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Laurina C. Felius

Combining building automation control systems with envelope retrofitting to improve the energy performance of cold climate housing

Doctoral thesis

NTNU
Norwegian University of Science and Technology
Thesis for the Degree of
Philosophiae Doctor
Faculty of Engineering
Department of Civil and Environmental
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Trondheim, May 2021

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Preface

This work was carried out at the department of Civil and Environmental Engineering at the Norwegian University of Science and Technology (NTNU) from August 2016 to August 2020.

This project has been funded by the department of Civil and Environmental Engineering and the Energy and Sensor Systems group (ENERSENSE).

The work has been supervised by Associate Professor Bozena Dorota Hrynyszyn, Associate Professor Fredrik Dessen and Associate Professor Mohamed Hamdy of NTNU.

Parts of this thesis have been published, with the scientific papers included in the Appendices. The author of this thesis has been the main contributor to these scientific papers and the co-authors were involved with conceptualization, supervision and revision of the manuscripts.

Trondheim, 1st of May, 2021

Laurina Felius

Acknowledgements

It has been four+ years with a lot of new knowledge and expertise, many ups and downs, four offices (five if you count ’home office 2020’), and a lot of cups of tea (tea is the new coffee!). This dissertation and the years leading up to it would not have been possible without the support of my colleagues, friends and family. So I would like to thank those who supported my research and those that supported me attempting to do research.

I would first like to thank those that were involved in this project, publications and the dissertation. A special thank you to my supervisors Bozena Hrynyszyn and Fredrik Dessen, who have supported me from the start, and Mohamed Hamdy, who strengthened the team in year 3 and 4. Your support and dedication to this project were very helpful for my progress. And thank you to Mario, Eva, Alyssa, Thomas and Kjersti for proofreading my thesis. I would also like to thank all co-authors and colleagues that I have collaborated with as part of scientific papers, book chapters, seminars and conferences.

I would like to thank my colleagues at the former Bachelor in Civil Engineering (HiST), where my first office was located, and my colleagues at ENERSENSE, in particular the PhD/PostDoc group from 2016/2017, for the nice lunch-breaks, fun seminars, and after-work activities.

During my stay in Norway, I met some awesome people that made the dark winters and not-so-warm-summers a lot better. Kjersti, Ellen Synnøve, Jake, Katie and others (you know who you are!). Thank you for your friendship. You are my family-away-from-home. Most of you are/were fellow PhD-candidates, and it was really helpful to discuss PhD related topics with you. But most of all I appreciate the fun (and serious) times we had during lunch and (too long) coffee breaks, dinners, game nights and short trips. It was the perfect remedy to relax and forget about my PhD troubles. And of course thank you for listening to my rants. To Jon, Jaime and Gary, you are the fluffiest! Wheek-wheek-purrrrrrr. Krr-krr-SQUEAK.

As any (ex-) PhD-candidate can tell you, you will experience periods with a lot of physical and mental stress. I found that yoga was the perfect solution to cope with body aches due to long hours of sitting behind a computer and to balance out the emotional roller coaster that is being a PhD-candidate. Therefore, I want to thank my yoga-teacher, July, for her inspirational yoga-lessons and wisdom on and off the mat.

Living abroad can be tough and I am so grateful for everyone in the Netherlands that kept in touch, came to visit and sent or brought me care-packages. Lieve vrienden en familie, bedankt voor alle steun in deze (soms zware) jaren. Bedankt voor alle goede gesprekken, theeleut-avonden, gezellige uitjes, familie-etentjes, zomer-barbecues en spellenavonden (klinkt als, ruikt als, boos-woede-woede-boos). Alyssa en Eva, bedankt voor jullie steun en vriendschap. Bedankt dat jullie altijd naar mijn gezeur en geklaag wilde luisteren als ik het even niet meer zag zitten. Bedankt voor alle grappige foto's en filmpjes die ik wekelijks, soms dagelijks, mocht ontvangen. Verder wil ik mijn ouders bedanken voor alle steun en adviezen, hun gastvrijheid, en voor alle bezoeken aan mij door de jaren heen (met drop, hagelslag, chocotoffs en andere snuisterijen als bagage). Dit heeft ontzettend geholpen tegen de heimwee die ik na 7-8 jaar als immigrant soms nog steeds ervaar.

The last person to thank is probably the most important one. Kjære Thomas, du er alt. Takk for at du alltid er der for meg og takk for at du tar vare på meg når jeg har det for travelt å gjøre det selv. Jeg elsker deg, liefste.

As a reminder to myself, I would like to finish with the following lesson I have learned (though not yet mastered completely):

Breathe in. Breathe out. Smile.

Summary

Improving the energy efficiency of buildings by combining envelope and energy systems retrofitting with smart technologies is recommended by the Energy Performance of Buildings Directive. The largest share of the existing building stock consists of residential buildings, so retrofitting these is essential to reduce the energy consumption of the building stock. Retrofitting projects and research studies of dwellings have mainly focused on improving the performance of the thermal envelope and systems, while smart technologies, such as building automation control systems (BACS), are not often used to their full potential. There are only few studies that estimated the potential energy savings from implementing BACS in residential buildings. They demonstrated that significant energy savings were achieved and that the energy label of the building improved. The literature also showed that the effect of BACS was higher when the original delivered energy was higher. Most of these studies focused on warm climates and the knowledge on the impact of BACS as retrofitting measure in cold climates is limited. This thesis evaluates the impact of combining building automation control systems (BACS) with envelope and energy systems retrofitting for residential buildings in Norway.

An analysis of the building stock and of the literature was conducted to investigate the retrofitting status and typical energy consumption of residential buildings in cold European climates and specifically in Norway. Based on this analysis, two typical building typologies that represent a large number of buildings and a large share of the total energy consumption were chosen, i.e. a detached single-family house and an apartment block. Building performance simulation models of these building typologies were created in IDA ICE. The descriptions of BACS measures given in the building automation standard EN 15232 were used to define relevant BACS for the case study buildings. As the standard can be interpreted in different ways, two approaches were used to illustrate the impact of system design and choice of setpoints. The impact of BACS as individual retrofitting measures as well as in combination with building envelope and energy systems retrofitting was assessed. Optimal retrofitting combinations were also found, using IDA ICE with GenOpt. The results were assessed in terms of achieved energy savings, cost-effectiveness and thermal comfort.

It was found that the energy consumption was reduced by up to 24% when BACS were implemented as a retrofitting measure. Heating control strategies had the largest impact on decreasing the energy consumption. The other control strategies did not individually improve the energy performance of the buildings, though most energy savings were achieved when all control strategies (i.e. heating, lighting, ventilation and shading control) were combined. The energy saving potential depends highly on the system design and choice of setpoints. When BACS were combined with envelope and energy systems retrofitting, energy savings up to 57% and 46% were achieved for the detached single-family house and apartment block, respectively. Installing an air source heat pump was the most effective retrofitting measure. Upgrading the heating and lighting control strategies was essential for cost-effective retrofitting. The control strategies for ventilation and blind control did not affect the energy consumption, but the latter improved the thermal comfort by reducing the number of overheating hours. The results showed that BACS had a bigger impact on more compact buildings, such as apartments.

To conclude, BACS has a significant energy saving potential in residential retrofitting projects. The impact of BACS on the energy performance increased when the building was more compact. Its impact was lower than that of building envelope and energy systems retrofitting measures, though large enough to be an attractive retrofitting measure when other measures are challenging. Combining BACS, especially heating and lighting control strategies, with a high-performance building envelope resulted in the highest energy savings and was the most cost-effective. When a deep retrofit of the building envelope is not possible, high-performance BACS are an attractive and profitable retrofitting measure.

List of Publications

Papers included in the thesis

L.C. Felius, F. Dessen, and B.D. Hrynyszyn, "Retrofitting towards energy-efficient homes in European cold climates - a review", *Energy Efficiency*, vol. 13, pp. 101–125, 2020.

Including: L.C. Felius, F. Dessen, and B.D. Hrynyszyn, Correction to: Retrofitting towards energy-efficient homes in European cold climates: a review. *Energy Efficiency*, vol. 13 pp.101–125, 2020.

Contribution of the PhD candidate: Conceptualization – Investigation – Methodology – Visualization – Writing - original draft.

L.C. Felius, M. Hamdy, B.D. Hrynyszyn and F. Dessen, "The impact of building automation control systems as retrofitting measures on the energy efficiency of a typical Norwegian single-family house", in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, vol. 410, 2020, p. 012 054.

Contribution of the PhD candidate: Conceptualization – Formal analysis – Investigation – Methodology – Software – Visualization – Writing - original draft.

L.C. Felius, M. Hamdy, F. Dessen, and B.D. Hrynyszyn, "Upgrading the smartness of retrofitting packages towards energy-efficient residential buildings in cold climate countries – two case studies", Submitted to and under review for *Buildings*, September 2020.

Contribution of the PhD candidate: Conceptualization – Formal analysis – Investigation – Methodology – Software – Visualization – Writing - original draft.

Papers not included in the thesis (in chronological order of publication)

B.D. Hrynyszyn, and **L.C. Felius**, "Upgrading of a Typical Norwegian Existing Wooden House According to the EnerPHit Standard", in *Cold Climate HVAC Conference*, pp. 183-193, 2018.

Contribution of the PhD candidate: Investigation – Methodology – Visualization – Writing - original draft – Writing - review & editing.

L.C. Felius, M. Thalfeldt, L. Georges, B.D. Hrynyszyn, F. Dessen and M. Hamdy, "Wood burning habits and its effect on the electrical energy demand of a retrofitted Norwegian detached house", in *IOP Conference Series: Earth and Environmental Sciences*, vol. 352, p 012 022, 2019.

Contribution of the PhD candidate: Conceptualization – Data curation – Formal analysis – Investigation – Methodology – Resources – Visualization – Writing - original draft.

L.C. Felius, B.G. Pollet, and J.J. Lamb, "Introduction to energy efficiency in buildings", in *Energy-Smart Buildings*, IOP Publishing, 2020, ch.1, pp. 1-1–1-7.

Contribution of the PhD candidate: Conceptualization – Visualization – Writing - original draft.

L.C. Felius, and J.J. Lamb, "Basic principles of energy use in buildings", in *Energy-Smart Buildings*, IOP Publishing, 2020, pp. ch.2, 2-1–2-25.

Contribution of the PhD candidate: Conceptualization – Visualization – Writing - original draft.

L.C. Felius, J.J. Lamb, F. Dessen and B.D. Hrynyszyn, "Building design and envelope", in *Energy-Smart Buildings,* IOP Publishing, 2020, ch. 3, pp. 3-1–3-21.

Contribution of the PhD candidate: Conceptualization – Visualization – Writing - original draft.

L.C. Felius, J.J. Lamb, B.D. Hrynyszyn, and F. Dessen, "Smart components and systems", in *Energy-Smart Buildings*, IOP Publishing, 2020, ch. 4, pp. 4-1–4-16.

Contribution of the PhD candidate: Conceptualization – Visualization – Writing - original draft.

B. Hamre, T. Bracchi, **L.C. Felius**, O.S. Burheim, B.G. Pollet, and J.J. Lamb, "Energy production in buildings", in *Energy-Smart Buildings*, IOP Publishing, 2020, ch. 5, pp. 5-1–5-13.

Contribution of the PhD candidate: Writing - original draft.

Abbreviations

AHU	Air handling unit
ASHP	Air source heat pump
BAC	Building automation control
BACS	Building automation control systems
BEM	Building energy management
CAV	Constant air volume
DDH	Discomfort degree hours
DHW	Domestic hot water
dLCC	Difference in life cycle cost
DPP	Discounted payback period
EED	Energy efficiency directive
EPDB	Energy performance of buildings directive
HVAC	Heating ventilation and air conditioning
LCC	Life cycle cost
PPD	Predicted percentage of dissatisfied
SFM	Simple factor method
SFP	Specific fan power
TBM	Technical building management
TEK17	Norwegian regulations on technical requirements for buildings and constructions introduced in 2017
VAV	Variable air volume

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1 | Introduction

1.1 Motivation

Norwegians spend up to 90% of their time indoors [1]. This means that buildings must not only protect the occupant from weather conditions, they also play an important part in the social environment. Buildings have evolved from simple constructions used for sheltering, to high-tech spaces that provide many additional functions, such as comfort and entertainment. As a result, buildings account for 40% of the total energy consumption in Europe [2]. The building sector is still expanding, which will most likely result in an increased energy consumption. Most experts agree that energy efficiency is the most cost-effective tool to reduce global emissions. Energy efficiency is in this thesis defined as services (output) provided per unit of energy input. To improve the energy efficiency, either the output should increase per unit of input, or the required energy input should decrease per output. In the case of buildings, energy efficiency will in most cases be achieved by decreasing the required energy input (i.e. energy consumption) to achieve the same services (e.g. comfortable indoor climate) as before.

Because of this, the European Union has a focus on decreasing the total energy consumption of new and existing buildings. The relevant targets and requirements to achieve these goals are listed in the Energy Efficiency Directive (EED) [3] and the Energy Performance of Buildings Directive (EPBD) [4]. These directives are part of the *Clean Energy for All Europeans* package, which has five objectives: to prioritize energy efficiency, emphasizing the building sector; to increase the use of renewable energy; to improve governance; to give consumers more rights on energy production, storage and sales; and to improve the electricity market to be smarter and more efficient [5]. The EED and EPBD set targets for energy efficiency, energy retrofitting and overall energy performance of buildings. The EPDB amendment of 2018 [6] increased the focus on implementing smart technologies to improve the energy performance, as well as the thermal and visual comfort, of buildings.

It is estimated that around 75% of the European building stock is inefficient [7]. A Norwegian study [8] estimated that in Norway, roughly one third of the existing building stock is in a good and satisfying condition, while the remaining buildings are in a partly satisfying to poor condition and require partial or complete renovation. Residential buildings represent around 60% of the heated floor area in Norway [8]. Older buildings typically have a higher energy consumption per heated floor area than new buildings, resulting in a significant energy saving potential for building retrofitting, especially of housing. The EPBD and EED state four important points concerning retrofitting:

1. Both new and existing buildings that undergo renovation should meet certain minimum energy performance criteria [4].
2. The amount of renovation projects needs to be increased [3] to a yearly average of 3% [6].
3. Each member state should develop and enforce their own national regulations on the energy performance of buildings [4] and on technical system requirements [6].
4. Improving the energy performance should include retrofitting of the building envelope and all relevant technical systems [6].

Space heating accounts for most of the energy consumption of existing houses in cold climates. There is a high energy saving potential in reducing the space heating demand by decreasing the heat losses of the building and increasing the system efficiencies. Retrofitting of dwellings in cold climates typically focuses on improving the energy efficiency through building envelope and energy systems retrofitting [9]. However, sometimes it may not be feasible and/or profitable to upgrade to a high-performance envelope, which is necessary to fulfill the minimum energy performance requirements. Another category of energy saving measures with potential in retrofitting projects are building automation control systems (BACS). BACS can reduce the operational energy of a building, while maintaining comfortable indoor conditions. This is done by optimizing the control and setpoints of heating, ventilation, cooling, lighting, domestic hot water and blind systems. BACS also offer potential to reduce and shift peak loads to further reduce the energy costs for the consumer and the pressure on the energy grid. BACS are well developed and studied for commercial buildings, though rarely used to its full potential in residential buildings [10]. Though BACS have many advantages, their potential energy savings are rather low compared to what can be achieved through building envelope and energy systems retrofitting [11]. Therefore, this thesis evaluates the impact of building automation control systems in combination with other retrofitting measures on the energy performance of residential buildings in Norway.

1.2 Research Questions

The ambition of this thesis is to contribute to energy-efficient retrofitting of the Norwegian residential building stock. For this purpose, the main research question is defined as: *What is the impact of integrating building automation measures with envelope retrofitting on the energy performance of housing in Norway?*. The research question is divided into the following sub-questions:

1. What is the current status of the housing stock and of retrofitting in Norway?
2. What are the energy performance characteristics of a typical Norwegian house?
3. How can an energy performance simulation model of a reference building be defined, created and validated?
4. What is the effect of building automation control strategies on the energy consumption and thermal comfort of the reference buildings?
5. What are the optimal retrofitting packages for the reference buildings where building automation control systems are combined with building envelope and energy systems retrofitting?
6. What is the cost-effectiveness of optimized retrofitting packages for the reference buildings where building automation control systems are combined with building envelope and energy systems retrofitting?

1.3 List of Papers and Contribution

This section describes each of the papers included in the thesis and how they fit together. Three papers were the basis of this thesis and seven additional publications were produced. These are not included, because their main objectives were outside the scope of this thesis. For each of the three papers, a short description of the content and the contribution of the PhD candidate is given. An overview of the other publications can be found in the *List of Publications*. Here, the contribution of the PhD candidate to each paper is described using the Contributor Roles Taxonomy (CRediT) roles.

The elements that needed to be investigated to answer the research questions are presented in *Figure 1.1*. The topics that are covered by each of the three papers is indicated with colored lines. The main research question requests knowledge of the existing building stock, i.e. its typical energy use and the retrofitting status. It is also critical to investigate what retrofitting measures are commonly used and how effective they are, as well as how BACS can be used in combination with those. Paper A is a literature review that provided an overview of the retrofitting status in European cold climates and typically used retrofitting measures and their impact on energy performance. It was concluded that there are few studies investigating the impact of BACS. Therefore, papers B and C focused on evaluating this. To provide results that were valid for a large part of the Norwegian residential building stock, typical building typologies were defined. These were used for the analysis in papers B and C. Paper B studied the impact of BACS classes in combination with retrofitting packages for a single-family house. Paper C focused on refining the BACS modelling approaches and defining optimal retrofitting packages for a single-family house and apartment block. In the optimal packages, implementation of BACS was combined with building envelope and energy systems retrofitting. The main objective was to evaluate the impact of retrofitting combinations on the energy performance of housing. Retrofitting also affects the thermal comfort and profitability, which were evaluated in papers B and C. Paper B presents a simplified approach and paper C a more detailed approach.

