Energy retrofitting effect on perceived indoor climate

A case study of Estonian multi-family buildings

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Master thesis in Energy-efficient and Environmental Buildings
Faculty of Engineering | Lund University

Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

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The degree project is the final part of the master programme leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Keywords: indoor environment, thermal comfort, indoor air quality, window airing habits, energy renovation, occupant survey

Publication year: 2023

Abstract

Energy renovations are an important measure for achieving the European Union's target of climate neutrality by 2050. To meet the EU goal, Estonia needs to fully renovate 14 000 multi-family buildings by that time, affecting the indoor environment conditions of a large number of people. To gain knowledge for the upcoming renovations, the experience of the people living in the multi-family buildings is a valuable source of information on how the current energy renovation methods affect people's indoor climate perception.

The study compared occupants' indoor environment experience in the same type of buildings in five different groups, where one of the buildings was renovated in recent years and the other building was still in its original state. The case study buildings were five renovated and six non-renovated multi-family houses built between the 1960s and 1990s in the Tallinn area in Estonia. A questionnaire survey regarding inhabitants' indoor climate experience and window airing habits was conducted and information about energy retrofitting methods used in the buildings was gathered. Additionally, buildings' measured energy consumption was examined.

The result showed that occupant satisfaction with indoor climate in terms of thermal comfort and air quality could be improved significantly in renovated buildings, compared to their control building in the original state. Still, there are factors such as overheating in the summer, insufficient soundproofing between the apartments, and smell disturbances from inside and outside the building that the current level of renovation solutions does not resolve. However, energy renovation benefits to the occupant include reduced heating energy consumption and increased satisfaction with their overall living environment.

Acknowledgement

The study topic was chosen based on my 10-year experience working on architectural and energy retrofits in Anmeri OÜ, a company specializing in energy retrofits in Tallinn, Estonia. During that time, many multi-family houses were transformed and connections with technical consultants and housing association leaders were established. These connections were a prerequisite for selecting the buildings for the study and conducting the questionnaire survey. Here I would like to thank all the housing association leaders and technical consultants, Anvar Kima, Marek Paju, Tarmo Savi, and Ülar Haug, who agreed to participate in this project and helped with the practicalities of conducting the survey and provided the necessary information.

I would also like to express my appreciation for all the people who responded to the survey. Since the uncertainty of the study was the response rate, an insufficient amount of responses would have failed the experiment. However, there were 182 people who took their time to respond and without whom the study would not have been possible.

Moreover, I would like to thank Dennis Johansson, who found my degree project idea interesting and connected me with my main supervisor Birgitta Nordquist and examiner Victor Fransson. I am grateful to Birgitta for providing valuable knowledge for the project and for her positive support throughout the process. I would also like to thank Victor for the advice at the beginning of the project and for the examination at the end of the process.

Lastly, I would like to thank my colleagues Andrus Taliaru and Risto Taliaru for their help throughout the work course, and Jana Lastotškina for the Russian language version of the survey.

The author gratefully acknowledges permission to use photos in Figure 5, Figure 6, and on the cover, photo courtesy of Tarmo Savi.

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List of abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
BEEN	Baltic Energy Efficiency Network for the Building Stock
BETSI	Byggnaders Energianvändning, Teknisk Status och Inomhusmiljö
EPS	Expanded Polystyrene
ETICS	External Thermal Insulation Composite System
EU	European Union
EURIBOR	Euro Interbank Offered Rate
IAQ	Indoor air quality
IEQ	Indoor environment quality
LPS	Large Panel System
LEED	Leadership in Energy and Environmental Design
NECP 2030	National Energy and Climate Plan 2030
PEIRE	People Environment Indoor Renovation Energy
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PV	Photovoltaic
SBS	Sick Building Syndrome
SIEQ	Stockholm Indoor Environment Questionnaire
SUNET	Swedish University Computer Network
U-value	Thermal transmittance
VOC	Volatile organic compound
WHO	World Health Organization

1 Introduction

To act against climate change, European Union (EU) has a target of becoming climate neutral by 2050 (European Council, 2022a). To achieve this goal, the European Green Deal implements several sustainability policies concerning climate, environment, and energy (European Council, 2022b). Part of the European Green Deal is designated to green energy transition and making existing buildings more energy efficient, as currently buildings are a major energy user in Europe and account for more than a third of EU's carbon emissions (European Council, 2022b). Therefore, energy renovation of existing buildings is a substantial tool for achieving climate neutrality by 2050, as by making existing buildings energy efficient and elongating their lifespan, the need for new constructions is reduced and the emittance of greenhouse gases is lowered (EEA, 2022).

As a member of the EU, Estonia is striving towards reducing the country's energy consumption and lowering carbon emissions. To meet the agreed goals from European Unions' climate and energy policy, Estonia has a National Energy and Climate Plan for the year 2030 (NECP 2030) (Ministry of Economic Affairs and Communications & Ministry of the Environment and the Ministry of Rural Affairs, 2019). In the light of COVID crisis and war in Ukraine, the plan was modified and a draft version was released in 2023 (Ministry of Economic Affairs and Communications & Ministry of the Environment and the Ministry of Rural Affairs, 2023). The draft plan has several updated goals, for example reducing carbon emissions to zero by 2050 and increasing the use of renewable energies to 65 % in 2030. A part of the Estonian NECP30 plan provides for reconstructing the existing building stock.

Though in Estonia the energy renovation process of multi-family buildings started more than 15 years ago, and more than 1000 apartment buildings have already improved their energy efficiency, there are still 14 000 multi-family houses that need to complete their energy renovation by 2050 to meet the national goal (TalTech & Ministry of Economic Affairs and Communications, 2020). Since the beginning of the process, the retrofitting methods have changed and improved, as the knowledge increases, and the targets are altered. The focus of energy renovations up to now has been on energy and financial savings, and the technical condition of the buildings. Although correctly executed energy renovation could improve indoor environment factors such as thermal comfort, indoor air quality, acoustical and visual comfort, this aspect has not been emphasized to a similar extent to the energy argument. However, the importance of indoor environment should not be dismissed, as research on indoor environment shows that a satisfactory indoor climate reduces stress and increases productivity, provides a feeling of well-being, as well as reduces health risks (Kallio et al., 2020).

The experience from the energy retrofits conducted so far is crucial for improving the quality of the renovation outcome in the future. Further, the feedback regarding the indoor environment from the people living in the renovated buildings is valuable information for evaluating the methods used so far and for improving them. Additionally, the example of high satisfaction from improved indoor climate and reduced utility costs can inspire other buildings to undertake the renovation process as well (Thomsen et al., 2016).

Previous research regarding energy retrofits in multi-family buildings shows that they are effectively saving energy, but to satisfy the inhabitant, indoor climate aspects must be recognized as well (Liu et al., 2015). The studies where occupant survey was conducted, show that energy retrofits improve satisfaction mainly with indoor air quality and thermal comfort (Liu et al., 2015; Mikola et al., 2017; Prasauskas et al., 2016). For improving air quality, efficient ventilation is needed (Liu et al., 2015), as failing to improve the ventilation during the retrofitting process can impair the indoor environment (Földváry et al., 2017). Since the perception of indoor climate factors differs among people, personal control is needed, as several studies (Frontczak & Wargocki, 2011; Pedersen et al., 2021) suggest. Moreover, the possibility to regulate technical systems such as ventilation and heating, improves indoor environment perception for the occupant (Pedersen et al., 2021) and helps to save energy by reducing window airing as a method for indoor environment control (Fransson, 2014).

Knowingly there has not been a comprehensive occupant survey regarding indoor climate in Estonian multi-family houses built between the 1960s and 1990s, that involves several aspects of indoor environment quality, inhabitant's window airing habits, and general well-being. The aim of the current study is to research the indoor environment experience in buildings that have completed the energy renovation process or are doing it in the coming years.

The paper consists of background information about energy renovations in Estonia, mainly about how and why the renovations are performed. This is followed by a short overview of indoor environment factors and their importance on human health and well-being. A literature review introduces previous studies regarding energy renovations and indoor climate in multi-family buildings. In the method part, case study buildings and the questionnaire survey about indoor environment quality and window airing are introduced. Later, the results are presented, including the outcome of the survey, comparing the results between different buildings, or building groups. Finally, the discussion and conclusion emphasize the main findings and connections with previous studies and possibilities for further research.

1.1 Background

1.1.1 The housing stock

According to Bruns (1993), World War II destroyed a big part of the housing stock in Estonia, including nearly half of Tallinn's dwellings. The industrialization and following fast growth of city dwellers resulted in a lack of housing. This induced a planning and building process, which gained momentum in the 1950s when the first new residential areas were built. Building scope further increased after 1960, when an abundance of new multi-family housing was constructed. The new houses were mostly Large Panel System (LPS) buildings, alike the constructions built in many other countries at the time due to the worldwide industrialization in the building sector (Kalamees et al., 2009). The LPS buildings are constructed of multi-layer (sandwich-type) or single-layer prefabricated panels (Kalamees et al., 2009). From 1960s until 1990, substantial residential areas such as Mustamäe, Õismäe, and Lasnamäe in Tallinn and Annelinn in Tartu were built using the new construction methods. Besides the LPS buildings, the multi-family dwellings in several residential areas were constructed of small blocks and brick, the housing type that is referred to as "khrushchevka". The new houses had several amenities and central heating, which were lacking in many older buildings, that used wood-burning stoves for room heating and had poor bathing facilities. Therefore, new modern housing was welcomed by the inhabitants.

The building scope between 1960 and 1990 was considerable, but the quality of the construction was often questionable. While the load-bearing constructions were decent, the materials of the walls' exterior layer and insulation were often of lower class and faulty (Masso, 2001). The thermal properties of the exterior wall and roof constructions were insufficient for the local climate, and the heat losses through the exterior constructions exceed today's requirements significantly (Masso, 2001). The default constructions included thermal bridges in many instances, typically between the panel joints, i.e., between parapet panels and external wall panels. The thermal bridges were also in the connecting points at balcony slabs and exterior wall panels. But the shortcomings of the constructions were not seen as problematic, since energy efficiency was not a consideration at the time (Ministry of Finance of the Republic of Estonia, 2022).

By the 1990s – 2000s the housing that was built decades ago had started deteriorating. The life span of the LPS buildings was stated to be 50 years, which was nearing the end for some of the buildings. The main problem was not load-bearing constructions, but the constructions that were more exposed to the outdoors, such as balconies and canopies, which were showing signs of carbonization. There are ongoing discussions about whether the buildings are still in good condition for use, whether there is a purpose in conducting the renovations as energy consumption, the indoor climate, and the room plan do not meet today's standards; or should the buildings instead be demolished. The issues are complicated because most of the apartments are under private ownership and homes for many people. Moreover, the existing building stock accounts for a lot of embodied energy. Some areas, where the number of inhabitants has decreased significantly, have managed to demolish some of the empty houses, but this is not the case in more populated areas such as Tallinn and Tartu.

1.1.2 Reconstructions of multi-family houses in Estonia

1.1.2.1 The reconstructions

The first reconstruction of an LPS multi-family house was made in 1993 (Kalamees et al., 2009). The beginning of the renovation process was slow, but the renovation pace has gained momentum since the end of the 2000s due to European Union subsidy. Currently, the need for energy retrofitting is intensifying due to the new long-term energy efficiency and renovation targets for 2050.

To reach the energy efficiency goals of the European Union's Operational Programme for Cohesion Policy Funds, non-recurrent support from European Structural and Investment Funds is used. The funds are targeted for making positive changes in development in Estonia with longstanding effect (Ministry of Finance of the Republic of Estonia, 2022). One part of the structure funds is aimed at retrofitting multi-family buildings and small residential houses (Ministry of Finance of the Republic of Estonia, 2022). Until recently the financial aid was targeted for the houses built before 1993, but the latest subsidy terms in effect from March 2023, have extended the subsidy opportunity to all the multi-family dwellings built before 2000 (Ministry of Economic Affairs and Communications, 2023b). The subsidy to reach energy efficiency in buildings is implemented by KredEx, a foundation by the Ministry of Economic Affairs and Communications that was created in 2001 for financial assistance (KredEx, 2023).

The beginning of a large-scale renovation program with the aid from the EU could be marked from 2006 when KredEx arranged a competition to find a multi-family house to be awarded 1 million Estonian kroons for a complex reconstruction funded by Baltic Energy Efficiency Network for the Building Stock (BEEN) project (KredEx, 2008). The winning house had to reach at least 30 % energy savings and insulate facades, roof, and renovate heating and ventilation systems (KredEx, 2008). The report from the BEEN project concludes that the inhabitants appreciated the increased thermal comfort and the appearance of the renovated building as well as the decreased utility costs (KredEx, 2008). By the time of the compilation of the report, the building's heating energy consumption from November and December in 2007 was 71 % of the heating energy of the same period in 2006 (KredEx, 2008).

The program gained popularity since then and between 2010 and 2020 1114 multi-family houses were retrofitted using the subsidy system (TalTech & Ministry of Economic Affairs and Communications, 2020). The most recent funds for the next renovation period is 80 million euros for around 200 multi-family buildings (KredEx, 2023), though the number of applying housing associations is higher. As an indicator of the ongoing energy crisis, the terms from 2023 (Ministry of Economic Affairs and Communications, 2023b) also have a focus on renovating the inefficient heating systems by replacing them with district heating or a system that uses renewable energy (KredEx, 2023).

The program subsidizes the cost of the renovation project and appraisal of the project, as well as the cost of the construction, building supervision, and consultants throughout the retrofitting process (Ministry of Economic Affairs and Communications, 2023b). The conditions to be qualified for financial aid have changed throughout the years since the program has been efficient. Also, the proportion of the subsidy varies in different areas of Estonia. Currently, the levels of the subsidy depend on the region, cities like Tallinn and Tartu receive less support (30 % of the renovation cost), and in rural areas where the value of the real estate and inhabitants' income is lower, the percentage of financial aid is 50 % (Ministry of Economic Affairs and Communications, 2023b). The wealthier regions bordering Tallinn and Tartu have a support rate of 40 % (Ministry of Economic Affairs and Communications, 2023b).

According to a regulation that determines the subsidy terms (Ministry of Economic Affairs and Communications, 2023b), the renovated building must meet energy class C, which means the energy use intensity is between 125 kWh/(m²·a) and 150 kWh/(m²·a), including the energy used for heating, cooling, hot water, ventilation, lighting, and electrical appliances (TTJA, 2023). There are several other requirements for the construction and technical systems, the main ones are shown in Table 1.

Table 1: Main requirements for reconstruction according to the current subsidy terms

CONSTRUCTIONS	
U-value exterior walls / (W/(m²·K))	≤ 0,20
U-value roof / (W/(m²·K))	≤ 0,12
U-value windows / (W/(m²·K))	≤ 1,10
Window-wall linear thermal transmittance / (W/(m·K))	≤ 0,05
VENTILATION SYSTEM	
Type	Mechanical intake-exhaust ventilation or exhaust ventilation with heat recovery
Heat recovery efficiency / (%)	> 70
Minimum intake air rate	10 l/s in living rooms and bedrooms
Intake air noise level / (dB(A))	25
Extract air rate in 1-room apartments	10 l/s in toilets and bathrooms, 6 l/s in kitchens
Extract air rate in 2-room apartments	15 l/s in toilets and bathrooms, 8 l/s in kitchens
Extract air rate in 3-room and larger apartments	10 l/s in toilets, 15 l/s for bathrooms, 8 l/s in kitchens
HEATING SYSTEM	
Temperature regulating interval / (º C)	18-23

1.1.2.2 The long-term renovation strategy

Estonian long-term strategy for reconstruction (TalTech & Ministry of Economic Affairs and Communications, 2020) involves the whole building stock built before 2000. The strategy states that all buildings built before the year 2000 need to be renovated to reach Estonian energy class C by 2050. The main targets of the plan are to reach energy efficiency while taking account of the environmental impact of the renovations, also to improve the quality of indoor climate, and make the buildings more convenient to use. Another goal is to develop new reconstruction methods to improve building practices and cost-efficiency. Additionally, the strategy has a goal of mitigating the effect of climate change and ensuring housing in all regions. The strategy states that the methods affect around 80 % of the population, improving the quality of their living environment. Out of the total building stock that is influenced by the long-term reconstruction plan, there are around 14 000 multi-family buildings that need to be fully renovated.

According to the long-term renovation strategy (TalTech & Ministry of Economic Affairs and Communications, 2020), annually around 400 multi-family buildings have some level of renovation work carried out. The strategy finds that the number of full renovations needs to be doubled to reach the renovation goal by 2050 and does not consider it impossible if the partial renovations are replaced with full renovations.

1.1.2.3 The limitations

There are still some limitations to reaching the long-term renovation strategy target. It is considered to be unrealistic due to a lack of investments (Ministry of Finance of the Republic of Estonia, 2022) and a lack of competent designers and builders in the small market of Estonia. Technological solutions need to be developed to advance the renovation works, for example reconstructing with factory-made panels, which would unify and speed the process (TalTech & Ministry of Economic Affairs and Communications, 2020). This solution has already been used in some reconstructions, but currently, the cost of this type of renovation is too high for an average housing association.

The limitations for renovation often include the inhabitants, who are against the costly retrofitting. As stated in the long-term renovation strategy, the most important factor is the owner of the building who has to have the will to renovate (TalTech & Ministry of Economic Affairs and Communications, 2020). The multi-family houses are often homes for pensioners, many of them have lived in these buildings since they were built. Currently, the inflation in Estonia is around 17 %, and the inflation of dwellings, electricity, and gas is more than 30 % (European System of Central Banks, 2023), therefore the everyday costs and energy costs are high. The Euro Interbank Offered Rate (EURIBOR) for the bank loans, that are used to cover the renovation works has exceeded 3 % (Swedbank, 2023). According to the representatives of the housing associations, the usual monthly renovation fund is now 4 – 5 €/m², compared to 2 €/m² some years ago. Around 2015-2018, the post-renovation savings from heating costs were approximately equal to the renovation loan payments, however, currently the renovation loan payments exceed the savings from reduced heating costs.

Most of the dwellings (98 %) are in private ownership (Ministry of Finance of the Republic of Estonia, 2022). Each multi-family building is required to form an apartment association, a legal person in private law that includes all the apartment owners and manages the building (Riigikogu, 2023). The decisions in the apartment associations are made through voting, furthermore, the vote of more than one-half of the members is needed to reach a resolution (Riigikogu, 2023). Therefore, the housing associations rely on the vote of the majority of the members to make the decision to renovate. Considering so many limiting factors, the vote is often against it. According to the housing association leaders, there is a lot of skepticism around the renovations that are based on a few unsuccessful retrofitting cases and on occurrences where the newly renovated building experienced problems with new technical systems.

Another limiting factor is the situation in Estonian rural areas. Outside of cities the subsidy system often does not cover the gap in needed funds to renovate a multi-family building. It is difficult to get a loan from the banks to cover the rest of the renovation cost after the subsidy, yet the rural areas have the highest financial aid rate of 50 % (TalTech & Ministry of Economic Affairs and Communications, 2020). Moreover, in these areas, the value of real estate is still low after renovation.

1.1.3 Indoor environment

As the study focuses on indoor environment factors in multi-family buildings, the main components contributing to the indoor climate experience are introduced through a literature review.

The indoor environment is formed from environmental aspects such as thermal comfort, indoor air quality (IAQ), lighting, and acoustics (Khovalyg et al., 2020). Additional factors affecting the indoor experience among many others are perception of scents, view out, colors, construction vibrations, and feeling of security (Sarbu & Sebarchievici, 2013). Moreover, the perception of these conditions is very subjective, depending on the occupants' preferences, age, gender, clothing, and several other factors (Rupp et al., 2015).

Up to 80 % - 90 % of the time is spent indoors (Republic of Estonia Health Board, 2023), therefore indoor environment has a big impact on health, well-being, and work performance (Kallio et al., 2020). Even seemingly insignificant factors, such as noise, can have adverse effects - fatigue and headaches can be caused by a stress reaction induced by noise disturbance (Boverket, 2009). Indoor climate related health nuisances are collected under the umbrella term of Sick Building Syndrome (SBS). The term SBS was initially used in offices with inadequate indoor environment, where the workers experienced a number of temporary health symptoms like headache, fatigue, and irritation of skin and mucous membranes, that appeared only while using the building (Bernstein et al., 2008). It is suggested that dissatisfaction with indoor environment factors such as thermal comfort, air quality, relative humidity, lighting, and acoustics are the culprits for SBS, along with other stressors like work dissatisfaction (Bernstein et al., 2008).

Not only environmental factors themselves influence the way the indoor environment quality is perceived, but also the feeling of having control over the indoor environment (Pedersen, Gao, et al., 2021). A literature review study by Frontczak & Wargocki, (2011) finds that the opportunity to regulate the indoor climate by the occupants themselves improves the satisfaction with many aspects of the indoor environment. Therefore it is important that the inhabitants have the opportunity to change the indoor climate parameters themselves, for example changing heating or ventilation system settings according to their individual needs, and are also well-informed about the possibilities for regulating (Pedersen et al., 2021). Additionally, sustainable building certification systems such as LEED and BREEAM give points for buildings where personal environmental control is included in the design (Mujan et al., 2019).

Accordingly, the indoor environment is a combination of the design of the building, its systems, and user behavior (Nordquist et al., 2014). Buildings' energy use is strongly tied to its heating system, ventilation, and lighting settings (Sarbu & Sebarchievici, 2013). In turn, these systems are influenced by people's behavior, their interactions with technical systems, and their window-opening habits, which sometimes can lead to higher energy consumption than expected in the design phase (Pedersen et al., 2020).

Mujan et al. (2019) studied the impact of all four indoor environment components and finds that they need to be studied holistically. Indoor air quality and thermal comfort depend on each other since they have overlapping parameters (Mujan et al., 2019). Furthermore, dissatisfaction with visual and acoustic comfort can lead to discontentment with the thermal environment (Mujan et al., 2019).

1.1.3.1 Thermal comfort

One of the main components contributing to the indoor climate is thermal comfort and from the occupants' perspective, it is the most relevant indoor environment factor (Frontczak & Wargocki, 2011). The study by Geng et al. (2017), finds that the changes in thermal conditions can also affect the sensation of other indoor environment components, especially affecting the contentment with indoor air quality and lighting. Thermal comfort is also one of the key factors in IEQ and is studied the most (Mujan et al., 2019).

Human beings' body temperature is adjusted to around 37 º C and any minor fluctuations away from that can cause stress (Lechner, 2015). According to ISO standard SS-EN 7730:2006 (Swedish Standards Institute, 2006), that balance is impacted by peoples' clothing and activity level, and by four main environmental factors - temperature, relative humidity, air movement, and mean radiant temperature. These six conditions are also noted as principal factors for thermal comfort by ASHRAE, (2010). The ISO standard further notes that the balance of thermal comfort can be interrupted by some additional factors, such as substantial differences in radiant temperature, draught, contrast in vertical air temperature, and uncomfortable floor temperature (Swedish Standards Institute, 2006).

A mix of the aforementioned four environmental factors determines the sensation of thermal comfort and there are particular combinations of these components that the majority of occupants perceive as comfortable (Lechner, 2015). The comfort zone, a combination of environmental factors that the majority of people are satisfied with, is shown in a psychometric chart in Figure 1.

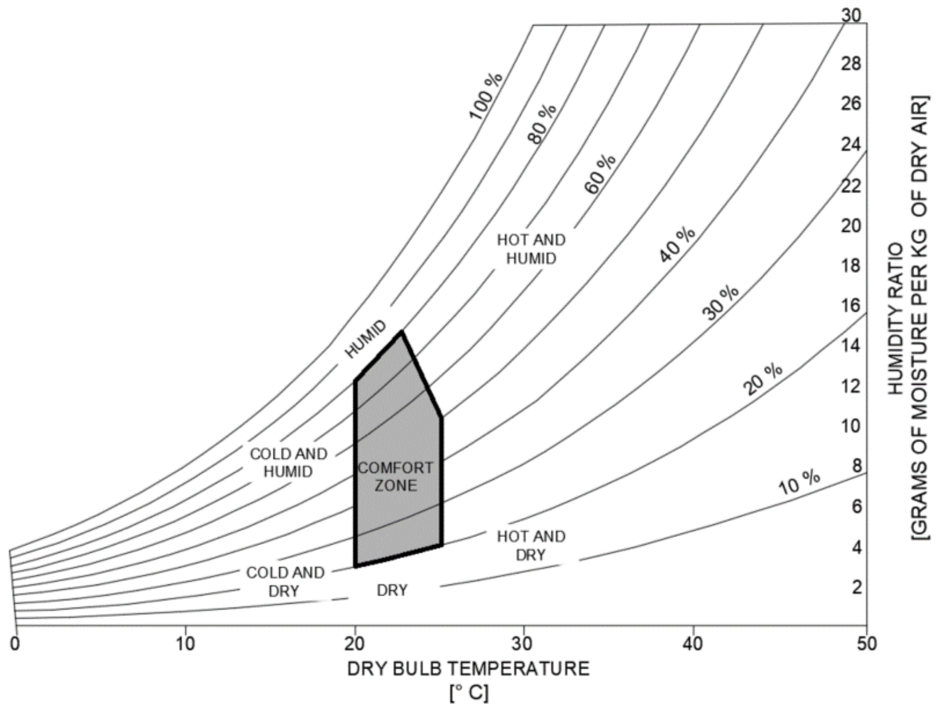

Figure 1: Thermal comfort zone shown in ASHRAE psychrometric chart, adopted from Lechner (2015)

Due to the large variations in preferences for thermal comfort, it is challenging to meet individual needs in a space (ASHRAE, 2010). For example, in addition to the environmental factors and the influence of peoples' clothing and activity, the thermal sensation is also influenced by inhabitants' cultural background, habits, personal preferences, age, gender, room plan, and the option to regulate indoor climate (Rupp et al., 2015).

Related to thermal comfort is adaptive comfort, which is a phenomenon occurring for example in naturally ventilated buildings, where the occupants have more options to regulate their environment (Lechner, 2015). Lechner describes three different manners of adaptive comfort, first, behavioral adaption, where the residents implement different measures to relieve the discomfort, such as wearing more clothes when it is too cold or opening windows with excessive heat. Secondly, the physiological adaptation, meaning the body adjusts the blood flow to the skin according to the thermal sensation or regulates sweating. Thirdly, psychological adaptation, which means the expectations of the occupants change, for example, people can tolerate higher temperatures in the summer and lower temperatures in the winter without having a deteriorating effect on thermal comfort.

Thermal comfort has a notable effect on productivity, where steady temperatures between 20-25 º C are considered the most suitable for work tasks (Mujan et al., 2019). Simultaneously, dissatisfaction with the room temperature lowers work performance (Sarbu & Sebarchievici, 2013). The study by Geng et al. (2017) finds similarly, that enhanced thermal comfort increases work performance and neutral or somewhat cool temperatures are the best for productivity.

