement of windows	X	X	X	
Insulation of external walls (non-structural)	X	X	X	
Insulation of external walls (structural)	X			
Filling of crawl space	X	X	X	
Space heating	**Type A**	**Type B**	**Type C**	**Type D**
Water-based radiators	Bedrooms	X	X	X
Standard radiator thermostatic valve	Bedrooms	X	X	X
Water-based floor heating	Living room			
Central setpoint scheduling panel + room thermostats	Living room			
Mechanical ventilation	**Type A**	**Type B**	**Type C**	**Type D**
Balanced mechanical ventilation with heat recovery	X	X	X	
Exhaust in kitchen and bathrooms	X	X	X	
Supply: diffusers high on the wall	X		X	
Supply: Grilles on the floor under radiators		X		
Constant air volume	X	X	X	
Turbo mode activated by moisture sensor	X		X	
Turbo mode activated manually	X			

Questionnaire design, distribution and processing

The questionnaire consisted of 113 questions, of which 15 were background questions, 81 were closed questions rated on a 5-point Likert-type response format, and 17 were open questions where respondents commented on their answers to the closed questions or precised them. The themes developed in the questionnaire were: thermal comfort in summer and winter; satisfaction with heating system usability; satisfaction with indoor air quality; satisfaction with the ventilation supply air quality; satisfaction with the ventilation system usability; adaptive thermal behavior in summer and winter; window opening behavior in summer and winter; and interest in diverse proposals regarding indoor climate information and control.

This study was carried out in January 2019. The questionnaire was distributed to all 2007 houses in the social housing area in paper form. A letter was attached to the questionnaire, containing a web address and a QR code for respondents who wished to answer the questionnaire digitally. It was also possible to fill in the paper version and return it in several points located in the different neighborhoods of the area. A lottery was organized as an incentive to participate, with four different prizes to win (each had a value of about 100€). Two weeks after the initial distribution date, posters were displayed in each neighborhood with a reminder to participate. The deadline for participating was four weeks after the initial distribution date. After collection of the responses, all paper answers were digitized. Replies that were less than 70% complete were discarded.

RESULTS

Response rate

After data collection and cleaning, 344 responses were considered usable for the analysis, giving an overall response rate of 17.1%. 201 of these were answered online and 143 in paper version. The individual response rates for each house type are shown on Table 2.

Table 2. Participation Figures

House type	A	B	C	D	ALL
Number of houses	552	495	258	702	2007
Number of usable responses	69	78	94	103	344
Response rate (%)	12.5	15.8	36.4	14.7	17.1

Thermal comfort and indoor air quality

Thermal comfort. The participants' evaluation of thermal comfort in their living room and master bedroom, in summer and winter, is shown on Figure 1. Each stacked bar corresponds to a house type. The first three questions were related to the thermal sensation in three moments of the day, while the remaining two questions were related to excessive temperature fluctuations in time (temperature swings) and in space (temperature asymmetry).

As expected, occupants of the three retrofitted house types A, B and C reported less cold discomfort in winter than occupants of the non-retrofitted house type D, for all periods of the day and for both living room and bedroom (Figures 1a and 1b). Temperature swings and asymmetry in living rooms were also greatly reduced with the retrofit. Differences in winter comfort between retrofitted house types were small, but type B houses seemed to offer the most comfortable and stable temperature. In their comments, several respondents mentioned cold discomfort due to draft from mechanical ventilation, in particular in living rooms. Notable comfort improvements are also seen in bedrooms; however, the gap between retrofitted and non-retrofitted houses was less striking. Indeed, cold discomfort and excessive temperature swings were less frequent in bedrooms than in living rooms, across all house types.