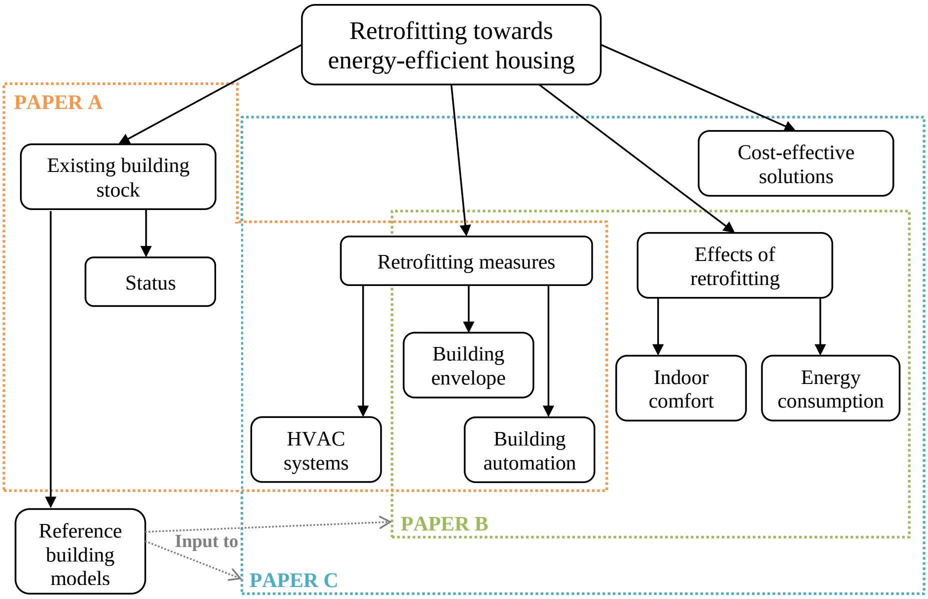


FIGURE 1.1. Contribution to the thesis.

1.3.1 Paper A

L.C. Felius, F. Dessen, and B.D. Hrynyszyn, "Retrofitting towards energy-efficient homes in European cold climates - a review", *Energy Efficiency*, vol. 13, pp. 101–125, 2020.

Including: L.C. Felius, F. Dessen, and B.D. Hrynyszyn, Correction to: Retrofitting towards energy-efficient homes in European cold climates: a review. *Energy Efficiency*, vol. 13 pp.101–125, 2020.

This paper summarized retrofitting measures to improve the energy efficiency of residential buildings in European cold climates. An overview of the status and challenges of retrofitting, the energy performance requirements in cold climates, and energy-saving retrofitting measures was presented. Finally, research directions for future work were discussed.

Contribution of the PhD candidate: Conceptualization of the study in collaboration with the other authors; defining the research methods and executing the literature analysis; visualization of all figures in the paper; writing the original draft; and revising the draft in collaboration with the other authors.

1.3.2 Paper B

L.C. Felius, M. Hamdy, B.D. Hrynyszyn and F. Dessen, "The impact of building automation control systems as retrofitting measures on the energy efficiency of a typical Norwegian single-family house", in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, vol. 410, 2020, p. 012 054.

This paper estimated the impact of (BACS on the energy performance of a Norwegian single-family house. This was done by evaluating the achieved energy savings and cost-effectiveness of BACS integrated with building envelope improvements. Two methods for calculating savings from implementing BACS were compared: energy performance simulation and the BACS factor method in line with the building automation standard EN 15232.

Contribution of the PhD candidate: Conceptualization of the study in collaboration with the other authors; defining the research methods and creating and validating the simulation model; analyzing the simulation results; visualization of all figures in the paper; writing the original draft; and revising the draft in collaboration with the other authors.

1.3.3 Paper C

L.C. Felius, M. Hamdy, F. Dessen, and B.D. Hrynyszyn, "Upgrading the smartness of retrofitting packages towards energy-efficient residential buildings in cold climate countries – two case studies", Submitted to and under review for *Buildings*, September 2020.

This paper presented optimal energy retrofitting packages for two Norwegian case studies: a single-family house and an apartment block. Retrofitting of building automation control systems was combined with building envelope and energy systems retrofitting. The associated difference in life-cycle cost was calculated for each retrofitting combination. Thermal comfort was assessed for the optimal retrofitting solutions.

Contribution of the PhD candidate: Conceptualization of the study in collaboration with the other authors; defining the research methods and creating and validating the simulation models and post-processing algorithms; analyzing the simulation results; visualization of all figures in the paper; writing the original draft; and revising the draft in collaboration with the other authors.

1.4 Structure of the Thesis

Chapter 2 gives an overview of relevant research context and background for the work.

Chapter 3 describes the different methodologies used to answer the research questions, including the limitations of the work.

The main results of the thesis are presented in *Chapters 4* to *7*.

Chapter 4 analyzes the Norwegian residential building stock, its energy consumption, and retrofitting status. This chapter answers research questions 1 and 2.

Chapter 5 describes in detail the two building energy performance models used in this study. How the control strategies were defined and modelled is also presented here. This chapter answers research questions 2 and 3.

Chapter 6 assesses the impact of building automation control systems (BACS) on the energy consumption, thermal comfort and profitability for the two case studies. This chapter answers research question 4.

Chapter 7 defines optimal retrofitting packages that combine building envelope retrofitting with upgrading BACS. The profitability and thermal comfort is assessed as well. This chapter answers research questions 5 and 6.

Chapter 8 outlines the main conclusions and discusses research directions for future work.

2 | Theoretical Framework

2.1 Energy-Efficient Buildings

An energy-efficient building should not only conserve energy, but also optimize its operational energy use and reduce its environmental impact. *Figure 2.1* illustrates the four strategies towards achieving energy-efficient buildings.

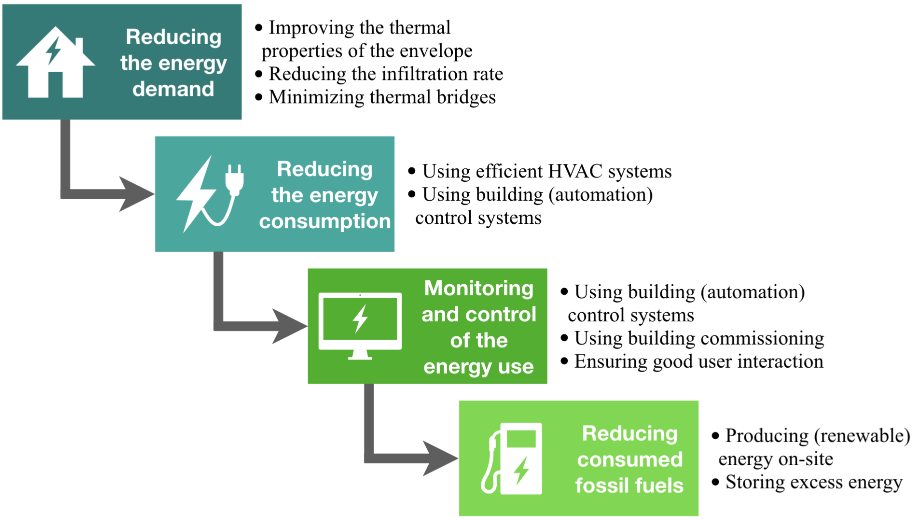


FIGURE 2.1. Holistic design approach towards energy-efficient buildings in cold climates.

The first strategy focuses on reducing the energy demand by improving the thermal envelope of the building. This includes optimizing the thermal properties of the envelope, ensuring proper installation of transparent building components in the opaque envelope, minimizing thermal bridges and creating an airtight building envelope. In cold climates, this means minimizing the transmission and infiltration heat losses while making optimal use of solar heat gains, i.e. maximizing solar gains during the heating season and balancing solar gains during the cooling season to avoid overheating. In addition, a mechanical ventilation system should be installed to provide sufficient fresh air to the building after the building becomes more airtight.

The building's energy consumption and energy demand should be reduced simultaneously. These two strategies are crucial for achieving energy-efficient buildings. The second strategy is about reducing the energy consumption and can be achieved by increasing the efficiency of heating, ventilation and air conditioning (HVAC) and energy systems.

The energy consumption can be further reduced by implementing building energy management and control strategies (third strategy). Monitoring and control of the energy use lowers the energy consumption, ensures a comfortable indoor climate and can increase the awareness of the user towards energy efficiency.

The fourth strategy focuses on environmental concerns, and says that the remaining energy consumption should be covered by on-site renewable energies where possible. The excess of the generated energy should be stored so that peak loads can be minimized and the use of the generated energy optimized. This strategy is not a part of the thesis and is not further discussed.

Significant energy savings already can be achieved by only implementing the first and second strategies. Several studies showed that the energy consumption of residential buildings in cold climates was reduced by 20% to 70% [12–18]. However, these buildings cannot be considered as intelligent or smart. When the third strategy is implemented in addition to the first two strategies, the energy consumption of the building decreases further and the smartness of the building improves.

2.2 Intelligent Buildings

Energy efficiency in the building stock requires intelligent buildings, meaning a building can "integrate and optimize building structures, systems, services and management to create a productive, cost-effective and environmentally approved environment for building occupants" [19, 20] as well as learn and adapt to its environment to constantly strive for the optimal performance [21]. The EPBD amendment of 2018 included several articles that focused on implementing smart technologies to improve the energy performance of buildings [6]. An intelligent building uses a building energy management (BEM) system to fulfil intelligent building functions. The BEM system monitors and optimizes the energy consumption of the building by controlling the HVAC and lighting systems. Automating these controls is done with a building automation control system (BACS). Combining BEM and BACS results in a control system that monitors, automates and optimizes the energy consumption of the building by implementing three vital functions [22]:

- Minimizing the effect of disturbances on the desired output.
- Minimizing the difference between the set-point and the desired output.

- Minimizing the reaction time between detecting a deviation and adjusting the system.

There are several other benefits of installing a BEM system with BACS (see the first column of *Table 2.1*). The system can easily detect faults and gives an overview of the whole system, including when components require maintenance. This, in combination with optimal energy use, reduces the cost of building operation and maintenance. The system also allows for energy flexibility, which can be used to minimize and shift peak loads. A well-functioning BEM system with BACS achieves a high level of indoor comfort and indoor air quality [23]. Settings for the HVAC systems can easily be adapted, for example for room function, time schedules or user preference. These aspects will positively influence the well-being and productivity of the occupants. Compared to other energy saving measures for buildings, such as adding insulation, it is relatively easy to install this measure in new buildings and to upgrade and expand the existing system with new technologies.

TABLE 2.1. Benefits, opportunities and challenges when using a building energy management system and building automation control system from a user, building manager and engineer point of view [24].

	Benefits and opportunities	**Challenges**
User	- Individual room climate adaption. - Improved indoor comfort. - Energy flexibility - Improved user safety and security. - Increased productivity and well-being.	- Perceived freedom of choice. - Faulty user interaction. - Disturbances and system override. - User interference.
Building manager	- Reduced energy consumption. - Reduced costs. - Improved fault detection. - Improved control of security.	- Incorrect operation. - Storage of massive amounts of data. - Safety of storing sensitive data. - Cybersecurity.
Engineer	- Easy system upgrades and expansion. - Installation in new buildings.	- Compatibility of different brands. - Installation in existing buildings. - Design of the user interface. - Life cycle maintenance.

Despite its many advantages, a BEM system with BACS also poses several challenges (see the second column of *Table 2.1*). An advanced control system is more complex than standard control of HVAC and lighting systems, which can result in incorrect use by the user and building manager. This can lead to discomfort and increased cost for operation and maintenance. A lack of service to the system can result in significant deviations from the desired optimization, which results in less energy savings. To overcome these challenges, the building manager should receive technical training on system operation and users should be informed on how to interact with the system. In addition, the user interface should be easy to use and present relevant and understandable feedback to the user. Besides challenges concerning the use of the system, there are several technical challenges. These include storing huge amounts of (sensitive) data safely, ensuring cybersecurity, component compatibility between brands, life cycle maintenance of old components and installation of intelligent systems in existing buildings. These challenges can be overcome or avoided if they are taken into account from the start of the project.

2.3 Building Automation Control Systems

Standard EN 15232 [25] describes the various BACS and technical building management (TBM) functions for four automation classes ranging from no automation (D) to high-performance automation (A). The functions are divided into seven categories: heating, cooling, ventilation, domestic hot water, lighting, blind control and finally data monitoring and diagnosis. A summary of the automated functions for each class for residential buildings is given in *Tables 2.2* to *2.7*. Not all functions are applicable to every building typology. When a BACS or TBM function is not relevant for the building (e.g. the system is not installed) or when it does not have a significant impact on the energy consumption, it does not have to be taken into account. The impact is not significant when "the share of energy consumption related to the service controlled by the function is less than about 5% of the total energy consumption of the building" [25].

The lowest level of automation is class D and has no automated systems installed, i.e. setpoints and system settings have to be adjusted manually. This the typical automation class of existing dwellings. Class C is defined as the standard level of automation for new buildings. In general, it corresponds to central control of the main systems in combination with a fixed time program (e.g. a day-night schedule). If the minimum functions required for class C are not achieved, a building is considered to be class D. In class B, there is advanced automation of BACS functions with some TBM functions. Systems are typically presence-controlled for individual rooms. All room controllers should be able to communicate with the BACS. In addition, the energy use is monitored and fault detection is possible. The most advanced class is A, in which all BACS and TBM functions are fully automated and integrated. Systems are demand-controlled for individual rooms. This class also includes integration of HVAC systems and other building services, such as lighting and solar shading.

Standard EN 15232 also defined user profiles for different building typologies. For each user profile, the following boundary conditions were defined: occupied hours; temperature setpoints for heating and cooling; operation times for heating, cooling and lighting; lighting power; heat gains for people and equipment; ventilation air changes per hour; solar shading factor; and number of weekdays/workdays. It was assumed that the heat gains from equipment and people only occur during the occupied hours. More detailed information about the model and boundary conditions can be found in Annex C of Standard EN 15232 [25]. Unfortunately, the standard does not give boundary conditions and user profiles for residential buildings.

Table 2.2. Heating and cooling BACS functions [25].

Function	**D**	**C**	**B**	**A**
No automatic control	x			
Individual room control on the unit		x		
Individual room control from the system			x	x
Intermittent control following a time schedule		x		
Automatic intermittent control with optimum start/stop			x	
Automatic intermittent control with demand evaluation				x
Temperature control depending on the outdoor temperature		x	x	x
Partial interlock between heating and cooling to minimize simultaneous operation		x	x	
Total interlock between heating and cooling that warrants no simultaneous operation				x

Table 2.3. Lighting BACS functions [25].

Function	**D**	**C**	**B**	**A**
Manual on/off switch	x	x		
Manual on/off switch with sweeping extinction signal			x	
Automatic occupancy detection				x
Central control of luminaires	x			
Manual room control of luminaires		x		
Luminaires are automatically switched off when enough daylight is present			x	
Luminaires are dimmed and switched off when enough daylight is present				x

Table 2.4. Domestic hot water BACS functions [25].

Function	**D**	**C**	**B**	**A**
Automatic on/off	x			
Automatic on/off with scheduled charging		x		
Automatic on/off with scheduled charging and demand based supply temperature			x	x
Continuous operation of circulation pumps	x			
Time-scheduled operation of circulation pumps		x	x	x

TABLE 2.5. Blind BACS functions [25].

Function	D	C	B	A
Manual operation	x			
Motorized operation with manual control		x		
Motorized operation with automatic control			x	
Integrated lighting, blind and HVAC control				x

TABLE 2.6. Ventilation BACS functions [25].

Function	D	C	B	A
No automatic control of the air flow rate	x			
Time schedule control of the air flow rate		x	x	
Demand-control of the air flow rate				x
On/off control of the room air temperature	x			
Continuous control of the room air temperature		x		
Optimized control of the room air temperature			x	x
No automatic control of the supply air temperature setpoint	x			
Constant setpoint of the supply air temperature		x		
Variable setpoint of the supply air temperature with compensation for outdoor temperature			x	
Variable setpoint of the supply air temperature with load dependent compensation				x
Constant outdoor air supply	x	x		
Outdoor air supply depending on a time schedule or occupancy			x	
Outdoor air supply depending on occupancy or variable control				x
Continuous supply air flow for a maximum load	x			
On/off time control of supply air flow with maximum supply during occupied hours		x		
Multi-stage control of the supply air flow			x	
Automatic control of the supply air flow				x
No automatic control for free cooling	x			
Free night cooling		x	x	x
No humidity control	x			
Humidity control through dew point temperature		x		
Direct humidity control			x	x

Table 2.7. Data monitoring and diagnosis functions (TBM functions) [25].

Function	**D**	**C**	**B**	**A**
Manual setting adjustments	x			
Central setting adjustments		x	x	x
Settings following predefined schedules			x	x
No fault detection	x	x		
Central indication of detected faults and alarms			x	x
Alarms and diagnostic functions				x
Reporting current information only	x	x		
Reporting trending functions and current information			x	
Analyzing and reporting trending functions and current information				x
Management of waste heat	x	x	x	x
Optimized use and storage of generated energy			x	x
Grid interaction and demand side management			x	x

2.4 Energy Saving Potential of Intelligent Buildings

One of the main benefits of intelligent buildings with a BEM system in combination with BACS is operational energy savings and a reduction of related costs. The energy saving potential depends on:

- The building's energy consumption.
- The building's current automation class.
- The automation class to be implemented.
- The occupancy and internal gains schedules.
- The setpoints for the HVAC systems.

The building's energy consumption is a function of: the local climate and orientation of the building; thermal properties of the building envelope; thermal bridges; air tightness; solar heat gains; and internal gains. Not all these parameters are variables that can be adjusted. For example, the location of the building, its current automation class and internal gains are fixed values. The energy performance characteristics can be improved, though this can be an expensive and complex process. The factors that are easiest and cheapest to adjust are the automation class to upgrade to and the setpoints for the HVAC systems, such as temperature setpoints for heating and cooling. It should be mentioned that not all systems have to be upgraded to the same automation class, i.e. lighting can be upgraded to class A while ventilation might be upgraded to class B.

There are only few studies that investigate the impact of BACS on the energy performance of residential buildings. Most of them focused on residential buildings in warm climates. Several studies estimated the energy savings of residential buildings in Italy [26–29] and Spain [30]. Upgrading BACS in a dwelling from automation class D to A resulted in significant energy savings and an improvement of the dwelling's energy label. Only one study was found that used a detailed calculation method for a dwelling located in a cold climate, though they did not consider all BACS functions. Reda et al. [31] did building performance simulations in IDA ICE to investigate the effect of ICT-driven intelligent solutions for controlling the heating setpoints and ventilation system in a generic apartment building. They demonstrated that in the climate of Helsinki, intelligent control decreased the space heating demand up to 60%, but increased the space heating demand when the system could not respond to window opening by occupants. However, they did not investigate the other BACS functions. This was identified as the research gap.