An article by van Hoof et al. (2017) finds that the perception of thermal comfort is different for elderly people and young grown-ups. The common health issues that elderly people have make them more sensitive to more extreme indoor environment conditions such as cold and hot temperatures. The extreme temperatures in winter and summer increase health risks for the elderly but are also setting a higher heating or cooling need, which can have a negative effect on their finances. The study finds that elderly people prefer adjusting the indoor climate by behavioral measures, such as regulating their clothing or opening windows, if possible. It was also found that the possibility for older people to regulate their thermal conditions is an important factor for comfortable aging. Moreover, pleasant indoor conditions reduce certain health risks, which are associated with poor thermal comfort.

1.1.3.2 Indoor air quality (IAQ)

Since most of the time is spent indoors and the consumption of air is continuous, the air quality has a strong effect on health and well-being. Indoor air quality is influenced by physical components such as air temperature, relative humidity, and air movements; chemical factors like dust, organic and non-organic compounds, and biological agents such as viruses, microbes, mold, animals, people, and pollen (Republic of Estonia Health Board, 2023). It also depends on people's habits, such as cooking and showering practices, and the window opening frequency (Pedersen et al., 2020). Poor IAQ, especially the volatile organic compounds (VOCs) in the air, can cause allergies, skin, and eye irritation (Bernstein et al., 2008) as well as asthma and impaired lung function (Wang et al., 2023).

Bernstein et al. (2008) investigated the effect of air pollution on human health. The study states that the most common contaminators of indoor air are particles in the air, VOCs, cigarette smoke, and various gases (i.e., carbon monoxide, ozone, sulfur dioxide). VOCs originate from building materials, such as paints, carpets, and linoleum, and also from furniture, curtains, equipment, and cleaning products; all together around 50-300 VOCs create an odorous mix and cause complaints from the occupants. People occupying the buildings have an impact on it too, common sources of VOCs from people are tobacco smoke, personal hygiene and cosmetic products such as deodorants, lotions and makeup. Mold, often caused by moisture problems inside the building, releases microbial VOCs, resulting in a musty smell. The study also finds that microbial VOCs have been suspected of being the cause of several health problems such as irritation of the mucous membranes and headaches. Indoor particulate matters carry allergens to the respiratory system.

Moisture problems in buildings can cause dampening of the building materials which can subsequently release chemicals and particulate matter into the air (Bernstein et al., 2008). Moreover, microbial agents accompanying moisture damage in the buildings are the culprit for different allergies and irritations (Bernstein et al., 2008). The study by Wang et al. (2023) associates moisture and mold problems in people's homes with impaired lung function.

World Health Organization (WHO) states that 99 % of people on Earth today breathe air that is polluted above the WHO's recommendations, and currently air contamination is the greatest environmental hazard to human health, causing respiratory diseases, heart diseases, and cancer (World Health Organization, 2021). The main pollutants in outdoor air that have an adverse impact on health, are particulate matter and ozone (O_3), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) (World Health Organization, 2021), originating from land, air, and water transport, various industry and power plants (Leung, 2015). The contamination from outdoor air can enter buildings via opened windows and doors, infiltration, or mechanical ventilation, moreover, the pollution of indoor air is related to the infiltration and ventilation rates, as well as the quality of outdoor and indoor air (Leung, 2015).

Besides the compounds occurring in the indoor air, and the state of the outdoor air, the quality of the indoor air also depends on the ventilation type and air exchange rates. It was noted that the occurrence of asthma and allergies was lower among children, who lived in homes with higher ventilation air flows (Bornehag et al., 2005). A study by Persson et al. (2019) investigated newly-built low-energy preschools in Sweden and concluded that an airtight envelope, which is a prerequisite for an energy-efficient building, requires a properly working ventilation system, otherwise the emissions from the building materials can pollute the indoor air and result in health problems associated with the VOCs.

From the occupant's perspective the quality of air is seen as good, when there are no apparent disturbances, such as smell (Frontczak & Wargocki, 2011). The lack of smell is not a good indicator of air quality, since there are many elements including radon, carbon monoxide, and pathogens that are odorless but toxic (Abel et al., 2014).

Finally, indoor air quality is linked to the energy efficiency of a building, as well as operating costs. When the air exchange rates are higher, the ventilation system is consuming more energy and therefore has a negative effect on the buildings' energy efficiency (Mujan et al., 2019). Mujan et al. (2019) also find that the focus of building design is shifting from achieving low energy consumption to creating a healthy environment in a well-functioning building.

1.1.3.3 Visual comfort and daylight

Visual comfort is one of the most important factors of health, productivity, and indoor comfort, both in homes and in office buildings; moreover, visual comfort is the best with daylight (Mujan et al., 2019). Daylight has a positive effect on visual performance and it helps synchronize circadian rhythm (Knoop et al., 2020). Additionally, good daylight conditions help with energy savings in the form of reduced usage of electric lighting (Lechner, 2015).

As visual comfort is crucial for productivity, lighting conditions in workplaces have high importance. The European Standard EN 12464-1:2011 which regulates lighting conditions in workplaces, and states that lighting conditions need to ensure visual comfort, visual performance, and safety (Swedish Standards Institute, 2011). These factors contribute to well-being and productivity and allow to carry out needed tasks (Swedish Standards Institute, 2011). The visual conditions are affected by luminance dispersion, illuminance, direction, and changeability of light, color rendering, glare, and flicker (Swedish Standards Institute, 2011). Factors such as glare, reflections and a much too bright environment can cause discomfort (Lechner, 2015). Even experiencing low levels of glare has an impact on visual performance and can cause tiredness (Knoop et al., 2020).

An article by Knoop et al. (2020) notes that a way to control well-being indoor environment from the factors outside, for example, smells, noise, and temperature, are windows. Windows allow a view out, and provide daylight, ventilation, and information about outdoors; factors which all impact the feeling of well-being indoors. Additionally, the paper finds that view out influences physical and mental satisfaction, i.e., it can reduce stress. For this purpose, deeper views that provide relaxation to the eyes and mind, are preferred.

1.1.3.4 Acoustics

The sounds that contribute to the acoustical comfort originate both from outside and inside of the building; the noise can be transported by air or by constructions and can carry through the exterior walls, floors, ventilation system, and technical installations (Torresin et al., 2020). Acoustical comfort is also reliant on the physical characteristics of the room and sound, and from the occupants' point of view it is more expressed as a lack of acoustic dissatisfaction (Frontczak & Wargocki, 2011). The unwanted sounds indoors can cause stress, frustration can affect the ability to concentrate, and can cause tiredness and loss of hearing (Roumi et al., 2023).

A literature review by Al horr et al. (2016) found that although there has been sufficient research regarding acoustics and indoor environment, acoustic well-being is still poor. The study marks that sustainable building certification systems such as LEED have acoustics as one of the assessment criteria, but it is not seen as a first concern, even though acoustical comfort has a direct impact on productivity. It was noted that acoustic discomfort in office buildings was mostly addressed as disturbance from different ambient noises and privacy issues while communicating.

1.1.4 Indoor climate standards and regulations

According to the critical review paper by Khovalyg et al. (2020), the requirements for indoor environment are divided between various standards. Indoor environment in general is covered in EN 16798 (it replaced an earlier standard EN 15251), and ISO 17772. The thermal environment is covered in ISO EN 7730 and ASHRAE 55 and indoor air quality in ASHRAE 62.1 and ASHRAE 62.2. Out of these, the European Union uses mainly EN and ISO standards.

The ISO EN 7730 standard describes the predicted percentage dissatisfied (PPD) index, which shows the anticipated percentage of people who are dissatisfied with their thermal comfort, finding it too warm or too cold, in a certain indoor environment (Swedish Standards Institute, 2006). The PPD can also be derived from the predicted mean vote (PMV), an index that predicts the mean value of votes of a big group of people evaluating their thermal comfort on a seven-point scale (Swedish Standards Institute, 2006). The PPD and PMV are used for determining indoor environment categories, which are applied for designing thermal environment in mechanically heated and cooled buildings (Swedish Standards Institute, 2019). The categories are shown in Table 2. The PPD of the current study results can be used as an indicative measure for understanding if the indoor environment is satisfactory or not.

Table 2: Categories of thermal environment, adopted from SS-EN 16798-1:2019 (Swedish Standards Institute, 2019) and SS-EN 15251:2007 (Swedish Standards Institute, 2007)

Category	**Explanation**	**Thermal state of the body as a whole**	
		PPD (%)	**PMV**
I	High level of expectation, recommended for spaces occupied by very sensitive and fragile persons	< 6	- 0,2 < PMV < + 0,2
II	Normal level of expectation, used for new buildings and renovations	< 10	- 0,5 < PMV < + 0,5
III	An acceptable, moderate level of expectation and may be used for existing buildings	< 15	- 0,7 < PMV < + 0,7
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year	< 25	- 1,0 < PMV < + 1,0

The European Standard regulating light and lighting in indoor work places (Swedish Standards Institute, 2011) focuses on regulating visual comfort, visual performance, and safety. The same European Standard is used for designing Estonian workplaces.

The Estonian acts give more general guidelines and various standards are used for more precise requirements. For example, the local act “Requirements for a dwelling” (Ministry of Economic Affairs and Communications, 2020), which is applied to new buildings and for buildings that undergo substantial renovations, states that dwellings must have ventilation that provides sufficient air exchange, the indoor air temperature must be optimal, the indoor air temperature must be minimum 18 º C in dwellings heated by district heating or local heating plant. Additionally, relative humidity must be in such a range that it has no threat to human health, desirably between 40 % - 60 %, and the noise from outside of the building must not exceed 40 dB at daytime and 30 dB at nighttime. The act states that the maximum level of room air temperature, indoor air speed, and harmful compounds in the air must meet the established requirements. The referred requirements are EN and ISO standards and Estonian standards. According to the Estonian Building Code (Riigikogu, 2023b), the indoor climate must not be impaired while achieving energy efficiency. Finally, Estonian Health Board states that currently there is no legislation for pollutant level in indoor air in residential buildings, though there are norms for kindergartens and schools (Republic of Estonia Health Board, 2023).

1.1.5 Previous studies

1.1.5.1 Studies about indoor climate in renovated multi-family buildings in Estonia

The study about energy use and indoor environment in recently renovated multi-family houses by Tallinn University of Technology (TalTech) (Kõiv et al., 2014) focuses mostly on the measured properties of the indoor environment. Indoor air temperature, relative humidity and CO_2 concentrations, and ventilation rates were studied and their compliance with standards were observed. The occupant survey within the study examines the contentment with indoor air quality and thermal comfort. The study finds that natural ventilation is not sufficient to achieve the target ventilation values and room-based ventilation systems often provide the necessary air amount at the maximum speed, which as a result creates so much noise that the inhabitants reduce the air rates. The CO_2 measurements in the apartments were indicating that the room air was stuffy, yet the survey questionnaire results did not demonstrate that. The study notes that this could be because often the airtight new windows were installed before the renovations and people were used to the bad air quality and unaware of the health hazards from insufficient air exchange. Additionally, the study finds that the energy savings can reach 50 % with the renovations, though the savings would be smaller if the required air exchange rates were met. The occupants were generally pleased with the renovation outcome though the savings from the reduced energy consumption were replaced with the reconstruction loan payments.

Similar research, also from TalTech (Mikola et al., 2017) focuses on energy use and measured indoor climate quality, but also examines occupant satisfaction in renovated buildings and evaluates the situation before and after the renovation. The result shows satisfaction with the renovation, especially with increased thermal comfort and the possibility to regulate room temperature. The satisfaction with indoor air quality and the appearance of their dwelling were also high. The primary energy savings compared to the pre-reconstruction state were on average 30 % throughout all the case study buildings.

Research among INSULAtE program, a European Union funded project to develop a code to estimate the influence of energy efficiency on the indoor climate and well-being (EUROPEAN COMMISSION, 2021), focuses on reconstructions in Finnish, Lithuanian, and Estonian multi-family buildings (Prasauskas et al., 2016). The study examines indoor air quality, temperature, relative humidity, CO_2, and pollutants by their measured properties. Additionally, an occupant survey about indoor climate was used. The study indicates that indoor air quality and thermal comfort enhances in all the studied buildings after the renovations, but relative humidity in Lithuanian buildings surged, which was accounted for the reconstruction methods where the airtightness of the building was improved but the ventilation remained insufficient.

1.1.5.2 Studies elsewhere

Similar research has been conducted elsewhere in Europe. Research by Földváry et al. (2017) studies the outcome of simpler energy renovations in Slovakia. The study focuses on indoor climate and analyses three pairs of buildings. The pairs had one renovated building and a non-renovated control building. Besides air quality and temperature measurements inside the apartments, an occupant survey was conducted. Since the renovations focused mainly on energy savings, no improvements were made to the ventilation system and the results showed that the occupants in renovated buildings were less satisfied with the indoor air quality. The study concludes that failing to address indoor climate during energy reconstructions can have adverse effects on indoor air quality (Földváry et al., 2017).

A Swedish study by Liu et al. (2015) describes a similar experiment comparing renovated and not yet renovated multi-family buildings. Alongside measurements on site and energy simulations, a survey about the indoor environment and health was organized. The installation of a more efficient ventilation system in the retrofitted building resulted in higher occupant satisfaction with indoor air quality, compared to the non-retrofitted building. Other positive effects of retrofitting such as fresher air and increased thermal comfort were also noted.

Similarly to Földváry et al. (2017), the study indicates that retrofitting is an effective measure in achieving energy efficiency targets, but the influence of indoor climate must be acknowledged as well.

Research about the effect of energy renovations on indoor air quality and occupants' health in Finnish and Lithuanian multi-family buildings was done within the framework of INSULAtE project (Haverinen-Shaughnessy et al., 2018). The buildings were studied before and after the renovations using measurements and occupant survey. The research concluded that energy renovations could enhance the inhabitants' satisfaction with their indoor climate. The study also notes a negative effect of ventilation system noise on the indoor environment.

A journal article by Thomsen et al. (2016) describes a Danish study in multi-family buildings in Traneparken area, where extensive retrofit methods were applied to achieve energy efficiency. The focus of the study is energy savings from the retrofit and inhabitants' perspective of indoor environment pre- and post-renovation. Ventilation air rates, indoor air temperature, relative humidity, and CO_2 concentrations were measured, and an occupant survey was conducted. The results from the study demonstrate that even though the retrofitting process is not convenient, the tenants are satisfied with the outcome due to the substantially improved indoor climate. The study points out that the high satisfaction rates after the renovations from the occupant survey and lower energy costs are helpful for implementing energy retrofits in the future and inspire the tenants in other dwellings to undergo the renovation process as well.

Nordquist et al. (2014) compared energy use, indoor environment, and window airing habits in newly built houses in Malmö, Sweden with the outcome from a follow-up study some years later. The original study was conducted in freshly built multi-family houses by Hansson & Nordquist (2010), and the follow-up study a few years later after the buildings had been in operation. The research consists of occupant survey, indoor air quality measurements, and interviews among the occupants. The results point out the importance of the occupants' knowledge of how the technical systems in the apartments work since a lack of knowledge might lead to unsatisfactory indoor climate experience. The study finds that the ventilation rates are often lowered due to noise and low ventilation rates make the occupants open windows. Moreover, sometimes the ventilation is switched off or is put on the wrong setting since the information about the system is inadequate (Nordquist et al., 2014).

Within the framework of the study in Malmö by Nordquist et al. (2014), Fransson (2014) observed window airing habits. The objective was to understand the reasons behind the frequent window opening noted in the study from 2010, causing higher energy consumption than predicted. The Stockholm Indoor Environment Questionnaire (SIEQ) was used to study indoor climate and questions about window airing were added to the survey. As a result, the study notes that the predominant reasons for airing were too warm room temperature, dissatisfaction with indoor air quality, and a habit to open windows. The problems with adjusting the heating system and ventilation supply air rates could lead to window airing as a method to regulate the indoor environment (Fransson, 2014).

In Sweden, Boverket's BETSI (Boverket, 2009) project was researching buildings' energy use, technical status, and indoor environment. The project included large-scale research including nearly 10 000 respondents in multi-family houses and private houses. The study examined the occurrence of environmental factors and their relation to user behavior and health problems among the occupants. The research concluded that many inhabitants in multi-family houses are unaware of their ventilation system's type, and they use window airing more often compared to the people living in detached houses. The study also notes frequent moisture damage problems occurring in the studied houses. Skin and mucous membrane related health problems were more common in the houses built in 1976-1985, where the satisfaction with air quality and smells was also lowest. The satisfaction with the indoor environment was better among the respondents who lived in newer dwellings and in detached houses. 20 % of the residents of multi-family houses were disturbed by the noise from the neighbors and roughly the same percentage of respondents noted the disturbance from traffic noise. The noise problem was less common in private houses (Boverket, 2009).

The BETSI study (Boverket, 2009) connects several health problems to the indoor environment. Cough and headache were more prevalent symptoms for people living in multi-family houses with natural ventilation, but other health problems could not be related to the type of ventilation. In all types of housing, the occurrence of mold was related to the heightened number of health problems. The sounds from outside such as traffic and ventilation devices and noises inside the dwelling, for example from technical systems and neighbors, were related to the occupants feeling fatigued or having a headache. It was also noted that often the inhabitants did not connect the health problems with poor indoor climate factors, such as mold growth. One of the main observations was the notable contrast of satisfaction rates among the inhabitants in multi-family houses and private houses, where the satisfaction rates were much higher for detached houses. Also, contentment with indoor climate is generally higher in newer houses.

Lund University has a PEIRE research project, that investigates indoor climate and the effect of renovations on energy use in multi-family buildings (Lund University, 2020). A study by Pedersen et al. (2021), a part of PEIRE project, studied indoor environment quality in renovated houses, mainly focusing on the effect of the ability to control the indoor environment. The project involved 14 3-story buildings in Sweden built in the 1970s. An occupant survey in the buildings showed that the majority of the respondents saw the positive effects of the renovations and expressed satisfaction with the ability to regulate ventilation. However, the occupants who had skin irritation symptoms did not experience noticeable improvement regarding their indoor experience.

Another study by Pedersen et al. (2021) in the framework of PEIRE research, was examining the measures achieving acceptable indoor climate along with low energy use, where the focus was on the occupant's experience. The project involved residential areas in Sweden and consisted of interviews with the tenant groups. The study notes among other findings that the cooperation between the building and the inhabitants determines energy efficiency. The tenants' perspective and education regarding the controls cannot be ignored because it is important for occupants to know how to operate the systems that influence their indoor environment quality. Also, there is a need for further research into the interaction between technical systems and inhabitants. The study notes that often the occupants did not associate indoor climate quality and energy use. Further, people did not know how to regulate systems because of the unclear design of the controls.

1.2 Goal

The paper is investigating occupant satisfaction with the indoor environment in multi-family buildings in the Tallinn area in Estonia. The goal is to research the occupants' indoor climate experience after the energy retrofits through an occupant survey and compare the indoor environment aspects to the results from the control building in its original state. The study aims to discover which perceived indoor environment factors have improved after energy retrofitting and which factors would need further improvement. As it is assumed based on previous research that perceived indoor environment has improved post-renovation, the outcome of the survey could influence the people in non-renovated buildings to undertake the energy renovation process as well.

1.3 Scope

The study is comparing two or three multi-family houses of the same type, in five different groups. One of the buildings in the group has been renovated in recent years and the other building is in its original state operating as a reference case. All the multi-family houses are in the Tallinn area and the total number of buildings where the survey was conducted is 11.

The buildings' constructions, energy renovation measures, and technical systems regarding heating, ventilation, and the options for regulating indoor climate were gathered from the retrofitting projects using the project database from Anmeri OÜ. Housing associations provided measured energy use for the year 2022, presented per m² of the heated floor area.

To compose the questions for the occupant survey regarding indoor climate experience, research about previously conducted surveys was done. The survey questions were adopted from similar research projects in Sweden and in Estonia and were covering thermal comfort, indoor air quality, mold and moisture, noise, and daylight aspects as well as occupants' window airing habits. Additional questions were about general information about the occupant and the apartment as well as general satisfaction with the living conditions. The survey was bilingual, in Estonian and in Russian and it was distributed via online version or on paper to 881 apartments. The survey lasted three weeks in March.

The result was analyzed by comparing the results among buildings in one group and between all the renovated and non-renovated buildings. For some aspects, such as thermal comfort and window airing habits among elderly people, the study results were sorted by the respondents' age. The main aspects for assessing indoor climate in the buildings were thermal comfort and indoor air quality. Window airing habits and measured energy use were studied as well. Further, the outcome was compared to the result of a similar study conducted in renovated multi-family buildings in Estonia in 2014.

The project lasted 4 months from compiling the survey questionnaire in January to finalizing the study in May.

1.4 Limitations

The limitations of the study are listed as follows.

- The questions about health aspects were excluded from the study due to ethical reasons.
- Buildings' measured energy consumption does not include apartments' electricity (everything that households consume) and general electricity (i.e., electricity for general lighting in the stairwells).
- There were no indoor environment parameter measurements in the apartments to compare the measured indoor environment properties to the result from the occupant survey.
- The study was conducted in two or three similar buildings, not in the same building pre- and post-renovation. As the respondents are not the same, different people can have different perceptions of indoor climate factors, which can affect the result.
- Only three people responded to the survey in group 5 renovated building, therefore major conclusions about perceived indoor climate in that building could not be made.
- Two questions in the online questionnaire did not allow multiple-answer options, though the format of the question should have permitted it.

2 Methodology

2.1 Selection of the case study buildings

The multi-family buildings selected for the case study represent some of the most common dwelling types constructed in Estonia between the 1960s and 1990s. Therefore, many multi-family houses of the same type as the case study buildings, are the target of the future renovation process.

The type codes of the multi-family houses referred to in the following description of case study buildings are series codes that were used for the industrially produced buildings in USSR. The series codes refer to building documentation, which consists of the building design and the types of prefabricated elements (Malaia, 2020). These designs could be replicated at nearly unlimited times in the house-building factories, with only minor modifications made at the site (Malaia, 2020). The type codes of the building series are commonly used in Estonian studies. Therefore, the codes have more significance for the local context, allowing the reader, who is familiar with the building series types to envision the building just by the type code.

The renovated multi-family buildings that participated in the case study were selected from the project database of Anmeri OÜ (renovated buildings groups 1, 2, 3, and 4), or proposed by their technical consultant (renovated building in group 5). The selection criteria were that the buildings had to be renovated in recent years, moreover, the renovated building had to have a matching original state control building nearby. Furthermore, the housing association leaders or technical consultants managing the buildings had to be willing to take part in the survey.

The matching non-retrofitted buildings participating in the study were either managed by the same people as in the renovated buildings or were in the middle of the renovation design process with Anmeri OÜ.

Not all the buildings participating in the case study that are grouped together are identical. Identical buildings of the same size and orientation were difficult to find due to the time restriction of the study, as it limited the survey to be conducted in the buildings where connections with the housing association representatives or technical consultants were already made. However, the non-identical buildings that are grouped together are still of the same type and have the same or very similar floor plans, the same number of floors, and the same external wall and roof constructions. Mainly the differences are in the number of floor plan modules (stairwell and apartments around it) repetitions placed next to each other.

Group 1 buildings were chosen because the renovated building was recently renovated and has an identical control building of the same type next to it. The orientation of the buildings is the same. The buildings were managed by the same housing association leader.

Group 2 renovated building finished energy renovations a few years ago. The control building beside is of the same type, has identical floor plan modules, and has the same number of floors. However, the control building has longer facades, consisting of six stairwell modules, while the renovated building has two stairwell modules. The two buildings have the same orientation and are joined by one end wall.

The three multi-family houses in group 3 were recommended by a technical consultant working with the buildings. The renovated building in this group finished reconstruction some years ago. The original building and the non-retrofitted control building A have identical floor plan modules and number of floors, however, control building A has eight stairwell modules, while the renovated building has six. The non-retrofitted building B is not identical to the other two buildings in group 3 regarding its floor plan, however, it still is a modification of the same building type. The original building B has four stairwell modules, and the number of floors is the same as in the retrofitted building and original building A. Initially, control building B in group 3 was grouped with another renovated building of the same type, but the matching renovated building resigned to participate in the survey. Since the original building B was a modification of the same building type as group 3 multi-family houses, the building was used as a second reference building in group 3. In this group, the buildings are not located side by side, though they are in the same neighborhood and maximum of 1,5 km apart.

Group 4 buildings were recommended by their technical consultant. The multi-family houses are of the same type as group 3 buildings, as this type is one of the most common LPS buildings series in Tallinn. Both buildings have six stairwell modules, the same floor plan, and the number of floors. The buildings are beside each other, though the orientation of the longer facades is different. The energy renovation of the renovated building was finished some years ago.

Group 5 buildings were proposed by their technical consultant, as the retrofitted building was renovated some years ago and was side by side with an identical control building.

A more detailed description of the case study buildings is in Chapters 2.2.4, 2.2.5, 2.2.6, 2.2.7, and 2.2.8.

2.2 Case study buildings

The original buildings and the renovated buildings are identical in three case studies, in group 1, group 4, and group 5, where the dwellings are next to each other, thus the external conditions are very similar. In the other groups, there are a few deviations between the original and renovated case. The information about the multi-family houses was gathered using the project database from Anmeri OÜ, Estonian Register of Buildings (Ministry of Economic Affairs and Communications, 2023a), and from the representatives of the apartment associations. The general parameters of the buildings are shown in Table 3. The layouts and images of the case study buildings are shown in Chapters 2.2.4, 2.2.5, 2.2.6, 2.2.7 and 2.2.8.

Table 3: Case study buildings

Group	Type	State of building	Year built	Net floor area (m²)	U-value (W/(m²·K)) External wall	Roof	Windows	No of apartments	No of floors
Group 1	111-121	Original	1987	1 964,1	0,91	0,67	1,5-3,0	30	5
		Renovated	1992	1 970,4	0,18	0,09	1,1	30	5
Group 2	1-464D-84	Original	1972	14 336,6	0,90	0,20*	1,5-3,0	216	9
		Renovated	1972	5 026,8	0,20	0,18	1,1	72	9
Group 3	1-464A	Original A	1969	7 452,4	0,91	0,25**	1,5-3,0	119	5
		Original B	1964	4 511,2	0,91	0,69	1,5-3,0	80	5
		Renovated	1966	5 660,0	0,19	0,11	0,9	90	5
Group 4	1-464A	Original	1968	5 653,5	0,91	0,69	1,5-3,0	90	5
		Renovated	1967	5 669,0	0,20	0,13	1,1	90	5
Group 5	1-317	Original	1961	1 512,4	0,88	0,98	1,5-3,0	32	4
		Renovated	1959	1 504,5	0,18	0,12	1,1	32	4
Total original			-	-	-	-	-	567	
Total renovated			-	-	-	-	-	314	

**The roof construction had 150 mm of insulation added to the roof during the previous reconstruction*
***The roof construction had approximately 100 mm of insulation added to the roof during the previous reconstruction*

2.2.1 The existing constructions

2.2.1.1 Walls and roofs

The multi-family dwellings investigated in this study are built between 1959 and 1992, in the period when the construction of multi-family Large Panel System (LPS) houses was the most active in Estonia. The buildings from this period still account for about 60 % of the total area of residential building stock (Eesti Statistika, 2021). Among other issues, the common problems of LPS concrete houses from that era are non-airtight envelope and insufficient thermal insulation (Prasauskas et al., 2016).