In summer (Figures 1c and 1d), overheating issues were reported in all house types, all rooms and across the day, even though house type C offered the most satisfying thermal conditions. The non-retrofitted houses (type D) came second, whereas retrofitted house types A and B caused the largest overheating issues to their occupants. Type A houses,

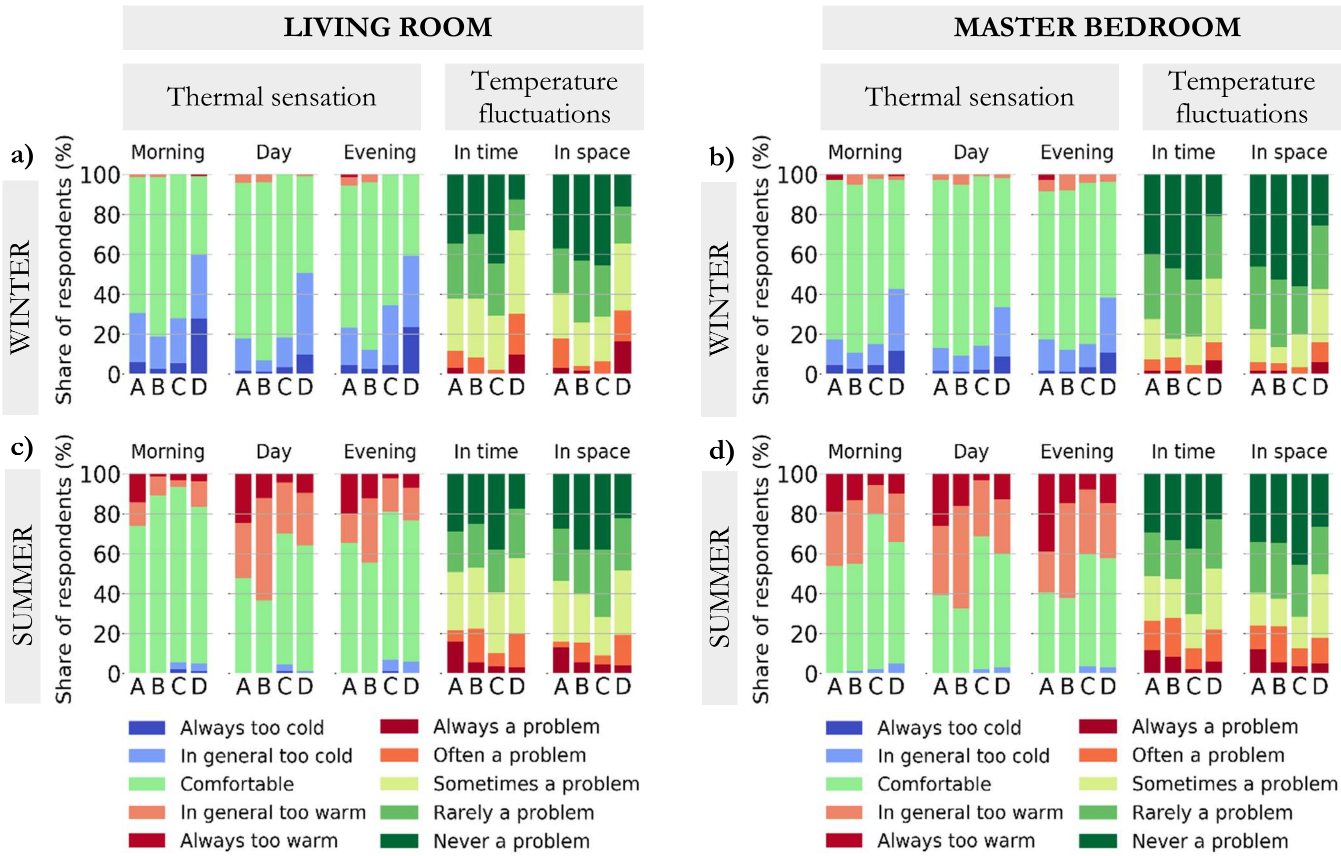

Figure 1 Thermal comfort: (a) in the living room in winter, (b) in the master bedroom in winter, (c) in the living room in summer, (d) in the master bedroom in summer.

which were row houses on two floors, had the highest share of very dissatisfied occupants regarding overheating; in particular, evening temperature was systematically too high in bedrooms for 40% of them. In general, occupants suffered more often from overheating problems in bedrooms than in living rooms, pointing at a need for colder temperatures at night. Several of them wrote in the comment section that they had issues sleeping, as temperature was very high and they did not dare keeping windows open all night out of safety concerns. Finally, excessive temperature fluctuations were more frequent in summer than in winter; in their comments, residents explained this by larger solar gains.