2.5 Building Performance Optimization

Defining optimal solutions is typically done by adjusting relevant design variables until the objective function(s) is (are) minimized. The design variables should be defined beforehand, either with an option range for continuous variables (e.g. insulation thickness varies between 0.2 and 0.4 m) or with options for discrete variables (e.g. various windows types). Optimization can be done through parametric runs, though it is extremely time-consuming to combine design variables and run simulations for every possibility. In addition, when advanced BACS are implemented, the simulation time for each run increases significantly due to the complexity of the model. Automatic simulation-based optimization can be used to find the optimal combinations within a set of given parameters to improve the time-efficiency of the optimization process.

The process of simulation-based optimization consists of three phases [32]. In the pre-processing phase, the simulation model is created, objective functions and solution space are defined, and the optimization algorithm is chosen. Decisions made in this phase highly influence the outcome of the optimization study. The optimization phase is characterized by running the optimization and detecting errors. During the post-processing phase, interpretation of the results plays a central role. Other elements in this phase include verification of the results, performing further analysis (optimal) and visualisation of the results.

The selection of simulation and optimization tools should be adapted to the research objective, and many combinations are possible. Some studies that performed optimization for retrofitting of residential buildings in cold climates are mentioned here, followed by studies that optimized new dwelling designs in cold climates. Hasan et al. [33] performed a single-objective optimization using GenOpt with IDA ICE for a Finnish detached house. They used a generalized pattern search particle swarm optimization combined with the Hookes Jeeves algorithm. The objective function was the difference in life cycle cost and considered three continuous variables (i.e. insulation thickness of the walls, roof and floor) and two discrete variables (i.e. window type and heat recovery system). La Fleur et al. [34] performed a single-objective optimization to minimize life cycle cost using OPERA-MILP for a Swedish multi-family building. Three discrete variables for wall and roof insulation, windows, heating system and ventilation system were used as the design variables. In addition, they defined three grid rent tariffs based on different energy supply systems. Hirvonen et al. [35] performed a multi-objective optimization with the Pareto-Archive NSGA-II genetic algorithm, coupled to IDA ICE simulations. They minimized CO_2 emissions and life cycle cost for energy retrofitting of Finnish apartment buildings. Niemelä et al. [15] used the same methodology to find optimal retrofitting solutions for Finnish apartment buildings. Their objectives functions were the net present value of the life cycle cost and the primary energy consumption. In both studies, the design variables were the U-values of the building envelope (continuous) and various space heating systems (discrete).

Tokarik and Richman [36] performed a multi-objective optimization for a house in Toronto, Canada, using EnergyPlus and a NSGA-II algorithm in jEPlus + EA. The total peak design load, annual energy savings and difference in life cycle cost as objective functions. Their design variables included only discrete variables, including predefined options for retrofitting of the opaque elements, windows and ventilation system. Hamdy and Sirén [37] introduced a novel multi-aid optimization scheme for performing optimization resulting in robust, cost-optimal solutions for designing energy-efficient buildings, in this case a Finnish single-family house. The multi-objective optimization used a genetic algorithm in combination with energy simulations in IDA ICE to minimize the primary energy and life cycle cost. They used a large scale solution space with design variables including measures to reduce the energy demand (such as building envelope retrofitting, heat recovery), characteristics of renewable energy sources (such as efficiency and area of PV and solar collectors) and mechanical systems (such as a space heating system). Hamdy and Mauro [38] performed a multi-objective optimization for the same case study building using a genetic algorithm and IDA ICE. The objective functions were CO_2 emissions and discounted payback time. Their design variables were building envelope insulation thickness of walls, roof and floor (continuous) and various options for windows, heat recovery, shading, airtightness and space heating system (discrete).

2.6 Energy Performance Requirements

Each country is responsible for developing a national building code with requirements for the energy performance of buildings. All regulations on technical requirements for buildings and constructions in Norway are written in TEK17 [39]. Most energy efficiency requirements have become stricter over the years. *Figure 2.2* shows the evolution of the minimum requirements for component U-values. Since 2007, the U-value requirements have stabilized and an additional requirement for the maximum net energy demand was included in the TEK17 (see *Table 2.8*).

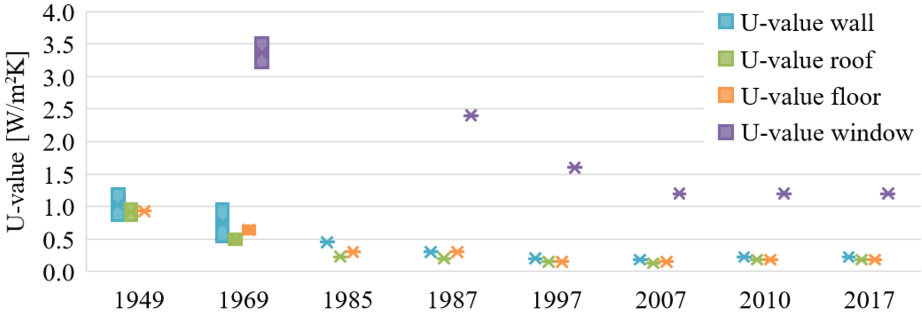


FIGURE 2.2. Evolution of U-value requirements in the Norwegian regulations on technical requirements for buildings and constructions, including the current energy requirements for U-values taken from TEK17.

TABLE 2.8. Evolution of the maximum net energy demand for single-family housing (SF) and multi-family housing (MF) including the current energy requirements for net energy demand as a function of the heated floor area (BRA).

	2007		**2010**		**2017**	
	SF	**MF**	**SF**	**MF**	**SF**	**MF**
Net energy demand [kWh/m^2 year]	$125 + \frac{1600}{BRA}$	120	$100 + \frac{1600}{BRA}$	95	$100 + \frac{1600}{BRA}$	95

In 2010, the Norwegian regulations on technical requirements for buildings and constructions included a second energy efficiency requirement in case the net energy demand criteria could not be achieved. This method could be used as an alternative method (i.e. instead of having a net energy demand lower than the requirements) to achieve an acceptable energy performance. From 2017, in TEK17, the alternative method can only be used for residential buildings. It consists of requirements for U-values, heat recovery, specific fan power, infiltration rate and thermal bridge value. These requirements are stricter than the minimum energy requirements, but it is allowed to deviate from the alternative method criteria as long as the total heat loss factor does not increase and the minimum energy efficiency requirements are met. The main advantage of the alternative method is that as long as the criteria are met, it is not necessary to calculate the net energy demand of the building. Norway also developed energy performance criteria for low-energy buildings and passive houses [40]. This standard has not been updated recently and the minimum requirements in TEK17 are similar to the criteria for low-energy buildings. *Table 2.9* presents the minimum energy performance criteria, the alternative method criteria (Alt.) for single-family housing (SF) and for multi-family housing (MF) and the Norwegian passive house criteria. Requirements for the net energy demand (TEK17), space heating demand (NS 3700) and heat loss factor (NS 3700) are not included in the table.

TABLE 2.9. Norwegian minimum energy requirements, including the minimum requirements in the alternative method and the Norwegian criteria for passive houses [39, 40].

	Minimum energy criteria [1]	**Single-family housing (Alt.)**	**Multi-family housing (Alt.)**	**Passive house criteria**
U-value external wall [W/m^2K]	≤ 0.22	≤ 0.18	≤ 0.18	0.10–0.12 [2]
U-value roof [W/m^2K]	≤ 0.18	≤ 0.13	≤ 0.13	0.08–0.09 [1]
U-value floor [W/m^2K]	≤ 0.18	≤ 0.10	≤ 0.10	0.08 [1]
U-value windows and doors [W/m^2K]	≤ 1.2	≤ 0.80	≤ 0.80	≤ 0.80
Annual average heat recovery rate [%]	–	≥ 80	≥ 80	≥ 80
Specific fan power (SFP) [kW/m^3s]	–	≤ 1.5	≤ 1.5	≤ 1.5
Airtightness at 50 Pa [h^{-1}]	≤ 1.5	≤ 0.6	≤ 0.6	≤ 0.6
Normalized thermal bridge value [W/m^2K]	–	≤ 0.05	≤ 0.07	≤ 0.03

[1] These requirements are in addition to a requirement for maximum energy demand.
[2] Typical U-values for building components, not minimum requirements.

These requirements are valid for new buildings and for buildings that undergo major renovation. Major renovation is not defined in the TEK17, but the EPBD defines this as when the total renovation cost is higher than 25% of the building value or when more than 25% of the building envelope area is renovated [4]. The following additional statements are given in TEK17 [39]:

- All buildings should be designed such that the energy use is reasonable.
- The energy requirements apply to the heated floor area (BRA) of the building.
- U-values should be calculated as average for each building component.
- The energy requirements do not apply to buildings or rooms with an indoor temperature below 15°C during the heating season.
- In case of heritage or protected buildings, the energy requirements apply to the extent which is feasible in relation to the building's status.
- The total net energy demand shall not exceed the values given in column "2017" in *Table 2.8*.
- In addition to the requirement for net energy demand, the energy requirements for components shall not exceed the values given in *Table 2.9*.
- For housing, the alternative method can be used as an alternative method for achieving energy performance requirements. It is allowed to deviate from these

values as long as the overall heat loss factor does not increase and the minimum energy requirements are not exceeded (see table *Table 2.9*).

- It is not allowed to install heating systems that run on fossil fuels.
- Small houses shall be built with a chimney unless there is a waterborne heating system installed or the house fulfills the Norwegian passive house requirements.

Variations of the last statement have been part of the Norwegian regulations on technical requirements for buildings and constructions since 1969, and chimneys were commonly installed in houses before that. The majority of older dwellings are heated with direct electricity and are also equipped with a wood stove or fireplace. The potential effect of using a wood stove on the energy demand and overheating risk for a Norwegian single-family house was discussed in one of our studies [41]. Norwegian habits and reasons for using a wood stove were analysed and used as input data for building performance simulations. The study showed that active use of a wood stove resulted in a decrease of the electrical energy consumption of up to 32%. It also showed that user behavior had a big impact on the actual savings. However, wood stove behavior is a very complex behavior to simulate [42] and multiple user patterns should be investigated. Therefore, it was decided that the use of a wood stove would not be further investigated as part of this dissertation.

2.7 Indoor Climate Requirements

TEK17 also presents requirements related to the indoor climate to prevent health issues and discomfort [39]. These requirements cover indoor air quality, thermal comfort, radiation, sound and vibrations, light and visual comfort and moisture. Standard EN 16798 presents indoor comfort criteria that are valid internationally [43]. When the Norwegian code does not specify requirements, the requirements stated in EN 16798 can be used. The most important indoor climate requirements relevant to this thesis are summarized, i.e. criteria for thermal comfort and ventilation.

2.7.1 Thermal Comfort

TEK17 [39] gives the following requirements for thermal comfort in buildings:

- Thermal comfort in rooms that are permanently used shall take into account health and comfort for the expected use of the room.
- It is recommended that the air temperature is kept below 22°C during the heating season.
- For housing, the temperature should be between 19°C and 26°C. The upper limit can be exceeded during warm summer days by a maximum of 50 hours per year. If no active cooling is installed, temperatures exceeding the upper limit can be accepted for short periods.

- To ensure thermal comfort, the temperature difference between feet and head shall not exceed 3–4°C and the temperature fluctuations over a day or period shall not exceed 4°C.
- In rooms that are permanently used, it should be possible to open at least one window or door towards the outdoor.

The SINTEF Building Research Design Guides, a widely used source for technical building solutions in Norway, recommends indoor operative temperature limits for residential buildings as given in *Table 2.10* [44]. In addition, they recommend a relative humidity of at least 20%.

TABLE 2.10. Recommended minimum operative temperatures given by Norwegian Building Research Design Guides [44].

Type of room	**Minimum [°C]**	**Maximum, summer [°C]**	**Maximum, winter [°C]**
Permanently used rooms	20	26 (28)	24
Bathrooms	24	26 (28)	24
Other rooms	16	26 (28)	24

For buildings without mechanical cooling, Standard EN 16798 [43] recommends ranges of indoor operative temperature during the summer and shoulder seasons, further referred to as adaptive comfort criteria. Prerequisites for this method are that the building is mainly used for sedentary activities, that there is easy access to openable windows or doors, that occupants can freely adjust their clothing, and that the thermal comfort is regulated by opening and closing of windows or doors [43]. This adaptive comfort method defines upper comfort limits of indoor operative temperature as a function of the outdoor running mean temperature. During the winter, the same temperature limits as for mechanically cooled buildings are used (see *Table 2.11*). The temperature limits are divided into three categories. The normal acceptable level is category II or higher. The other categories will be perceived as less comfortable, but do not pose any health risk. The outdoor running mean temperature is calculated as in *Equation 2.1*, or as in *Equation 2.2* when there is no record of the daily mean outdoor air temperature.

$$\theta_{rm} = (1-\alpha)[\theta_{ed-1} + \alpha \cdot \theta_{ed-2} + \alpha^2 \cdot \theta_{ed-3}] \qquad [^\circ C] \tag{2.1}$$

where θ_{rm} is the outdoor running mean temperature for the day in degrees Celsius, θ_{ed-1} is the daily mean outdoor air temperature for the previous day, θ_{ed-i} is the daily mean outdoor temperature for the i-th previous day and α is a constant between 0 and 1.

$$\begin{aligned}\theta_m = [\theta_{ed-1} + 0.8 \cdot \theta_{ed-2} + 0.6 \cdot \theta_{ed-3} + 0.5 \cdot \theta_{ed-4} \\ + 0.4 \cdot \theta_{ed-5} + 0.3 \cdot \theta_{ed-6} + 0.2 \cdot \theta_{ed-7}]/3.8 \qquad [^\circ C]\end{aligned} \tag{2.2}$$

Table 2.11. Recommended minimum indoor operative temperature in EN 16798 [43].

	Category	Minimum [°C]	Maximum [°C]
Residential buildings, living spaces (bedrooms, living rooms, kitchens, etc.)	I	21.0	25.5
	II	20.0	26.0
	III	18.0	27.0
	IV	16.0	28.0
Residential buildings, other spaces (utility rooms, storage, etc.)	I	18.0	–
	II	16.0	–
	III	14.0	–

The adaptive indoor operative temperature limits are given in *Table 2.12*. The optimal operative temperature is $\theta_o = 0.33 \cdot \theta_{rm} + 18.8$. The upper and lower limit only apply when the outdoor running mean temperature is between $10°C$ and $30°C$. Building design and passive thermal controls are used to avoid overheating above the adaptive upper limit.

Table 2.12. Recommended upper and lower temperature limits for indoor operative temperature in EN 16798 [43].

Category	Upper limit	Lower limit
I	$\theta_o = 0.33 \cdot \theta_{rm} + 18.8 + 2$	$\theta_o = 0.33 \cdot \theta_{rm} + 18.8 - 3$
II	$\theta_o = 0.33 \cdot \theta_{rm} + 18.8 + 3$	$\theta_o = 0.33 \cdot \theta_{rm} + 18.8 - 4$
III	$\theta_o = 0.33 \cdot \theta_{rm} + 18.8 + 4$	$\theta_o = 0.33 \cdot \theta_{rm} + 18.8 - 5$

Peeters et al. [45] presented adaptations to the thermal comfort criteria in EN 16798 for residential buildings. In dwellings, there are many variables that impact the acceptable comfort range, such as the outdoor temperature, the room function and activity, the ability to adapt clothing and open windows, and the price of the consumed energy. They stated that indoor comfort criteria for residential buildings should represent these adaptation effects and presented thermal comfort criteria for three zones: bathrooms, bedrooms and other rooms. These criteria are a function of the reference temperature, $T_{e,ref}$, as calculated with *Equation 2.3*.

$$T_{e,ref} = \frac{T_{ed} + 0.8 \cdot T_{ed-1} + 0.4 \cdot T_{ed-2} + 0.2 \cdot T_{ed-3}}{2.4} \qquad [°C] \tag{2.3}$$

where $T_{e,ref}$ is the reference external temperature in degrees Celcius, T_{ed} is the arithmetic average of today's maximum and minimum temperature in degrees Celcius and T_{ed-i} is the arithmetic average of the maximum and minimum temperature of the i-th previous day in degrees Celcius. The thermal comfort criteria for the three rooms were adapted to the typical clothing level and the activity.

The neutral temperature for the bedroom is described in *Equations 2.4* to *2.7*.

$$T_{n,bed} = 16°C \quad when \quad T_{e,ref} < 0°C \tag{2.4}$$
$$T_{n,bed} = 0.23 \cdot T_{e,ref} + 16°C \quad when \quad 0°C \leq T_{e,ref} < 12.6°C \tag{2.5}$$
$$T_{n,bed} = 0.77 \cdot T_{e,ref} + 9.18°C \quad when \quad 12.6°C \leq T_{e,ref} < 21.8°C \tag{2.6}$$
$$T_{n,bed} = 26°C \quad when \quad T_{e,ref} \geq 21.8°C \tag{2.7}$$

The neutral temperature for the bathroom is described in *Equation 2.8* and *Equation 2.9*.

$$T_{n,bath} = 0.112 \cdot T_{e,ref} + 22.65°C \quad when \quad T_{e,ref} < 11°C \tag{2.8}$$
$$T_{n,bath} = 0.306 \cdot T_{e,ref} + 20.32°C \quad when \quad T_{e,ref} \geq 11°C \tag{2.9}$$

The neutral temperature for other rooms, such as the kitchen, living room and study is described in *Equation 2.10* and *Equation 2.11*.

$$T_{n,other} = 0.06 \cdot T_{e,ref} + 20.4°C \quad when \quad T_{e,ref} < 12.5°C \tag{2.10}$$
$$T_{n,other} = 0.36 \cdot T_{e,ref} + 16.63°C \quad when \quad T_{e,ref} \geq 12.5°C \tag{2.11}$$

Peeters et al. [45] also defined acceptable upper and lower limits, see *Equations 2.12* and *2.13*. These equations take into account the increased sensitivity of humans towards cold, in comparison to the sensitivity for heat. Some room functions required restrictions to the upper and lower limits. The absolute lower limit was set to 16°*C* for bedrooms and 18°*C* for bathrooms and other rooms. The absolute upper limit was set to 26°*C* for bedrooms, while the other rooms had no absolute upper limit. These assumptions are also summarized in *Table 3.3*, located in *section § 3.5*.

$$T_{upper} = T_n + w \cdot \alpha \tag{2.12}$$
$$T_{lower} = T_n - w(1 - \alpha) \tag{2.13}$$

where T_{upper} is the upper limit of the comfort band in degrees Celsius, T_{lower} is the lower limit of the comfort band in degrees Celsius, w is the width of comfort band in degrees Celsius and α is a constant, independent on the season, representing an asymmetrical split around the neutral temperature. The parameter w is set to 5°C and 7°C for a 10% and 20% predicted percentage of dissatisfied (PPD), respectively.