Nine out of eleven multi-family buildings (types 111-121, 1-464D-84, and 1-464A) examined are LPS buildings, where industrially produced panels for walls and ceilings are used (Talviste, 1983). For this type of construction fibrolite, mineral wool, and expanded polystyrene were commonly used as the insulation layer and concrete for the inner and outer panel layers (Kalamees et al., 2009). The 5-story dwellings have exterior walls constructed of 250 mm triple layer panels. The U-value calculations for the exterior walls for the case study buildings are calculated using 100 mm reinforced concrete, 80 mm insulation, and an outer layer of 70 mm reinforced concrete, shown in Figure 2.

The 9-story buildings (type 1-464D-84) have a similar triple-layer panel construction with a total thickness of 300 mm. The material layers used for calculating U-value for exterior walls were 150 mm reinforced concrete, 80 mm insulation, and 70 mm reinforced concrete, shown in Figure 2.

The U-values of the walls and roofs shown in Table 3 are calculated using Ubakus calculator (u-wert.net GmbH, 2023).

The wall constructions described diverge somewhat from the material thicknesses provided in the study about LPS multi-family buildings (Kalamees et al., 2009), where the common outer concrete layer thickness is 60-65 mm, inner concrete layer is 80-130 mm and insulation thickness is 110 or 125 mm. The insulation thicknesses used in the calculations for the case study buildings were assumed to be thinner and the concrete layers thicker. Lowering the design values was used to ensure that the wanted U-value for the reconstructed wall was reached after adding the insulation layer. Reaching the required U-value would be more probable if the U-value of the original wall is assumed to be higher. Furthermore, several test drills in the exterior wall constructions have shown that the real situation of the exterior wall construction differs from the design, in practice the insulation layer often has uneven thickness. Kalamees et al. (2009) also mention that the technology used for creating the exterior wall panels was imprecise, therefore the construction layers of the exterior wall panels were often deviant from the original design.

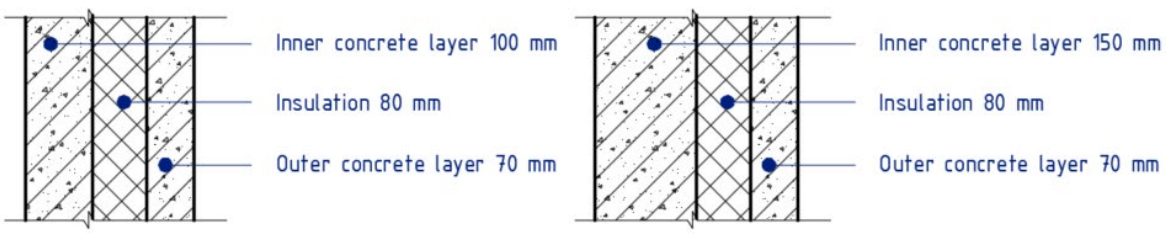

Figure 2: Wall constructions of a 5-story LPS building (left) and a 9-story LPS building (right)

Roof construction for all LPS dwellings is a panel consisting of 50 mm reinforced concrete, 150 mm fibrolite insulation, an air layer with various heights, and a 50 mm reinforced concrete layer. The roofs are flat and are covered with a bituminous waterproofing membrane.

Two buildings of group 5 (type 1-317, also known as "khrushchevka") are 4-story multi-family houses. These buildings are not LPS houses, instead the dwellings have a 430 mm silicate brick exterior wall construction. The exterior wall consists of a 250 mm brick layer, a 60 mm mineral wool layer, and a 120 mm exterior brick layer. This building type has a pitched roof with a cold attic. The attic floor is a 220 mm hollow core slab, insulated with 100 mm slag wool.

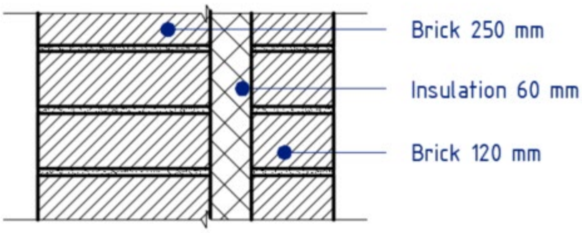

Figure 3: The wall construction of type 1-317 building

2.2.1.2 Loggias and balconies

The group 1, type 111-121 building has loggias and balconies with concrete railing panels, which have become hazardous due to the disintegration of the concrete and the corrosion of its metal fixtures. The common and strictly recommended practice is to replace the concrete panels with lighter railings.

The other typical projects such as 1-464A that have regular balconies with lighter railings, also have similar problems, such as carbonization of concrete floor slabs, which results in corrosion of the metal rods exposed to the weather. A recent audit (Structure Engineering OÜ, 2021) on a similar 1-464A building marks that the metal fixtures of the railings were designed to be renovated every 30 years due to outdoor exposure. Often the renovation requirement is ignored, which leads the audit to the conclusion that the state of the railings is hazardous, and they need to be replaced. Additionally, the reinforced concrete balcony slabs had signs of carbonization, a 10 mm carbonization depth was measured on the bottom side of the slab.

2.2.1.3 Windows

In many situations, the windows in the multi-family dwellings have been replaced by the inhabitants themselves, though several apartments still have the original windows. The quality and U-value of the windows are therefore diverse, depending on the manufacturer, installer, and the time of the replacement. The U-values of the windows shown in Table 3 for the renovated buildings are based on the information from the reconstruction project. The original buildings' windows' U-value is between 1,5 W/(m²·K) as an estimated value of an older double pane plastic window and 3,0 W/(m²·K) for an original wooden frame window.

2.2.2 Renovation measures used in case study buildings

All the renovated buildings in the case study have an ETICS façade system. ETICS is a uniform insulation and finishing system, that is fixed on a concrete or brick base layer. The system consists of adhesive, insulation boards, a reinforcement layer (glass mesh and reinforcement mortar) and finishing layers such as primer and plaster. For additional fastening, plastic dowels with metal cores are used. The typical ETICS system is shown in Figure 4. Generally, in the current renovation practices 150 mm – 200 mm mineral wool or EPS insulation is added to the exterior walls. The thickness of the insulation on exterior walls is chosen according to the desired U-value. If the subsidy system is used, the U-value needs to be ≤ 0,20 W/(m²·K).

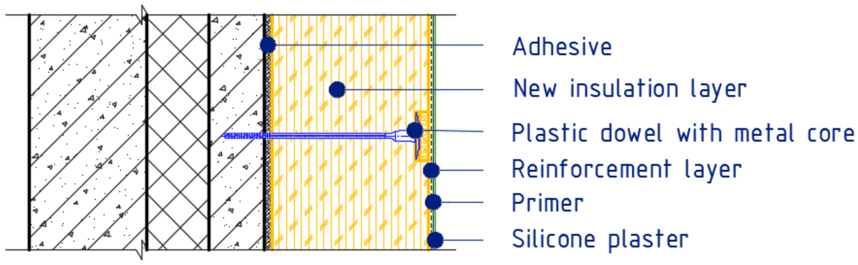

Figure 4: Typical ETICS construction

The roof panels are generally insulated with 250 mm – 350 mm mineral wool. The thickness of the roof insulation is chosen to reach U-value ≤ 0,12 W/(m²·K) for the whole roof construction to meet the criteria from the subsidy system. The main insulation layers are constructed of lamella wool with a compressive strength between 30 kPa and 50 kPa. The top insulation layer is usually 50 mm rigid mineral wool with grooves, which helps to ventilate roof construction. The top layer insulation normally has 60 kPa – 80 kPa compressive strength to resist the load of people and equipment during the building process and when the roof is in operation. The photovoltaic (PV) system installations that are becoming more popular require even higher compressive strength for the roof insulation, which is a circumstance that needs to be addressed during the design process. The final layer is a double-layer bituminous waterproofing membrane.

Added insulation and finishing layers improve the moisture safety of the building and eliminate thermal bridges, which can cause mold. However, the building details, for example, façade and parapet junctions need to be joined carefully. The quality of these details is crucial to keep the constructions and ETICS from moisture damage. In the long run, the quality of the façade system and roof affects the lifespan of the whole building and determines the need for repairs.

2.2.3 Technical systems of case study buildings

2.2.3.1 Ventilation

Originally, the multi-family buildings had natural ventilation. There was no designated ventilation solution as the ventilation of the original design accounted for the non-airtight constructions as the low-quality wood windows and panel joints provided enough air for natural ventilation. The exhaust air ducts are in kitchens and bathrooms, allowing the air to enter from living rooms and bedrooms and exit from kitchens and bathrooms. Sometimes there are problems with clogged and not airtight ventilation ducts, especially in the top floor apartments where the height of the duct is insufficient.

In most of the renovated case study buildings (groups 2, 3, 4, and 5) natural ventilation was replaced with mechanical exhaust ventilation with heat recovery. In group 1, the renovated building has mechanical intake-exhaust ventilation with heat recovery. The case study buildings' ventilation types are shown in Table 4.

2.2.3.2 Hydronic system

Mainly the case study buildings use district heating, except for the group 2 original building, which has its own gas plant. District heating is the most used heating type for multi-family buildings in Tallinn (Energiakontsern Utilitas, 2023). Currently, the fuel used for the system is wood chips from Estonian sources (Energiakontsern Utilitas, 2023). The hydronic systems in the case study buildings are in different conditions, as shown in Table 4. The buildings have 1-pipe or 2-pipe systems with radiators, whereas some of the non-renovated buildings have no option to regulate the room temperature. The renovated buildings all have the option to regulate indoor air temperature through radiators' thermostat valves.

2.2.3.3 Overview of technical systems

A short overview of main technical systems is shown in Table 4.

Table 4: Technical systems of case study buildings

Group	State of building	Ventilation system	Hydronic system
Group 1	Original	Natural	District heating Radiators with thermostat valves allow regulating room temperature
	Renovated	Mechanical intake-exhaust ventilation with heat recovery	District heating 2-pipe system with radiators Thermostat valves allow regulating room air temperature in the range of 18-23 º C
Group 2	Original	Natural	Based on a local gas plant Radiators with thermostat valves allow regulating room temperature
	Renovated	Mechanical exhaust ventilation with heat recovery Fresh-air intake through radiators	District heating 2-pipe system with radiators Thermostat valves allow regulating room air temperature in the range of 18-23 º C
Group 3	Original A	Natural	District heating Radiators without thermostats in most apartments
	Original B	Natural	District heating Radiators without thermostats
	Renovated	Mechanical exhaust ventilation with heat recovery Fresh-air intake through radiators	District heating 2-pipe system with radiators Thermostat valves allow regulating room air temperature in the range of 18-23 º C
Group 4	Original	Natural	District heating Radiators with thermostat valves allow regulating room temperature
	Renovated	Mechanical exhaust ventilation with heat recovery Fresh-air intake through fresh air valves above radiators	District heating 2-pipe system with radiators Thermostat valves allow regulating room air temperature in the range of 18-23 º C
Group 5	Original	Natural	District heating Radiators without thermostats
	Renovated	Mechanical exhaust ventilation with heat recovery Fresh-air intake through radiators	District heating 2-pipe system with radiators Thermostat valves allow regulating room air temperature ± 2 degrees from the setpoint

2.2.4 Group 1 buildings

Multi-family buildings in group 1 (type 111-121) are located in a Saku suburb near Tallinn. This group represents the newest build among the case study buildings. The reconstructed multi-family house was built in 1992 and the reference building was built in 1987. The floor plans and original constructions are identical, and so are the number of apartments (30). The 111-121 building type has loggias on the main façade and balconies at the back façade. The 5-story buildings are next to each other and have the same orientation, the longer facades with windows are facing east and west. The west-facing facades are shown in Figure 5 and Figure 6. A typical floor plan of the type 111-121 is shown in Figure 7.

Figure 5: The original building, type 111-121

Figure 6: The renovated building, type 111-121

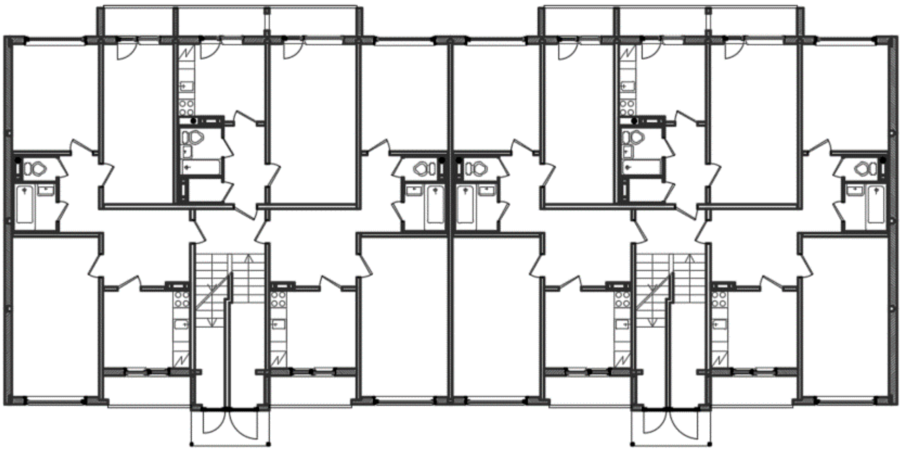

Figure 7: Ground floor plan of type 111-121 building

2.2.4.1 The original building

The reference building was constructed in 1987. The wall and roof constructions correspond to the constructions described in Chapter 2.2.1. There are no large-scale renovations done previously. Most of the original wooden frame windows have been replaced with newer double-glazed windows with PVC-frame.

2.2.4.2 The renovated building

The complex reconstruction of the renovated building was finished in 2021. The renovation means consisted of 200 mm additional mineral wool insulation on exterior walls, and 270 mm lamellar wool on the roof, in addition to the 80 mm expanded polystyrene which was added during previous small-scale reconstruction. The ventilation channels for the new intake-exhaust ventilation system were placed inside the additional insulation layer of the exterior walls and roof. All windows were replaced with triple-glazed windows with a U-value of 1,1 W/(m²·K). The balconies' concrete railings were replaced by new glass panel railings and a foldable balcony glazing system was installed to protect the balcony from wind and rain.

The ventilation was designed according to indoor environment class II, according to the standard EN 15251:2007 (Swedish Standards Institute, 2007) which was valid at the time of the design process. The minimum intake air flow rate for the living rooms and bedrooms was designed as 12 l/s, and for bedrooms smaller than 11 m², 8 l/s. Extraction air flow rates from bathrooms were designed as 15 l/s, and in 1-room apartments as 10 l/s. Extraction air flow from kitchens was designed generally as 8 l/s, and in 1-room apartments 6 l/s.

In living rooms and bedrooms, the calculated air temperature in the winter was +21 º C, and the maximum noise level was 25 dB(A). In kitchens, the calculated air temperature in the winter was designed as +20 º C and maximum noise level as 35 dB(A).

2.2.5 Group 2 buildings

Buildings in group 2 (type 1-464D-84) are located in the Mustamäe district in Tallinn. Mustamäe is one of the first areas in Tallinn that was developed as an LPS residential area, with the oldest buildings constructed in 1964 (Lankots, 2009). The buildings in this group are two 9-story multi-family dwellings, that are partially connected by the end walls. The longer facades are oriented towards the east and west. Both dwellings were built in 1972 and are in an inner living quarter. The floor plan modules and original constructions are identical. The reference building has six stairwells, and the renovated dwelling has two. This type of building has balconies on the front façade and loggias on the back façade. The front facades are shown in Figure 8 and Figure 9. The typical floor plan of group 2 buildings is shown in Figure 10.

Figure 8: The original building, type 1-464D-84

Figure 9: The renovated building, type 1-464D-84

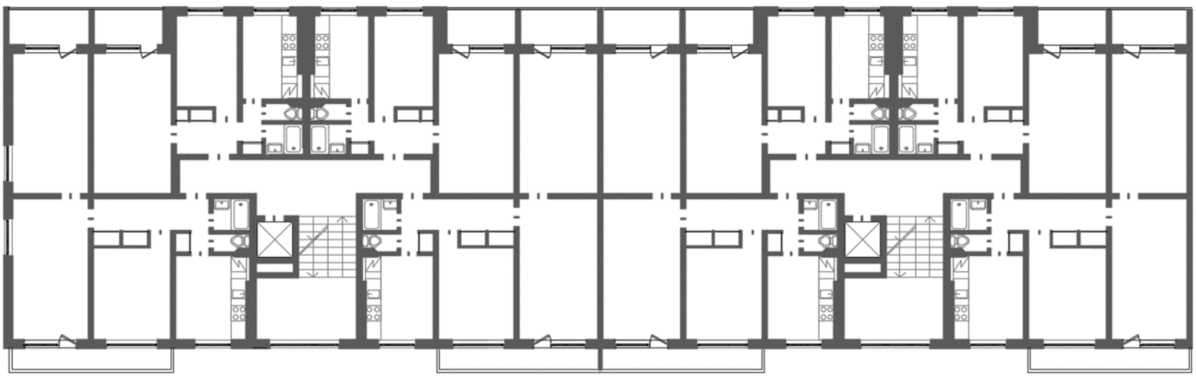

Figure 10; Typical floor plan of type 1-464D-84 building

2.2.5.1 The original building

The wall and roof constructions of the reference building are described in Chapter 2.2.1. During previous reconstructions, 150 mm of additional mineral wool was added to the roof, and around 100 mm of insulation was added to the end walls. Additionally, a local gas plant was added on the rooftop for providing heating and domestic hot water. Most of the original wooden frame windows have been replaced with newer double-glazed windows with PVC-frame.

2.2.5.2 The renovated building

The full reconstruction of the renovated building was finished in 2016. The renovation included adding 150 mm mineral wool insulation on exterior walls. The roof already had 170 mm of additional mineral wool before the full renovation. The heating system was reconstructed due to the changed energy need after insulating the exterior walls. All windows were replaced with triple glass windows with a U-value of 1,1 W/(m²·K). Additionally, the building had a 20,5 kWp PV system added to the roof. Foldable glazing systems were installed on the balconies at the main façade and on the loggias at the back façade.

The ventilation was designed according to the subsidy system terms from 2015, valid at the time of the design process. Extraction air flow rates from bathrooms were designed as 15 l/s, and in 1-room apartments as 10 l/s. Extraction air flow from kitchens was designed generally as 8 l/s, and in 1-room apartments 6 l/s.

2.2.6 Group 3 buildings

The multi-family houses in group 3 are all variations of a standard project 1-464A. This is one of the most common building types in the Mustamäe neighborhood in Tallinn and therefore it has some modifications in plan layout and the number of stairwells. All the buildings in group 3 are in the Mustamäe district in Tallinn, constructed in the 1960s, and have 5 stories, but have some differences regarding their room plan and size. This type of housing has balconies at the front and back façade, typically in front of living rooms. The distance between the buildings in this group is a maximum of 1,5 km. The original exterior wall and roof constructions of the buildings are identical, they correspond with the LPS constructions described in Chapter 2.2.1. There are two original buildings for reference in this group. The facades of the original buildings are shown in Figure 11 and Figure 12 and the renovated building in Figure 13. The floor plans of group 3 buildings are shown in Figure 14 and Figure 15.

Figure 11: The original building A, type 1–464

Figure 12: The original building B, type 1–464

Figure 13: The renovated building, type 1-464A

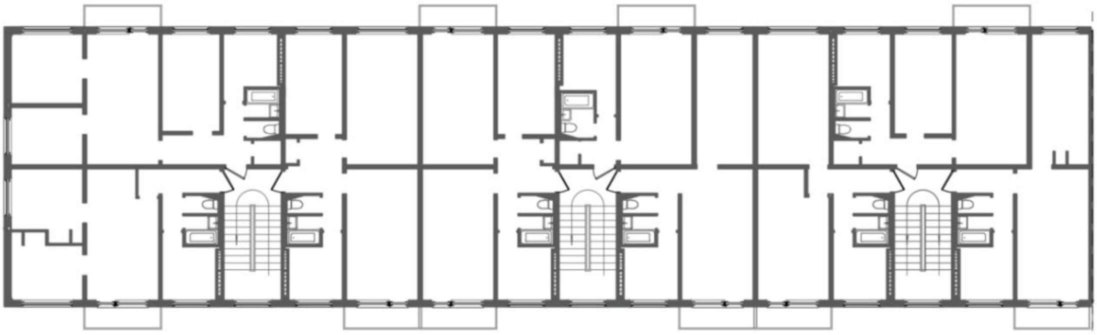

Figure 14: Floor plan variation (fragment) of type 1- 464 multi-family house of group 3 – original building A and renovated building.

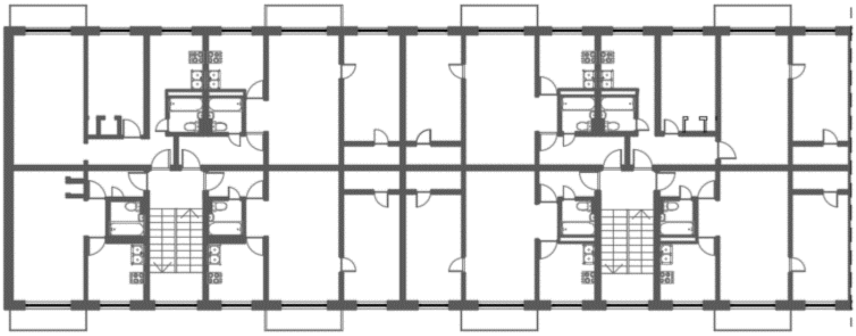

Figure 15: Floor plan variation (fragment) of type 1-464A multi-family house of group 3 - original building B.

2.2.6.1 The original buildings

Original building A was built in 1969 and has 119 apartments. The main facades are orientated north and south. During previous reconstructions around 2010, approximately 100 mm of insulation was added to the roof, and around 100 mm of insulation was added to the end walls. The exact thickness of added insulation is not known, but 10-15 years ago the added insulation layers were modest compared to recent years. Most of the original wooden frame windows have been replaced with newer double-glazed windows with PVC-frame.

Original building B with 80 apartments was built in 1964 and it represents the older type of typical project 1-464A. The older type has one more room in the typical plan module, compared to the design of the newer version of 1-464A. The width of the building and constructions are the same for both project variants. The longer facades of original building B face east and west. The end walls have been insulated previously with approximately 100 mm of insulation; the year of the reconstruction work is unknown. Knowingly there have not been any previous reconstructions carried out regarding the roof of the building.

2.2.6.2 The renovated building

The renovated building was constructed in 1966 and the reconstruction was finished in 2017. The renovation measures included adding 150 mm expanded polystyrene insulation on the exterior walls and 300 mm mineral wool on the roof. All windows were replaced with triple glass windows with a U-value of 0,9 W/(m²·K). The building also got a 15 kWp PV system installed on the rooftop. The balcony railings were replaced with glass panels and foldable glazing systems were installed on all the balconies. The ventilation was designed according to the subsidy system terms from 2015, valid at the time of the design process. Extraction air flow rates from bathrooms were designed as 15 l/s, and in 1-room apartments as 10 l/s. Extraction air flow from kitchens was designed generally as 8 l/s, and in 1-room apartments 6 l/s.

2.2.7 Group 4 buildings

These two multi-family houses are also located in the Mustamäe district in Tallinn and represent type 1-464A as well. These buildings are identical in size and plan and are next to each other, but the orientations of the longer facades are different. The building in its original state has longer facades facing north and south, but the renovated building has longer facades facing east and west. Both houses were built in the late 1960s and have 90 apartments. The original wall and roof constructions are identical, described in Chapter 2.2.1. The non-renovated multi-family house faces a busy road, the renovated building is in an inner living quarter behind the original building. The façades of group 4 buildings are shown in Figure 16 and Figure 17. The plan layout of group 4 buildings is shown in Figure 18.

Figure 16: The original building, type 1–464

Figure 17: The renovated building, type 1–464

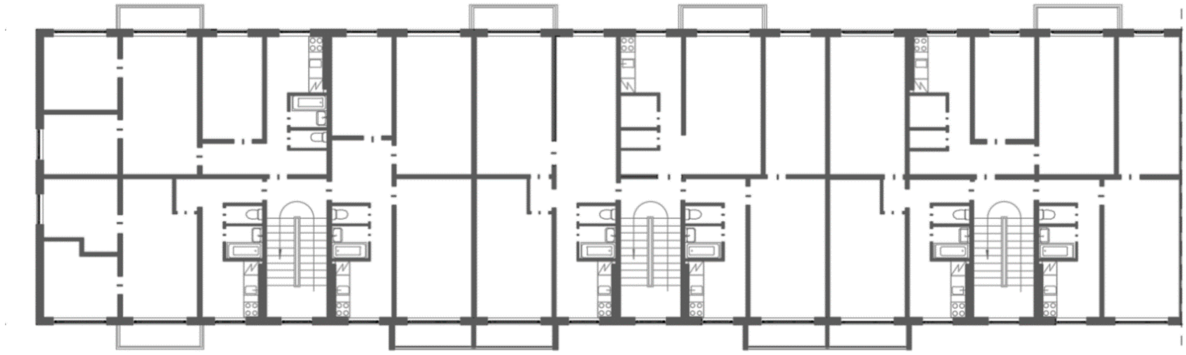

Figure 18: Typical floor plan (fragment) of group 4 buildings, type 1-464A

2.2.7.1 The original building

The original multi-family house was built in 1967. The end walls have around 100 mm of additional insulation. Most of the original wooden frame windows have been replaced with newer double-glazed windows with PVC-frame.

2.2.7.2 The renovated building

The renovated building was constructed in 1967 and the reconstruction was finished in 2017. The renovation measures included adding 150 mm expanded polystyrene insulation on the exterior walls and 250 mm mineral wool on the roof. The windows that were depreciated, were replaced with triple glass windows with a U-value of 1,1 W/(m²·K). Foldable glazing systems were installed on all the balconies.

The ventilation was designed according to the subsidy system terms from 2015, valid at the time of the design process. Extraction air flow rates from bathrooms were designed as 15 l/s, and in 1-room apartments as 10 l/s. Extraction air flow from kitchens was designed generally as 8 l/s, and in 1-room apartments 6 l/s.

2.2.8 Group 5 buildings

The group 5 buildings differ from the other buildings included in the study because they are not LPS buildings but constructed of silicate brick masonry. The typical design is named 1-317, better known as "khrushchevka", a well-known building type from the Soviet era. The group 5 buildings have 4 stories and a low attic under a pitched roof. The multi-family dwellings of type 1-317 usually do not have balconies. The original wall and roof construction are described in Chapter 2.2.1.

The buildings in group 5 are identical in their size. They are located next to each other beside a busy road in the Tallinn Kesklinn district. The longer facades are orientated southeast and northwest. The façades of the buildings are shown in Figure 19 and Figure 20. The plan layout of group 5 buildings is presented in Figure 21.