Indoor air quality. Figure 2 shows the respondents' evaluation of indoor air quality in their houses. All three retrofitted house types offered comparable air quality satisfaction to their occupants, and the improvement with regards

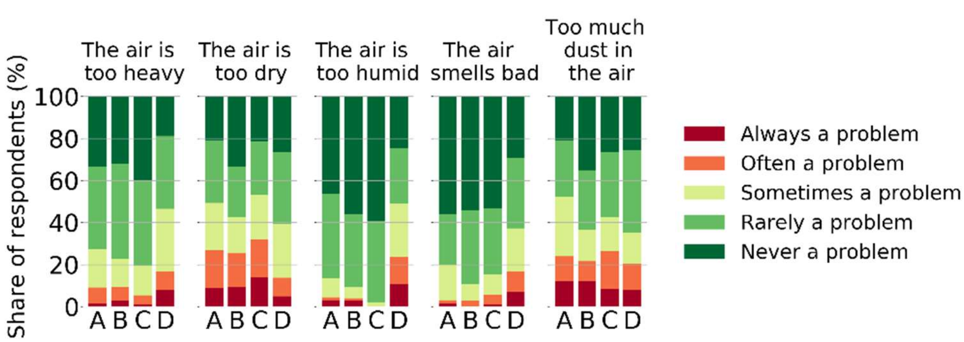

Figure 2 Indoor air quality perception.

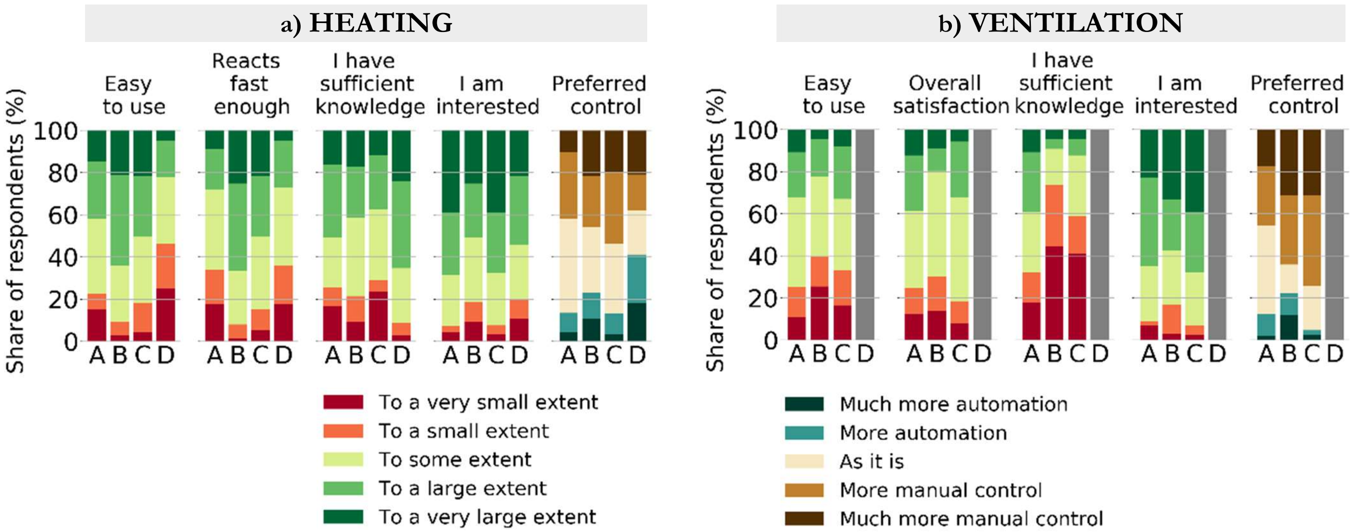

Figure 3 Usability of (a) heating systems and (b) ventilation systems.

to the non-retrofitted case is visible – most critically as to air humidity, and to a lesser extent as to air heaviness and smell. On the contrary, excessive air dryness was experienced more frequently in retrofitted houses. Presence of dust in the air was experienced relatively similarly in all four house types, arguably due to the ongoing retrofit works in the area.