2.7.2 Ventilation

TEK17 specifies recommendations for ventilation and air flow rates of residential and non-residential buildings. Standard EN 16798 also recommends design ventilation air flow rates for four comfort categories and for different rooms, but these are not discussed here. The following requirements should be fulfilled [39]:

- The ventilation system shall be adjusted to the room's layout, function, moisture load, pollution and smell to ensure a good indoor air quality.

- The intake of supply air and outlet of exhaust air shall be placed so that the quality of the supply air is ensured. The outdoor air shall be filtered if the quality is poor.

- In housing, the supply air flow shall be minimum 1.2 m^3/h per m^2 floor area when it is occupied.

- Rooms can be ventilated by opening vents and windows if the outdoor air has a satisfactory quality. It is recommended to install balanced ventilation with heat recovery to fulfil the energy requirements and requirements for thermal comfort.

- Bedrooms shall be ventilated with minimum 26 m^3/h per person when the room is occupied.

- Rooms that are not meant for permanent use (e.g. storage) shall be ventilated with minimum 0.7 m^3/h per m^2 floor area. This requirement also counts for rooms that are temporarily not occupied.

- The kitchen, bathroom, toilet and laundry room shall be ventilated according to the air flow rates given in *Table 2.13*. The supplied air to the room should be equal to the minimum air flow rate.

TABLE 2.13. Ventilation criteria for wet rooms in TEK17 [39].

Room function	**Minimum air flow rate**	**Forced air flow rate**
Kitchen	36 m^3/h	108 m^3/h
Bathroom	54 m^3/h	108 m^3/h
Toilet	36 m^3/h	36 m^3/h
Laundry room	36 m^3/h	72 m^3/h

3 | Research Methodology

3.1 Literature Study

An extensive literature study was carried out to investigate the status of retrofitting and to summarize retrofitting measures that improve energy efficiency for residential buildings in cold climates. Only literature published in the period from 2000 to early 2019 was considered to provide an up-to-date literature overview. The literature study refers to countries in European cold climates. These were defined as countries with an average of more than 4000 annual heating degree days over the last 10 years according to the database of Eurostat [46]. Non-European cold climate countries in Asia and North America were not considered.

3.2 Energy Performance Simulations

As building performance modelling was a significant part of the thesis, a whole chapter is devoted to explaining the development and validation of the models. Here, only a short summary is given. The full description of the methodology can be found in *Chapter 5*.

Two typical Norwegian houses, a detached, single-family house and an apartment block, were modeled in ArchiCAD. The files were exported to the simulation tool IDA ICE [47] and adjusted to dynamic multi-zone models. All room functions were modeled as individual zones, so that the effect of advanced building automation control systems with individual room control could be evaluated. Adjacent rooms with the same room functions were merged to simplify the model. *Section § 5.1* gives a detailed description of the case studies.

The buildings were located in Trondheim, using the climate of Værnes. Trondheim is one of the bigger cities in Norway with a large amount of the defined case study buildings. In a previous study, it was found that the climate of Trondheim was the most challenging retrofitting climate out of Bergen, Oslo and Trondheim [48]. Building performance simulations over a one year period with a time step of one hour were performed. *Section § 5.4* describes how the advanced control strategies were modeled and what setpoints were used. The modelling assumptions are partly described in *Section § 5.1* and at the start of *Chapter 6* and *Chapter 7*.

3.2.1 Model validation

The representativeness of the simulation models was evaluated in two steps. First, models with a high validity were created by using typical and normalized input data. The input data for the energy performance requirements of the models is summarized in *Table 5.1*. The original reference models were simulated twice: with the standardized (normative) internal gain loads from NS 3031 [49] and with typical internal gain loads, presented in *§ 5.2.3*. The simulation were compared with theoretical data. As the case studies are representative for a group of buildings, the results were compared to average data from real measurements, statistics and typical values from other studies [50, 51]. They were validated for two main heating systems: a direct electrical heating system in the entire house and an air source heat pump (ASHP) in the living room, with direct electric radiators in other rooms. The validation is further described in *Section § 5.3*.

In addition to validating the simulation models, the control strategies were validated. This was done to verify the interpretation of the control strategies as described in EN 15232 [25] and to ensure that a more advanced control strategy resulted in a reduction of energy consumption. The definition and modelling of the control strategies is given in *Section § 5.4* and the validation of the control strategies is presented in *Section § 5.3*.

3.2.2 Custom Control Strategies

Control strategies that represent the four classes of automation for heating, ventilation, lighting and blind were created using the custom control function in IDA ICE. Two approaches with different setpoints and system designs were used, both based on the descriptions of the automation classes given in EN 15232. In addition, two approaches for window opening behavior were modeled. A detailed description of each control strategy and setpoints is given in *Section § 5.4*. *Chapter 6* presents the simulation results that validate the control strategies. The control strategies in approach II were validated to ensure that each improvement lead to a reduced energy consumption and to ensure that the thermal comfort did not worsen. EN 15232 does not give setpoints or other input parameters for residential buildings. Some boundary conditions are presented for other building typologies in the climate in Germany. As the choice of setpoints and boundary conditions can significantly affect the impact of the control strategy, it was essential to validate the choices described in *Section § 5.4*.

3.3 Estimating BACS Energy Savings

Standard EN 15232 presents two methods to calculate the impact of BACS on the energy performance of a building [25]. The first method is the simple factor method

(SFM) that estimates energy savings based on efficiency factors. The second method is a detailed calculation method, which uses a detailed building energy performance simulation model to calculate energy savings. Both methods were used in Paper B and only the detailed method was used in Paper C.

3.3.1 Simple Factor Method

The SFM uses efficiency factors, calculated based on results from a large set of energy performance simulations with TRNSYS, to estimate energy savings [25]. The efficiency factors were calculated for a single node room temperature model located in the climate of Würzburg, Germany, for different user profiles representing the most common building typologies. *Table 3.1* gives an overview of the efficiency factors for residential buildings, assuming that the current automation class is C.

TABLE 3.1. Efficiency factors for residential buildings [25].

	D	**C**	**B**	**A**
Electrical, overall	1.08	1.00	0.93	0.92
Thermal, overall	1.10	1.00	0.88	0.81
Thermal, heating	1.09	1.00	0.88	0.81
Thermal, domestic hot water	1.11	1.00	0.90	0.80

The achieved energy savings were calculated by subtracting the new delivered energy from the original delivered energy. The new delivered energy was calculated by multiplying the original delivered energy with the correct efficiency factors, as listed in *Table 3.1*. The delivered energy consists of three elements: thermal energy, electrical energy and energy for equipment. The thermal energy consists of the energy for heating and cooling, including the heating and cooling in the ventilation system, and domestic hot water. The electrical energy consists of the energy for lighting and auxiliary devices and pumps. BACS do not impact the energy for electrical appliances. This resulted in the following equation:

$$E_{sav} = E_{del,tot} - [(\sum E_{th} \cdot \eta_{th}) + (\sum E_{el} \cdot \eta_{el}) + E_{eq}] \qquad [kWh] \tag{3.1}$$

where E_{sav} are the achieved energy savings in kWh/year, $E_{del,tot}$ is the total delivered energy of the original automation class in kWh/year, E_{th} is the original thermal energy in kWh/year, E_{el} is the original electrical energy in kWh/year, E_{eq} is the energy for equipment in kWh/year and η is the relevant BACS efficiency factor.

The main advantage of the SFM is that it quickly estimates the impact of BACS on the yearly energy consumption. This method is also preferred when there is insufficient data and knowledge about the BACS and TBM functions and the energy systems, such as in the early design stages. However, the SFM has several disadvantages: it only gives one yearly result; the efficiency factors were calculated for a German climate and might not be suitable for other climates; the user profile and boundary conditions for residential buildings are not provided; and it is not possible to estimate the effect of upgrading individual systems to different classes of automation.

3.3.2 Detailed Calculation Method

A detailed calculation method calculates in yearly, monthly or hourly time steps. There are five approaches to calculate the impact of the BACS and TBM functions: direct approach, operating mode approach, time approach, setpoint approach, and correction coefficient approach. With the direct approach, the impacts of some functions, such as heating setpoints and dynamic solar shading, can be directly calculated from the building performance simulation results or from an hourly simulation method. In the operating mode approach, the energy consumption is calculated for each operating mode (e.g. 'occupied' and 'not occupied'). The total energy consumption can be obtained by summing these together. The time approach is used when BACS directly impact the operating time of a device, such as for lighting. The energy consumption for a certain time step can be calculated by multiplying the power of the device with the characteristic coefficient and the time step. The characteristic coefficient is the ratio between the time when the control is active and the total time step. The setpoint approach is used when the BACS directly impact the control accuracy, i.e. the deviation between the desired setpoint and the controlled variable. The energy consumption is a function of the transfer coefficient, a time step, the equivalent temperature setpoint, and the outside temperature. If the control system impacts more than one parameter, the correction coefficient approach is used. The energy consumption of the reference case is multiplied with a correction coefficient that represents the change in energy consumption compared to the reference case. The correction coefficient depends on factors such as the local climate and the building typology. In this study, the direct approach was used to calculate the energy savings from BACS.

3.4 Single-Objective Optimization

Optimization was done with GenOpt [52], a standalone optimization tool that is built in IDA ICE. This tool automates the simulation-based optimization process. GenOpt receives input from the simulation program in the form of text files and returns the output as text files. Though GenOpt was originally developed for cost minimization, any user defined single-objective function could be minimized. GenOpt calls the simulation tool (i.e. IDA ICE) and calculates the objective function based on the chosen design variables. The design variables are changed in each iteration until the objective function is minimized. GenOpt can use various algorithms, and in this case, a hybrid optimization algorithm was used. This algorithm combines a generalized pattern search particle swarm optimization combined with the Hookes Jeeves algorithm. This method was validated by Hasan et al. [33], who compared the optimization results with simulation results from a brute-force search method. The hybrid algorithm first performs a particle swarm optimization to iteratively find combinations of design variables. Once the objective function is minimized, the Hookes Jeeves algorithm refines the continuous design variables to find their optimal value (see *Figure 3.1*). The markers lined with black in *Figure 3.1* illustrate when the design variable refining process started. GenOpt ran between 270 and 330 models to find the optimal solutions for each building performance simulation model.

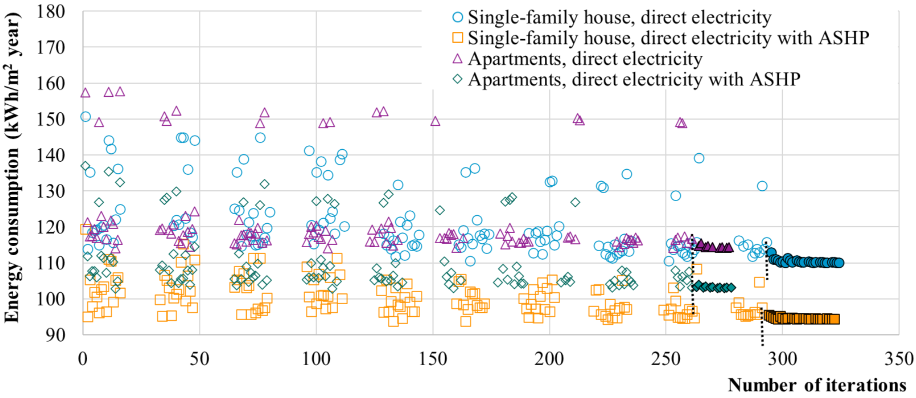


FIGURE 3.1. Decreasing yearly energy consumption with an increasing number of iterations illustrating the GenOpt hybrid algorithm.

3.4.1 Defining the Solution Space

GenOpt can read discrete and continuous variables, further referred to as design variables. *Table 3.2* presents the solution space with the design variables and type of variables.

TABLE 3.2. Characteristics of the optimization parameters.

	Continuous	Discrete
Insulation thickness of the external walls	x	
Insulation thickness of the basement walls	x	
Insulation thickness of the roof	x	
Insulation thickness of the floor	x	
Thermal bridges[1]	x	
Airtightness[1]	x	
Windows		x
Heating control strategy		x
Ventilation control strategy		x
Lighting control strategy		x
Blinds control strategy		x

[1] The thermal bridge value and airtightness are continuous variables as a function of the chosen insulation thickness of the envelope.

The design variables considering the thermal envelope of the building were continuous variables with a lower and upper bound. The control strategy design variables and the window design variable were discrete variables with a defined number of options. A detailed description of the solution space can be found in *Section § 7.1*.

3.5 Thermal Comfort Assessment

Two different methods were used to assess thermal comfort: comparing total discomfort hours and comparing total indoor discomfort degree hours. Assessment of overheating hours was chosen as the thermal comfort assessment method for paper B as a simple estimation of thermal comfort was sufficient. In paper C, thermal comfort was assessed by calculating the total indoor discomfort degree hours. It should be noted that the two presented methods use two different thermal comfort upper and lower limits. The methods concur with the chosen adaptive setpoints, i.e. thermal comfort was assessed according to EN 16798 when adaptive setpoints from EN 16798 were used, and thermal comfort was assessed with the criteria from Peeters et al. [45] when their adaptive setpoints were used.

3.5.1 Annual Discomfort Hours

A simple assessment of annual discomfort hours was done to evaluate the effect of retrofitting and BACS on the thermal comfort. The discomfort hours were calculated according to EN 16798 for buildings without mechanical cooling. This is a built-in function in IDA ICE that returns the total annual hours for each defined zone in each of the four thermal comfort categories (see *Table 2.12*). The annual discomfort hours were assessed for all rooms that are permanently used (i.e. bedrooms, living rooms, kitchen, bathroom) and the discomfort hours were summed to one value. Everything outside of category III is considered unacceptable. The normal acceptable level of thermal comfort is category II or better.

3.5.2 Indoor Discomfort Degree Hours

The thermal comfort of one representative room for each case study was assessed after energy optimization was carried out. The representative room was defined as the room with most overheating hours in the reference case (i.e. no retrofitting). This were the west-facing living room on the upper floor of the single-family house, and the living room of the south-west corner apartment facing south. These rooms had the largest glazed area, resulting in most heat losses during the winter and most heat gains during the summer. It was assumed that when the overheating and undercooling is acceptable for these rooms, it will be acceptable for the rest of the house.

Thermal comfort was evaluated by calculating the number of indoor discomfort degree hours for the representative rooms. This is the temperature difference between the upper and lower limit (for overheating and undercooling, respectively) and the operative room temperature when the bounds are exceeded, see *Equations 3.2* to *3.4*. This was done for each hour time-step and summed to get the annual indoor discomfort degree hours (DDH). Only the discomfort hours when the room was occupied were taken into account, as the energy saving control strategies with night setback and extreme setback when the room is not occupied will result in DDH. However, this discomfort is acceptable as the room is not occupied.

$$\text{If} \quad T_l \leq T_{op} \geq T_u \quad \text{then} \quad DDH = 0 \tag{3.2}$$

$$\text{If} \quad T_{op} > T_u \quad \text{then} \quad DDH = \sum_{i=1}^{8760}(T_{op} - T_u) \tag{3.3}$$

$$\text{If} \quad T_{op} < T_l \quad \text{then} \quad DDH = \sum_{i=1}^{8760}(T_l - T_{op}) \tag{3.4}$$

where T_{op} is the indoor operative temperature, T_u is the upper temperature limit and T_l is the lower temperature limit. The upper and lower temperature limits are given in *Table 3.3*. Instead of comparing the operative temperature to the adaptive comfort criteria given in EN 16798 [43], the criteria as proposed by Peeters et al. [45] were used. These adaptive criteria represent more realistic boundaries for residential buildings, as the boundaries are adapted to room function. Discomfort hours were defined as when the operative room temperature exceeds the 20% PPD bound (see *Table 3.3*). The adaptive criteria are described in more detail in *Section § 2.7.1*.

Table 3.3. Lower and upper limits (20% PPD) for evaluating the thermal comfort [45].

Room function	**Lower limit (PPD=20%)**	**Upper limit (PPD=20%)**
Bedrooms	$T_{bed,l} = max(16, T_{bed,n} - 2.1)°C$	$T_{bed,u} = min(26, T_{bed,n} + 4.9)°C$
Bathrooms, living rooms and other	$T_l = max(18, T_n - 2.1)°C$	$T_u = T_n + 4.9°C$

3.6 Economic Assessment

Two different methods were used for economic assessment: discount payback period and life cycle cost. The discounted payback method was used for a simple cost assessment in paper B. Due to its limitations, it was decided to perform a more detailed cost assessment in further studies. Therefore, a life cycle cost assessment was done in paper C.

3.6.1 Discounted Payback Period

The discounted payback period (DPP) was used to preliminary assess the profitability of four retrofitting packages for the single-family house in combination with four automation classes. The DPP compares the yearly energy savings with the initial investment, taking into account the time value of money. This gives the number of years it takes to break even. The DPP is calculated according to *Equation 3.5*.

$$\text{Discounted payback period} = \frac{ln[(1 - \frac{dIC}{ES \cdot EP} \cdot r)^{-1}]}{ln[1 + r]} \tag{3.5}$$

where dIC is the difference in investment cost between the model version and the original in NOK, ES is the energy savings in kWh per year, EP is the energy price in NOK/kWh and r is the real interest rate as calculated in *Equation 3.6.*.

$$r = \frac{i-f}{1+f} \qquad and \qquad r_e = \frac{r-e}{1+e} \tag{3.6}$$

where r is the real interest rate, i is the nominal interest rate, f is the inflation rate, r_e is the real interest rate including the escalation of the energy price and e is the energy price for electricity in NOK/kWh. The interest rate was assumed to be 3.0% because of the low nominal interest on housing loans, and the inflation rate was set to 2.1%. The energy price for electricity, including taxes and grid rent, was 1.23 NOK/kWh with a yearly price escalation assumed at 3.15% [53]. The investment costs were taken from Norsk Prisbok [54] and included the removal of old components. The cost were summed for each retrofitting and automation package. Maintenance, replacement and recycling costs were not taken into account.