Figure 19: The original building, type 1-317

Figure 20: The renovated building, type 1-317

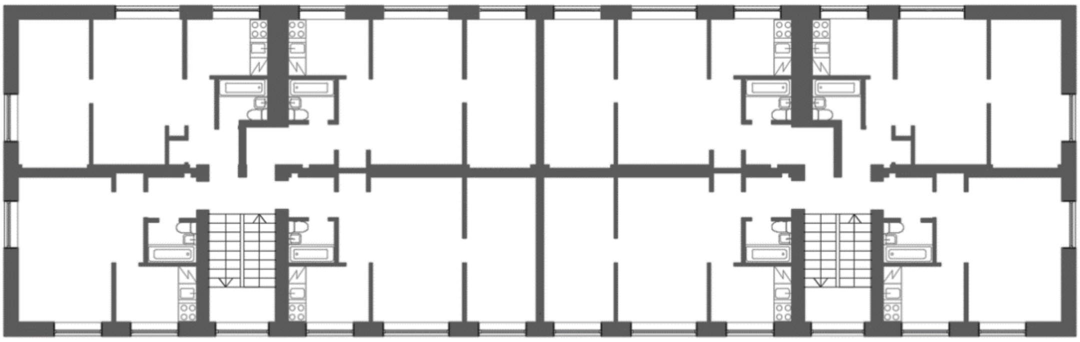

Figure 21: Typical floor plan of group 5 buildings, type 1-317

2.2.8.1 The original building

The reference building was built in 1961 and has 32 apartments. The roof is covered with asbestos cement tiles. Knowingly there are no major reconstruction works carried out in the building.

2.2.8.2 The renovated building

The renovated building was constructed in 1959 and the reconstruction was finished in 2017. The renovation measures included adding 150 mm expanded polystyrene insulation on the exterior walls and 300 mm mineral wool on the attic floor. All windows are new triple glass windows with a U-value of a maximum of 1,1 $W/(m^2·K)$. An 11 kWp PV system was installed on the roof.

The ventilation was designed according to subsidy terms valid at the time of the design process. Extraction air flow rates from bathrooms were designed as 15 l/s, and in 1-room apartments as 10 l/s. Extraction air flow from kitchens was designed generally as 8 l/s, and in 1-room apartments 6 l/s.

2.3 The occupant survey

To understand how the commonly practiced renovation methods affect the occupants' indoor environment quality as well as satisfaction with their living conditions, a questionnaire survey was conducted. An occupant survey is an efficient way of assessing the thermal conditions in a building, if conducted correctly (ASHRAE, 2010). The results can help with the design process and can contribute to discovering and addressing the causes of discomfort (ASHRAE, 2010).

2.3.1 The questionnaire

The questions used in the current survey are adopted from Swedish studies, more specifically the questionnaires used for research in Malmö (Nordquist et al., 2014) and in PEIRE projects. Additionally, some questions were included from a similar study conducted in Estonia in 2014 (Kõiv et al., 2014), to later compare the results from the current study.

The Swedish studies are based on The Stockholm Indoor Environment questionnaire (SIEQ). The SIEQ questionnaire is a verified self-administered study, which focuses on sociological, technical, and medical aspects (Engvall et al., 2004). Although it was established for Scandinavian countries, it can be used elsewhere in tempered climate zones (Engvall et al., 2004).

The structure of the questionnaire in the current study follows the structure of the SIEQ, where general questions about satisfaction or dissatisfaction regarding the occupants' housing are asked first and the basic information i.e., the number of inhabitants and size of the apartment is inquired at the end of the questionnaire. The SIEQ questionnaire also includes health and wellbeing questions, which are placed in the middle of the question pack due to their sensitive nature (Engvall et al., 2004).

The questions regarding the occupants' health were not included in the current study due to ethical reasons. Instead, the questionnaire focused on thermal comfort, indoor air quality, and window airing habits. Daylight and noise as well as mold and moisture questions were covered on a smaller scale. The questions were formulated in everyday language and small adjustments were made to accommodate the questionnaire more to the local conditions, i.e., the question about window airing regarding the position of the window was adapted to the window type most used in local reconstructions. Also, fresh air valves were added as an answer option for the questions about draught and indoor temperature regulation. The form of the questionnaire survey allowed leaving additional comments in the free text on several questions and at the end of the questionnaire.

The same questionnaire was implemented in all the case study multi-family buildings, for the renovated houses as well as reference buildings. The answers from the renovated and reference buildings were compared to examine the differences in survey results between the two dwellings. Some results were compared between all the renovated and all the original state buildings.

The online questionnaire was constructed using SUNET Survey (Sunet, 2023) tool and was shared via a link as a public survey. The questionnaire survey had an introductory letter, which explained the purpose of the study and how the data will be used. The letter also contained practical information about filling in the questionnaire. The questionnaire part of the survey had 48 questions. The study was bilingual, in Estonian and in Russian, considering the demographic of the buildings, so the nuances of the language used in the questionnaire would be intelligible for all the participants. The English language version of the introductory letter and questionnaire is shown in Appendix I.

On several occasions, the leaders of the housing associations pointed out the need for paper questionnaires. It was assumed that the people needing the paper version were mostly elderly and to not exclude this demographic group from the survey, a paper survey was also used.

2.3.2 Conduction of the questionnaire survey

The buildings chosen to participate in the survey have motivated housing association representatives or technical consultants, who had an interest in the project. The motivation of these people was a prerequisite for a successful survey because it was their task to introduce the survey to the inhabitants. Moreover, the representatives had to distribute the online version of the questionnaire and encourage the inhabitants to participate in the study. To nudge the occupants to answer the survey questionnaire, 3 gift cards of 100 euros were raffled among the respondents.

The survey started on the 7th of March 2023 and was open for 3 weeks. The representatives of the housing associations sent the link to online questionnaire to the inhabitants' email addresses and a request to send a reminder email was sent to the representatives on the 20th of March. 670 occupants received an online request to participate in the survey.

The paper survey was distributed to the mailboxes of the inhabitants, whose email addresses were not available. Altogether 211 paper questionnaires were delivered to the mailboxes. The filled-out questionnaires were asked to be placed in the housing associations' mailboxes, in most cases available in every stairwell next to the inhabitants' mailboxes. Later the housing association representatives collected the paper results.

The results from the online questionnaires were first analyzed using a SUNET Survey report tool. The results from the paper questionnaires were combined with the online results using MS Excel.

2.3.3 Comparison with the 2014 Estonian study

Eight of the questions regarding thermal comfort, air quality, and noise from technical systems in the current survey were adopted from an Estonian study about energy use and indoor environment in renovated multi-family houses by Kõiv et al. (2014). The study is described in Chapter 1.1.5.1 about previous research. Since the survey in 2014 covered renovated buildings, the survey result from 2014 was only compared to the result of renovated buildings in the current study. Additionally, as most of the case study renovated buildings have mechanical exhaust ventilation, the outcome of the current study was compared to the result from 2014 regarding buildings with the same type of ventilation. Group 1 renovated building was excluded from this comparison because this multi-family house has mechanical supply and exhaust ventilation.

2.3.4 Weather conditions throughout the study

The questionnaire survey started on the 7th of March 2023 and ended on the 28th of March 2023, during a heating season. The average daily temperatures were between - 6,4 º C and + 10 º C, and average relative humidity was between 50 % and 98 %. The duration of hours with sunshine varied between 10,7 and 0 hours in a day. Weather information throughout the survey period is based on the data from Estonian Environment Agency (2023) for the Tallinn-Harku weather station.

2.4 Data for measured energy use in case study buildings

The housing associations provided data about their annual measured energy use for the year 2022. The information included energy consumption for heating, ventilation, and domestic hot water. The consumption and production from heat pumps and PV system were added to renovated buildings provided these systems were installed. Electricity for ventilation systems' fans and pumps was included, but electricity for the apartments (everything that the households consume) and for and general electricity (i.e., electricity for general lighting) was excluded. The energy use was calculated per heated area of the building.

3 Result

3.1 Questionnaire survey response

The questionnaire survey received altogether 182 individual answers. 142 answers were submitted online, and 40 answers were on paper. 79 of the respondents were living in renovated multi-family buildings and 103 in non-retrofitted buildings. The average age of people who answered the online survey was 50 years and the average age of respondents to the paper survey was 70. The majority of respondents lived in apartments that had two or three rooms and a kitchen, smaller and larger apartments were rarely marked. Most often, the apartment had one inhabitant (44 %), followed by two (37 %) and three (14 %) inhabitants.

The participation rates were under 30 % in this study for most of the buildings, as shown in Table 5.

Table 5: Questionnaire survey response rates

Group	State of the building	Number of apartments	Number of respondents	Response rate (%)
Group 1	Original	30	6	20
	Renovated	30	13	43
Group 2	Original	216	31	14
	Renovated	72	29	40
Group 3	Original A	119	21	18
	Original B	80	19	24
	Renovated	90	17	19
Group 4	Original	90	17	19
	Renovated	90	17	19
Group 5	Original	32	9	28
	Renovated	32	3	9
	Total original	**567**	**103**	**18**
	Total renovated	**314**	**79**	**25**

As pointed out by one of the housing association representatives, the habitants "are not very active". Moreover, some of the apartments are usually rental apartments, but the contact email addresses belong to the apartment owners. Therefore, it is probable that in several cases the real inhabitants did not receive the request to answer the survey. The response rate was very low in group 5 renovated building, where only three people responded to the survey. Therefore, the results from this building are seen more as an indicator but not a basis for major conclusions. Better results, around a 40 % response rate, were achieved in multi-family buildings where the housing association leaders have good contact with the building occupants. Such examples are the renovated buildings in group 1 and group 2.

During the survey, there was feedback from some of the respondents, that the online questionnaire format did not let them select all the answers they wanted in question 14 about solar shading methods and in question 43 about window airing time in different seasons. Also, some respondents on some occasions marked more answer options in the paper questionnaire, which was not possible for the same question online.

3.2 General satisfaction

The first part of the questionnaire survey included questions about general satisfaction with the apartment, the building, and overall perception of indoor climate. Mostly the inhabitants were pleased with their apartment in general, and with its size. The floor plan was appreciated slightly less. General satisfaction with the apartment was higher in renovated buildings, where just above 60 % of respondents were "quite satisfied" and 30 % were "very satisfied". In non-renovated buildings, the same proportion (60 %) of respondents were "quite satisfied" with their apartment, but the proportion of people who were "very satisfied" was 7 %. Around 70 % of respondents in non-renovated buildings were content with their neighborhood, in renovated buildings the satisfaction rate was 80 %.

The satisfaction rates for the factors that are influenced by energy renovations the most, such as appearance, maintenance, and utility costs, are shown in Figure 22. The results are presented separately for two groups, all renovated and all non-renovated buildings.

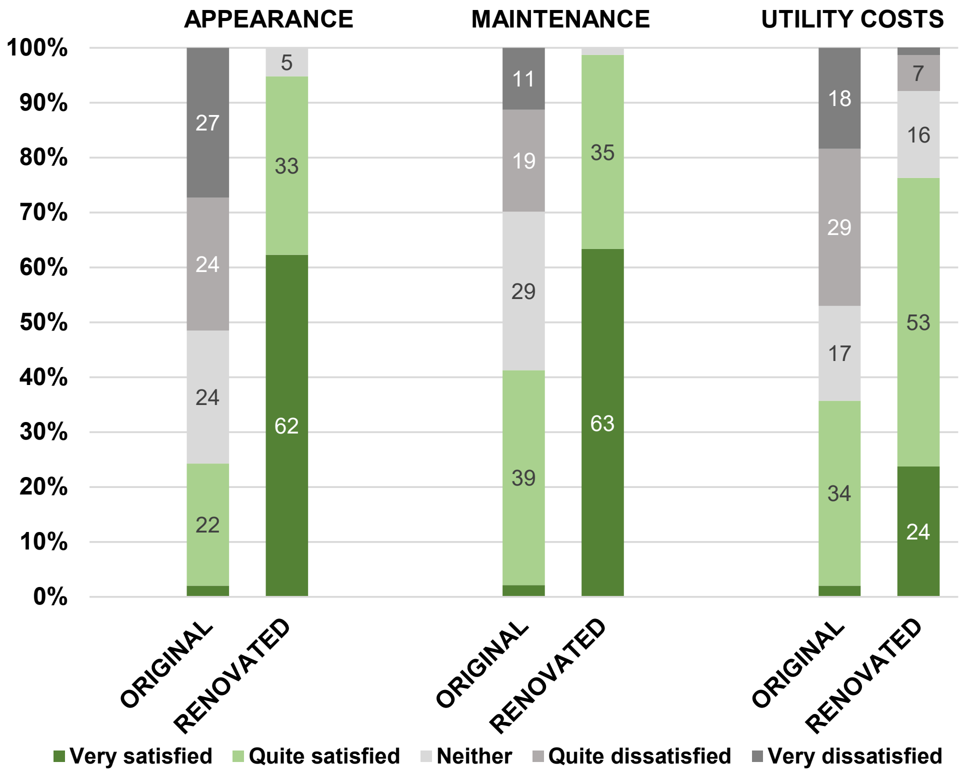

Figure 22: Satisfaction with buildings' appearance, maintenance, and utility costs in retrofitted and non-retrofitted multi-family buildings

Though the difference in results is more pronounced for some individual case study groups, the general comparison of all renovated and all non-renovated buildings provides a good overview of the overall satisfaction rates as well. The results show that contentment with buildings' appearance and maintenance were superior in renovated buildings than in non-renovated buildings. Though not all the inhabitants were content with the utility expense after the renovation, satisfaction with utility costs was higher in renovated buildings as well. However, currently the renovation loan expenses are higher than the savings from reduced heating energy. When the satisfaction with the utility costs was examined in more detail between two age groups, people over 65 years of age and people under 65 years old, it was noted that older people were more often "very satisfied" or "quite satisfied" compared to the younger respondents.

The result of the questions regarding indoor environment disturbances is shown in Figure 23 and is presented separately for all the renovated buildings and for all the non-renovated buildings. The figure indicates that thermal comfort is higher in renovated multi-family buildings. In non-renovated buildings, the satisfaction with thermal comfort is not as high as in retrofitted buildings, but it was still rated highest compared to the other indoor environment aspects. Issues with air quality, unwanted smells, and noise still exist in renovated buildings, but on a lesser scale than in non-renovated houses. When the PPD of both multi-family building groups is observed, it can be noted that satisfaction with indoor environment is higher in renovated houses. The following more detailed result analysis reflects the findings from the general satisfaction answers.

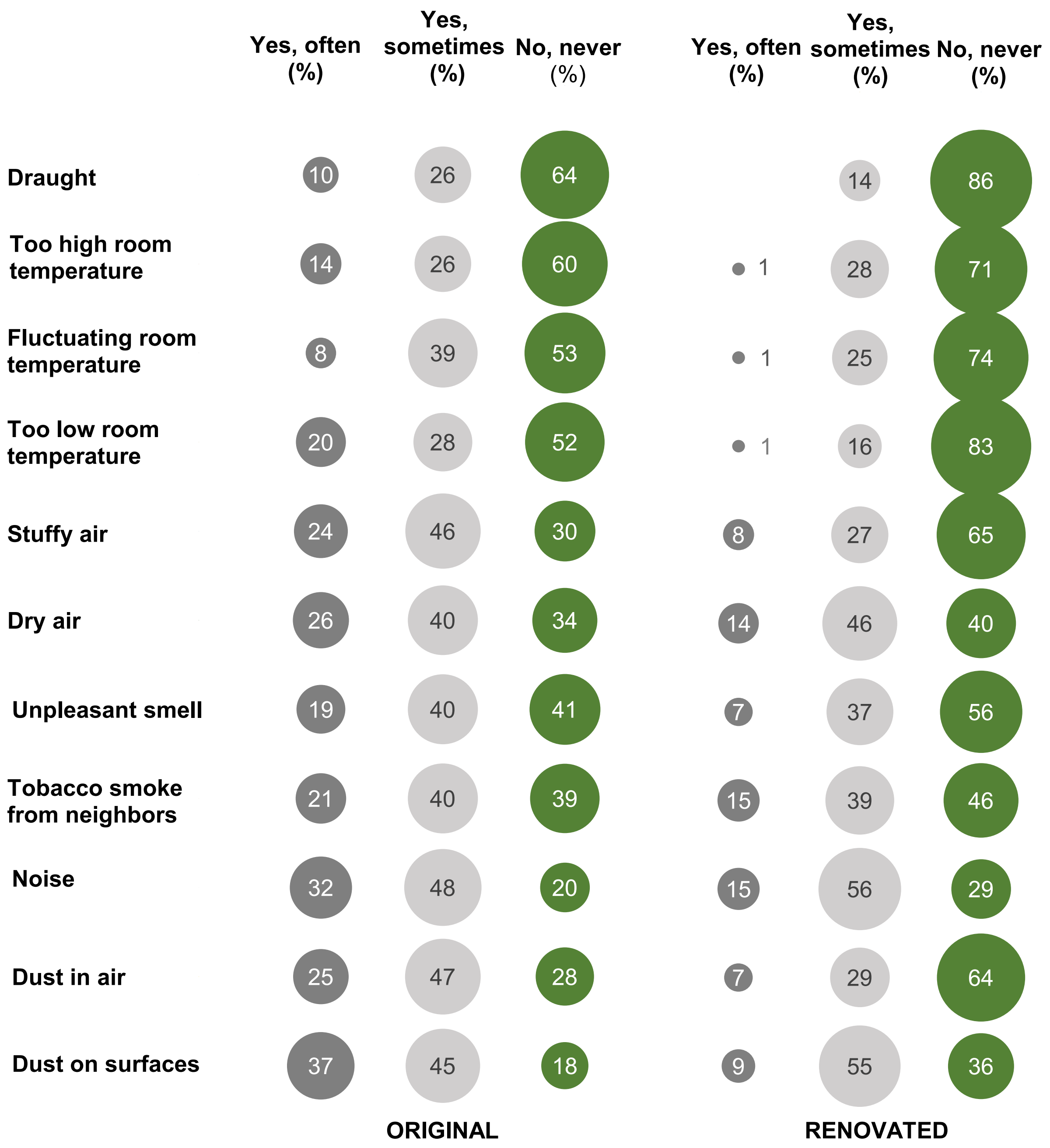

Figure 23: Have you been disturbed in <u>the last 3 months</u> by one or more of the following factors in your apartment?

3.3 Answers to thermal comfort questions

3.3.1 General thermal comfort

As shown in Table 6, the result regarding general thermal comfort shows higher satisfaction rates in renovated buildings. The PPD in renovated buildings indicates meeting the category I and II, normal and high expectations for thermal comfort. In most buildings in their original state, the PPD values indicate class III or lower, showing that thermal comfort is acceptable or outside the recommended values.

Table 6: How do you find the thermal comfort in your apartment in general?

Group	State of the building	Very satisfied	Quite satisfied	Acceptable	Quite dissatisfied	Very dissatisfied
Group 1	Original	33,3 %	33,3 %	33,3 %	0,0 %	0,0 %
	Renovated	**38,5 %**	**61,5 %**	**0,0 %**	**0,0 %**	**0,0 %**
Group 2	Original	9,7 %	38,7 %	29,0 %	9,7 %	12,9 %
	Renovated	**24,1 %**	**58,6 %**	**10,3 %**	**6,9 %**	**0,0%**
Group 3	Original A	4,8 %	42,9 %	38,1 %	14,3 %	0,0 %
	Original B	0,0 %	10,5 %	63,2 %	21,1 %	5,3 %
	Renovated	**41,2 %**	**47,1 %**	**11,8 %**	**0,0 %**	**0,0 %**
Group 4	Original	0,0 %	29,4 %	47,1 %	23,5 %	0,0 %
	Renovated	**17,6 %**	**64,7 %**	**17,6 %**	**0,0 %**	**0,0 %**
Group 5	Original	0,0 %	22,2 %	11,1 %	55,6 %	11,1 %
	Renovated	**66,7 %**	**33,3 %**	**0,0 %**	**0,0 %**	**0,0 %**
Total original		**36,9 %**				
Total renovated		**87,3 %**				

Table 7 shows satisfaction rates regarding indoor temperature in wintertime. It is apparent that in renovated multi-family houses most answers are in the desired "warm" and "acceptable" range. Only in group 3, 17,6 % of respondents in the renovated building found the room air temperature to be "too warm", and 11,8 % of respondents in group 4 renovated building found the indoor air temperature "cold". In the buildings in their original state, the variety is larger, ranging from "too warm" to "too cold". 36,7 % of respondents in renovated buildings and 32,0 % of respondents in non-renovated buildings found the indoor air temperature in winter either "warm" or "too warm", indicating a possibility for additional energy saving. Moreover, appropriate room air temperatures reduce window airing which is practiced to lower the room air temperature.

Table 7: How do you estimate indoor air temperature in your apartment in wintertime?

Group	State of the building	Too warm	Warm	Acceptable	Cold	Too cold
Group 1	Original	16,7 %	16,7 %	50,0 %	16,7 %	0,0 %
	Renovated	**0,0 %**	**38,5 %**	**61,5 %**	**0,0 %**	**0,0 %**
Group 2	Original	0,0 %	9,7 %	71,0 %	16,1 %	3,2 %
	Renovated	**0,0 %**	**31,0 %**	**69,0 %**	**0,0 %**	**0,0 %**
Group 3	Original A	23,8 %	38,1 %	28,6 %	9,5 %	0,0 %
	Original B	5,3 %	26,3 %	36,8 %	21,1 %	10,5 %
	Renovated	**17,6 %**	**52,9 %**	**29,4 %**	**0,0 %**	**0,0 %**
Group 4	Original	0,0 %	11,8 %	47,1 %	35,3 %	5,9 %
	Renovated	**0,0 %**	**11,8 %**	**76,5 %**	**11,8 %**	**0,0 %**
Group 5	Original	55,6 %	22,2 %	0,0 %	11,1 %	11,1 %
	Renovated	**0,0 %**	**33,3 %**	**66,7 %**	**0,0 %**	**0,0 %**
Total original		**32,0 %**				
Total renovated		**36,7 %**				

The original building in group 5 has "too warm" as the most popular option, while none of the respondents answered "acceptable" to this question. However, two people found the room temperature was either "cold" or "too cold". The heating system in group 5 original building does not allow regulating the room air temperature, and more than half of respondents are unhappy with the general thermal comfort in the apartment. The three people living in the renovated building of the same group found that the indoor air temperature in winter was either “warm” or “acceptable”. Moreover, they were satisfied with the thermal comfort in their apartment in general.

In buildings such as group 3 original building B, 21,1 % of respondents reported the indoor air temperature in winter is “cold” and 10,5 % find it “too cold”. Simultaneously, 26,3 % of respondents in the same building say it is “warm” and 5,3 % find it is “too warm”. The building also has one of the lowest satisfaction rates for thermal comfort in all the case study buildings. The variety of responses and reported fluctuating temperature indicate there might be a balancing problem with the current heating system.

Mostly the inhabitants from non-renovated buildings left extra feedback on thermal comfort. People mentioned uneven room temperatures in the apartment due to the different orientations of the rooms, while the provided room heating is the same. It was noted that the room air was too warm and stuffy, which was regulated by keeping windows constantly in a micro-airing position. Problems with the heating schedule were mentioned, such as temperature drops in the evenings and insufficient heating in autumn.

The results of occupants’ perception of floor temperature in renovated and non-renovated buildings are shown in Table 8.

Table 8: How do you estimate floor temperature in your apartment in wintertime?

State of the building	Too warm	Warm	Acceptable	Cold	Too cold
Original	2,0 %	16,7 %	40,2 %	32,4 %	8,8 %
Renovated	0,0 %	17,9 %	70,5 %	10,3 %	1,3 %

Alike the answers to the general thermal comfort question, floor temperatures are perceived as “warm” or “acceptable” in renovated buildings and “acceptable” or “cold” in non-renovated houses. The difference can be noticed depending on the location of the respondents’ apartment. In renovated houses, in the apartments that were on the first floor, 64 % of the respondents said the floor temperature was “acceptable”, 18 % “warm” and 18 % “cold”. In non-renovated buildings the floors on the first floor were generally perceived as “cold” (42 %) or “too cold” (32 %). The respondents who lived on other floors mainly found floor temperature “acceptable” (73 %) or “warm” (18 %) in renovated buildings and mostly “acceptable” (46 %) or cold (29 %) in non-renovated buildings.

The results of how people perceive temperature fluctuations in their apartments in winter are shown in Table 9.

Table 9: How do you estimate indoor air temperature stability in your apartment in wintertime?

Group	State of the building	Stable	Mostly stable	Appropriate	Somewhat fluctuating	Fluctuating
Group 1	Original	50,0 %	16,7 %	16,7 %	16,7 %	0,0 %
	Renovated	**30,8 %**	**15,4 %**	**53,8 %**	**0,0 %**	**0,0 %**
Group 2	Original	9,7 %	25,8 %	41,9 %	19,4 %	3,2 %
	Renovated	**36,7 %**	**40,0 %**	**16,7 %**	**6,7 %**	**0,0 %**
Group 3	Original A	19,0 %	28,6 %	19,0 %	19,0 %	14,3 %
	Original B	10,5 %	26,3 %	26,3 %	31,6 %	5,3 %
	Renovated	**12,5 %**	**75,0 %**	**12,5 %**	**0,0 %**	**0,0 %**
Group 4	Original	12,5 %	18,8 %	25,0 %	31,3 %	12,5 %
	Renovated	**5,9 %**	**58,8 %**	**23,5 %**	**11,8 %**	**0,0 %**
Group 5	Original	55,6 %	0,0 %	11,1 %	22,2 %	11,1 %
	Renovated	**0,0 %**	**66,7 %**	**33,3 %**	**0,0 %**	**0,0 %**
	Total original	**41,2 %**				
	Total renovated	**70,9 %**				

In renovated buildings the largest proportion of respondents found it “mostly stable” or “appropriate” and in a few cases, it was found “somewhat fluctuating”. In non-renovated buildings the variety of responses is larger, in some buildings, the majority of respondents found it “stable”, while some respondents in the same building answered “fluctuating” or “somewhat fluctuating”.

Table 10 shows the results of how people perceive indoor air temperature in summer. It is noticeable that there is a problem with overheating in nearly all the houses in summertime. 62,8 % of respondents in renovated buildings and 75,7 % of respondents in non-renovated buildings find summer indoor temperatures as “warm” or “too warm”.

In the renovated houses, most respondents found the indoor air temperature either “warm” or “acceptable”, but still many people thought the indoor air temperature in summer is “too warm”. In group 1, 2 and 5, the largest proportion of respondents in non-retrofitted buildings answered, “too warm”, while in other non-retrofitted buildings, the majority of respondents thought the room temperature was “warm”. The results indicate that the occupants in renovated buildings assess their summer conditions as “too warm” less frequently than their control buildings. Good examples are group 1 and group 2 buildings, where the summer indoor climate is more frequently perceived as “warm” or “acceptable” in renovated buildings and “too warm” in non-renovated buildings.

Table 10: How do you estimate indoor air temperature in your apartment in summertime?