Usability of building services. Figure 3 shows respondents' satisfaction with the usability of the heating and ventilation systems in their homes. Type D houses did not have mechanical ventilation and were therefore not asked these questions, hence the gray bars in the ventilation section. As seen on Figure 3a, radiators in retrofitted houses (types B and C) were perceived as more easy to use efficiently and reacting faster than radiators in non-retrofitted houses (type D) – this may in part be due to the difference in envelope quality rather than the radiators themselves. However, about 25% of the occupants in retrofitted houses felt they did not have sufficient knowledge to operate radiators. As to the floor heating in type A houses, it was perceived as more difficult to use than radiators in house types B and C, and its reaction time was judged as severely as that of type D radiators. 25% of occupants stated lacking knowledge to operate the floor heating; however, interest in its operation was the largest (together with type C). In their comments, several respondents mentioned being irritated by the difference in floor temperature from room to room, due to the presence of one thermostat per room. In type D houses, preferences in terms of heating control were almost perfectly distributed among the five levels of automation proposed. Conversely, less than 20% of occupants of retrofitted houses wished a higher degree of automation: occupants of these houses were generally in favor of unchanged or more manual control. The setpoint control system in place in type A houses, offering setpoint scheduling together with manual adjustments centrally or at room level, was the one giving the largest share of satisfied occupants.

Occupants' opinion on ventilation system usability was more negative than on heating system (Figure 3b). Lack of sufficient knowledge to operate it was very strongly expressed in house types B and C, where the change to ventilation was done the most recently and where ventilation was not user-controlled. The overall interest in the system was however large in all three house types. As to the preferred level of control, type A houses were again those where the current mode of control (moisture-controlled turbo mode with a possibility of manual activation) was the most satisfying. In type B houses, where ventilation operated with a simple CAV mode without any moisture control, about 25% of occupants wished more automation (possibly moisture control), while more than 60% would prefer manual control on the ventilation operation. In type C houses, which had CAV ventilation with automatic moisture control in the bathroom, this share was over 75%, while less than 5% wished more automation. A combination of automatic pollutant removal and manual user control thus seemed to satisfy occupants the most. In the comments section, several occupants regretted a lack of detailed information and guidance on heating and ventilation operation after move-in.

Figure 4 shows the respondents' evaluation of the ventilation air supply in retrofitted houses. Occupants responded

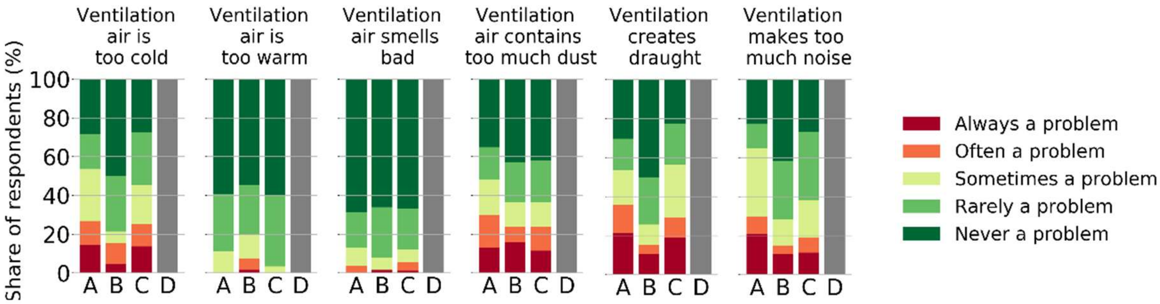

Figure 4 Satisfaction with ventilation air supply.

similarly when asked if the ventilation air was too cold or if ventilation created draught; these issues were the least frequent in house type B, where air supply occurred at floor level. In house type C, some respondents commented on inappropriate diffuser placement (above the sofa area). Almost none of the respondents were concerned with the ventilation supply air being too warm or carrying unpleasant smells. About 25% of respondents indicated frequent problems with dusty ventilation air, about the same as for the question related to presence of dust in the air. Finally, occupants of house type A were more often disturbed by noise from the ventilation system than their neighbors.