3.6.2 Difference in Life Cycle Cost

The life cycle cost were calculated for each solution that GenOpt returned to evaluate the economic feasibility of the retrofitting packages. Instead of calculating the life cycle cost for the reference case (i.e. no retrofitting) and each retrofitting package, the difference in life cycle cost (dLCC) between the reference case and the retrofitting package was calculated (see *Equation 3.7*), following the methodology introduced by Hamdy et al. [55].

$$dLCC_i = LCC_i - LCC_r \qquad [NOK] \tag{3.7}$$

The investment cost for the retrofitting measures and the operating cost for the building and services were taken into account. Maintenance costs were assumed to be constant and were therefore neglected. The replacement costs for the building envelope measures were neglected as well, because it was assumed that no components had a lifetime shorter than the calculation period of 30 years. The automation measures and the heat pump were replaced once during the calculation period. It was also assumed that the original construction of the building was in a good state. Following these assumptions, the difference in life cycle cost was simplified to *Equation 3.8*. With this equation, a negative dLCC indicates that the retrofitting design is more profitable than the reference case (dLCC = 0). The selected reference case significantly impacts the outcome of the calculation. Therefore, dLCC assessment results with different references cannot be compared.

$$dLCC_i = dIC + dOC \qquad [NOK] \tag{3.8}$$

where dIC is the difference initial investment cost for the retrofitting measures in NOK and dOC is the difference in operation cost between the retrofitted model and the reference model in NOK. The difference in initial investment cost (*Equation 3.9*) was calculated by summing the cost for each optimization parameter, excluding thermal bridges and airtightness. This resulted in a total of 8 parameters per model. All cost were taken from Norsk Prisbok 2018 [54] and included the material and labour cost of removing the original components and installing new components, excluding taxes, and were corrected to the price index of December 2019 to follow the price changes due to inflation.

$$dIC = \sum_{j=1} IC_j \tag{3.9}$$

The difference in operational cost was calculated as shown in *Equation 3.10*. This was the energy cost related to the total energy consumption covered by electricity. The energy price included taxes and grid rent.

$$dOC = a \cdot e_p \cdot dE_j \tag{3.10}$$

where a is the discount factor including the escalation of the energy price, calculated as in *Equation 3.11*, e_p is the energy price for electricity in NOK and dE_j is the difference in the annual electric energy consumption in kWh/year. The energy price for electricity was set to 1.23 NOK/year [53] with an annual price escalation of 3.15% [11]. The interest rate was assumed to be 3.0% because of the low nominal interest on housing loans, and the inflation rate was set to 2.1% [56]. This resulted in a real interest rate of 0.008%.

$$a = \frac{1-(1+r_e)^{-n}}{r_e} \tag{3.11}$$

where r_e is the real interest rate including the escalation of the energy price, as shown in *Equation 3.6* and n is the calculation period of 30 years.

3.6.3 Limitations

The following points were outside the scope of this research:

- Only one climate zone was considered.
- Only one occupancy profile was considered.
- BACS setpoints were assumed at the start of the analysis and changed according to the validation results, but they were not further optimized.
- Control strategies for domestic hot water and cooling systems were outside the scope.
- In the apartment case study block, energy, cost and thermal comfort were assessed for two representative apartments and not for the whole building. For example, retrofitting of the ground floor was not taken into account as the representative apartments were located on the top floor.
- Energy systems were not the primary focus of this study and were not investigated in detail. Only the air source heat pump was considered as retrofitting measure for energy systems.

- A single-objective optimization of the energy consumption was done, as energy was the main focus of this study. Multi-objective optimization with energy consumption and difference in life cycle cost as objective functions is more suitable for presenting cost-optimal energy retrofitting solutions.

- Thermal comfort was assessed for some rooms only. For a full thermal comfort analysis, all zones in the house should be considered.

- The economic analysis did not take into account maintenance or replacement cost. The profitability of the solutions will be lower than presented.

- In the economic analysis, a fixed energy price with and without price escalation was considered. Different grid rent tariffs were outside the scope.

How the limitations of this work can result in future research directions is discussed in *Chapter 8*.

4 | Status of the Norwegian Residential Building Stock

This chapter answers research question 1: *What is the current status of the housing stock and of retrofitting in cold climates?*. This question was the main topic of paper A.

4.1 Analyzing the Building Stock

After the Second World War there was a large demand for housing in Norway. The Housing Bank was established to control the quality of housing and to limit excess. They controlled layout, cost and mechanical systems by providing complete designs and drawings of catalogue houses, which were typically rational and simple. After establishing building legislation in 1965, the technical control was given to the local governments, though the Housing Bank still controlled the layout and design. The Housing Bank had certain rules for size and financing of the houses, and from the 1960s, houses (80–120 m^2) with a full basement designed for sloped terrain received favorable financing. As a result, this housing typology is still a common housing typology, also on flat terrain [1].

Guidelines about rational and non-wasteful housing construction forced the Housing Bank to adapt from detached houses to semi-detached and multi-dwelling buildings. This meant more compact and dense housing, which ultimately resulted in smaller residential units and "high-density low-rise" buildings. Multi-dwelling buildings were often between 2 and 4 floors high and each dwelling consisted typically of 3 rooms and had a total area of 70–80 m^2. Even though houses were traditionally built with wood, large-scale residential buildings were built with load-bearing masonry constructions. This meant narrow buildings with good access of daylight in each dwelling. Towards the end of the 60s, the demand for inexpensive housing increased. The introduction of prefab concrete offered new layouts and high-rise buildings. As external walls were expensive to build, long multi-dwelling buildings with narrow dwellings were constructed. In the 1970s and 1980s, prefab concrete was replaced by load-bearing concrete walls placed in between units, creating a modular dimension for the width of one dwelling based on economic and structural conditions. Within the dwelling, the layout could be adjusted freely by the resident, though bathrooms and stairs were often fixed elements [1].

Outside the cities, detached houses on large lots still dominated. However, as flat lots became occupied, residents were forced to build on sloped lots. This increased the construction cost, resulting in smaller lots with little space between the houses. Since the 1980s there has been a trend towards more compact dwellings. Detached houses still dominate, but it has become more common to live in multi-dwelling buildings. There has been an increased focus on energy efficiency and on proper indoor climate to prevent sick building syndrome (i.e. acute health or discomfort symptoms correlated with the time spent indoors) [1]. The focus on energy efficiency is visible in, for example, the adaption of building codes to improve the thermal properties of the building envelope, in the use of energy saving strategies (e.g. passive solar energy, heat recovery, heat pumps) and in reducing the heated floor area per person.

In February 2020, Norway counted 4.2 million buildings, of which 37% were residential buildings and 63% non-residential buildings. *Figure 4.1* shows the division of different building typologies based on the total number of buildings with residential buildings marked in blue. Within the group of residential buildings, detached houses were most common (75%), followed by rowhouses (11%) and semi-detached houses (11%). Multi-dwelling buildings represented 3% of the number of residential buildings and community residences 1%.

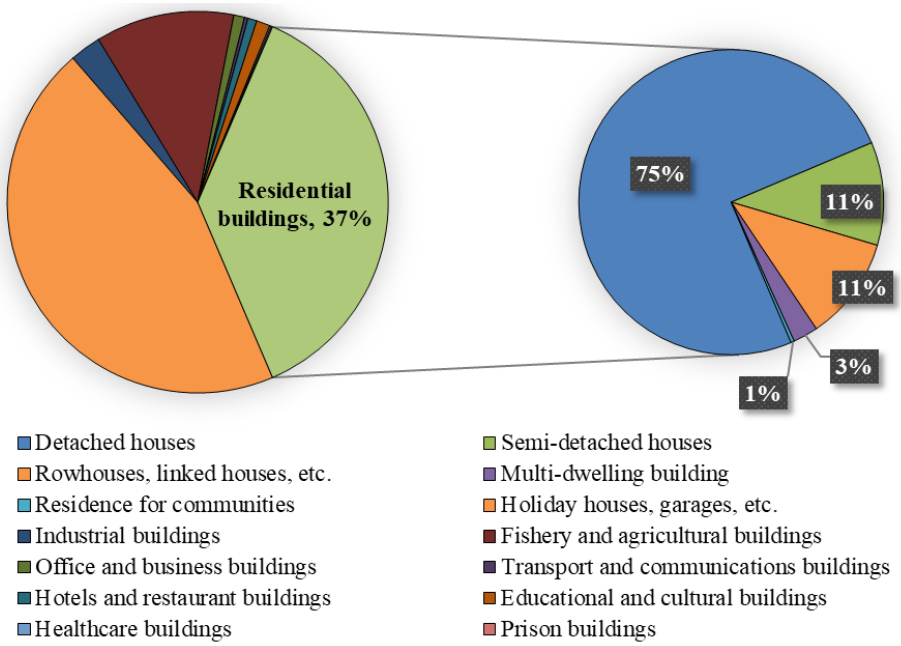


FIGURE **4.1.** Number of buildings in Norway, February 2020 [57, 58].

Figure 4.2 shows the number of houses built in each decade, divided by housing typology. As mentioned, detached houses dominate the residential building stock. However, the figure clearly shows a decrease in number of detached houses after 1990. The number of multi-dwelling buildings has increased since 2000. Overall, the number of new residential buildings has significantly decreased from the 1990s until today.

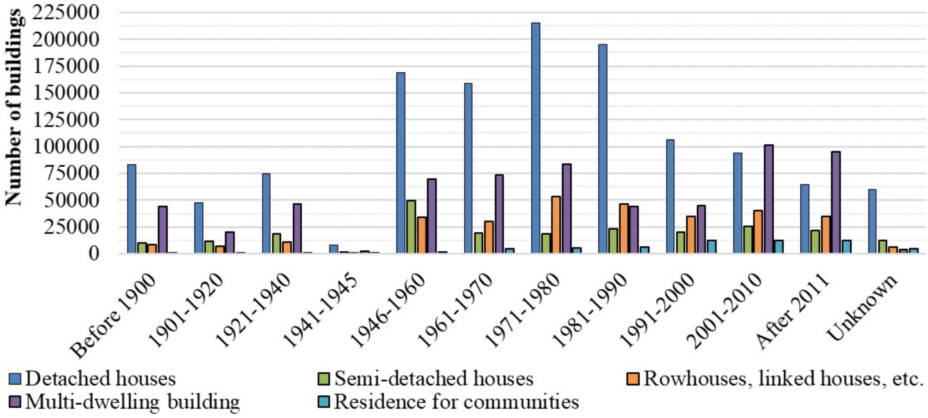


FIGURE 4.2. Number of houses divided by built year and housing typology [59].

Residential buildings can vary greatly in size and the number of buildings might not give a realistic impression of the built area. *Figure 4.3* shows the estimated total floor area for each residential building type. These numbers are estimated, as the statistics only give the number of dwellings within a floor area range (e.g. 40–49 m^2 or 200–249 m^2) [60]. For each floor area range, the average floor area was multiplied with the number of dwellings in this group. Dwellings with an unknown floor area were left out of the estimation. In terms of floor area, detached houses represented the largest group with 65%. Multi-family buildings, such as apartment blocks, represented with 15% the second largest group.

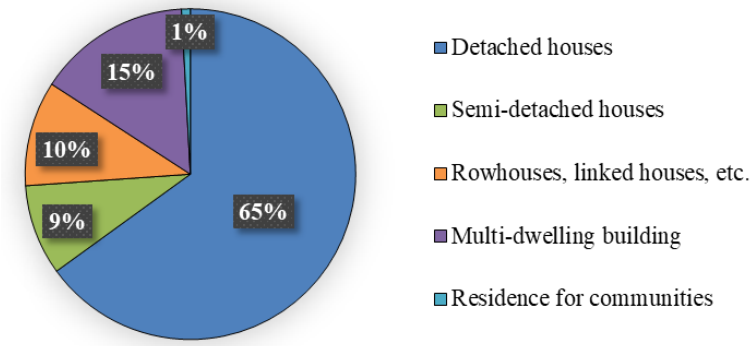


FIGURE 4.3. Estimated total floor area of the residential building stock [60].

4.2 Energy Consumption

In 2018, Norwegian households accounted for 11% of the total energy consumption and 32% of the electricity consumption [61], see *Figure 4.4*. Electricity in Norway is mainly produced in hydropower plants, which makes it possible to have low prices for electricity. Therefore, it is often used as the main energy source for space heating in households. Secondary sources of space heating are biofuels, such as wood, and oil products. However, from 2020 it is no longer allowed to use oil products for space heating, so it is expected that this share (5%) will decrease. Households accounted for 47% of the biofuel consumption [61] and biofuels covered around 16% of the national energy consumption for households [62].

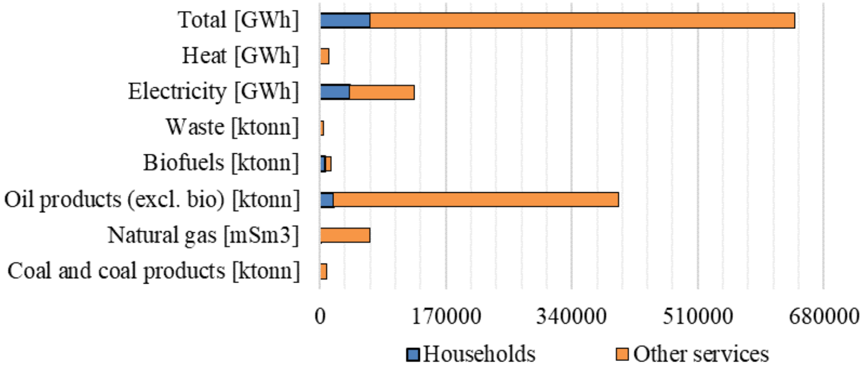


FIGURE 4.4. Total energy consumption and energy consumption per energy carrier in Norway, for households and other services [61].

Figure 4.5 shows the estimated energy use for dwellings. Statistics Norway gives the energy consumption in kWh/m^2 for each built year [63] and for the housing typology [64]. These statistics were combined with the estimated total floor area to calculate a weighted average energy consumption for each housing type in kWh/m^2 year, which is shown in the figure. First the average energy consumption per built year [63] was multiplied with a weighing factor for building typology (detached houses=1.07, semi-detached and row houses=0.97, multi-dwelling buildings=0.84 and other typologies=1.0), based on statistics [64]. This resulted in an average energy consumption for each housing typology and for each category of built year (see the bar chart on the right in *Figure 4.5*). These values were multiplied with a weighing factor representing the percentage of buildings typologies in each built year to take into account that there are more older buildings, and that older buildings are less energy-efficient. The estimated weighted average energy consumption for detached houses was 196.8 kWh/m^2; 179.3 kWh/m^2 for semi-detached houses; 175.8 kWh/m^2 for rowhouses; 153.9 kWh/m^2 for multi-dwelling buildings; and 177.9 kWh/m^2 for community residences. These values were multiplied with the total estimated floor area (see *Figure 4.3*) to give an estimate of the total energy consumption for each housing typology (see the pie chart on the left of *Figure 4.5*).

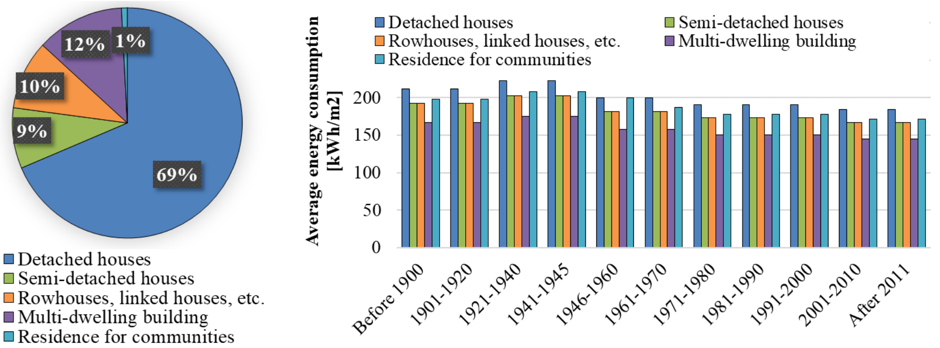


FIGURE 4.5. Estimated share of the total residential energy consumption per housing typology (left) and estimated average energy consumption divided by built year (right) [63, 64].

Figure 4.5 clearly shows a decrease in energy consumption for newer buildings. The built period with the highest energy consumption was 1921–1946. From this period to today, the energy consumption decreased by 17% for all building typologies. Detached houses had the highest energy consumption per heated floor area, while multi-dwelling buildings had the lowest average. Semi-detached houses, rowhouses and community dwellings had similar energy consumption to each other. This can be explained by the exterior surface area in relation to the heated floor area, i.e. the volume-to-surface ratio. With a higher volume-to-surface ratio (e.g. more compact buildings and non-detached buildings) the energy consumption per heated floor area is typically lower, due to less heat losses through the building envelope.

Based on these results, it was decided that two building typologies were of interest for further investigation: detached houses and multi-dwelling buildings. Detached houses represented the largest floor area and largest energy consumption of all residential buildings and retrofitting this group is essential for improving the energy efficiency of the (residential) building stock. Multi-dwelling buildings are of interest as they represented the second largest group based on floor area. It was chosen to focus on these cases built in the period 1971–1980 as there was a peak in number of buildings, and buildings from this period had a high energy consumption.