Group	State of the building	Too warm	Warm	Acceptable	Cold	Too cold
Group 1	Original	66,7 %	33,3 %	0,0 %	0,0 %	0,0 %
	Renovated	**15,4 %**	**53,8 %**	**30,8 %**	**0,0 %**	**0,0 %**
Group 2	Original	67,7 %	16,1 %	16,1 %	0,0 %	0,0 %
	Renovated	**27,6 %**	**37,9 %**	**34,5 %**	**0,0 %**	**0,0 %**
Group 3	Original A	38,1 %	47,6 %	14,3 %	0,0 %	0,0 %
	Original B	26,3 %	36,8 %	31,6 %	5,3 %	0,0 %
	Renovated	**25,0 %**	**43,8 %**	**31,3 %**	**0,0 %**	**0,0 %**
Group 4	Original	17,6 %	41,2 %	41,2 %	0,0 %	0,0 %
	Renovated	**17,6 %**	**29,4 %**	**52,9 %**	**0,0 %**	**0,0 %**
Group 5	Original	44,4 %	22,2 %	33,3 %	0,0 %	0,0 %
	Renovated	**0,0 %**	**66,7 %**	**33,3 %**	**0,0 %**	**0,0 %**
	Total original	**75,7 %**				
	Total renovated	**62,8 %**				

In renovated buildings, the respondents commented that in the future the cooling option should be added as a renovation measure. Moreover, in summer the mechanical ventilation is not enough, but low g-value window glazing on the southern side windows keeps the rooms cooler than before the renovation. In both buildings in group 2, people commented about very hot temperatures in summer, while the options for cooling are very limited and do not provide the wanted result. Glazed balconies of the renovated house create a greenhouse effect with high temperatures.

3.3.2 Draught

The responses to the question about the perception of draught in the apartment are shown in Table 11.

Table 11: How do you perceive draught in your apartment?

Group	State of the building		No draught	Little draught	Some draught	Draught	Big draught
Group 1	Original	*N**	16,7 %	66,7 %	16,7 %	0,0 %	0,0 %
	Renovated	*M**	**86,4 %**	**7,7 %**	**7,7 %**	**0,0 %**	**0,0 %**
Group 2	Original	*N**	45,2 %	35,5 %	9,7 %	3,2 %	6,5 %
	Renovated	*FAVR, ME**	**69,0 %**	**24,1 %**	**6,9 %**	**0,0 %**	**0,0 %**
Group 3	Original A	*N**	47,6 %	28,6 %	23,8 %	0,0 %	0,0 %
	Original B	*N**	42,1 %	26,3 %	26,3 %	5,3 %	0,0 %
	Renovated	*FAVR, ME**	**64,7 %**	**17,6 %**	**17,6 %**	**0,0 %**	**0,0 %**
Group 4	Original	*N**	47,1 %	23,5 %	17,6 %	11,8 %	0,0 %
	Renovated	*FAV, ME**	**37,5 %**	**50,0 %**	**12,5 %**	**0,0 %**	**0,0 %**
Group 5	Original	*N**	66,7 %	33,3 %	0,0 %	0,0 %	0,0 %
	Renovated	*FAVR, ME**	**66,7 %**	**0,0 %**	**33,3 %**	**0,0 %**	**0,0 %**
Total original			**77,7 %**				
Total renovated			**88,5 %**				

** N – natural ventilation, M – mechanical supply-exhaust ventilation, FAVR – fresh air valves through radiators, FAV – fresh air valves above radiators, ME – mechanical exhaust ventilation*

In general, people found there is "little draught" or "no draught" in both renovated and non-renovated houses. Mainly, the biggest proportion of the respondents in renovated buildings answered, "no draught", though in group 4 retrofitted building the option "little draught" was more popular (50,0 %) than "no draught" (37,5 %). In that building, fresh air valves were installed above the radiators, not through them, and 42,9 % of respondents reported draught from fresh air valves. Solving ventilation through fresh air valves has its downside, as for the additional question about where the draught is from, 44,9 % of respondents in renovated buildings answered, "through fresh air valves". Fresh air valves are a common solution for Estonian renovations, where no mechanical supply air ventilation is designed.

In non-renovated buildings, the most common answer to the question of where the draught is coming from, was "through windows" by 41 %. The options "through the exterior door" and "through balcony door" had similar proportions (around 20 % and 18 % respectively) of respondents in both renovated and non-renovated buildings. The draught from the floor was not perceived in renovated houses but was noticed by 13 % of respondents in non-retrofitted buildings.

3.3.3 Options and methods for regulating the indoor air temperature

The result for room temperature altering possibilities is shown in Table 12. The questionnaire enabled choosing more than one option; therefore, the result shows the proportion of responses.

When asked about the possibilities for regulating indoor temperature, in the buildings where the heating system allowed temperature regulating, the occupants answered mostly "regulating radiators using thermostats" and "window airing". In non-retrofitted buildings, where were no thermostats, "window airing" was the most popular choice, followed by "no option to regulate". "Solar shading" was not a possibility for many respondents.

Table 12: How can you change temperature indoors?

Group	State of the building	Window airing	Regulating radiators using thermostats	Closing fresh air valves	Solar shading	No option to regulate
Group 1	Original *R**	38,5 %	46,2 %	7,7 %	7,7 %	0,0 %
	Renovated *R**	**37,0 %**	**48,1 %**	**3,7 %**	**11,1 %**	**0,0 %**
Group 2	Original *R**	40,7 %	49,2 %	1,7 %	8,5 %	0,0 %
	Renovated *R**	**43,1 %**	**39,7 %**	**6,9 %**	**8,6 %**	**0,0 %**
Group 3	Original A *N***	57,6 %	6,1 %	3,0 %	12,1 %	21,2 %
	Original B *N**	58,6 %	0,0 %	6,9 %	17,2 %	17,2 %
	Renovated *R**	**41,2 %**	**47,1 %**	**0,0 %**	**11,8 %**	**0,0 %**
Group 4	Original *R**	40,0 %	46,7 %	6,7 %	3,3 %	3,3 %
	Renovated *R**	**33,3 %**	**31,3 %**	**31,3 %**	**4,2 %**	**0,0 %**
Group 5	Original *N**	50,0 %	0,0 %	0,0 %	7,1 %	42,9 %
	Renovated *R**	**40,0 %**	**60,0 %**	**0,0 %**	**0,0 %**	**0,0 %**

** R – radiators with thermostats, N – no thermostats on radiators*
*** Some apartments have thermostat valves on radiators*

The answers to the question about what measures people use for indoor temperature regulation in winter are shown in Table 13.

Table 13: How do you change the temperature indoors in wintertime?

Group	State of the building	Window airing	Regulating radiators using thermostats	Closing fresh air valves	Solar shading	No option to regulate
Group 1	Original *R**	36,4 %	54,5 %	9,1 %	0,0 %	0,0 %
	Renovated *R**	**31,6 %**	**68,4 %**	**0,0 %**	**0,0 %**	**0,0 %**
Group 2	Original *R**	33,3 %	62,5 %	2,1 %	2,1 %	0,0 %
	Renovated *R**	**36,0 %**	**52,0 %**	**4,0 %**	**8,0 %**	**0,0 %**
Group 3	OriginalA *N***	66,7 %	6,7 %	0,0 %	6,7 %	20,0 %
	Original B *N**	64,0 %	0,0 %	8,0 %	8,0 %	20,0 %
	Renovated *R**	**37,9 %**	**55,2 %**	**3,4 %**	**3,4 %**	**0,0 %**
Group 4	Original *R**	32,3 %	48,4 %	9,7 %	3,2 %	6,5 %
	Renovated *R**	**22,5 %**	**40,0 %**	**35,0 %**	**2,5 %**	**0,0 %**
Group 5	Original *N**	63,6 %	0,0 %	0,0 %	0,0 %	36,4 %
	Renovated *R**	**25,0 %**	**75,0 %**	**0,0 %**	**0,0 %**	**0,0 %**

** R – radiators with thermostats, N – no thermostats on radiators*
*** Some apartments have thermostat valves on radiators*

While the inhabitants listed window airing often as an option to change room temperature in the winter, in reality it is practiced less. Instead, the most popular option in the buildings where the heating system allowed adjusting room temperature, was "regulating radiators using thermostats". Window airing was the most common method for temperature regulating in non-renovated buildings where radiator heating control was not possible. Window airing was additionally used in buildings that allow temperature regulation, but on a lesser scale compared to buildings without temperature regulating options. The fresh air valves, which have the purpose of providing sufficient fresh air to the occupants, were mostly not an option for temperature regulation, except in the renovated building in group 4, where this alternative was one of the prevalent ones. The popularity of this option is likely caused by the fresh air valves' solution, which is a source of draught.

In the free text comments, a respondent in a renovated building was very pleased with thermostat regulating options but said it could be even more convenient with electronic displays. While in buildings where is no option to regulate room temperature, people commented on the need for thermostats. In group 4 original building, inhabitants said they use extra electric heaters. Simultaneously, in the group 4 renovated building, an inhabitant noted the thermostat regulating is not necessary because the lowest setting mostly provides enough thermal comfort.

Responses to a similar question about indoor temperature regulation in summer are shown in Table 14. Several answer options were enabled for these questions and the results show the proportion of responses.

Table 14: How do you change the temperature indoors in summertime?

Group	State of the building	Window airing	Regulating radiators using thermostats	Closing fresh air valves	Solar shading	No option to regulate
Group 1	Original	55,6 %	11,1 %	0,0 %	33,3 %	0,0 %
	Renovated	**54,5 %**	**27,3 %**	**0,0 %**	**18,2 %**	**0,0 %**
Group 2	Original	65,1 %	4,7 %	0,0 %	18,6 %	11,6 %
	Renovated	**50,0 %**	**18,0 %**	**2,0 %**	**26,0 %**	**4,0 %**
Group 3	Original A	64,5 %	0,0 %	0,0 %	22,6 %	12,9 %
	Original B	74,1 %	0,0 %	3,7 %	14,8 %	7,4 %
	Renovated	**65,2 %**	**0,0 %**	**0,0 %**	**26,1 %**	**8,7 %**
Group 4	Original	57,1 %	17,9 %	3,6 %	17,9 %	3,6 %
	Renovated	**45,7 %**	**17,1 %**	**22,9 %**	**11,4 %**	**2,9 %**
Group 5	Original	72,7 %	0,0 %	0,0 %	9,1 %	18,2 %
	Renovated	**66,7 %**	**33,3 %**	**0,0 %**	**0,0 %**	**0,0 %**

The options for controlling indoor air temperature in the summer are limited for the occupants in both retrofitted and non-retrofitted multi-family buildings. The main method is window airing, used slightly less in renovated buildings. In some houses "regulating radiators using thermostats" is used for temperature control. Solar shading is not very commonly used in buildings. There is a slight correlation between the houses that reported summer indoor temperature as "too warm" and their use of solar shading. In buildings, where overheating is a problem, people mention additional measures such as constantly working ventilators.

The methods that are used for solar shading do not differ in renovated and non-renovated buildings. The most common method for solar shading is curtains, counting for around 40 % of the total responses in both renovated and not retrofitted houses. Inner Venetian blinds were a method for solar shading in around 30 % of the answers, and the option of "there is no solar shading" was the third most popular answer with nearly 20 %. The other solar shading methods such as Venetian blinds between windowpanes and external solar shade were reported less frequently. External fixed solar shade and automatic solar shade were only marked in a few responses. The respondents also commented on using additional methods such as blackout curtains, windowpanes with low g-factor, and solar protection curtains.

Curtains were mostly used for solar shading in living rooms (approximately 50 %) and bedrooms (around 30 %), less in kitchens. Inner Venetian blinds were used in nearly equal proportions in living rooms, bedrooms, and kitchens, while "living room" was slightly more popular. It is assumed that the result is affected by the circumstance where the online questionnaire did not let choose a certain option, i.e., "curtains" for all the rooms, and the respondents had to limit themselves to one option, i.e., "living room".

The results regarding perceived summer indoor air temperatures indicate an overheating problem in most of the buildings. However, the usage of solar shading is currently irregular, and options for summer indoor air temperature regulating are limited. Therefore, future renovation solutions should integrate a solar shading design. If mechanical cooling is added as a renovation measure, it will increase energy use in the buildings.

The results of the question regarding heating system regulating are shown in Table 15.

Table 15: Is there much possibility or little possibility to regulate the room temperature yourself by adjusting the heating system?

Group	State of the building		Great possibilities	Some possibilities	No option to regulate
Group 1	Original	*R**	60,0 %	40,0 %	0,0 %
	Renovated	*R**	**76,9 %**	**23,1 %**	**0,0 %**
Group 2	Original	*R**	35,5 %	64,5 %	0,0 %
	Renovated	*R**	**44,4 %**	**51,9 %**	**3,7 %**
Group 3	OriginalA	*N***	0,0 %	4,8 %	95,2 %
	Original B	*N**	0,0 %	5,3 %	94,7 %
	Renovated	*R**	**35,3 %**	**64,7 %**	**0,0 %**
Group 4	Original	*R**	35,3 %	52,9 %	11,8 %
	Renovated	*R**	**56,3 %**	**37,5 %**	**6,3 %**
Group 5	Original	*N**	0,0 %	0,0 %	100,0 %
	Renovated	*R**	**33,3 %**	**66,7 %**	**0,0 %**

** R – radiators with thermostats, N – no thermostats on radiators*
*** Some apartments have thermostat valves on radiators*

In the buildings, where the occupants can control the radiator heating, the majority say either there are “great possibilities” or “some possibilities”. “No option to regulate” is answered by the inhabitants who do not have radiators with thermostats.

The people who stated they had “great possibilities” for adjusting the heating system, also were very satisfied (31 %) or quite satisfied (55 %) with general thermal comfort in their apartment. The people who answered they had “no option to regulate”, found general thermal comfort in their dwelling mostly “acceptable” (41 %), followed by “quite satisfied” (26 %) and “quite dissatisfied” (26 %). The people who answered, “no option to regulate”, mainly lived in non-renovated buildings, therefore other factors besides personal control affect the result.

Table 16 shows the results for the frequency of regulating radiator settings. The answers vary by the building, in some renovated houses where is an opportunity to regulate radiator settings, most people answer that they regulate rarely or never, but in group 1 renovated building, many respondents regulate radiators every day.

Table 16: How often do you change the settings of the radiators?

Group	State of the building		Every day	Every week	Every month	More rarely/ Never
Group 1	Original	*R**	16,7 %	16,7 %	50,0 %	16,7 %
	Renovated	*R**	**53,8 %**	**15,4 %**	**23,1 %**	**7,7 %**
Group 2	Original	*R**	30,0 %	13,3 %	26,7 %	30,0 %
	Renovated	*R**	**14,8 %**	**7,4 %**	**18,5 %**	**59,3 %**
Group 3	Original A	*N***	0,0 %	0,0 %	13,3 %	86,7 %
	Original B	*N**	0,0 %	0,0 %	0,0 %	100,0 %
	Renovated	*R**	**17,6 %**	**29,4 %**	**17,6 %**	**35,3 %**
Group 4	Original	*R**	17,6 %	23,5 %	35,3 %	23,5 %
	Renovated	*R**	**0,0 %**	**25,0 %**	**31,3 %**	**43,8 %**
Group 5	Original	*N**	0,0 %	0,0 %	0,0 %	100,0 %
	Renovated	*R**	**0,0 %**	**33,3 %**	**0,0 %**	**66,7 %**

** R – radiators with thermostats, N – no thermostats on radiators*
*** Some apartments have thermostat valves on radiators*

The results about how informed people are regarding technical systems in their dwellings indicate that people in renovated buildings are better informed, as shown in Table 17. Still, around 25 % of the inhabitants of renovated buildings are not informed about their possibilities for regulating technical systems.

Table 17: Have you received information on how heating (radiators) and ventilation systems (ventilation aggregates, fresh air valves) work in your apartment?

State of the building	Yes, orally	Yes, written	Yes, both orally and written	No, I have not got any information	I do not know/ remember
Original	11,1 %	5,1 %	4,0 %	52,5 %	27,3 %
Renovated	25,6 %	10,3 %	37,2 %	10,3 %	16,7 %

3.3.4 Thermal comfort among elderly people

Elderly people perceive thermal comfort differently from young adults; therefore, a separate chapter is analyzing the results from older peoples' responses. The answers from the elderly (respondents over 65 years of age in this study) were compared with the results from all the other respondents under 65 years of age. Also, the results are presented separately for all the renovated and non-renovated buildings. The results regarding satisfaction with general thermal comfort for the two age groups are shown in Table 18.

Table 18: How do you find the thermal comfort in your apartment in general? Answers by age group

State of the building	Respondents' age	Very satisfied	Quite satisfied	Acceptable	Quite dissatisfied	Very dissatisfied
Original	23-64	5,6 %	33,3 %	36,1 %	19,4 %	5,6 %
	65-99	**10,0 %**	**23,3 %**	**43,3 %**	**16,7 %**	**6,7 %**
Renovated	23-64	24,2 %	66,7 %	6,1 %	3,0 %	0,0 %
	65-99	**32,0 %**	**52,0 %**	**16,0 %**	**0,0 %**	**0,0 %**
Total original (23-64)		**38,9 %**				
Total original (65-99)		**33,3 %**				
Total renovated (23-64)		**90,9 %**				
Total renovated (65-99)		**84,0 %**				

The response to the general thermal comfort question shows a rather good satisfaction rate, especially in the renovated buildings. Compared to the younger age group, the elderly answered more often that they were "very satisfied" or found thermal comfort "acceptable". However, compared to the elderly, younger people were more likely to answer they were "quite satisfied" with thermal comfort. Combined results indicate that younger people were more satisfied with general thermal comfort than older people. The dissatisfaction rates were similar among younger and older people.

Satisfaction rates with winter indoor temperatures are shown in Table 19 and satisfaction with summer indoor temperatures is shown in Table 20.

Table 19: How do you estimate indoor air temperature in your apartment in wintertime?

State of the building	Respondents' age	Too warm	Warm	Acceptable	Cold	Too cold
Original	23-64	16,7 %	23,6 %	37,5 %	18,1 %	4,2 %
	65-99	**0,0 %**	**10,0 %**	**63,3 %**	**20,0 %**	**6,7 %**
Renovated	23-64	12,1 %	39,4 %	45,5 %	3,0 %	0,0 %
	65-99	**0,0 %**	**16,0 %**	**84,0 %**	**0,0 %**	**0,0 %**
Total original (23-64)		**40,3 %**				
Total original (65-99)		**10,0 %**				
Total renovated (23-64)		**51,5 %**				
Total renovated (65-99)		**16,0 %**				

Even though the general thermal comfort was in overall rated well and the responses did not differ much from the younger people, some difference can be seen in the perception of winter and summer indoor air temperatures. Older people did not answer "too warm" about their winter indoor temperature and were less likely to answer "warm" than the younger inhabitants. When the answers "too warm" and "warm" were combined, it became obvious that younger people perceived indoor temperatures as warmer compared to the older inhabitants. Winter indoor air temperature was mostly found "acceptable" by the elderly in both renovated and non-renovated buildings. The response rates for options "cold" and "too cold" are similar for older and younger people in renovated buildings and buildings in their original state.

Table 20: How do you estimate indoor air temperature in your apartment in summertime?

State of the building	Respondents' age	Too warm	Warm	Acceptable	Cold	Too cold
Original	23-64	45,8 %	36,1 %	18,1 %	0,0 %	0,0 %
	65-99	**40,0 %**	**23,3 %**	**33,3 %**	**3,3 %**	**0,0 %**
Renovated	23-64	31,3 %	40,6 %	28,1 %	0,0 %	0,0 %
	65-99	**16,0 %**	**44,0 %**	**40,0 %**	**0,0 %**	**0,0 %**
Total original (23-64)		**81,9 %**				
Total original (65-99)		**63,3 %**				
Total renovated (23-64)		**71,9 %**				
Total renovated (65-99)		**60,0 %**				

Regarding the question about indoor air temperature in summer, people over 65 years old answered less likely "too warm" than the younger age group. They also answered "warm" less often than younger people in non-retrofitted houses but responded "warm" more often than younger age group in renovated houses. The summer indoor temperatures were found "acceptable" by more older people than by younger people. A few elderly people found indoor air temperature to be "cold" in non-retrofitted houses. Younger people were more likely to answer that indoor air temperature in summer is "warm" or "too warm" and more so in non-retrofitted buildings.

The result shows that the same conditions that younger people find "too warm" and "warm", older people perceive more as "warm" and "acceptable".

3.4 Answers to air quality questions

3.4.1 General air quality

Table 21 shows that there is a considerable difference in perception of air quality between the retrofitted and non-retrofitted houses. Most of the respondents in renovated houses perceived general air quality as "good", while most people in non-retrofitted houses found it "acceptable". The people in non-renovated houses rarely responded air quality was "very good", and they were more likely to answer the air quality is "bad" or "very bad". Simultaneously, respondents in renovated houses did not answer "very bad" and only a few found it "bad".

Table 21: How do you find the air quality in your apartment in general?

Group	State of the building	Very good	Good	Acceptable	Bad	Very bad
Group 1	Original *N**	0,0 %	33,3 %	33,3 %	33,3 %	0,0 %
	Renovated *M**	**23,1 %**	**76,9 %**	**0,0 %**	**0,0 %**	**0,0 %**
Group 2	Original *N**	3,3 %	20,0 %	56,7 %	16,7 %	3,3 %
	Renovated *FAVR, ME**	**10,3 %**	**69,0 %**	**20,7 %**	**0,0 %**	**0,0 %**
Group 3	Original A *N**	0,0 %	30,0 %	55,0 %	5,0 %	10,0 %
	Original B *N**	5,3 %	15,8 %	63,2 %	10,5 %	5,3 %
	Renovated *FAVR, ME**	**11,8 %**	**58,8 %**	**29,4 %**	**0,0 %**	**0,0 %**
Group 4	Original *N**	0,0 %	29,4 %	64,7 %	5,9 %	0,0 %
	Renovated *FAV, ME**	**11,8 %**	**76,5 %**	**5,9 %**	**5,9 %**	**0,0 %**
Group 5	Original *N**	0,0 %	0,0 %	44,4 %	33,3 %	22,2 %
	Renovated *FAVR, ME**	**0,0 %**	**66,7 %**	**33,3 %**	**0,0 %**	**0,0 %**
Total original		**23,8 %**				
Total renovated		**82,3 %**				

** N – natural ventilation, M – mechanical supply-exhaust ventilation, FAVR – fresh air valves through radiators, FAV – fresh air valves above radiators, ME – mechanical exhaust ventilation*

When asked about specific rooms, the combined results from all houses showed the air quality in bedrooms and living rooms was estimated to be slightly higher than in kitchens. However, the level of satisfaction with air quality in specific rooms was higher in renovated buildings.

The answers to the question about indoor air dryness are shown in Table 22.

Table 22: How do you estimate indoor air dryness in your apartment?

Group	State of the building	Dry	Quite dry	Appropriate	Quite moist	Moist air
Group 1	Original *N**	0,0 %	83,3 %	16,7 %	0,0 %	0,0 %
	Renovated *M**	**7,7 %**	**38,5 %**	**53,8 %**	**0,0 %**	**0,0 %**
Group 2	Original *N**	3,4 %	24,1 %	62,1 %	6,9 %	3,4 %
	Renovated *FAVR, ME**	**10,3 %**	**37,9 %**	**51,7 %**	**0,0 %**	**0,0 %**
Group 3	Original A *N**	23,8 %	42,9 %	19,0 %	9,5 %	4,8 %
	Original B *N**	5,3 %	42,1 %	42,1 %	10,5 %	0,0 %
	Renovated *FAVR, ME**	**11,8 %**	**47,1 %**	**35,3 %**	**5,9 %**	**0,0 %**
Group 4	Original *N**	5,9 %	23,5 %	64,7 %	5,9 %	0,0 %
	Renovated *FAV, ME**	**17,6 %**	**29,4 %**	**52,9 %**	**0,0 %**	**0,0 %**
Group 5	Original *N**	55,6 %	11,1 %	22,2 %	0,0 %	11,1 %
	Renovated *FAVR, ME**	**50,0 %**	**50,0 %**	**0,0 %**	**0,0 %**	**0,0 %**

** N – natural ventilation, M – mechanical supply-exhaust ventilation, FAVR – fresh air valves through radiators, FAV – fresh air valves above radiators, ME – mechanical exhaust ventilation*

The response result differs from building to building, there are houses in both renovated and non-renovated groups where the majority of respondents perceived the air as "quite dry" or "dry". The air is also perceived as mostly "appropriate" in several buildings, regardless of their renovation status. Moist air is reported less frequently in all the buildings. Additional comments from respondents marked dry air during the heating season.

The response to the air freshness question is shown in Table 23.

Table 23: How do you estimate indoor air freshness in your apartment?

Group	State of the building	Fresh	Quite fresh	Appropriate	Quite stuffy	Stuffy
Group 1	Original *N**	0,0 %	33,3 %	33,3 %	16,7 %	16,7 %
	Renovated *M**	**7,7 %**	**46,2 %**	**38,5 %**	**7,7 %**	**0,0 %**
Group 2	Original *N**	0,0 %	10,0 %	60,0 %	30,0 %	0,0 %
	Renovated *FAVR, ME**	**6,9 %**	**37,9 %**	**41,4 %**	**10,3 %**	**3,4 %**
Group 3	Original A *N**	5,0 %	15,0 %	45,0 %	15,0 %	20,0 %
	Original B *N**	0,0 %	10,5 %	68,4 %	21,1 %	0,0 %
	Renovated *FAVR, ME**	**5,9 %**	**58,8 %**	**35,3 %**	**0,0 %**	**0,0 %**
Group 4	Original *N**	0,0 %	45,5 %	50,0 %	4,5 %	0,0 %
	Renovated *FAV, ME**	**0,0 %**	**58,8 %**	**35,3 %**	**5,9 %**	**0,0 %**
Group 5	Original *N**	0,0 %	11,1 %	22,2 %	44,4 %	22,2 %
	Renovated *FAVR, ME**	**33,3 %**	**0,0 %**	**66,7 %**	**0,0 %**	**0,0 %**
	Total original	**20,8 %**				
	Total renovated	**53,2 %**				

** N – natural ventilation, M – mechanical supply-exhaust ventilation, FAVR – fresh air valves through radiators, FAV – fresh air valves above radiators, ME – mechanical exhaust ventilation*

People in renovated buildings estimated the freshness in their dwellings higher, mostly as "quite fresh". Most people in non-renovated houses perceived the air freshness in their apartment as "appropriate". The responses in non-renovated buildings were diverse, in some buildings a notable proportion of respondents answered that indoor air is "quite fresh" and in others, most perceived it as "quite stuffy".

3.4.2 Problems with smells and ventilation

The results regarding the perception of indoor air smell are shown in Table 24. Mostly the air was said to be "odorless", or it has "some odor" in both renovated and non-renovated buildings. However, people rarely reported odors or bad smells in renovated buildings but did it more often in buildings in their original state.

Table 24: How do you estimate indoor air smell in your apartment?