Occupant behavior. Occupants were also asked to report the frequency of adaptive actions in case of cold discomfort in winter and of warm discomfort in summer. However, it was found that occupants rather reported the frequency of these adaptive actions in general, and therefore the answers were largely correlated to the frequency of discomfort itself. Therefore, Figure 5a and Figure 5b show the ranking of the four proposed options in terms of adoption frequency for each season. The options mentioned with equal frequency were give the same ranking. Adapting one's clothes to the season was one of the actions most often chosen by occupants, both in summer and in winter and in all house types. In winter, the type of house and of heating system did not significantly affect the thermal adaptation. Turning heat up was in the top two choices for about 80% of residents, while very few of them used an extra heater. In summer, opening windows to cool down was priviledged by most of the occupants. Closing blinds and turning on fans were prioritized higher by occupants of retrofitted houses than occupants of non-retrofitted houses, with occupants of type A and B houses (who suffered the most from overheating) resorting to these actions the most frequently.

Respondents were also asked how often they aired out by opening windows in winter and in summer (Figure 5c). Over 90% of all occupants aired out several times a day in summer (most probably keeping windows and doors open a large share of the day). Airing out in winter was also a daily practice for most respondents, even though the improved indoor climate after the retrofit and the installation of ventilation made airing out practically unnecessary for about 15%

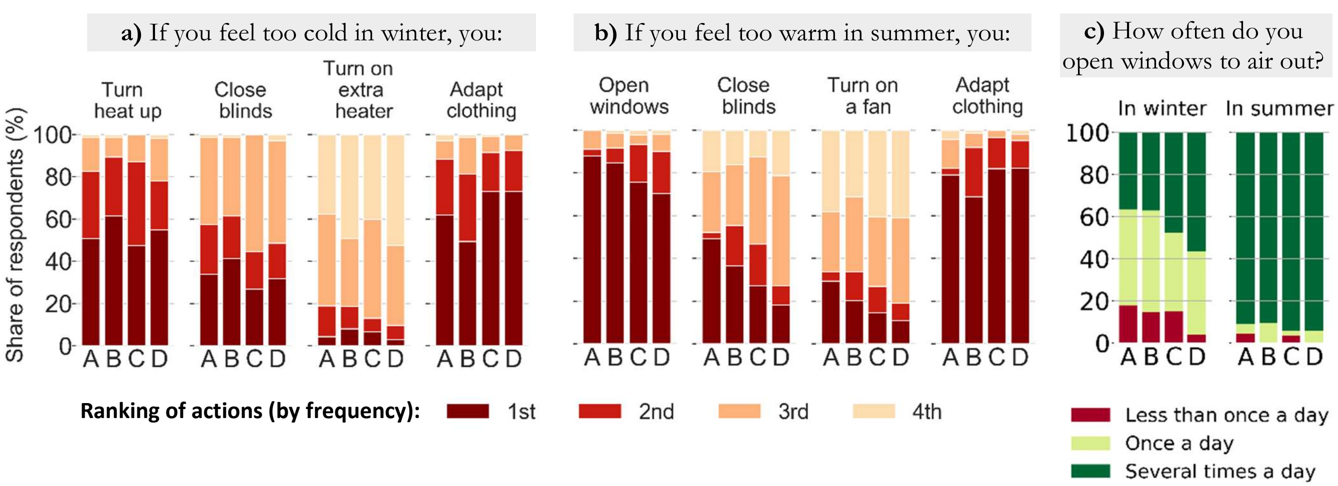

Figure 5 Adaptive actions in case of thermal discomfort (a) in winter and (b) in summer; (c) airing frequency.

Table 3. Five proposals on information, diagnosis and control

Proposal 1	To receive advice regarding the control of the indoor climate
Proposal 2	To be able to visualize the temperature and air quality in your home
Proposal 3	To be able to control heating and ventilation via an app
Proposal 4	To have a system that automatically identifies the operational errors in the building services
Proposal 5	To know how much energy you use in comparison to your neighbors