4.3 Retrofitting Status

A Norwegian study estimated that 70% of the the building stock in 2050 is already built [8]. This included demolition and new construction rates of buildings. This means that the largest share of the future building stock is already built. A European study concluded that existing buildings have the most substantial energy saving potential [7], as currently 75% of the building stock is inefficient. Residential buildings represent 75% of the total heated floor area in Europe [2] and around 60% of the heated floor area in Norway [8]. The existing building stock in Norway can be divided into three equally large groups. The first group is maintained well and is in a good or acceptable condition. The buildings in the second group are only partly satisfactory and therefore require upgrading of some of the building elements. The last group of buildings has a poor condition and requires deep retrofitting. Retrofitting the existing building stock to increase energy efficiency, specifically in the residential sector, is therefore a key element towards a more energy-efficient building stock.

There are three drivers that are vital for improving the energy efficiency of the residential building stock: regulations, finances and knowledge and awareness [7]. Investments in energy efficiency measures, including retrofitting, highly depend on policies and regulations and the enforcement of these [7, 65, 66], which is done on a national level. Norway does not have adjusted energy performance requirements for renovation projects, which can be challenging for those projects. Another challenge is the cost related to retrofitting. There is often a large investment and the project can have a long pay-back time. The potential energy savings from retrofitting are strongly linked to the investor's financial capacity, priorities and preferences, expected pay-back time and financial support in the form of subsidies [2, 7]. The retrofitting design can be costly, as there is no one-fits-all solution for buildings. The state of each building needs to be assessed so that possible structural and moisture issues can be taken into account. When assessing the profitability, energy savings and increased market values should also be taken into account, though the latter is difficult to predict on long-term. Cost are often the main decision-making criteria in retrofitting projects. Therefore, it is essential that retrofitting is cost-effective. Many studies took this into account, as can be seen in *Table 4.1*. The lack of knowledge and awareness of the investor and engineer is also linked to the energy saving potential of retrofitting measures [2, 7, 67]. Selecting retrofitting measures can be a complex process. It can be challenging to find the right information and it is time consuming to assess every possibility. As a result, decisions are often based on investment cost and previous experiences, which can result in not-optimal and outdated measures. Therefore, it is essential that information is readily available and easy to understand.

TABLE 4.1. Overview of residential case studies, built before 1990, that evaluated the potential energy savings of retrofitting [9]. The topics that were evaluated in the study are marked with *x*. Topics that were only partly explored (e.g. only one option is considered) are marked with *(x)*.

Case study typology	**Envelope retrofitting**	**HVAC or energy systems retrofitting**	**Economic assessment**	**Indoor comfort assessment**	**Country**	
Single-family house	x	x	x	–	Estonia	[68]
	(x)	(x)	–	–	Norway	[69]
	(x)	(x)	–	–	Norway	[17]
	(x)	(x)	–	–	Norway	[70]

Continues on the next page.

Table 4.1. (continued)

Case study typology	Envelope retrofitting	HVAC or energy systems retrofitting	Economic assessment	Indoor comfort assessment	Country	
	(x)	x	x	–	Sweden	[71]
	(x)	x	x	–	Sweden	[72]
Single- and multi-family house	x	x	x	–	Estonia	[73]
	x	x	x	–	Estonia	[14]
	x	x	x	–	Finland	[74]
	(x)	(x)	–	–	Sweden	[75]
	(x)	(x)	x	–	Sweden	[76]
Multi-family house	x	x	x	–	Estonia	[12]
	(x)	(x)	–	x	Estonia	[77]
	x	x	x	–	Estonia	[13]
	(x)	(x)	x	–	Estonia	[14]
	x	x	x	–	Estonia	[78]
	(x)	(x)	x	x	Estonia	[79]
	–	x	–	x	Finland	[80]
	x	x	x	–	Finland	[35]
	(x)	(x)	x	–	Finland	[81]
	x	x	x	–	Finland	[82]
	x	x	x	–	Finland	[15]
	x	x	x	–	Finland	[83]
	x	x	–	–	Finland	[84]
	(x)	(x)	–	–	Norway	[85]
	(x)	(x)	–	–	Norway	[69]
	x	x	–	–	Norway	[18]
	x	–	x	–	Sweden	[86]
	x	(x)	x	–	Sweden	[87]
	x	–	x	(x)	Sweden	[88]
	(x)	(x)	–	x	Sweden	[89]
	(x)	(x)	–	x	Sweden	[90]
	(x)	–	x	–	Sweden	[34]
	x	x	x	–	Sweden	[91]
	(x)	(x)	–	x	Sweden	[16]

The literature review (paper A) investigated typical retrofitting measures for residential buildings in cold climates. *Table 4.1* gives an overview of residential case studies in cold climates that estimated significant energy savings from retrofitting. Most studies focused on envelope retrofitting and retrofitting of HVAC systems and/or energy systems. Many studies also took into account cost-effectiveness of retrofitting measures. Only few studies assessed the effect of retrofitting on the indoor comfort. From the literature, it was concluded that the potential energy savings from retrofitting are case specific and should be assessed individually. However, there is a consensus that in cold climates, retrofitting the building envelope has the largest impact on the energy consumption. Savings ranging between 20% and 70% were reported for retrofitting housing in cold climates [12–18]. Improving the system efficiency of HVAC and energy systems also significantly impacted the energy consumption and could reduce the delivered energy to the building, for example when energy was generated on-site. BACS also reduced the energy consumption of residential buildings. In some cases, implementing BACS improved the energy label of the building by one class [26–30]. However, these studies did not include case studies in cold climates.

4.4 Short Conclusions

The following was concluded from this analysis:

- Residential buildings accounted for 11% of the total energy consumption and 32% of the electricity consumption in Norway.
- Detached single-family houses accounted for the most heated floor area, and had the highest average energy consumption per heated floor area.
- Multi-dwelling buildings accounted for the second most heated floor area, and had the lowest average energy consumption per heated floor area.
- There is a large energy saving potential for retrofitting residential buildings.
- Literature on retrofitting of residential buildings focused mostly on building envelope retrofitting and retrofitting of energy systems. Only few studies assessed the impact of BACS as a retrofitting measure.
- The demand for improving the energy efficiency is strongly influenced by regulations, finances and knowledge and awareness.

5 | Building Energy Performance Models

This chapter explains the modelling assumptions and inputs. It also answers research question 2: *How can an energy performance simulation model of a reference building be defined, created and validated?*. These questions were included in papers B and C.

5.1 Case Study Buildings

The case study buildings were selected based on the dominating building types in the Norwegian residential building stock. The analysis of the building stock in *Section § 4.1* showed that single-family houses and apartment blocks were most often built in the period 1960s to 1990s, with a peak in the period 1971–1980. *Figure 5.1* and *Figure 5.2* illustrate how the two selected case studies typically look. There are many variations on this typology, but the construction and energy performance characteristics are the same. These are described in *Sections § 5.2*, *§ 6.1* and *§ 6.2*.

FIGURE 5.1. Examples of a typical single-family house.

FIGURE 5.2. Examples of a typical apartment block.

5.1.1 Single-Family House

The single-family house has two floors and was designed to be placed on sloped terrain. Because of this, the lower floor is partially submerged in the terrain. Half of the lower floor can be separated from the main house and converted into a rental unit. *Figure 5.3* shows the floor plan of the house. On the lower floor, there is a bedroom, living room and bathroom as well as a laundry room and storage. The upper floor has three bedrooms, the main living room, a kitchen, bathroom and separate toilet. This housing type can have various orientations and is adjusted to the slope of the hill. In this case, the house has a east-west orientation with the living rooms facing west.

Basement floor

Top floor

FIGURE 5.3. Floor plans of a typical single-family house.

The external walls of the partly submerged floor, further referred to as basement walls, are typically constructed of LECA blocks. These blocks are made of expanded clay and have a lower thermal conductivity than concrete. There is often no insulation added to these walls, as the LECA blocks could fulfill the energy performance requirements for basement walls, even though not all walls are below ground. The external walls on the upper floor are timber frame walls with 10 cm mineral wool. The house has a cold loft with 15 cm insulation in the ceiling. The ground floor is a concrete slab on grade with no or very little insulation. *Figure 5.4* shows a section of the house from east to west. The vapour barrier (red), wind barrier (blue) and existing thermal insulation (yellow) are marked. The basement walls are plastered and this layer functions as a wind barrier. There are thermal bridges in the joint between the exterior walls, floor and basement walls. Windows are typically poorly insulated and not correctly installed, causing thermal bridges and air leakage.

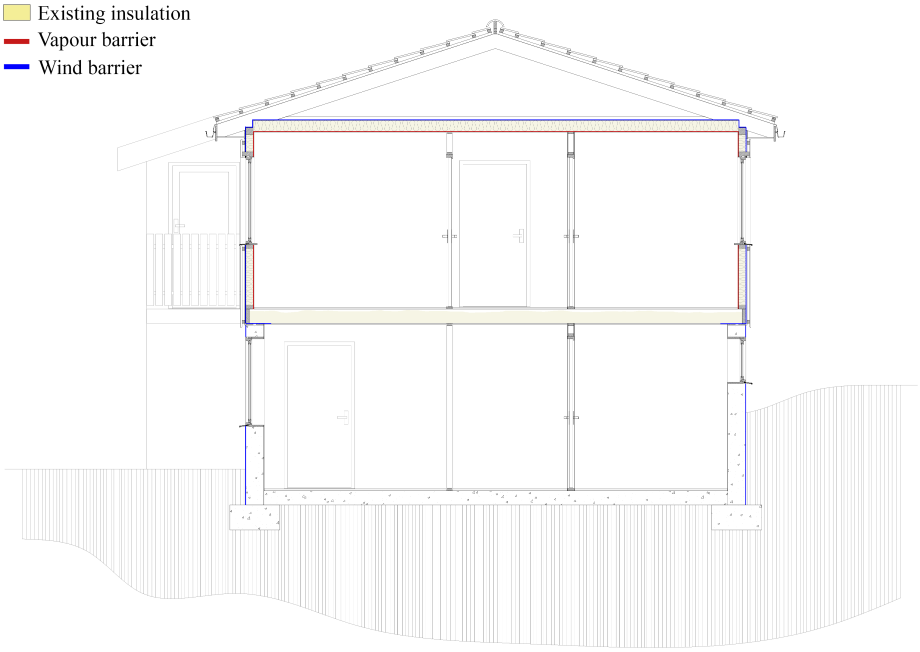


FIGURE 5.4. Section of a typical single-family house with the insulation layer, wind barrier and vapour barrier marked.

5.1.2 Apartment Block

The apartment block typically has four floors with a modular floor plan. Often there is a basement with storage units. The apartments in the middle span the whole depth of the building, while the corner apartments span half the depth of the building. The corner apartments are one-bedroom apartments and the middle apartments have two or three bedrooms. Each staircase provides entrance to two apartments (or three in case of the corner apartments) per floor. Because of the modular floor plan, this apartment block typology can have varying lengths and orientations. Most often the balconies face south or west. The modelled block has 12 apartments per floor, of which two representative apartments on the top floor were modelled, surrounded by a building body that represented the rest of the building. These were a corner apartment, with south-east orientation, and one of the middle apartments, with east-west orientation (see *Figure 5.5*). This was done to reduce the computational time, which significantly increased due to the implementation of advanced room control strategies. The apartments were selected based on an analysis of the heating and cooling demand, that showed that those apartments had the highest envelope heat losses and highest solar heat gains. It can be assumed that the other apartments will have a better performance in terms of energy and thermal comfort.

FIGURE 5.5. Floor plans of a typical apartment block with the two representative apartments marked in green (corner apartment) and blue (middle apartment).

The external walls on the long side are timber frame walls with 10 cm insulation. The external walls on the short side are load-bearing concrete walls with 10 cm insulation. Load-bearing concrete walls are also placed around the staircases and between the apartments and protrude beyond the envelope to support the balconies, causing large thermal bridges. The roof construction is concrete with 10 cm hard insulation. The floor is a concrete slab on grade with sometimes 10 cm hard insulation and sometimes no insulation. *Figure 5.6* shows a section through the building from east to west. The vapour barrier (red), wind barrier (blue) and existing thermal insulation (yellow) are marked. There are clear thermal bridges at the joints between the exterior walls and the floors and the exterior walls and roof. Windows are typically poorly insulated and not correctly installed, causing thermal bridges and air leakage.

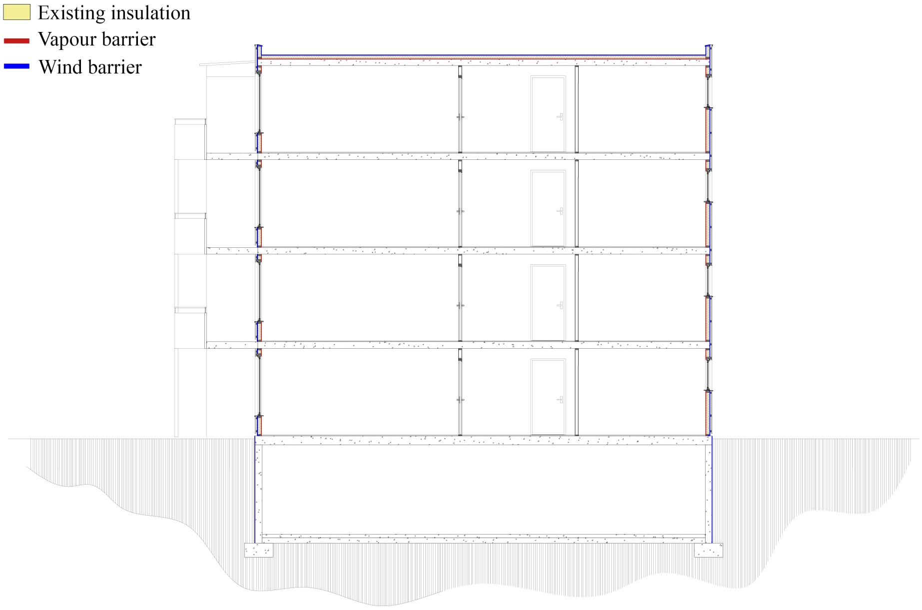


FIGURE 5.6. Section of a typical apartment block with the insulation layer, wind barrier and vapour barrier marked.

5.2 Modelling inputs and outputs

Figure 5.7 illustrates the modelling inputs and outputs of this study with their relevant parameters. Post-processing inputs and outputs are not included in this figure. The parameters are described in more detail in the sections that follow.

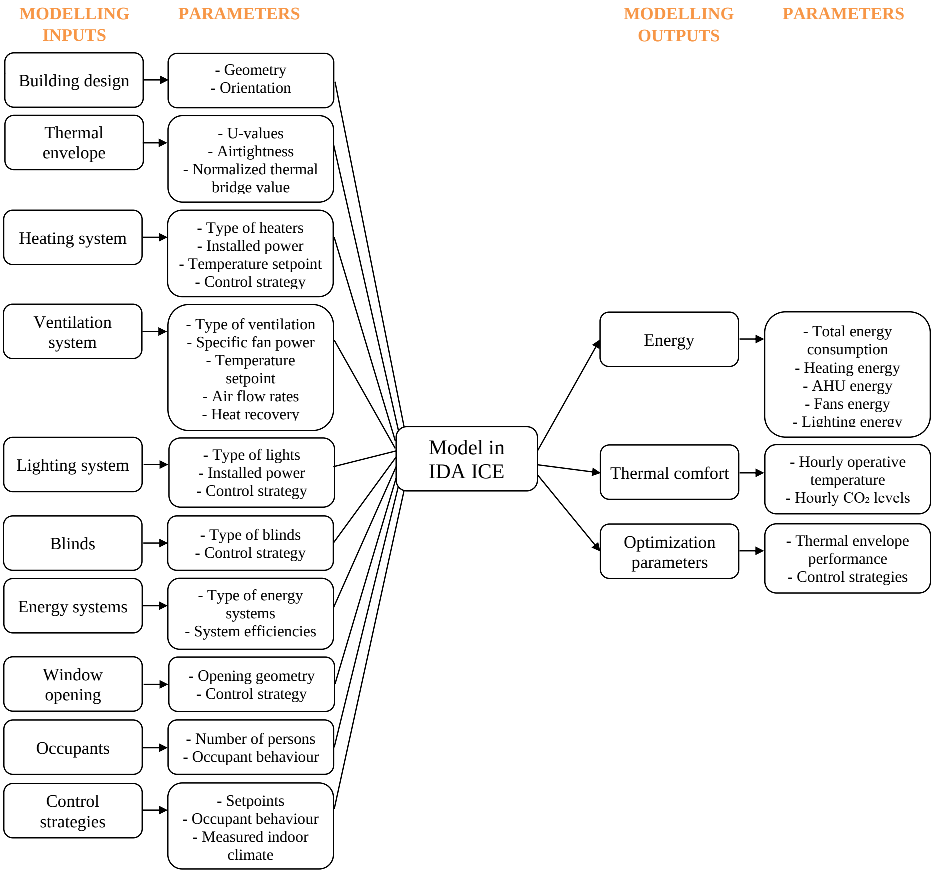


FIGURE 5.7. Modelling inputs and outputs with their relevant parameters.

5.2.1 Thermal envelope performance

Table 5.1 shows the assumed energy performance characteristics of houses built after 1969. These were based on typical values. When no typical values were given, the values from the regulations on technical requirements for buildings and constructions of 1969 [92] or recommended input values given in NS 3031 [49] were used. The U-values for external walls, roof and floors was taken from a study that analyzed the energy use of the Norwegian residential building stock [50]. This study presented energy performance characteristics for typical housing typologies and depending on their built year. The minimum requirement for walls below the ground in the building code valid from 1969–1985 was used [92]. For the U-values for windows and doors, airtightness and normalized thermal bridge value, recommended simulation input values were used [49]. NS 3031 gives typical values for different building types and built year.

Infiltration, using the value for airtightness in air changes per hour, was added as wind driven infiltration with pressure coefficients for a sheltered building. The pressure coefficients are automatically generated in IDA ICE. Leaks are automatically introduced in each external wall in IDA ICE and were distributed proportional to the external surface area. Internal leaks were introduced between the zones through leak areas in the doors. This method, as opposed to using fixed infiltration flows, is more realistic when unbalanced mechanical ventilation is used, such as in the not retrofitted cases.

The normalized thermal bridge value was modelled as a overall value for the total envelope (including roof and ground) measured on the internal side of the envelope.

TABLE 5.1. Overview of used modelling input parameters before retrofitting.