Group	State of the building	Odorless	Some odor	Odor	Quite bad odor	Bad odor
Group 1	Original *N**	50,0 %	16,7 %	16,7 %	16,7 %	0,0 %
	Renovated *M**	**38,5 %**	**65,1 %**	**0,0 %**	**0,0%**	**0,0 %**
Group 2	Original *N**	36,7 %	33,3 %	23,3 %	3,3 %	3,3 %
	Renovated *FAVR, ME**	**55,2 %**	**37,9 %**	**6,9 %**	**0,0 %**	**0,0 %**
Group 3	Original A *N**	23,8 %	57,1 %	9,5 %	4,8 %	4,8 %
	Original B *N**	15,8 %	63,2 %	15,8 %	5,3 %	0,0 %
	Renovated *FAVR, ME**	**47,1 %**	**47,1 %**	**0,0 %**	**0,0 %**	**5,9 %**
Group 4	Original *N**	50,0 %	37,5 %	6,3 %	6,3 %	0,0 %
	Renovated *FAV, ME**	**23,5 %**	**70,6 %**	**5,9 %**	**0,0 %**	**0,0 %**
Group 5	Original *N**	44,4 %	33,3 %	22,2 %	0,0 %	0,0 %
	Renovated *FAVR, ME**	**33,3 %**	**33,3 %**	**33,3 %**	**0,0 %**	**0,0 %**
	Total original	**77,2 %**				
	Total renovated	**93,7 %**				

** N – natural ventilation, M – mechanical supply-exhaust ventilation, FAVR – fresh air valves through radiators, FAV – fresh air valves above radiators, ME – mechanical exhaust ventilation*

The proportion of answers regarding food smell disturbance from inside the building is shown in Table 25 and Table 26. The respondents who live in renovated buildings were less bothered by food smells originating from their own apartments or from neighbors' apartments. Despite this, around 60 % of them were still distressed about smell disturbances sometimes or more often.

Table 25: Are you bothered by the smells from inside the building, for example as smell of food that originates from own apartment?

State of the building	Yes, often (every week)	Yes, sometimes	No, never
Original	9,9 %	61,5 %	28,6 %
Renovated	5,6 %	54,2 %	40,3 %

Table 26: Are you bothered by the smells from inside the building, for example as smell of food from the neighbors?

State of the building	Yes, often (every week)	Yes, sometimes	No, never
Original	27,3 %	42,3 %	34,0 %
Renovated	11,3 %	47,9 %	40,8 %

The percentage of respondents, who found tobacco smell disturbing sometimes or more often, is very similar in both renovated and non-renovated buildings, as shown in Table 27. In additional comments about smell disturbances, respondents mentioned most often tobacco smell from neighbors smoking on balconies, on windows, and in stairwells.

Table 27: Are you bothered by the smells from inside the building, for example as tobacco smoke or other smell from neighbors?

State of the building	Yes, often (every week)	Yes, sometimes	No, never
Original	21,7 %	42,4 %	35,9 %
Renovated	18,1 %	43,1 %	38,9 %

The main source of outside smells is traffic emissions, see Table 28. The results are given separately for each of the buildings since the disturbance depends on the location of the building. More dissatisfaction is noticed in buildings next to busy roads, such as renovated buildings in group 3, the original buildings in group 4 and both group 5 buildings, where some respondents commented extra on the traffic emission disturbance. Besides the location, the disturbance depends on the floor and the location of the apartment, as some apartments do not have road-facing windows.

Table 28: Are you bothered by the smells from outside of the building, for example as traffic emissions?

Group	State of the building		Yes, often (every week)	Yes, sometimes	No, never
Group 1	Original		16,7 %	16,7 %	66,7 %
	Renovated		**0,0 %**	**54,5 %**	**45,5 %**
Group 2	Original		3,4 %	37,9 %	58,6 %
	Renovated		**3,6 %**	**10,7 %**	**85,7 %**
Group 3	Original A	*BR**	10,0 %	50,0 %	40,0 %
	Original B	*BR**	15,8 %	52,6 %	31,6 %
	Renovated	*BR**	**23,5 %**	**29,4 %**	**47,1 %**
Group 4	Original	*BR**	29,4 %	41,2 %	29,4 %
	Renovated		**0,0 %**	**31,3 %**	**68,8 %**
Group 5	Original	*BR**	55,6 %	11,1 %	33,3 %
	Renovated	*BR**	**0,0 %**	**100,0 %**	**0,0 %**

** BR – Busy road in proximity*

The other sources, such as smell from industries or restaurants were reported less often. Smell disturbance from outside sources is also location dependent, while the inhabitants in Tallinn rarely noticed it, 50 % of respondents in both houses in Saku (group 1 buildings), marked "yes, sometimes" about the frequency of smell disturbances from factories and restaurants. Also, wood-burning smoke in general is not a problem, but the respondents in group 1 renovated building noted wood-burning smoke as a cause of disturbance sometimes (41 %) or more often (17 %). Inhabitants commented that there is a communal sauna next to their house, which is heated with wood. Moreover, they noted that in the future this kind of situation should be considered when designing the ventilation.

The answers to the question about perceiving smell of mold, stagnant air, or musty smell, are shown in Table 29.

Table 29: Have you noticed some of the following smells in your apartment?

Smell of mold			
State of the building	**Yes, often (every week)**	**Yes, sometimes**	**No, never**
Original	4,3 %	23,4 %	72,3 %
Renovated	0,0 %	4,1 %	95,9 %
Smell of stagnant air			
State of the building	**Yes, often (every week)**	**Yes, sometimes**	**No, never**
Original	10,2 %	56,1 %	33,7 %
Renovated	4,0 %	22,7 %	73,3 %
Musty smell			
State of the building	**Yes, often (every week)**	**Yes, sometimes**	**No, never**
Original	5,4 %	25,8 %	68,8 %
Renovated	0,0 %	8,5 %	91,5 %

The majority of people in renovated buildings were never bothered by the smell of mold or musty smell, but people in non-renovated houses experienced these smells more often, nearly 30 % of the respondents were sometimes or more often bothered by the smell of mold or musty smell. The smell of stagnant air was more common in both retrofitted and non-retrofitted buildings, though in renovated buildings the most popular answer was “no, never” (73,3 %), and for the building in its original state, “yes, sometimes” (56,1 %).

The answers to several questions regarding ventilation problems are shown in Table 30, Table 31, Table 32 and Table 33. The PPD, considering answers “yes, sometimes” and “yes, often”, is lower in renovated buildings, but still fails to meet category III, an acceptable level of expectation. In the original state buildings, the PPD values are well under the acceptable level of expectation. The PPD for existing buildings should be less than 15 % and in renovated buildings less than 10 % (Swedish Standards Institute, 2007).

Table 30: Are you bothered in your apartment by ventilation problems, such as difficulties to get rid of troublesome smells?

State of the building	Yes, often (every week)	Yes, sometimes	No, never
Original	24,5 %	48,9 %	26,6 %
Renovated	2,7 %	31,1 %	66,2 %

Table 31: Are you bothered in your apartment by ventilation problems, such as difficulties to get rid of moist air in bathrooms?

State of the building	Yes, often (every week)	Yes, sometimes	No, never
Original	33,0 %	36,1 %	30,9 %
Renovated	5,4 %	24,3 %	70,3 %

Table 32: Are you bothered in your apartment by ventilation problems, such as fog on the window while cooking?

State of the building	Yes, often (every week)	Yes, sometimes	No, never
Original	32,6 %	49,5 %	17,9 %
Renovated	8,1 %	21,6 %	70,3 %

Table 33: Are you bothered in your apartment by ventilation problems, such as difficulties to regulate ventilation yourself?

State of the building	Yes, often (every week)	Yes, sometimes	No, never
Original	48,9 %	35,6 %	15,6 %
Renovated	6,9 %	31,9 %	61,1 %

People in renovated buildings had less trouble with ventilation issues, compared to the inhabitants in non-renovated buildings. However, there were more than 30 % of respondents in renovated buildings, who had problems removing troublesome smells or struggled regulating ventilation themselves. People living in non-retrofitted buildings most frequently answered “yes, sometimes” to questions regarding ventilation troubles and nearly half of them often had difficulties regulating ventilation by themselves.

The people who answered that they have trouble regulating ventilation used daily window airing more (65 %) than the people who did not have this problem (57 %). The main reasons for window airing among people who had ventilation regulating problems were bad air quality and insufficient ventilation. People without ventilation regulating problems also had bad air quality as the main reason for window airing, but the next most popular reasons were too warm indoor temperatures and habit. People having difficulties regulating ventilation themselves also kept windows open all night/day more (20 %) compared to the people who did not have trouble with regulating ventilation (8 %).

The possibilities for regulating air quality are shown in Table 34. The respondents in non-renovated multi-family houses answered most likely “no option to regulate” and some respondents marked that there are “some possibilities”. The people in renovated buildings had a more positive outlook on their air quality regulation, indicating there are “great possibilities” or “some possibilities”. There is a variance in the results in some buildings, where some respondents saw the regulating possibilities as great, while other people in the same building said they had „no option to regulate”. It was further noted that people who reported their options for regulating ventilation were great, perceived air quality more as “good” and “very good”, whereas people who had no option to regulate ventilation, answered more often “acceptable” and “good”.

Table 34: Is there much possibility or little possibility to regulate the air quality yourself by adjusting the ventilation system?

Group	State of the building	Great possibilities	Some possibilities	No option to regulate
Group 1	Original *N**	0,0 %	16,7 %	83,3 %
	Renovated *M**	**38,5 %**	**23,0 %**	**38,5 %**
Group 2	Original *N**	6,5 %	9,7 %	83,9 %
	Renovated *FAVR, ME**	**7,1 %**	**42,9 %**	**50,0 %**
Group 3	Original A *N**	0,0 %	14,3 %	85,7 %
	Original B *N**	0,0 %	10,5 %	89,5 %
	Renovated *FAVR, ME**	**17,6 %**	**52,9 %**	**29,4 %**
Group 4	Original *N**	0,0 %	25,0 %	75,0 %
	Renovated *FAV, ME**	**43,8 %**	**43,8 %**	**12,5 %**
Group 5	Original *N**	0,0 %	22,2 %	77,8 %
	Renovated *FAVR, ME**	**0,0 %**	**33,3 %**	**66,7 %**

** N – natural ventilation, M – mechanical supply-exhaust ventilation, FAVR – fresh air valves through radiators, FAV – fresh air valves above radiators, ME – mechanical exhaust ventilation*

In the survey, inhabitants left additional comments about ventilation. In renovated buildings, people noted that kitchen ventilation could have been solved better as kitchen ventilators cause overpressure. Also, the extract from toilets is insufficient. Furthermore, people in renovated houses sometimes used window airing, to remove troublesome smells. In non-renovated buildings, people mentioned on several occasions that ventilation is nonexistent or needs improvement, as does the overall indoor environment.

3.4.3 Problems with mold and moisture

The results for the question about visible water stains are shown in Table 35.

Table 35: Have you noticed in the past 12 months in your apartment visible water stains on walls, floors or ceilings?

Group	State of the building	Yes, in bathroom	Yes, in other room	No
Group 1	Original	33,3 %	0,0 %	66,7 %
	Renovated	**0,0 %**	**0,0 %**	**100,0 %**
Group 2	Original	34,5 %	10,3 %	55,2 %
	Renovated	**24,1 %**	**3,4 %**	**72,4 %**
Group 3	Original A	22,7 %	9,1 %	68,2 %
	Original B	16,7 %	22,2 %	61,1 %
	Renovated	**11,8 %**	**0,0 %**	**88,2 %**
Group 4	Original	16,7 %	27,8 %	55,6 %
	Renovated	**0,0 %**	**0,0 %**	**100 %**
Group 5	Original	22,2 %	11,1 %	66,7 %
	Renovated	**0,0 %**	**0,0 %**	**100,0 %**

The respondents in renovated buildings most frequently answered ”no” to this question, but in two renovated multi-family houses some people noticed water stains in bathrooms. One of these buildings is a renovated building in group 2, where according to the inhabitants, ventilation air exchange rates were lowered for energy-saving purposes. People in non-renovated buildings had moisture problems more often and noticed it also in other rooms besides bathrooms.

In Table 36, the proportion of respondents who reported mold problems is shown. In renovated buildings, most responses were “no” when asked about visible mold growth. There are a few cases where people did report mold growth in bathrooms or in other rooms in renovated buildings. The situation is worse in non-renovated buildings, all these buildings have people who reported mold in bathrooms, in other rooms, or in both. Combined results in non-renovated buildings show that 30 % of respondents noticed mold in at least one room. In two houses, in the original buildings in group 2 and group 4, more than 40 % of respondents noticed mold in at least one room.

Table 36: Have you noticed in the past 12 months in your apartment visible mold growth on walls, floors or ceilings?

Group	State of the building	Yes, in bathroom	Yes, in other room	No
Group 1	Original	16,7 %	0,0 %	83,3 %
	Renovated	**0,0 %**	**0,0 %**	**100,0 %**
Group 2	Original	13,8 %	27,6 %	58,6 %
	Renovated	**0,0 %**	**4,2 %**	**95,8 %**
Group 3	Original A	10,0 %	10,0 %	80,0 %
	Original B	15,8 %	10,5 %	73,7 %
	Renovated	**5,9 %**	**0,0 %**	**94,1 %**
Group 4	Original	16,7 %	27,8 %	55,6 %
	Renovated	**5,9 %**	**0,0 %**	**94,1 %**
Group 5	Original	0,0 %	11,1 %	88,9 %
	Renovated	**0,0 %**	**0,0 %**	**100,0 %**

Out of all the people who reported mold growth, more than 40 % said they sensed the smell of mold sometimes or more often, and more than 80 % of them had trouble removing moist air sometimes or more often in the bathroom. The people who had mold complaints also had difficulties regulating ventilation themselves (58 % of respondents had the problem often and 34 % sometimes). 51 % of them found the general air quality in their apartment “acceptable” and 21 % “good”, the rest found it either “very bad” or “bad”. The people who did not mention mold mostly said their air quality is “good” (46 % of responses), “acceptable” (36 %), or “very good” (8 %). More than 90 % never smelled mold in their apartment. The people who did not have mold problem had less difficulty regulating ventilation themselves (55 % of respondents had difficulties sometimes or more often) or removing moist air from the bathrooms (43 % of responses indicated difficulties sometimes or more often).

Several respondents in non-renovated houses added additional comments about mold problems, especially in group 1, group 3, and group 4, such as having mold on the last floor’s ceiling and wall junction and on window reveals. People expressed dissatisfaction with the indoor climate, which is damp, cold and causes mold in several rooms.

3.5 Answers to noise questions

The result regarding general acoustic comfort in respondents’ homes is shown in Table 37.

Table 37: How do you find the acoustic conditions in your apartment in general?

Group	State of the building		Very good	Good	Acceptable	Bad	Very bad
Group 1	Original		0,0 %	16,7 %	66,7 %	0,0 %	16,7 %
	Renovated		**0,0 %**	**61,5 %**	**38,5 %**	**0,0 %**	**0,0 %**
Group 2	Original		0,0 %	13,3 %	46,7 %	20,0 %	20,0 %
	Renovated		**10,3 %**	**20,7 %**	**44,8 %**	**13,8 %**	**10,3 %**
Group 3	Original A	*BR**	5,0 %	10,0 %	65,0 %	10,0 %	10,0 %
	Original B	*BR**	0,0 %	15,8 %	47,4 %	36,8 %	0,0 %
	Renovated	*BR**	**0,0 %**	**35,3 %**	**47,1 %**	**11,8 %**	**5,9 %**
Group 4	Original	*BR**	11,8 %	0,0 %	41,2 %	29,4 %	17,6 %
	Renovated		**13,3 %**	**33,3 %**	**40,0 %**	**13,3 %**	**0,0 %**
Group 5	Original	*BR**	0,0 %	11,1 %	33,3 %	33,3 %	22,2 %
	Renovated	*BR**	**0,0 %**	**0,0 %**	**33,3 %**	**66,7 %**	**0,0 %**
Total original			**13,9 %**				
Total renovated			**39,0 %**				

** BR – Busy road in proximity*

Most respondents found the acoustic conditions “acceptable”. In renovated buildings people perceived their acoustic environment more often as “good” or “very good” than people in non-renovated buildings, who sensed it more frequently as “bad” or “very bad”. This could partially be caused by reduced traffic noise in renovated buildings, where the windows and wall constructions are more airtight and outside noises are less perceptible. Though the acoustic conditions improved after the renovations, the satisfaction level was not as high as with thermal comfort or air quality.

The difference in outside noise perception is shown in Table 38.

Table 38: How do you perceive noise in your apartment? Noise that comes from outside

Traffic					
State of the building	**Not noticeable**	**Noticeable, but it does not disturb**	**Does not disturb very much**	**Disturbs**	**Disturbs a lot**
Original	13,9 %	42,6 %	18,8 %	9,9 %	14,9 %
Renovated	32,9 %	39,7 %	17,8 %	8,2 %	1,4 %
Waste disposal					
State of the building	**Not noticeable**	**Noticeable, but it does not disturb**	**Does not disturb very much**	**Disturbs**	**Disturbs a lot**
Original	46,8 %	29,8 %	13,8 %	5,3 %	4,3 %
Renovated	22,7 %	54,7 %	17,3 %	5,3 %	0,0 %
Industry					
State of the building	**Not noticeable**	**Noticeable, but it does not disturb**	**Does not disturb very much**	**Disturbs**	**Disturbs a lot**
Original	90,8 %	1,1 %	8,0 %	0,0 %	0,0%
Renovated	92,5 %	6,0 %	0,0 %	1,5 %	0,0 %
Ventilation aggregates, heat pumps					
State of the building	**Not noticeable**	**Noticeable, but it does not disturb**	**Does not disturb very much**	**Disturbs**	**Disturbs a lot**
Original	80,4 %	8,7 %	8,7 %	1,1 %	1,1 %
Renovated	80,8 %	12,3 %	2,7 %	4,1 %	0,0 %
Children playing					
State of the building	**Not noticeable**	**Noticeable, but it does not disturb**	**Does not disturb very much**	**Disturbs**	**Disturbs a lot**
Original	58,5 %	22,3 %	10,6 %	5,3 %	3,2 %
Renovated	60,3 %	20,5 %	16,4 %	2,7 %	0,0 %
Parties outside					
State of the building	**Not noticeable**	**Noticeable, but it does not disturb**	**Does not disturb very much**	**Disturbs**	**Disturbs a lot**
Original	60,0 %	14,4 %	13,3 %	8,9 %	3,3 %
Renovated	61,6 %	19,2 %	11,0 %	6,8 %	1,4 %

As noticed earlier, traffic noise was less noticeable in renovated buildings. People did detect waste disposal noise but were generally not disturbed by this. Sounds from the industry were not noticeable for most respondents. Most respondents did not notice sounds from ventilation aggregates or heat pumps, and the ones who noticed were generally not disturbed by this. Children playing and parties outside disturbed occupants slightly more, but for the majority, these factors were “not noticeable”. Respondents left additional comments on the traffic noise, especially when windows are open.

Noise from inside the building and the perception of it is shown in Table 39.

Table 39: How do you perceive noise in your apartment? Noise from other parts of the building

Ventilation system					
State of the building	**Not noticeable**	**Noticeable, but it does not disturb**	**Does not disturb very much**	**Disturbs**	**Disturbs a lot**
Original	86,8 %	7,7 %	5,5 %	0,0 %	0,0 %
Renovated	73,6 %	16,7 %	9,7 %	0,0 %	0,0 %
Kitchen ventilator					
State of the building	**Not noticeable**	**Noticeable, but it does not disturb**	**Does not disturb very much**	**Disturbs**	**Disturbs a lot**
Original	42,4 %	27,2 %	14,1 %	13,0 %	3,3 %
Renovated	29,2 %	37,5 %	16,7 %	16,7 %	0,0 %
Fridge					
State of the building	**Not noticeable**	**Noticeable, but it does not disturb**	**Does not disturb very much**	**Disturbs**	**Disturbs a lot**
Original	55,4 %	31,5 %	10,9 %	1,1 %	1,1 %
Renovated	40,8 %	35,2 %	15,5 %	7,0 %	1,4 %

In renovated buildings, people perceived the sounds from ventilation systems more, but in general, people found it “not noticeable”. People noticed more home appliances such as kitchen ventilators and fridges, but they were generally not disturbed by them.

Table 40 shows the result of disturbances caused by technical systems in respondents’ apartments. The noise from technical systems depends on the buildings and not so much on their renovation status. Most people found there is “no noise” or the noise “does not disturb” or “does not disturb much”. Sometimes the technical rooms in the buildings can cause annoyance, as is commented by a respondent whose apartment is above a boiler room.

Table 40: How do you estimate noise from technical systems in your apartment?

Group	**State of the building**	**No noise**	**Noise, but it does not disturb**	**Noise, but it does not disturb much**	**Some noise**	**Noise**
Group 1	Original *N**	66,7 %	0,0 %	33,3 %	0,0 %	0,0 %
	Renovated *M**	**53,8 %**	**23,1 %**	**15,4 %**	**7,7 %**	**0,0 %**
Group 2	Original *N**	50,0 %	26,7 %	10,0 %	10,0 %	3,3 %
	Renovated *FAVR, ME**	**66,7 %**	**14,8 %**	**7,4 %**	**11,1 %**	**0,0 %**
Group 3	Original A *N**	61,9 %	19,0 %	9,5 %	9,5 %	0,0 %
	Original B *N**	44,4 %	27,8 %	5,6 %	22,2 %	0,0 %
	Renovated *FAVR, ME**	**52,9 %**	**11,8 %**	**23,5 %**	**11,8 %**	**0,0 %**
Group 4	Original *N**	70,6 %	11,8 %	5,9 %	11,8 %	0,0 %
	Renovated *FAV, ME**	**58,8 %**	**29,4 %**	**5,9 %**	**5,9 %**	**0,0 %**
Group 5	Original *N**	22,2 %	11,1 %	55,6 %	11,1 %	0,0 %
	Renovated *FAVR, ME**	**66,7 %**	**0,0 %**	**0,0 %**	**33,3 %**	**0,0 %**
	Total original	**64,4 %**				
	Total renovated	**75,3 %**				

** N – natural ventilation, M – mechanical supply-exhaust ventilation, FAVR – fresh air valves through radiators, FAV – fresh air valves above radiators, ME – mechanical exhaust ventilation*

One issue mentioned most frequently in the survey’s free text answers was noise. People in renovated buildings and non-renovated buildings commented alike on noise from neighboring apartments, mainly because neighbors’ life activity was heard too well. Moreover, apartment exterior doors are not soundproof enough to suppress the sounds from the hallway. People mentioned disturbance from renovation works and parties in neighboring apartments and houses. There were additional comments about neighbors' ventilators causing noise disturbance.

The poor sound isolation between the apartments has been confirmed in the study by Kalamees et al. (2009), finding that the walls and ceilings between the apartments in LPS buildings do not meet the modern criteria, and sometimes the acoustic conditions are considerably under the recommended levels. The study additionally proposes reconstruction measures to improve inner constructions' soundproofing, though it is not a common practice in full renovations in Estonia.

3.6 Answers to daylighting questions

The occupants' perception of daylighting conditions is shown in Table 41. Mostly the respondents found daylighting conditions in their dwellings "good". In some buildings "acceptable" was the next popular answer, and in some other buildings the answers inclined towards "very good".

Table 41: How do you find daylighting conditions in your apartment in general?

Group	State of the building	Very good	Good	Acceptable	Bad	Very bad
Group 1	Original	50,0 %	50,0 %	0,0 %	0,0 %	0,0 %
	Renovated	**53,8 %**	**30,8 %**	**15,4 %**	**0,0 %**	**0,0 %**
Group 2	Original	29,0 %	35,5 %	35,5 %	0,0 %	0,0 %
	Renovated	**27,6 %**	**55,2 %**	**13,8 %**	**3,4 %**	**0,0 %**
Group 3	Original A	9,5 %	61,9 %	28,6 %	0,0 %	0,0 %
	Original B	0,0 %	47,4 %	36,8 %	15,8 %	0,0 %
	Renovated	**11,8 %**	**76,5 %**	**5,9 %**	**5,9 %**	**0,0 %**
Group 4	Original	18,8 %	50,0 %	25,0 %	6,3 %	0,0 %
	Renovated	**12,5 %**	**56,3 %**	**18,8 %**	**6,3 %**	**6,3 %**
Group 5	Original	22,2 %	33,3 %	33,3 %	11,1 %	0,0 %
	Renovated	**0,0 %**	**66,7 %**	**33,3 %**	**0,0 %**	**0,0 %**
	Total original	**64,7 %**				
	Total renovated	**80,8 %**				

The results to question about whether the apartment is too bright or dark, are shown in Table 42.

Table 42: Do you think your apartment is too bright or too dark?

Group	State of the building	Much too bright	Too bright	Appropriate	Too dark	Much too dark
Group 1	Original	0,0 %	0,0 %	100,0 %	0,0 %	0,0 %
	Renovated	**0,0 %**	**7,7 %**	**92,3 %**	**0,0 %**	**0,0 %**
Group 2	Original	3,3 %	13,3 %	76,7 %	6,7 %	0,0 %
	Renovated	**6,9 %**	**3,4 %**	**86,2 %**	**3,4 %**	**0,0 %**
Group 3	Original A	0,0 %	9,5 %	90,5 %	0,0 %	0,0 %
	Original B	5,3 %	5,3 %	68,4 %	21,1 %	0,0 %
	Renovated	**0,0 %**	**0,0 %**	**94,1 %**	**5,9 %**	**0,0 %**
Group 4	Original	0,0 %	6,3 %	81,3 %	6,3 %	6,3 %
	Renovated	**0,0 %**	**0,0 %**	**81,3 %**	**12,5 %**	**6,3 %**
Group 5	Original	0,0 %	11,1 %	77,8 %	11,1 %	0,0 %
	Renovated	**0,0 %**	**0,0 %**	**100,0 %**	**0,0 %**	**0,0 %**

Mostly the conditions were found "appropriate". The dissatisfaction with general daylighting conditions seems to be connected more to the lack of light than an abundance of light. The buildings where people answered, "too dark" and "much too dark" more often, are also the same houses where more respondents found their general daylighting conditions "bad" or very bad".

The results about how direct sunlight is perceived in winter and in summer, are shown in Table 43 and in Table 44. The direct sunlight conditions in winter were mostly “good” or “very good” in some buildings but in other buildings, the answers were more equally distributed, though “bad” and “very bad” were less frequent answers. Expectedly, the direct sunlight conditions were evaluated higher in the summer, where inhabitants found the conditions mostly “very good” and “good”.

Table 43: How do you perceive the direct sunlight conditions in your apartment in winter?

Group	State of the building	Very good	Good	Acceptable	Bad	Very bad
Group 1	Original	66,7 %	33,3 %	0,0 %	0,0 %	0,0 %
	Renovated	**61,5 %**	**23,1 %**	**7,7 %**	**7,7 %**	**0,0 %**
Group 2	Original	26,7 %	26,7 %	30,0 %	16,7 %	0,0 %
	Renovated	**13,8 %**	**55,2 %**	**17,2 %**	**13,8 %**	**0,0 %**
Group 3	Original A	14,3 %	47,6 %	33,3 %	4,8 %	0,0 %
	Original B	15,8 %	26,3 %	31,6 %	21,1 %	5,3 %
	Renovated	**23,5 %**	**52,9 %**	**23,5 %**	**0,0 %**	**0,0 %**
Group 4	Original	23,5 %	23,5 %	29,4 %	17,6 %	5,9 %
	Renovated	**6,3 %**	**25,0 %**	**50,0 %**	**12,5 %**	**6,3 %**
Group 5	Original	55,6 %	11,1 %	0,0 %	22,2 %	11,1 %
	Renovated	**33,3 %**	**66,7 %**	**0,0 %**	**0,0 %**	**0,0 %**
	Total original	**55,9 %**				
	Total renovated	**66,7 %**				

Table 44: How do you perceive the direct sunlight conditions in your apartment in summer?