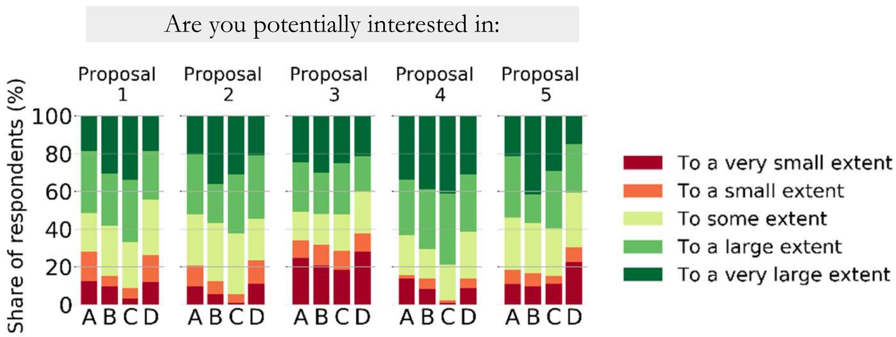

Figure 6 Interest in the five proposals.

of respondents in retrofitted houses (which they explicitely said in the comments section). Meanwhile, 35 to 50% of the respondents in retrofitted houses aired out several times a day in winter in spite of the presence of mechanical ventilation, possibly indicating some routines that were independent from the actual air quality.

Indoor environment and energy use visualization. The last section of the questionnaire contained a set of proposals for services aiming at providing occupants with in formation, control and diagnosis tools regarding their heating and mechanical ventilation systems. The detailed proposals are shown in Table 3. The occupants were asked to what extent they were interested in such proposals; their responses are shown in Figure 6.

All of the proposals were overall met positively. The most popular proposal overall was Proposal 4, related to automatic fault detection and diagnosis, possibly highlighting the lack of confidence occupants had in the good operation of the building services. The proposal gathering the most disinterest was Proposal 3, offering control of heating and ventilation systems via a mobile application. A large share of the respondents being elderly and retired, it is possible that the latter would have gathered a larger interest if made to a younger, more digital audience – but the data collected does not permit to verify this hypothesis. For all of the proposals, occupants of the non-retrofitted houses (type D) were among those showing the least interest for the proposed tools. An explanation was given in the occupants' comments: they knew that their houses were about to be retrofitted and did not see the interest in obtaining new tools to handle the indoor climate before the retrofit.

LIMITATIONS

The questionnaire yielded a relatively low response rate (17.1%). A probable reason for this was the length of the questionnaire: while most of the questions permitted to gather relevant data, some of them could have been avoided. For example, asking for satisfaction with the building systems' usability in both living room and bedroom, or asking about cold discomfort in summer and warm discomfort in winter, did not highlight any relevant nuances. Some questions were not understood well by the respondents and should have been formulated differently. The questionnaire was tested by several persons before distribution (including persons not belonging to the university), but this testing process could have been made on a larger scale and with an even more diverse test group. Because of the low response rate, the findings expressed here cannot be generalized to the entire population of retrofitted house tenants. However, this questionnaire may be used by other researchers on other target groups in order to obtain, collectively, a reliable picture of the impact of energy retrofit and new building technologies on occupants' satisfaction and comfort.

CONCLUSION

A questionnaire was distributed to 2007 social housing tenants living in four types of retrofitted and non-retrofitted houses, yielding a response rate of 17.1% (344 respondents). Indoor environmental quality was overall greatly improved after the retrofit; however, retrofitted house tenants were more affected by overheating, in particular in bedrooms, and perceived the air as being too dry more frequently. The new radiators installed in retrofitted houses were judged efficient and easy to use, while floor heating was considered slightly more difficult to use and reacted slower. A large number of respondents expressed a lack of knowledge about ventilation system. As to control options, programmable thermostats were the most praised by occupants; and for ventilation the combination of automated moisture control and a manual turbo mode. Some draught and noise issues from ventilation were reported by a share of respondents, but such issues were less frequently reported when ventilation was provided from the floor via grilles under the radiators.

Neither the retrofit nor the type of heating system showed any significant impact on occupant behavior in case of cold discomfort, whereas the increased frequency of overheating in some retrofitted houses made respondents adopt more adaptive actions in summer. A share of respondents reported airing out less after moving into a retrofitted house, while most of them carried on with their routine. Finally, respondents overall expressed a large interest in receiving more information and advice about indoor environment, energy use and possible building services failures, particularly in retrofitted houses. These findings highlight the importance of informing and training occupants, as well as providing them with usable and transparent indoor climate control options, in order for retrofitted houses to be both energy efficient and comfortable.

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