Modelling input	**Parameter**	**Single-family house**	**Middle apartment**	**Corner apartment**
Building design	Heated floor area	173.0 m^2	84.7 m^2	53.4 m^2
	Building volume	430.0 m^3	225.4 m^3	142.0 m^3
	External wall area	161.6 m^2	22.4 m^2	28.32 m^2
	Roof area	98.8 m^2	84.7 m^2	53.4 m^2
	Ground floor area	91.0 m^2	–	–
	Window and door area	33.8 m^2	17.1 m^2	11.5 m^2
Thermal envelope performance	U-value external walls	0.38 W/m^2K	0.38 W/m^2K	0.38 W/m^2K
	U-value basement walls	0.81 W/m^2K	–	–
	U-value roof	0.20 W/m^2K	0.20 W/m^2K	0.20 W/m^2K
	U-value ground floor	0.36 W/m^2K	–	–
	U-value external windows	2.8 W/m^2K	2.8 W/m^2K	2.8 W/m^2K
	Airtightness	4.0 h^{-1}	4.0 h^{-1}	4.0 h^{-1}
	Normalized thermal bridge value	0.07 W/m^2K	0.13 W/m^2K	0.13 W/m^2K
Occupants	Number of occupants	5	3	2
		For all housing typologies		
Heating system	Type of heaters	Electric heaters		
	Installed power	See *Table 5.3*		
	Temperature setpoint	22°C		
	Control strategy	No automatic control		
Ventilation system	Type of ventilation	Mechanical exhaust ventilation		
	Specific fan power	2.0 kW/m^3s		
	Temperature setpoint	No mechanical supply air		
	Air flow rates	See *Table 5.4*		
	Heat recovery	No heat recovery		

Continues on the next page.

TABLE 5.1. (continued)

Modelling input	**Parameter**	**For all housing typologies**
	Control strategy	No automatic control
Lighting system	Type of lights	Halogen lights
	Installed power	See *Table 5.3*
	Control strategy	No automatic control
Blinds	Type of blinds	External blinds
	Control strategy	No automatic control
Energy systems	Type of energy systems	Electricity
Window opening	Opening geometry	10% of the window area
	Control strategy	No automatic control
Occupants	Occupant behavior	Depending on the room function, see *Figure 5.8*
Control strategies	Setpoints	See *§ 6.1* and *§ 6.2*
	Occupant behavior	Depending on the room function, see *Figure 5.8*
	Measured indoor climate	Measured in the model

After retrofitting

The energy performance characteristics after retrofitting are summarized in *Table 5.2*. In some retrofitting cases, different parameters were used than those listed in the table. When this was the case, the assumed values are described (see *Chapter 6* and *Chapter 7*).

TABLE 5.2. Overview of used modelling input parameters before retrofitting.

Modelling input	**Parameter**	**Single-family house**	**Middle apartment**	**Corner apartment**
Building design	All parameters	See *Table 5.1*		
Thermal envelope performance	U-value external walls	≤ 0.22 W/m^{2}K	≤ 0.22 W/m^{2}K	≤ 0.22 W/m^{2}K
	U-value basement walls	≤ 0.22 W/m^{2}K	–	–
	U-value roof	≤ 0.18 W/m^{2}K	≤ 0.18 W/m^{2}K	≤ 0.18 W/m^{2}K
	U-value ground floor	≤ 0.18 W/m^{2}K	–	–
	U-value external windows	≤ 1.2 W/m^{2}K	≤ 1.2 W/m^{2}K	≤ 1.2 W/m^{2}K
	Airtightness	≤ 1.0 h^{-1}	≤ 1.0 h^{-1}	≤ 1.0 h^{-1}

Continues on the next page.

Table 5.2. (continued)

Modelling input	**Parameter**	**For all housing typologies**		
	Normalized thermal bridge value	≤ 0.05 W/m^{2}K	≤ 0.07 W/m^{2}K	≤ 0.07 W/m^{2}K
Occupants	Number of occupants	5	3	2
Heating system	Type of heaters	Electric heaters (with ASHP)		
	Installed power	See *Table 5.3*		
	Temperature setpoint	Depending on BACS strategy		
	Control strategy	See *Table 5.8* and *Table 5.10*		
Ventilation system	Type of ventilation	Balanced ventilation		
	Specific fan power	1.5 kW/m^{3}s		
	Temperature setpoint	Depending on BACS strategy		
	Air flow rates	See *Table 5.4*		
	Heat recovery	80 %		
	Control strategy	See *Table 5.8* and *Table 5.10*		
Lighting system	Type of lights	Halogen lights		
	Installed power	See *Table 5.3*		
	Control strategy	See *Table 5.8* and *Table 5.10*		
Blinds	Type of blinds	External blinds		
	Control strategy	See *Table 5.8* and *Table 5.10*		
Energy systems	Type of energy systems	Electricity		
Window opening	Opening geometry	10% of the window area		
	Control strategy	See *Table 5.8* and *Table 5.10*		
Occupants	Occupant behavior	Depending on the room function, see *Figure 5.8*		
Control strategies	Setpoints	See *§ 6.1* and *§ 6.2*		
	Occupant behavior	Depending on the room function, see *Figure 5.8*		
	Measured indoor climate	Measured in the model		

5.2.2 HVAC and energy systems

It was assumed that the single-family house and the apartments used the same HVAC and energy systems. Space heating was provided by direct electric heaters that were located in all rooms, except storage rooms. They were sized to the heating demand of each room before retrofitting and the reheating capacity needed to heat rooms from night to day setpoint was taken into account. *Table 5.3* shows installed space heating power as well as the installed lighting power for each room.

Fresh air was originally provided through natural ventilation, assisted by mechanical exhaust ventilation in the bathrooms, laundry room and kitchen. The return air flow rates before retrofitting are listed in *Table 5.4*. The value for the specific fan power (SFP) given in *Table 5.1* was taken from NS 3031 [49]. This is the recommended value for SFP for residential buildings built in the period 1969–1985.

There were no active cooling systems, as this is unusual for residential buildings in cold climates. Natural cooling was provided through opening of windows. Domestic hot water was heated with an electric boiler.

After retrofitting

The same heating system and sizing was used, though it was assumed that the heaters were upgraded to smart heaters connected to an energy management system. In some cases, an air-source heat pump (ASHP) was installed in the living room. The ASHP had a COP of 4.6 and a heating capacity of 6.5 kW. The heat pump was modelled using a standard air to air, non-ducted, heat pump object in IDA ICE. This predefined object was used as heat pump modelling was outside the scope of the study. The inputs required with this heat pump object were the COP and total heating capacity. Temperature control was adjusted to fit the control strategies in the four BACS classes. The variable heating setpoints according to the control strategies for heating were used to control the volume flow control signal.

As the airtightness of the building increased, natural ventilation could no longer provide enough fresh air. Therefore, a balanced ventilation system with 80% heat recovery was installed. The supply and return flow rates are listed in *Table 5.4*. The ventilation air flow rates were taken from TEK17 (see Section *§ 2.7.2*). There was no supply or return air flow in the halls, storage and stairs. The maximum flow rates were used for cases with constant air volume (CAV). The ventilation system was modelled using a standard air handling unit (balanced) in IDA ICE. Critical parameters were adapted and control strategies for supply air temperature setpoints corresponding to those defined in each BACS class were added. The heat recovery unit is a standard object in IDA ICE where prevention of frost formation is taken into account in all control strategies. This object does not have a dedicated overheating prevention, but the heat recovery unit tries to meet the temperature setpoint for the supply air. In this way, the maximum temperature after the heat recovery unit is limited.

There was no change to cooling systems and domestic hot water systems after retrofitting.

Table 5.3. Installed lighting and space heating power for the two case study buildings (before and after retrofitting).

Room function	Room code[1]	Area [m^2]	Lighting [W]	Heating [W]
Kitchens	SF-U-K-E	8.5	46	1000
	AP-C-K-S	6.6	46	800
	AP-M-K-W	– [2]	–	–
Living rooms	SF-U-LR-W	37.4	– [3]	3800
	SF-L-LR-WE	40.3	– [3]	3500
	AP-C-LR-E	22.6	– [3]	800
	AP-M-LR-W	33.0	– [3]	1200
Bedrooms	SF-U-BE-WE	20.4	2 x 46	2000
	SF-U-BE-E	9.1	46	1000
	SF-L-BE-W	11.2	46	1000
	AP-C-BE-E	11.2	46	1200
	AP-M-BE-E	35.1	3 x 46	3000
Bathrooms	SF-U-BA-E	3.5	46	500
	SF-U-WC-E	1.6	30	250
	SF-L-BA-0	1.9	30	250
	AF-C-BA-0	6.5	46	500
	AP-M-BA-0	9.8	46	500
Laundry	SF-L-LA-E	6.4	46	–
	AP-C-LA-0	– [4]	–	–
	AP-M-LA-0	– [4]	–	–
Halls	SF-U-H-E	7.4	46	500
	SF-L-H-W	4.8	30	250
	AP-C-H-0	6.5	30	500
	AP-M-H-0	7.4	30	500
Stairs	SF-L-ST-0	2.5	30	–
Storage	SF-L-ST-E	19.2	–	–

[1] Room code abbreviations: AP: apartment; SF: single-family house; U: upper floor; L: lower floor; C: corner apartment; M: middle apartment; K: kitchen; LR: living room; BE: bedroom; BA: bathroom; WC: toilet; LA: laundry; H: hall; ST: storage/stairs; S: south-facing windows; W: west-facing windows; N: north-facing windows; E: east-facing windows; 0: no windows;
[2] There was no separate kitchen in the middle apartment. The equipment loads for the kitchen were added to the living room.
[3] The lighting loads for living rooms were calculated using the model developed by Richardson et al. [93] and fit to the standardized yearly lighting load in NS 3031 [49].
[4] There was no separate laundry room in the apartments.

Table 5.4. Ventilation air flow rates (before and after retrofitting).

Room function	**Room code**[1]	**Return air flow rates before retrofitting [L/s m^2]**	**Supply air flow rates after retrofitting [L/s m^2]**		**Return air flow rates after retrofitting [L/s m^2]**	
			Min.	Max.	Min.	Max.
Kitchens	SF-U-K-E	1.17	–	–	0.64	1.17
	AP-C-K-S	1.51	–	–	0.78	1.5
	AP-M-K-W	0.30 [1]	–	–	0.15 [1]	0.3 [1]
Living rooms	SF-U-LR-W	–	0.12	0.33	–	–
	SF-L-LR-WE	–	0.12	0.33	–	–
	AP-C-LR-E	–	0.12	0.33	–	–
	AP-M-LR-W	–	0.12	0.33	–	–
Bedrooms	SF-U-BE-WE	–	0.12	0.8	–	–
	SF-U-BE-E	–	0.12	0.8	–	–
	SF-L-BE-W	–	0.12	0.8	–	–
	AP-C-BE-E	–	0.12	0.8	–	–
	AP-M-BE-E	–	0.12	0.8	–	–
Bathrooms	SF-U-BA-E	4.35	–	–	2.18	4.35
	SF-U-WC-E	6.34	–	–	3.17	6.34
	SF-L-BA-0	7.81	–	–	3.91	7.81
	AF-C-BA-0	2.30	–	–	1.16	2.31
	AP-M-BA-0	1.00	–	–	0.76	1.53
Laundry [2]	SF-L-LA-E	1.57	–	–	0.79	1.57

[1] There was no separate kitchen in the middle apartment. The ventilation loads for the kitchen divided by the floor area of the living room including kitchen.
[2] There was no separate laundry room in the apartments.

5.2.3 Occupancy, Lighting and Equipment Schedules

The operating hours and temperature setpoints significantly impact the energy performance of the building. Typically, normalized schedules and loads for internal gains are used in simulations, taken from NS 3031 [49]. The normalized occupancy schedule assumes an occupant is always present. To evaluate the impact of BACS, occupancy schedules should mimic more realistic behavior. Therefore, typical values for the occupancy schedules and distribution of electrical loads from equipment and lighting were used. The occupancy patterns were derived from dwelling occupancy schedules in a Norwegian study by Nord et al. [94] and adjusted to fit these cases. The patterns were originally step schedules, but were converted to linear schedules to reduce the computational time of the simulations. *Figure 5.8* shows the typical occupancy patterns for bathrooms, bedrooms, living rooms and halls. The kitchen occupancy followed the living room pattern and the laundry room occupancy followed the bathroom pattern. It was assumed that occupants were never present in storage rooms.

The number of occupants was as following: 5 people in the single-family house, 3 people in the middle apartment and 2 people in the corner apartment. The number of occupants was adjusted to each room to represent realistic internal heat gains, e.g. 1 or 2 occupants per bedroom. All occupants had a activity level of 1 met, which is equal to 105 W in IDA ICE. Occupants had a clothing level of 0.85 clo ± 0.25, meaning that clothing levels are automatically adapted between the given limits to obtain comfort.

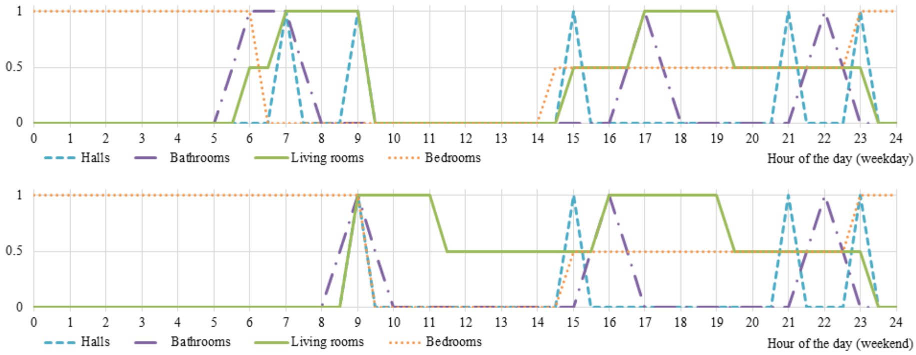


FIGURE 5.8. Occupancy patterns for bathrooms, bedrooms, living rooms and halls on weekdays and weekends.

The lighting loads are presented in *Table 5.3*. The schedules for lighting followed the occupancy patterns presented in *Figure 5.8*, with the living rooms as an exception. The lighting loads and schedules for the living rooms were calculated using an open-source model developed by Richardson et al. [93] (see *Figure 5.9*). This excel sheet simulates data with a one-minute time step based on a combination of active occupancy patterns and daily activity profiles derived from surveys in the United Kingdom. The annual total energy demand for each lighting appliance is based on their annual mean demand, the occupancy pattern, the number of occupants, the time of year, the type of day, and the probability of using that appliance at a given time on the type of day. The location and number of occupants were adjusted to fit the case studies before the simulation was run. This was done for one day in each month of the year to take into account seasonal variations. To simplify the output, it was assumed that the loads were the same within each month. The output was converted to the load in Watt in time steps of 30 minutes. The equipment load in IDA ICE was adjusted so that the yearly energy consumption fit the standardized consumption for lighting [49].

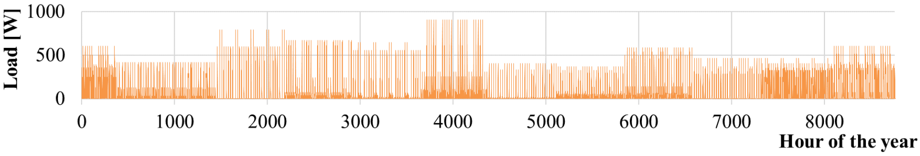


Figure 5.9. Lighting loads for the living room.

Figures 5.10 to *5.14* show the equipment loads used in the simulations. These were calculated using an open-source model by Richardson et al. [95]. This model worked similarly to the model described above. The relevant input parameters were adjusted to represent the case studies. Equipment loads were simulated for each room type, assuming the equipment described in *Table 5.5*. These items correspond to the input possibilities in the open-source model. It was assumed that there was no equipment in the rooms that are not listed. Loads were calculated for one day in each month of the year to take into account seasonal variations. To simplify the output, it was assumed that the loads were the same within each month. The output was converted to the load in Watt in time steps of 30 minutes. The equipment load in IDA ICE was adjusted so that the yearly energy consumption fit the standardized consumption for equipment [49]. The laundry equipment loads for the apartments were added to the bathrooms, as there were no separate laundry rooms.

Table 5.5. Electrical loads per room function.

Room function	Equipment [95]
Kitchens	Freezer, fridge, oven, microwave, kettle, small cooking, dishwasher
Living rooms	Television, TV receiver, HiFi, clock, personal computer
Bedrooms	Clock, cordless phone
Laundry	Iron, vacuum cleaner, washing machine, dryer

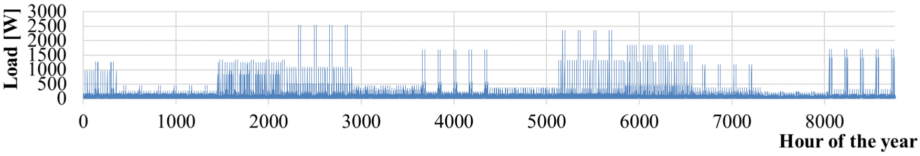


Figure 5.10. Equipment loads for the kitchens in the apartments.

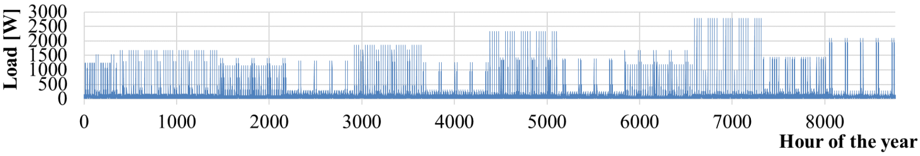


Figure 5.11. Equipment loads for the kitchen in the single-family house.

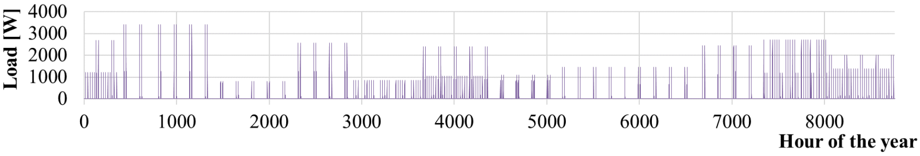


FIGURE 5.12. Equipment loads for the bathrooms (laundry) in the apartments.