Group	State of the building	Very good	Good	Acceptable	Bad	Very bad
Group 1	Original	83,3 %	16,7 %	0,0 %	0,0 %	0,0 %
	Renovated	**53,8 %**	**30,8 %**	**15,4 %**	**0,0 %**	**0,0 %**
Group 2	Original	33,3 %	36,7 %	30,0 %	0,0 %	0,0 %
	Renovated	**51,7 %**	**31,0 %**	**13,8 %**	**3,4 %**	**0,0 %**
Group 3	Original A	25,0 %	45,0 %	25,0 %	5,0 %	0,0 %
	Original B	21,1 %	26,3 %	31,6 %	21,1 %	0,0 %
	Renovated	**23,5 %**	**58,8 %**	**17,6 %**	**0,0 %**	**0,0 %**
Group 4	Original	22,2 %	38,9 %	27,8 %	5,6 %	5,6 %
	Renovated	**26,7 %**	**40,0 %**	**20,0 %**	**6,7 %**	**6,6 %**
Group 5	Original	37,5 %	0,0 %	12,5 %	25,0 %	25,0 %
	Renovated	**50,0 %**	**50,0 %**	**0,0 %**	**0,0 %**	**0,0 %**
	Total original	**63,4 %**				
	Total renovated	**80,3 %**				

3.7 Answers to window airing questions

Mainly, people living in renovated buildings used window airing in the heating season less frequently than people living in non-renovated buildings, as shown in Table 45. People in renovated buildings answered more likely that they air “rarely or never”. In renovated buildings, where people sometimes noted problems with ventilation, airing was more common during the heating season as well. Window airing was more frequent in buildings where the occupants did not have the option to regulate their heating system. When the result of window airing is compared to a similar Swedish study (Fransson, 2014) in the Flagghusen area in Malmö, where newly constructed buildings were examined, it can be noted that the extent of airing is similar in Estonian renovated buildings and higher in non-renovated multi-family buildings. The Swedish study found that 53 % of respondents aired daily, while 55 % of respondents in renovated buildings and 67 % in non-renovated buildings do so in Estonia, according to the current study.

Table 45: How often do you usually open the window for airing in heating season (September-April)?

Group	State of the building	Daily/ Nearly every day	About once a week	Few times in a month	Rarely or never
Group 1	Original	66,7 %	16,7 %	0,0 %	16,7 %
	Renovated	**30,8 %**	**46,2 %**	**0,0 %**	**23,1 %**
Group 2	Original	51,6 %	12,9 %	12,9 %	22,6 %
	Renovated	**69,0 %**	**24,1 %**	**0,0 %**	**6,9 %**
Group 3	Original A	85,7 %	9,5 %	4,8 %	0,0 %
	Original B	84,2 %	10,5 %	0,0 %	5,3 %
	Renovated	**76,5 %**	**17,6 %**	**0,0 %**	**5,9 %**
Group 4	Original	41,2 %	58,8 %	0,0 %	0,0 %
	Renovated	**31,3 %**	**37,5 %**	**6,3 %**	**25,0 %**
Group 5	Original	88,9 %	11,1 %	0,0 %	0,0 %
	Renovated	**33,3 %**	**33,3 %**	**0,0 %**	**33,3 %**
Total original		**67,0 %**	**19,4 %**	**4,9 %**	**8,7 %**
Total renovated		**55,1 %**	**29,5 %**	**1,3 %**	**14,1 %**

When asked about the duration of the window airing, having a window open for some hours, or creating cross ventilation for some minutes were the most common methods, as shown in Table 46. The duration of airing is comparable to the Flagghusen project (Fransson, 2014), where the same airing periods were the most popular. There is some difference in the results of keeping the window open all day or night. In the Flagghusen study, 12 % of people kept a window open all day or night, but less than 4 % of respondents in Estonian renovated buildings and more than 16 % in non-renovated buildings practiced this.

Table 46: When you air, do you usually have...?

Group	State of the building	Window/airing window open all day/night	Window/airing window open for some hours	Cross ventilation for some minutes	I never air
Group 1	Original	16,7 %	50,0 %	33,3 %	0,0 %
	Renovated	**7,7 %**	**53,8 %**	**38,5 %**	**0,0 %**
Group 2	Original	3,1 %	25,0 %	68,8 %	3,1 %
	Renovated	**0,0 %**	**57,1 %**	**39,3 %**	**3,6 %**
Group 3	Original A	33,3 %	42,9 %	23,8 %	0,0 %
	Original B	25,0 %	35,0 %	35,0 %	5,0 %
	Renovated	**11,8 %**	**29,4 %**	**58,8 %**	**0,0 %**
Group 4	Original	0,0 %	47,1 %	52,9 %	0,0 %
	Renovated	**0,0 %**	**35,3 %**	**64,7 %**	**0,0 %**
Group 5	Original	33,3 %	44,4 %	22,2 %	0,0 %
	Renovated	**0,0 %**	**66,7 %**	**33,3 %**	**0,0 %**
Total original		**16,2 %**	**37,1 %**	**44,8 %**	**1,9 %**
Total renovated		**3,8 %**	**46,2 %**	**48,7 %**	**1,3 %**

Mainly people used the airing position (window tilts inwards at the top) of the windows, to a lesser extent people preferred either creating cross ventilation with fully open windows or using a micro-airing position (a gap of a few millimeters is left between the window frames). The preference varies from house to house.

The results of occupants' preferences for window opening range are shown in Table 47. Using windows' airing position is the most common method for window airing.

Table 47: When you air, do you usually do it by...?

Group	State of the building	Using airing position of the window	Using micro-airing position of the window	Cross ventilation for some minutes with windows fully open	I never air
Group 1	Original	50,0 %	33,3 %	16,7 %	0,0 %
	Renovated	**61,5 %**	**7,7 %**	**30,8 %**	**0,0 %**
Group 2	Original	60,6 %	12,1 %	24,2 %	3,0 %
	Renovated	**67,7 %**	**16,1 %**	**16,1 %**	**0,0 %**
Group 3	Original A	80,0 %	20,0 %	0,0 %	0,0 %
	Original B	65,0 %	20,0 %	15,0 %	0,0 %
	Renovated	**66,7 %**	**27,8 %**	**5,6 %**	**0,0 %**
Group 4	Original	52,9 %	17,6 %	29,4 %	0,0 %
	Renovated	**81,3 %**	**6,3 %**	**12,5 %**	**0,0 %**
Group 5	Original	88,9 %	0,0 %	11,1 %	0,0 %
	Renovated	**33,3 %**	**66,7 %**	**0,0 %**	**0,0 %**
Total original		**65,7 %**	**16,2 %**	**17,1 %**	**1,0 %**
Total renovated		**67,9 %**	**17,3 %**	**14,8 %**	**0,0 %**

The reasons for window airing in the winter are presented in Table 48. The form of the questionnaire allowed the respondents to choose several answers, therefore the results show the proportion of answers each option received.

Table 48: Why do you air in the winter?

Group	State of the building	Out of a habit, usually air as a routine	Because the air is stuffy, or air quality is bad	It is too warm	Other ventilation is insufficient	I don't air
Group 1	Original	0,0 %	62,5 %	12,5 %	12,5 %	12,5 %
	Renovated	**20,0 %**	**40,0 %**	**20,0 %**	**13,3 %**	**6,7 %**
Group 2	Original	4,8 %	45,2 %	2,4 %	38,1 %	9,5 %
	Renovated	**27,0 %**	**43,2 %**	**10,8 %**	**13,5 %**	**5,4 %**
Group 3	Original A	2,4 %	42,9 %	26,2 %	28,6 %	0,0 %
	Original B	17,2 %	41,4 %	13,8 %	24,1 %	3,4 %
	Renovated	**28,0 %**	**24,0 %**	**32,0 %**	**12,0 %**	**4,0 %**
Group 4	Original	21,7 %	47,8 %	0,0 %	30,4 %	0,0 %
	Renovated	**30,4 %**	**43,5 %**	**8,7 %**	**17,4 %**	**0,0 %**
Group 5	Original	0,00 %	41,2 %	35,3 %	23,5 %	0,0 %
	Renovated	**0,0 %**	**50,0 %**	**0,0 %**	**25,0 %**	**25,0 %**
Total original		**8,1 %**	**44,7 %**	**14,3 %**	**29,2 %**	**3,7 %**
Total renovated		**23,0 %**	**39,2 %**	**18,1 %**	**13,9 %**	**5,7 %**

People in renovated houses aired out of habit more, when compared to the inhabitants in non-renovated control buildings. The most popular reason was the air being stuffy, or the air quality being bad, which can be noted more in non-renovated buildings. The more frequent airing in non-renovated buildings can be explained also by dissatisfaction with air quality, as people in non-renovated buildings brought out the reason for ventilation being insufficient more often than people living in renovated buildings. The option of "it is too warm" was marked more frequently by people who live in renovated buildings. Also, window airing was used as an option for lowering room temperature in buildings where there is no option to regulate radiator heating. When the reasons for window airing are compared to the Flagghusen study (Fransson, 2014), where people air mostly out of habit and bad air quality equally, the people in the current study aired mainly because the air quality is bad, followed by habit in renovated buildings and insufficient ventilation in non-renovated buildings.

In the free text, the inhabitants mentioned the need to air when cooking and they want to remove intense food smells. Window airing was used when there is a need to improve air quality quickly or to remove moist air when drying laundry in the apartment. Other reasons mentioned were fog on windows, mold, and traffic emissions.

People also commented that they air in the winter when they are sick or want to prevent illnesses. In buildings that are not yet renovated, the inhabitants more often commented on nonexistent ventilation, and sometimes said that it is too warm and stuffy, leading to sleep and work disturbances.

The results about how and in which room people open windows during the heating season are shown in Table 49. The questionnaire instructed only to fill out the options that were used by the inhabitants and leave other options empty. The results are a percentage of the total number of people who answered the questionnaire in either renovated or original buildings.

Table 49: When you air during the heating season, do you usually open the window in …?

Living room				
State of the building	**Open one window**	**Open several windows**	**Open balcony door**	**Open smaller airing window**
Original	39,8 %	6,8 %	34,0 %	8,7 %
Renovated	31,6 %	3,8 %	43,0 %	7,6 %
Bedroom				
State of the building	**Open one window**	**Open several windows**	**Open balcony door**	**Open smaller airing window**
Original	65,0 %	3,9 %	4,9 %	12,6 %
Renovated	63,3 %	1,3 %	7,6 %	16,5 %
Kitchen				
State of the building	**Open one window**	**Open several windows**	**Open balcony door**	**Open smaller airing window**
Original	65,0 %	3,9 %	4,9 %	12,6 %
Renovated	68,4 %	1,3 %	7,6 %	16,5 %

In living rooms, people usually opened either a balcony door or open one window. Smaller airing windows were used less, slightly more in kitchens and bedrooms than in living rooms. According to the typical layout of the case study buildings, most rooms have only one window, and opening several windows was mostly not a possibility. Therefore, opening only one window for airing was also the most popular answer in bedrooms and kitchens, while in the living room, there was also an opportunity to use a balcony door.

How the window is usually opened, is presented in Table 50.

Table 50: When you air during the heating season, how do you usually open the window in …?

Living room			
State of the building	**Ajar (up to 10 cm)**	**Half open (20-50 cm)**	**Fully open (more than 50 cm)**
Original	60,2 %	17,5 %	5,8 %
Renovated	54,5 %	25,3 %	10,1 %
Bedroom			
State of the building	**Ajar (up to 10 cm)**	**Half open (20-50 cm)**	**Fully open (more than 50 cm)**
Original	61,2 %	16,5 %	4,9 %
Renovated	59,5 %	19,0 %	10,1 %
Kitchen			
State of the building	**Ajar (up to 10 cm)**	**Half open (20-50 cm)**	**Fully open (more than 50 cm)**
Original	61,2 %	18,4 %	5,8 %
Renovated	64,6 %	16,5 %	7,6 %

The survey only asked to mark the methods that were used by the respondents and other options were left empty. The results are presented as a percentage of the total number of respondents in renovated and non-renovated buildings. The outcome shows that around 60 % of people had windows ajar for airing in all the rooms. Having windows half open was less common and fully open windows was the least occurring measure.

The results for reasons for window airing in the summer are presented in Table 51.

Table 51: Why do you air in the summer?

Group	State of the building	Out of habit, usually air as a routine	Because the air is stuffy, or air quality is bad	It is too warm	Other ventilation is insufficient	I don't air
Group 1	Original	0,0 %	30,8 %	46,2 %	23,1 %	0,0 %
	Renovated	**21,1%**	**21,1 %**	**52,6 %**	**5,3 %**	**0,0 %**
Group 2	Original	1,6 %	27,4 %	41,9 %	29,0 %	0,0 %
	Renovated	**15,4 %**	**21,2 %**	**44,2 %**	**19,2 %**	**0,0 %**
Group 3	Original A	2,1 %	31,3 %	37,5 %	29,2 %	0,0 %
	Original B	10,0 %	30,0 %	42,5 %	17,5 %	0,0 %
	Renovated	**14,8 %**	**25,9 %**	**48,1 %**	**11,1 %**	**0,0 %**
Group 4	Original	6,1 %	33,3 %	33,3 %	27,3 %	0,0 %
	Renovated	**16,0 %**	**32,0 %**	**44,0 %**	**8,0 %**	**0,0 %**
Group 5	Original	0,00 %	31,3 %	31,3 %	37,5 %	0,0 %
	Renovated	**0,0 %**	**33,3 %**	**33,3 %**	**16,7 %**	**16,7 %**
Total original		**3,8 %**	**30,2 %**	**39,2 %**	**26,9 %**	**0,0 %**
Total renovated		**15,5 %**	**24,8 %**	**45,7 %**	**13,2 %**	**0,8 %**

The form of the questionnaire allowed the respondents to choose several answers, therefore the results show the proportion of responses each option received. Similarly to window airing reasons in winter, in summer people in renovated buildings aired more out of the habit than people in non-renovated buildings. Compared to the Swedish window airing study (Fransson, 2014), where the indoor air temperature being too hot was the third most popular reason, followed by habit and bad air quality, the main reason for window airing in the summer in the current Estonian study was "it is too warm". This motive had a bigger proportion in retrofitted buildings, while in non-renovated buildings the options of "the air is stuffy, or air quality is bad" and "other ventilation is insufficient" was marked as a reason more often than in renovated buildings. In the free text, the residents mentioned the need to cool the building in the summer, and they keep windows open overnight to lower the temperature and get better sleep.

The reasons for ending window airing are shown in Table 52.

Table 52: What is the reason to end window airing?

State of the building	Out of a habit, usually have it open for a certain time	Have received enough fresh air	Outside air is too cold	Draught	Noise from outside	Too low tempera-ture at night	Too strong wind	Rain
Original	4,8 %	22,3 %	17,2 %	7,5 %	13,3 %	11,4 %	13,6 %	9,9 %
Renovated	8,9 %	31,3 %	13,0 %	7,3 %	9,4 %	8,3 %	11,5 %	10,4 %

Several answer options were possible for this question, the result presents the proportion of received answers. The main reason for ending window airing was "have received enough fresh air", collecting 31,3 % of responses in renovated buildings and 22,3 % of responses in non-renovated buildings. In correlation with the reasons for window airing, the reason for ending window airing "out of habit, usually have it open for a certain time", was more popular in renovated buildings. Several reasons regarding outside factors, such as "outside air is too cold", "noise from outside", "too low temperature at night" and "too strong wind" were more prevalent among the people living in buildings in their original state. The main reasons for ending window airing correspond with the results in the Flagghusen study (Fransson, 2014). Other reasons for ending window airing included sewage smell from outside, traffic emissions, and tobacco smell. There were noise reasons like nighttime traffic, birds, waste disposal, or people talking outside that caused inhabitants to end window airing. In some buildings, people noted street dust entering the room, or squirrels. Furthermore, the need to save energy and the need to feel secure at night were mentioned.

The results for daily window airing duration are shown in Table 53. The questionnaire instructed only to fill out the options that were used by the inhabitants and leave other options empty. The results are a percentage of the total number of people who answered the questionnaire in either renovated or original buildings.

Table 53: How long do you air daily?

I do not air			
State of the building	**Winter (November – March)**	**Spring, autumn (April, September - October)**	**Summer (May - August)**
Original	11,7 %	1,0 %	4,9 %
Renovated	12,7 %	1,3 %	1,3 %
0–15 minutes			
State of the building	**Winter (November – March)**	**Spring, autumn (April, September - October)**	**Summer (May - August)**
Original	49,5 %	13,6 %	1,9 %
Renovated	45,6 %	21,5 %	2,5 %
15–30 minutes			
State of the building	**Winter (November – March)**	**Spring, autumn (April, September - October)**	**Summer (May - August)**
Original	15,5 %	37,9 %	9,7 %
Renovated	22,8 %	39,2 %	7,6 %
1–2 hours			
State of the building	**Winter (November – March)**	**Spring, autumn (April, September - October)**	**Summer (May - August)**
Original	13,6 %	19,4 %	21,4 %
Renovated	3,8 %	16,5 %	22,8 %
2–6 hours			
State of the building	**Winter (November – March)**	**Spring, autumn (April, September - October)**	**Summer (May - August)**
Original	2,9 %	14,6 %	38,8 %
Renovated	0,0 %	8,9 %	25,3 %
6–12 hours			
State of the building	**Winter (November – March)**	**Spring, autumn (April, September - October)**	**Summer (May - August)**
Original	2,9 %	1,9 %	29,1 %
Renovated	0,0 %	0,0 %	24,1 %
More than 12 hours			
State of the building	**Winter (November – March)**	**Spring, autumn (April, September - October)**	**Summer (May - August)**
Original	1,0 %	3,9 %	26,2 %
Renovated	0,0 %	2,5 %	31,6 %
All the time			
State of the building	**Winter (November – March)**	**Spring, autumn (April, September - October)**	**Summer (May - August)**
Original	1,9 %	1,9 %	33,3 %
Renovated	0,0 %	0,0 %	17,7 %

The results regarding the duration of daily window airing show that nearly half the respondents, independent of their buildings' renovation status, aired for 0-15 minutes in winter. In spring and autumn, the most common airing time was 15-30 minutes. In summer, the most popular option in original state buildings was "2-6 hours", followed by "all the time". In renovated buildings, the airing duration in summer was usually "more than 12 hours", followed by "2-6 hours".

3.7.1 Window airing habits among elderly people

When the airing habits of the elderly were compared to younger people, it can be noted that older people used window airing more frequently. 81 % of respondents over 65 years of age aired every day, while 61 % of younger people aired daily. The results for the airing duration show that the elderly rarely kept their window open all day or night, but they mostly opened the window for some hours (46 %) or had cross-ventilation for some minutes (53 %). Cross-ventilation was also used more frequently by older people.

The main reasons for window airing for older people were bad air quality and insufficient ventilation which correlates with the overall result. It can be noted that the elderly aired out of a habit more than younger people, 25 % and 11 % respectively. Airing out of habit for the elderly was also more frequent in renovated buildings, which corresponds with the general result showing that in renovated buildings sometimes people air more out of habit. Older people practiced window airing for too warm room temperatures in winter and summer slightly less than the younger age group.

The most frequent reason for ending window airing among the elderly was the notion of having received enough fresh air, which was also a more prevalent reason compared to the younger age group. The external conditions had less importance for the elderly to end window airing, in comparison with younger people.

3.8 Comparison with the 2014 Estonian study

When comparing the current results in renovated buildings with mechanical exhaust ventilation to the result from 2014 (Kõiv et al., 2014), some differences can be noted. First, current results show that the inhabitants estimated their indoor air temperature in winter to be more on the warm side, compared to the results from 2014, shown in Table 54. For most respondents, the indoor air temperature was "acceptable" in both studies, but currently, more people found the indoor air temperature in winter as "warm" or "too warm", while more respondents stated it was "cold" or "too cold" in 2014. A similar tendency was noticed in the responses regarding floor temperature in winter, shown in Table 55. While most of the respondents found floor temperature "acceptable" in both studies, in the current survey the other responses inclined more towards "warm" and in the 2014 study the floor temperature was more often found as "cold". In the 2014 study, stronger draught was noticed compared to the current study, as shown in Table 56. The result regarding indoor air temperature stability resembles the 2014 result, shown in Table 57. In both studies, most participants found the indoor air temperature "mostly stable", followed by "stable" and "appropriate".

Table 54: How do you estimate indoor air temperature in your apartment in wintertime? Comparison with the result from 2014

Study	Too warm	Warm	Acceptable	Cold	Too cold
2014	0,0 %	8,0 %	76,0 %	12,0 %	4,0 %
2023	4,5 %	31,8 %	60,6 %	3,0 %	0,0 %

Table 55: How do you estimate floor temperature in your apartment in wintertime? Comparison with the result from 2014

Study	Too warm	Warm	Acceptable	Cold	Too cold
2014	0,0 %	0,0 %	72,0 %	16,0 %	12,0 %
2023	0,0 %	20,0 %	66,2 %	12,3 %	1,5 %

Table 56: How do you perceive draught in your apartment? Comparison with the result from 2014

Study	Big draught	Draught	Some draught	Little draught	No draught
2014	0,0 %	8,0 %	20,0 %	4,0 %	68,0 %
2023	0,0 %	0,0 %	12,3 %	27,7 %	60,0 %

Table 57: How do you estimate indoor air temperature stability in your apartment in wintertime? Comparison with the result from 2014

Study	Stable	Mostly stable	Appropriate	Somewhat fluctuating	Fluctuating
2014	32,0 %	40,0 %	24,0 %	4,0 %	0,0 %
2023	24,2 %	51,5 %	18,2 %	6,1 %	0,0 %

Second, in the current study respondents rated air quality higher than the respondents in the 2014 survey. In the present study, the air quality was perceived as fresher and fewer bad odors were reported, while in 2014 the air was found more often “quite stuffy” and having “quite bad smell”, as shown in Table 58 and Table 59. Also, indoor air was perceived as drier compared to 2014, as shown in Table 60.

Table 58: How do you estimate indoor air freshness in your apartment? Comparison with the result from 2014

Study	Fresh	Quite fresh	Appropriate	Quite stuffy	Stuffy
2014	0,0 %	44,4 %	20,0 %	28,0 %	8,0 %
2023	6,1 %	47,0 %	39,4 %	6,1 %	1,5 %

Table 59: How do you estimate indoor air smell in your apartment? Comparison with the result from 2014

Study	Odorless	Some odor	Odor	Quite bad odor	Bad odor
2014	40,0 %	24,0 %	8,0 %	20,0 %	8,0 %
2023	43,9 %	48,5 %	6,1 %	0,0 %	1,5 %

Table 60: How do you estimate indoor air dryness in your apartment? Comparison with the result from 2014

Study	Dry	Quite dry	Appropriate	Quite most	Moist
2014	4,0 %	20,0 %	56,0 %	16,0 %	4,0 %
2023	13,8 %	38,5 %	46,2 %	1,5 %	0,0 %

Finally, the noise from technical systems was found to be more noticeable in the current case study buildings compared to the buildings in the 2014 research. In 2014, 96,0 % of respondents did not experience noise disturbance from technical systems, while the answer “no noise” got 59,9 % of responses in the current study, as shown in Table 61.

Table 61: How do you estimate noise from technical systems in your apartment? Comparison with the result from 2014.

Study	No noise	Noise, but it does not disturb	Noise, but it does not disturb much	Some noise	Noise
2014	96,0 %	4,0 %	0,0 %	0,0 %	0,0 %
2023	59,7 %	15,6 %	14,3 %	10,4 %	0,0 %

3.9 Measured energy use in case study buildings

The annual measured energy use in different buildings for the year 2022 is shown in Figure 24.

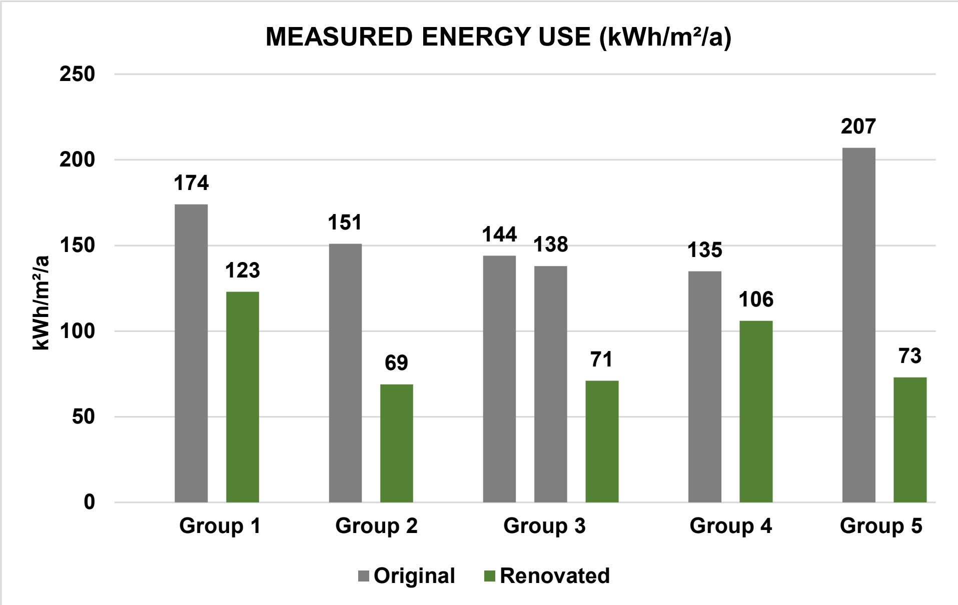

Figure 24: Measured energy use in 2022

Measured energy consumption in renovated buildings was in some cases half of the measured energy use in non-renovated multi-family houses. There were some exceptions, as the group 4 renovated building had higher energy consumption caused by malfunctioning of the ventilation heat recovery heat pumps. A similar situation was in the original building in group 1, where the ventilation system malfunctioned and elevated electricity consumption. A simple calculation with expected monthly electricity use of 700 kWh would lower annual measured energy use to 118 kWh/m²/a for group 1 renovated building.

As expected, the result from measured energy use reflects the survey result regarding the satisfaction-dissatisfaction with the utility costs. For example, in the original building in group 5 that had the highest energy consumption among the case study buildings, the proportion of respondents who were "very dissatisfied" with utility costs, was 67 %. Simultaneously, in the renovated building in group 2 that had the lowest measured energy use, 29 % of the respondents were "very satisfied" and 54 % "quite satisfied".

The findings from window airing show that people aired frequently and sometimes for longer periods in all the buildings, therefore it is difficult to see clear connections with energy use. There seems to be some correlation between energy use and window airing in group 5 original building, as this house had the highest measured energy use, and the biggest proportion of respondents (89 %), who aired every day for the longest duration. The main reasons for window airing in this building in winter were too warm temperatures and bad air quality, moreover, these reasons were more frequent compared to the other buildings in the study. It is assumed that in this multi-family house window airing contributes to the higher energy consumption more than in other buildings.

3.10 Result summary

3.10.1 Thermal comfort

- In renovated buildings, 87 % of inhabitants were pleased with general thermal comfort, while in the buildings in their original state, the percentage of satisfied people was 37 %.
- 32 % of people in non-retrofitted buildings and 37 % of people in renovated buildings perceived indoor air temperature in wintertime as "warm" or "too warm", indicating a possibility for further energy saving.
- The problem with overheating persists post-renovation, as 63 % of respondents in renovated buildings perceived indoor air temperature in summer as "warm" or "too warm". 76 % of respondents in non-retrofitted buildings answered "warm" or "too warm" about their summer indoor temperatures.
- Draught was mostly perceived through fresh air valves (45 %) in renovated buildings and through windows (41 %) in non-renovated buildings.
- The solution, where fresh air valves were installed above the radiators, increased the perception of draught. Moreover, fresh air valves that were installed above radiators were closed in the winter for temperature regulation.
- In buildings, where there was no option for regulating radiator heating, window airing was the most popular method of changing room air temperature in winter, used by more than 60 % of the respondents.
- Summer indoor air temperature regulating options are limited in both renovated and non-renovated buildings. The main method for regulating room temperature in summer was window airing.
- Solar shading is not common, less than 20 % of all respondents used this method for summer temperature regulation.
- Curtains (40 %) and inner Venetian blinds (30 %) were used most often for solar shading. Future renovation solutions should include an effective solar shading design, as overheating in summer is an issue also post-renovation.
- People who had "great possibilities" for adjusting the heating system, also were satisfied (86 %) with general thermal comfort in their apartment. Out of the people who answered "no option to regulate", 26 % found general thermal comfort in their dwelling satisfying.
- In renovated buildings, more than 70 % of respondents were informed about how their technical systems work, while only 20 % of the respondents in non-renovated buildings were informed.
- Younger people were more satisfied with general thermal comfort. 39 % of younger people in non-renovated buildings and 91 % of younger people in renovated buildings were "very satisfied" or "quite satisfied" with general thermal comfort. 33 % of older people in original buildings and 84 % of older people in renovated buildings were satisfied with general thermal comfort.
- Both summer and winter indoor air temperatures were perceived as warmer by younger inhabitants, demonstrating the importance of personal control options.

3.10.2 Air quality

- 82 % of respondents in renovated buildings perceived air quality in their apartment as "good" and "very good", while 24 % of respondents in non-renovated buildings had a similar perception.
- People in renovated buildings perceived air quality as fresher (53 %) compared to the inhabitants in non-renovated multi-family buildings (21 %).
- In renovated buildings, people reported less disturbance by food smells from inside the buildings compared to the non-renovated buildings. Still, around 60 % of them were bothered by food smells sometimes or more often.
- More than 60 % of respondents were disturbed by tobacco smell sometimes or more often, regardless of their buildings' renovation status.
- Ventilation regulating issues were less common in renovated buildings, though more than 30 % of respondents in renovated buildings had trouble removing smells or regulating ventilation. More than 70 % of people in non-renovated buildings had trouble with ventilation sometimes or more often.

- People who had trouble regulating ventilation used daily window airing more (65 %) than the people who did not have this problem (57 %).

3.10.3 Mold

- Mold problems in renovated buildings were reported in a few cases. Around 30 % of respondents noticed mold in non-renovated buildings.

3.10.4 Noise

- Satisfaction with acoustic conditions was low, especially due to the insufficient soundproofing between the apartments. 39 % of people in renovated buildings and 14 % of people in non-renovated buildings perceived acoustic conditions in their homes as "good" or "very good".
- Traffic noise perception was reduced in renovated buildings, as around 10 % of respondents found it disturbing in renovated buildings, but around 25 % of respondents in non-renovated buildings were disturbed by traffic.
- Ventilation noise was perceived more in renovated buildings, where under 10 % of respondents found it slightly disturbing.

3.10.5 Daylight

- Daylight conditions were perceived to be satisfying by more than 80 % of respondents in renovated buildings and nearly 65 % of people in non-renovated buildings.

3.10.6 Window airing

- People in renovated buildings used window airing less than people living in non-renovated buildings. Daily window airing during the heating season was practiced by 55 % of inhabitants in renovated buildings and 67 % of people living in non-renovated buildings.
- Windows were usually open for some hours (37 % in non-renovated buildings and 46 % in renovated buildings) or for a few minutes for cross-ventilation (45 % in non-renovated buildings and 49 % in renovated buildings).
- 4 % of respondents in renovated buildings and 16 % of respondents in non-renovated buildings kept windows open all day or night.
- Most commonly, airing position was used for window airing, practiced by more than 65 % of all respondents. Cross-ventilation with fully open windows or using a micro-airing position was used less often.
- People used window airing mainly because the air quality is bad (45 % of people in non-renovated buildings and 39 % of respondents in renovated buildings), followed by habit in renovated buildings (23 %) and insufficient ventilation (29 %) in non-renovated buildings.
- In renovated buildings, airing in winter because "it is too warm" was slightly more popular (18 %) than in non-renovated buildings (14 %).
- Window airing was used in the summer mainly because "it is too warm", reported by 46 % of respondents in renovated buildings and 39 % of non-renovated buildings. The next popular reason was bad air quality, marked by 25 % of respondents in renovated buildings and 30 % of respondents in non-renovated buildings.
- The main reason for ending window airing was "have received enough fresh air", marked by 31 % of respondents in renovated buildings and 22 % of respondents in non-renovated buildings.
- In winter, nearly 50 % of respondents, regardless of their buildings' renovation status, aired for 0-15 minutes. In spring and autumn, almost 40 % of respondents aired for 15-30 minutes.
- In summer, the most popular window airing duration in non-renovated buildings was "2-6 hours" (39 %), followed by "all the time" (33 %). In renovated buildings, the airing duration in summer was usually marked as "more than 12 hours" (32 %), followed by "2-6 hours" (24 %).

- 81 % of respondents over 65 years of age aired every day, compared to 61 % of younger people, who aired daily.
- The elderly aired out of a habit more than younger people, 25 % and 11 % respectively.

3.10.7 Other

- Comparison with the Estonian study from 2014, showed that indoor air temperatures in the 2023 case study buildings were perceived as “warm” and “too warm” more often (36 %) than in the buildings in the 2014 study (8 %). In the current study, the respondents perceived less draught; air was perceived as fresher and having fewer bad odors. However, noise from technical systems was more noticeable in the current case study buildings.
- A comparison of measured energy use in renovated and non-renovated buildings shows reduced energy consumption in all the renovated buildings compared to their control buildings. In some cases, the measured energy use was half of the control buildings’ energy consumption.

4 Discussion and Conclusion

The results from the questionnaire survey indicate that the recent energy renovation practices in Estonian multi-family buildings enhance the perceived indoor environment substantially. Thermal comfort in renovated buildings improved significantly, having a nearly 90 % general thermal comfort satisfaction rate. Satisfaction rates with buildings' appearance, maintenance, and utility costs were usually more than doubled in renovated buildings, compared to their control buildings. The perception of air quality shifted from mostly "acceptable" in non-renovated buildings to mainly "good" in retrofitted buildings. Furthermore, the perception of draught, smell and noise disturbances, and mold problems was reduced. Additionally, the measured energy use in renovated buildings reduced and sometimes even halved compared to their control building.

Though living conditions improve for the people in retrofitted buildings, there are dissatisfaction aspects that renovation methods used so far cannot alter. Even if the external noise is reduced with added insulation and better windows, inhabitants in renovated buildings continue to have noise disturbances, especially from bad soundproofing between the apartments, as also indicated in a previous study by Kalamees et al. (2009). Other disturbing factors that persist after renovations are tobacco smoke disturbance from inside the house and traffic emissions from outside, which are still perceived in all the buildings no matter their renovation status. The problem with overheating in the summer remains after the renovation as the options for regulating summer indoor temperatures are still limited. Overheating and the current lack of efficient solar shading options indicate a need to address the problem in future renovation designs. Additionally, more than 30 % of respondents found winter indoor temperature as "warm" or "too warm", suggesting a possibility for further energy saving. From an energy efficiency perspective, the indoor temperatures in winter should be more moderate, as it also prevents window airing used for regulating room air temperature.

The findings in the current study suggest that additionally to other renovation methods that improve indoor climate, options for regulating room temperature and ventilation enhance the indoor experience even more. Satisfaction with thermal comfort was higher in buildings where occupants had an option to regulate indoor air temperature and people who thought they had great possibilities for regulating ventilation, perceived better air quality. The result correlates with findings from other studies (Pedersen et al., 2021; Pedersen et al., 2021) that stress the importance of personal control in reaching a satisfactory indoor environment. Moreover, as the result from thermal comfort among elderly people showed, the elderly prefer slightly warmer temperatures than their younger neighbors. The outcome indicates once more the need for personal control due to different thermal comfort preferences among the occupants.

However, a lack of information can lead to difficulties regulating technical systems and discomfort with one's indoor climate, as indicates previous research (Nordquist et al., 2014). It is apparent that inhabitants in buildings that undergo a major renovation are better informed about their technical systems, but in the current survey still around 25 % of inhabitants in renovated buildings said they have not received any information regarding how the technical systems in their apartment work. Most likely during or soon after the renovation people are informed about the new systems through emails or housing association meetings, but the information is missed by new owners or tenants who move in after the buildings are renovated. Therefore, the information should be repeated after some periods, or it should be easily accessible all the time. The shortage of instructions in non-retrofitted buildings could be caused by the lack of complicated technical systems. Hydronic systems are an exception, but in some non-renovated houses, it is not possible for occupants to regulate them. Most other systems, such as kitchen or bathroom ventilators, the inhabitants generally install themselves and learn the usage independently.

Either due to a lack of regulating options or lack of information, more than 30 % of residents in renovated buildings experience ventilation troubles, such as removing food smells from the apartment and regulating the ventilation systems. Ventilation issues are even more frequent in non-renovated buildings. Such problems with ventilation in addition to lacking options for regulating room air temperature, lead to window airing as suggested by a study in Sweden (Fransson, 2014) and the outcome of the current study.

The survey result shows that window airing is used more in buildings where other options for regulating indoor climate are limited. Window airing is used to improve air quality when other ventilation is insufficient and regulating indoor air temperature has limited options or is not possible. Bad air quality is also the main reason for window airing, followed by habit in renovated buildings and insufficient ventilation in non-renovated buildings. The result diverges from the Swedish window airing study (Fransson, 2014) where the main reason for window airing was habit, followed by bad air quality. It is assumed that the newly built Swedish case study buildings had more efficient ventilation, which explains the different reasoning for window airing. Habit has bigger importance in renovated buildings. Habit was also a more prevalent reason among elderly people, who practiced more frequent window airing as well. Overall airing frequency, duration, and reasons for ending window airing are comparable to the result from the Swedish study.

The outcome of the study demonstrates reduced mold perception in renovated buildings, where very few respondents reported mold issues. The situation needs improvement in all the buildings in their original state, as visible mold was noticed in all these buildings. In two non-renovated buildings, around 40 % of respondents reported mold.

From the inhabitants' perspective, the renovations have an overall positive effect on their living environment. Though the neighborhoods with older multi-family buildings are sometimes considered inferior compared to the new developments, the inhabitants in the current study are satisfied with their living area, even more so in renovated buildings. People are quite satisfied with their apartments' size and room plan, and satisfaction levels are higher in renovated buildings. Even if the occupants are content, there are further improvements that need to be considered to modernize the building stock and improve living conditions for the inhabitants. One factor that needs improvement is accessibility. The typical 5-story buildings do not have an elevator, which is a critical issue for older people and people with mobility difficulties. This is not an indoor climate matter, but it is something that is related to well-being in people's homes and could be a consideration for future renovation practices.

In the future, if analogous research is conducted in similar buildings, it would benefit from a longer planning process and more introductory work among the inhabitants. The response rate could be higher if there was knowledge about rental apartments and how the tenants in these apartments prefer to receive the survey questionnaire. Moreover, longer planning and testing processes would help to eliminate mistakes, which appeared in a couple of online questionnaire questions where multiple-answer options were not allowed, though the format of the question should have permitted it. Further, the study indicates that paper questionnaires are currently still needed to not exclude elderly people. Though there were several people over 65 years of age who responded to the online questionnaire, the average age of paper questionnaire respondents was 70, while for the online questionnaire it was 50.

Moreover, the study suggests that the methods for energy renovation should consider indoor environment aspects more carefully. This was noticed in a case study building where fresh air valves were placed above the radiator instead of being connected through the radiator, causing discomfort from draught. As study results showed, increased draught made occupants close the fresh air valves, causing the air quality to deteriorate. Noise disturbance from ventilation systems increased slightly in renovated buildings, and though this was not an issue in the current study, previous research (Haverinen-Shaughnessy et al., 2018; Kõiv et al., 2014) points out that sometimes the ventilation systems are too loud for the inhabitants.

To conclude the study, it is obvious by comparing the buildings in renovated and non-renovated conditions, that correct energy renovations can improve many aspects of inhabitants' indoor environment quality and general satisfaction with their living conditions. In addition to the improved indoor climate, buildings' energy performance improves. Though there are issues that current-level renovations cannot entirely solve, such as noise and smell disturbances, energy renovations can increase occupant satisfaction in more ways than just energy savings and improved building's appearance.

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APPENDIX I

SURVEY ON INDOOR CLIMATE EXPERIENCE AND WINDOW AIRING HABITS

Dear Recipient,

I am a student *of Energy Efficient and Environmental Building design* at Lund University in Sweden, and I am working on a master's thesis that examines the indoor climate in renovated and unrenovated multi-family buildings. I want to investigate how you perceive the indoor environment as a resident, what are your ventilation habits and how you interact with the building and its technical systems.

I will be grateful if you answer the following questionnaire. There is one form to be filled out for one adult per apartment. The questions have multiple choice options, and the survey takes about 10-15 minutes to complete. All results are treated confidentially. The results of the survey are presented in such a way that it is not possible to identify the respondent or to see who participated or who answered what.

Answering the survey is voluntary, but your answers will help to improve knowledge about how residents of multi-family buildings perceive the indoor environment, as well as to raise awareness of the indoor climate in the renovation industry.

If you have any questions or would like to discuss the study, you can find the contact details below.

The survey is open for responses for 3 weeks, after which the results will be analyzed.

The master's thesis will be completed before the summer, and it will be publicly available. If you are interested in the study, please contact the representative of the apartment association, to whom I will forward the finished project.

Three €100 Partner gift cards will be raffled among all respondents. To participate in the raffle, please add your email or phone number to the corresponding field of the survey.

Contact:
Kadri Reinumägi
Department of Building & Environmental Technology, Lund University
Phone: +372 55 535 565
email: ka6753re-s@student.lu.se

General questions

1. **Address of the multi-family building: …………………………………………………**
2. **How satisfied or not satisfied are you with your residence in regards of…**

	1 = very satisfied	2 = quite satisfied	3 = neither	4 = quite dissatisfied	5 = very dissatisfied
...size of the apartment?	☐	☐	☐	☐	☐
…apartments' floor plan?	☐	☐	☐	☐	☐
…apartment in general?	☐	☐	☐	☐	☐
…appearance of the building?	☐	☐	☐	☐	☐
…maintenance of the building?	☐	☐	☐	☐	☐
…utility costs of the apartment?	☐	☐	☐	☐	☐
…neighborhood?	☐	☐	☐	☐	☐

Indoor environment

3. **Have you been disturbed in <u>the last 3 months</u> by one or more of the following factors in your apartment?**

	1 = Yes, often (every week)	2 = Yes, sometimes	3 = No, never
draught	☐	☐	☐
too high room temperature	☐	☐	☐
fluctuating room temperature	☐	☐	☐
too low room temperature	☐	☐	☐
stuffy air	☐	☐	☐
dry air	☐	☐	☐
unpleasant smell	☐	☐	☐
tobacco smoke from neighbors	☐	☐	☐
noise	☐	☐	☐
dust in air	☐	☐	☐
dust on surfaces	☐	☐	☐
other	…………………………………………………………		

Temperature and thermal comfort

4. **How do you find thermal comfort in your apartment in general?**

1 = very satisfied	2 = quite satisfied	3 = acceptable	4 = quite dissatisfied	5 = very dissatisfied
☐	☐	☐	☐	☐

5. **How do you estimate indoor air temperature in your apartment in wintertime?**

1 = too warm	2 = warm	3 = appropriate	4 = cold	5 = too cold
☐	☐	☐	☐	☐

6. **How do you estimate indoor air temperature stability in your apartment in wintertime?**

1 = stable	2 = mostly stable	3 = appropriate	4 = somewhat fluctuating	5 = fluctuating
☐	☐	☐	☐	☐

7. **How do you estimate the floor temperature in your apartment in wintertime?**

1 = too warm	2 = warm	3 = appropriate	4 = cold	5 = too cold
☐	☐	☐	☐	☐

8. **How do you estimate indoor air temperature in your apartment in summertime?**

1 = too warm	2 = warm	3 = appropriate	4 = cold	5 = too cold
☐	☐	☐	☐	☐

9. **How do you perceive draught in your apartment?**

1 = big draught	2 = draught	3 = some draught	4 = little draught	5 = no draught
☐	☐	☐	☐	☐

10. **If you perceive draught, where is it from?**

☐ Through window
☐ Through exterior door
☐ Through balcony door
☐ Through fresh air valves
☐ Through floor

11. **How can you change the temperature indoors?**

☐ Through window airing
☐ Regulating radiators using thermostats
☐ By closing fresh air valves
☐ Using solar shading
☐ No option to regulate
☐ Another way……………………………………………………………………

12. ***How do you change* the temperature indoors in wintertime?**

☐ Through window airing
☐ Regulating radiators using thermostats
☐ By closing fresh air valves
☐ Using solar shading
☐ No option to regulate
☐ Another way……………………………………………………………………

13. ***How do you change* the temperature indoors in summertime?**

☐ Through window airing
☐ Regulating radiators using thermostats
☐ By closing fresh air valves
☐ Using solar shading
☐ No option to regulate
☐ Another way……………………………………………………………………

14. **Which solar shading method do you use in summertime and in which rooms do you need to use it?** *Fill in the information about solar shades you use and regulate. Leave other options empty.*

	Living room	Bedroom	Kitchen	Other
There is no solar shade	☐	☐	☐	☐
Inner venetian blinds	☐	☐	☐	☐
Venetian blinds between the window glazing	☐	☐	☐	☐
Curtains	☐	☐	☐	☐
Exterior solar shade (i.e. marquis) that you pull down yourself when necessary	☐	☐	☐	☐
External automatic solar shade	☐	☐	☐	☐
External fixed solar shade	☐	☐	☐	☐

15. **Is there much possibility or little possibility to regulate the room temperature yourself by adjusting the heating system?**

☐ Great possibilities
☐ Some possibilities
☐ No option to regulate

16. **How often do you change the settings of the radiators?**

☐ Every day
☐ Every week
☐ Every month
☐ More rarely/ Never

17. **Is there much possibility or little possibility to regulate the air quality yourself by adjusting the ventilation system?**

☐ Great possibilities
☐ Some possibilities
☐ No option to regulate

18. **Have you received information how heating (radiators) and ventilation systems (ventilation aggregates, fresh air valves) work in your apartment?**

☐ Yes, orally
☐ Yes, written
☐ Yes, both orally and written
☐ No, I haven't got any information
☐ I don't know/ Don't remember

Air quality

19. **How do you find the air quality in your apartment in general?**

1 = very good	2 = good	3 = acceptable	4 = bad	5 = very bad
☐	☐	☐	☐	☐

20. How do you perceive the air quality is mostly in…

	1 = very good	2 = quite good	3 = acceptable	4 = quite bad	5 = very bad
…living room?	☐	☐	☐	☐	☐
…bedroom?	☐	☐	☐	☐	☐
…kitchen?	☐	☐	☐	☐	☐
…in the apartment in general?	☐	☐	☐	☐	☐

21. How do you estimate indoor air dryness in your apartment?

1 = dry	2 = quite dry	3 = appropriate	4= quite moist	5 = moist air
☐	☐	☐	☐	☐

22. How do you estimate indoor air freshness in your apartment?

1 = fresh	2 = quite fresh	3 = appropriate	4 = quite stuffy	5 = stuffy
☐	☐	☐	☐	☐

23. How do you estimate indoor air smell in your apartment?

1 = odorless	2 = some odor	3 = odor	4 = quite bad odor	5 = bad odor
☐	☐	☐	☐	☐

24. Are you bothered by the smells from inside the building, for example as…

	Yes, often (every week)	Yes, sometimes	No, never
…smell of food that originates from own apartment?	☐	☐	☐
…smell of food from the neighbors?	☐	☐	☐
…tobacco smoke or other smell from neighbors?	☐	☐	☐

25. Are you bothered by the smells from outside of the building, for example as…

	Yes, often (every week)	Yes, sometimes	No, never
…traffic emissions?	☐	☐	☐
…restaurants/industry?	☐	☐	☐
…wood burning smoke?	☐	☐	☐

26. Have you noticed some of the following smells in your apartment?

	Yes, often (every week)	Yes, sometimes	No, never
Smell of mold	☐	☐	☐
Smell of stagnant air	☐	☐	☐
Musty smell	☐	☐	☐

27. Are you bothered in your apartment by ventilation problems, such as…

	Yes, often (every week)	Yes, sometimes	No, never
…difficulties to get rid of troublesome smells?	☐	☐	☐
…difficulties to get rid of moist air in bathrooms?	☐	☐	☐
…fog on the window while cooking?	☐	☐	☐
…difficulties to regulate ventilation yourself?	☐	☐	☐

Mold and moisture

28. Have you noticed in the past 12 months in your apartment...

	Yes, in bathroom	Yes, in other room	No
Visible water stains on walls, floors or ceilings?	☐	☐	☐
Visible mold growth on walls, floors or ceilings?	☐	☐	☐

Noise and daylight

29. How do you find the acoustic conditions in your apartment in general?

1 = very good	2 = good	3 = acceptable	4 = bad	5 = very bad
☐	☐	☐	☐	☐

30. How do you perceive noise in your apartment?

	1 = not noticeable	2 = noticeable, but it does not disturb	3 = does not disturb very much	4 = disturbs	5 = disturbs a lot
Noise that comes from outside					
…traffic	☐	☐	☐	☐	☐
…waste disposal	☐	☐	☐	☐	☐
…industry	☐	☐	☐	☐	☐
…ventilation aggregates, heat pumps	☐	☐	☐	☐	☐
…children playing	☐	☐	☐	☐	☐
…parties outside	☐	☐	☐	☐	☐
Noise from other parts of the building					
…ventilation system	☐	☐	☐	☐	☐
…kitchen ventilator	☐	☐	☐	☐	☐
…fridge	☐	☐	☐	☐	☐
…something else: ………………………………	☐	☐	☐	☐	☐
…something else ………………………………	☐	☐	☐	☐	☐

31. **How do you estimate noise from technical systems in your apartment?**

1 = noise	2 = some noise	3 = noise, but it does not disturb much	4 = noise, but it does not disturb	5 = no noise
☐	☐	☐	☐	☐

32. **How do you find daylighting conditions in your apartment in general?**

1= very good	2 = good	3= acceptable	4 = bad	5 = very bad
☐	☐	☐	☐	☐

33. **Do you think your apartment is too bright or too dark?**

1 = much too bright	2 = too bright	3 = acceptable	4 = too dark	5 = much too dark
☐	☐	☐	☐	☐

34. **How do you perceive the direct sunlight conditions in your apartment in…**

	1 = very good	2 = good	3 = acceptable	4 = bad	5 = very bad
…winter?	☐	☐	☐	☐	☐
…summer?	☐	☐	☐	☐	☐

Window airing

35. **How often do you usually open the window for airing in heating season (September-April)?**

☐ Daily/ nearly every day
☐ About once a week
☐ Few times in a month
☐ Rarely or never

36. **When you air, do you usually have...?**

☐ …window/airing window open all day/night
☐ …window/airing window open for some hours
☐ …cross ventilation for some minutes
☐ I never air

37. **When you air, do you usually do it by...?**

☐ …using airing position of the window
☐ …using micro-airing position of the window
☐ …cross ventilation for some minutes with windows fully open
☐ I never air

38. **Why do you air in the winter?**

☐ Out of a habit, usually air as a routine
☐ Because the air is stuffy, air quality is bad
☐ It is too warm
☐ Other ventilation is insufficient
☐ Another
☐ I don't air

39. When you air during the heating season, do you usually open the window in …
Fill in the windows/doors you open. Leave others empty.

	Open one window	Open several windows	Open balcony door	Open smaller airing window
…living room?	☐	☐	☐	☐
…bedroom?	☐	☐	☐	☐
…kitchen?	☐	☐	☐	☐

40. When you air during the heating season, how do you usually open the window in …
Fill in the windows/doors you open. Leave others empty.

	Ajar (up to 10 cm)	Half open (20-50 cm)	Fully open (more than 50 cm)
…living room?	☐	☐	☐
…bedroom?	☐	☐	☐
…kitchen?	☐	☐	☐

41. Why do you air in the summer?

☐ Out of a habit, usually air as a routine
☐ Because the air is stuffy, air quality is bad
☐ It is too warm
☐ Other ventilation is insufficient
☐ I don’t air
☐ Another reason:

42. What is the reason to end window airing?

☐ Out of a habit, usually have it open for a certain time as a routine
☐ Have received enough fresh air
☐ Outside air is too cold
☐ Draught
☐ Noise from outside
☐ Too low temperature at night
☐ Too strong wind
☐ Rain
☐ Another reason:

43. How long time do you air daily?

	Winter (Nov-Mar)	Spring, autumn (Apr, Sept-Oct)	Summer (May-Aug)
I don’t air	☐	☐	☐
0-15 minutes	☐	☐	☐
15-30 minutes	☐	☐	☐
1-2 hours	☐	☐	☐
2-6 hours	☐	☐	☐
6-12 hours	☐	☐	☐
more than 12 hours	☐	☐	☐
all the time	☐	☐	☐

Additional information

44. **How big is your apartment?**
    - ☐ 1 room and kitchen
    - ☐ 2 rooms and kitchen
    - ☐ 3 rooms and kitchen
    - ☐ 4 rooms and kitchen
    - ☐ 5 rooms and kitchen or bigger

45. **On which floor is your apartment?**
    - ☐ First floor
    - ☐ Last floor
    - ☐ Neither first nor last

46. **How many people live in your apartment (count in yourself)?**

Adults 18 years or older	…….. persons
Children 13-17 years	…….. persons
Children 0-12 years	…….. persons
Total number of people	…….. persons

47. **What is your (the respondent's) year of birth?**
    ………………..

48. **Do you smoke?**
    - ☐ Yes
    - ☐ No

49. **If you have anything additional to add regarding your apartment, you are welcome to add it here:**

____

____

50. **Please fill in your contact (email or telephone number) if you want to participate in the raffle to win one of three €100 Partner gift cards:**

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THANK YOU FOR YOUR ANSWERS!

LUND UNIVERSITY

Divisions of Energy and Building Design, Building Physics and Building Services
Department of Building and Environmental Technology