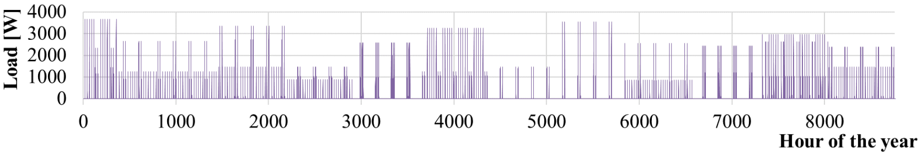


FIGURE 5.13. Equipment loads for the laundry room in the single-family house.

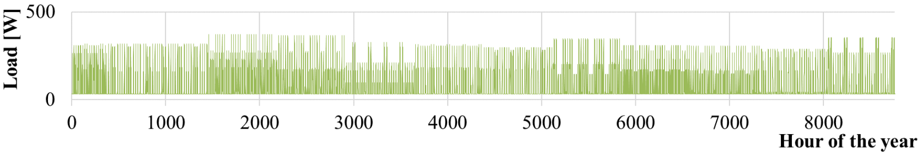


FIGURE 5.14. Equipment loads for the living rooms in the apartments and single-family house.

5.3 Building Performance Modelling and Validation

Two building performance models were created using the descriptions and input parameters given in the previous sections. The following modelling assumptions were made:

- The buildings were modeled in IDA ICE.
- The buildings were located in Trondheim, using the climate of Værnes.
- The buildings were not retrofitted previously, i.e. the energy performance characteristics are typical values from the built period.
- Space heating was provided by individual room heaters using direct electricity.
- There was no active cooling system, as Norwegian houses typically are cooled with natural ventilation.
- Automation of the domestic hot water system was outside the scope.
- Each room function was modelled as an individual zone. Adjacent rooms with the same room function were merged into one zone to decrease the computational time.

- All internal doors were kept closed to maintain different temperatures based on room function and to decrease the computational time. All internal doors had a leak area of 0.01 m^2.
- Typical schedules for occupancy, lighting and equipment were used, adjusted to the standardized yearly loads from NS 3031 (see *Section § 5.2.3*).
- Typical window opening behavior was implemented (see *Section § 5.4.5*) and the openable area of the windows was not variable.

The simulation model of the single-family house with zones is shown in *Figure 5.15*. The simulation model of the apartment building with zones of the two representative apartments is shown in *Figure 5.16*. In both figures, the living room that was used to assess thermal comfort in paper C is marked in dark green. The room codes corresponding with those in *Table 5.3* are written in the zones.

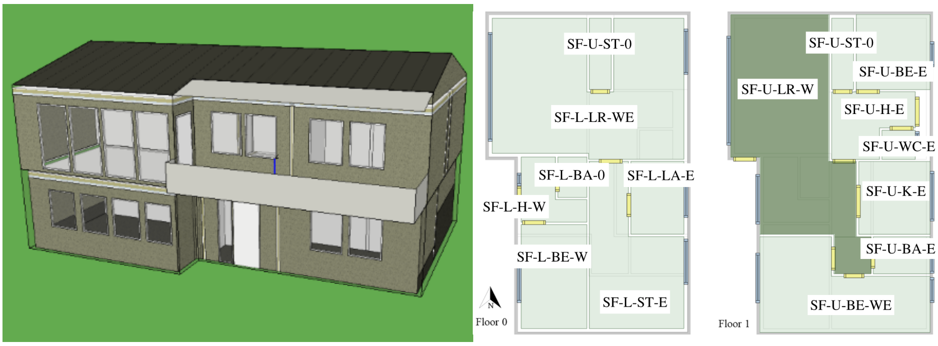


FIGURE 5.15. IDA ICE model (left) and creation of zones (right) for the single-family house with the living room used for thermal comfort assessment marked in dark green

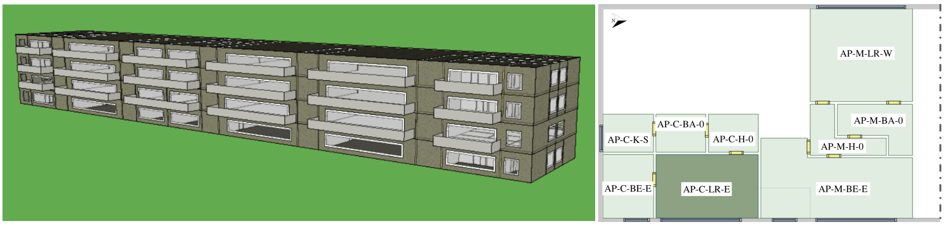


FIGURE 5.16. IDA ICE model (left) and creation of zones (right) for the apartment block with the living room used for thermal comfort assessment marked in dark green.

The simulation models were validated by comparing the energy consumption of the simulation models with standardized input values [49] and typical values [50, 51]. For each case study, two occupancy behavior scenarios were tested: NS 3031 occupancy schedules and internal gains, and typical occupancy schedules and internal gains with window opening behavior. In addition, two space heating sources were tested: direct electricity, and direct electricity in combination with an air source heat pump (ASHP).

The ASHP was installed in the living room (marked in *Figures 5.15* and *5.16* with dark green).

Table 5.6 shows the validation of the single-family house simulation model and *Table 5.7* of the representative apartments simulation model. The energy consumption for domestic hot water (DHW) was the same for all cases, i.e. 25.0 kWh/m^2 year, as control of DHW systems was not considered in this study. For the total energy consumption, two reference values were given: one based on literature describing typical dwellings in Norway [50] and one range of values based on real electricity use. The realistic occupancy patterns were adjusted to fit the normalized values.

The whole apartment block was only simulated with NS 3031 input values and no heat pump and had a total energy consumption of 149.8 kWh/m2 year. This was 8% higher than for the representative apartments. There were no reference values for the space heating energy consumption and HVAC auxiliary energy consumption. However, as the other energy consumption parameters and the total energy consumption were within the ranges of the reference values, it was assumed that the energy use for space heating and HVAC auxiliary was acceptable. As expected, the energy consumption when using NS 3031 input was lower than the average, while the energy consumption when using typical internal gains and window-opening behavior was higher than the average.

TABLE 5.6. Energy consumption of the single-family house model with window opening behavior.

	NS 3031 without ASHP	**NS 3031 with ASHP**	**Realistic without ASHP**	**Realistic with ASHP**	**Reference value**
Space heating [kWh/m^2 year]	118.0	65.0	160.4	95.2	–
HVAC aux [kWh/m^2 year]	7.6	12.6	7.6	13.4	–
Lighting [kWh/m^2 year]	11.4	11.4	11.9	11.9	11.4 [49]
Equipment [kWh/m^2 year]	17.4	17.4	17.7	17.7	17.5 [49]
Lighting and equipment [kWh/year]	4994.6	4994.6	5103.3	5103.3	2500–8000 [51]
Domestic hot water [kWh/m^2 year]	25.0	25.0	25.0	25.0	25.0 [49]
Domestic hot water [kWh/year]	4242.7	4243.2	4245.2	4245.1	2500–5000 [51]
Total energy consumption [kWh/m^2 year]	179.0	131.0	222.1	162.7	225 [50] 62.5–195.4[1]

[1] Average electricity consumption, gathered from published sales reports of houses on *finn.no*. The range only included houses of the correct building typology, built between 1969 and 1987, with an area of 150–250 m^2, located in Norway, and with direct electricity as main heating source.

TABLE 5.7. Energy consumption of the representative apartments model with window opening behavior.

	NS 3031 without ASHP	**NS 3031 with ASHP**	**Realistic without ASHP**	**Realistic with ASHP**	**Reference value**
Space heating [kWh/m^2 year]	76.9	43.4	129.8	96.3	–
HVAC aux [kWh/m^2 year]	7.1	10.3	7.1	10.3	–
Lighting [kWh/m^2 year]	11.5	11.4	11.7	11.7	11.4 [49]
Equipment [kWh/m^2 year]	17.5	17.5	17.7	17.7	17.5 [49]
Lighting and equipment[1] [kWh/year]	4001.1	4001.1	4042.6	4042.6	2500–8000 [51]
Domestic hot water [kWh/m^2 year]	25.0	25.0	25.0	25.0	25.0 [49]
Domestic hot water[1] [kWh/year]	3453.2	3453.2	3453.2	3453.2	2500–5000 [51]
Total energy consumption [kWh/m^2 year]	137.9	107.6	191.1	160.9	165 [50] 102.5–204.9[2]

[1] For two representative apartments, i.e. two households.

[2] Average measured data of electricity consumption in the period 1997–2013, after a retrofitting was carried out. The shown range was an average of apartments on the top floor. The range for the whole building, including all floors was 74–283 kWh/m^2 (on average, excluding communal, areas 157 kWh/m^2 year).

5.4 Custom control strategies - Approach I

It was necessary to create custom control strategies in IDA ICE to evaluate the effect of building automation control strategies on the energy consumption and thermal comfort. The definition of the control strategies was in line with EN 15232 [25]. This standard was interpreted in two different ways. In this section, the first approach is presented (summarized in *Table 5.8*). Window opening is not part of EN 15232, but is included in this section because a custom window opening strategy was created. Two similar approaches were modelled, and the first approach is presented here.

TABLE 5.8. Description of the control strategies used in approach I.

	Heating	Ventilation	Lighting
D	PI control with a constant temperature setpoint	CAV with a constant temperature setpoint	Manual on/off switch
C	PI control with a constant setpoint and adjusted setpoints depending on the room function	VAV following a day-night schedule with an outdoor compensated temperature setpoint	*As class D*
B	PI control with night setback and adjusted setpoints depending on the room function	VAV following a day-night schedule with an outdoor compensated temperature setpoint	Automatic on/off control with a day/night schedule, sweeping extinction signal and automatic off-switch when enough daylight is present
A	PI control with occupancy detection with night setback and adjusted setpoints depending on the room function	VAV based on demand with a temperature setpoint following indoor operative temperature	Automatic control with dimming following a day/night schedule, sweeping extinction signal and automatic off-switch when enough daylight is present and/or when the room is not occupied

5.4.1 Heating control strategies

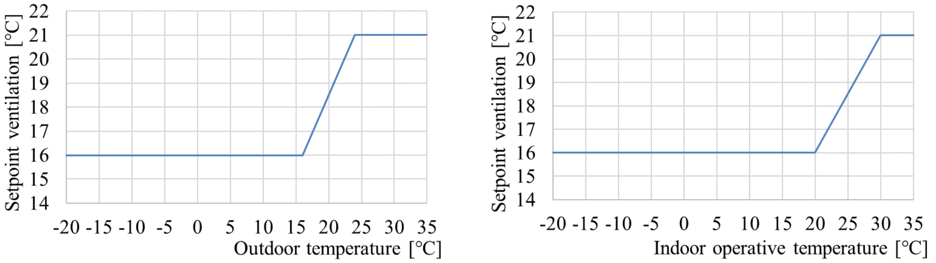
The heaters were controlled with a standard PI controller and a schedule. In class D, the setpoint was constant at 22°C, the normalized value in NS 3031 [49]. In class C, there was a constant setpoint depending on the room function. The room function setpoints were derived from survey data on Norwegian households [96] and are summarized in *Table 5.9*. In class B, there was an additional night setback to 19°C. Night was defined as from 23:00h to 05:00h on weekdays and from 23:00h to 08:00h on weekends. With this schedule, the heaters started reheating the room one hour before occupants were present. In class A, the temperature was set back to 19°C at night and when the room was not occupied.

TABLE 5.9. Heating temperature setpoints for day and night used in approach I [96].

Room function	Constant setpoint	Day setpoint	Night setpoint
Bedrooms	22°C	19.0°C	19°C
Bathrooms	22°C	23.0°C	19°C
Other rooms	22°C	21.5°C	19°C

5.4.2 Ventilation control strategies

The ventilation control strategies were implemented using the standard ventilation controls available in IDA ICE and adjusted values for VAV schedules and supply air temperature. In class D, the temperature setpoint was constant at 18°C. In class C and B, the temperature setpoint was compensated for the outdoor temperature and increased when the outdoor temperature increased. In class A, the temperature setpoint was compensated for the indoor operative temperature and increased when the indoor operative temperature increased. The setpoints are illustrated in *§ 5.4.2*. The ventilation air flow rates are listed in *Table 5.4*.



(A) Class C and B.

(B) Class A.

FIGURE 5.17. Ventilation setpoints.

5.4.3 Lighting control strategies

Class D and C were implemented with a built-in function for lighting control in IDA ICE following a user-defined schedule. The schedules were set to the occupancy schedules for the room function. In class B and A, lighting was controlled based on occupancy and daylight levels. In addition, a sweeping extinction signal (i.e. lights are switched off between 23:00 and 06:00) was introduced. In class B, the lights were switched off when enough daylight (> 200 lux) was present, while in class A the lights were dimmed and ultimately switched off when enough daylight (> 200 lux) was present. Daylight levels were measured in IDA ICE at first occupant level (assumed at 0,6 m above the floor). The occupants were placed in the center of the rooms in the model. The value of 200 lux was chosen as this represents a typical minimum illuminance level in homes. The lighting controls are illustrated by *Figure 5.18*.

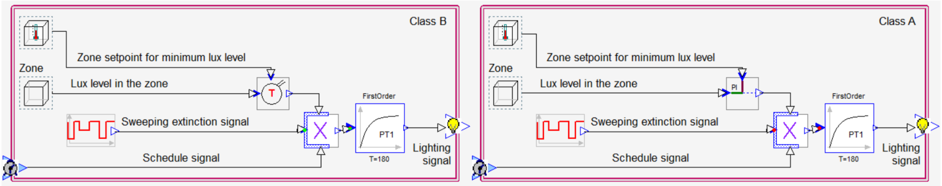


FIGURE 5.18. Control strategies for lighting used in approach I.

5.4.4 Blind control strategies

Blind control was not investigated in this approach. One fixed strategy was used in all cases to mimic typical behavior. It was assumed that blinds are manually put down when an occupant was present in the room and when the indoor temperature exceeded 23.5°C. A time delay of four hours was added, because it was assumed that occupants do not often operate the blinds. This strategy is illustrated in *Figure 5.19*

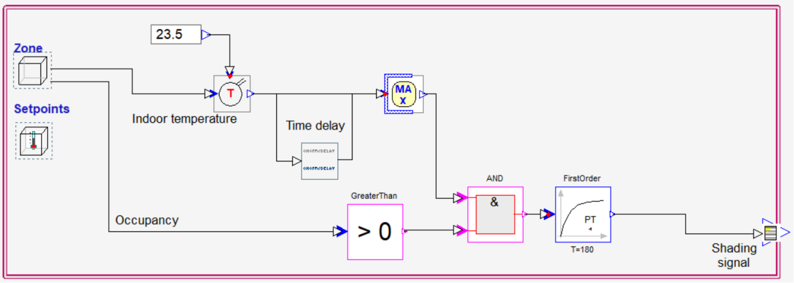


FIGURE 5.19. Fixed control strategy for blinds to mimic realistic behavior used in approach I.

5.4.5 Window opening behavior

The control strategy for window opening mimicked typical opening behavior. Window opening in residential buildings is mainly influenced by two parameters: room temperature and indoor air quality. The window opening strategy was created so that windows open realistically, e.g. when a temperature limit or CO_2 limit is exceeded while an occupant was present in the house. *Figure 5.20* illustrates this approach. The temperature limit for opening the windows was a function of the outdoor running mean temperature and had a deadband of 1°C. The CO_2 limit was set to 1000 ppm and had a deadband of 100 ppm. A time delay of 30 minutes was added, i.e. when a window is opened, it will stay open for 30 minutes and then the situation is re-evaluated. It was assumed that windows could be opened when an occupant was present in the house and that the windows were closed at night. Therefore, an occupancy schedule that represents occupancy in the house was created (see *Figure 5.21*).

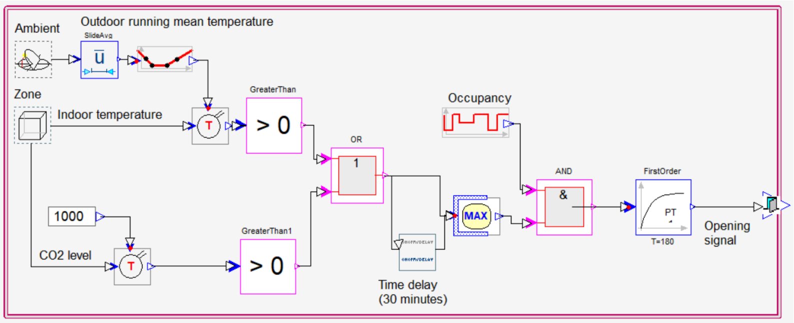


FIGURE 5.20. Control strategy for window opening behavior used in approach I.

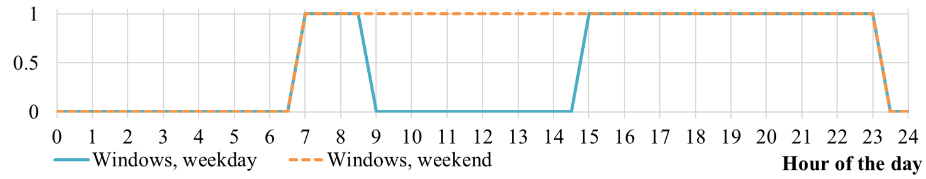


FIGURE 5.21. Occupancy schedule for window opening behavior used in approach I.

5.5 Custom Control Strategies - Approach II

In this section, the second approach of interpreting the description of control strategies in EN 15232 [25] is presented. *Table 5.10* gives an overview of the definitions used to model the control strategies. The second approach to the control strategy for window opening is also presented here.

TABLE 5.10. Description of the control strategies used in approach II.

	Heating	**Ventilation**	**Lighting**	**Blinds**
D	PI control with a constant temperature setpoint	CAV with a constant supply air temperature setpoint	Manual on/off lighting control	Manual control
C	PI control with a variable temperature setpoint depending on room function with night-setback (variable)	VAV with day/night time schedule and a constant supply air temperature setpoint	*As class D*	*As class D*
B	PI control with occupancy detection and a variable temperature setpoint depending on room function with night-setback (variable) and extreme setback when the house is not occupied	VAV with a day/night time schedule and a variable supply air temperature setpoint	Automatic on/off control with a day/night schedule, sweeping extinction signal and automatic off-switch when enough daylight is present	Automatic control based on incoming solar radiation
A	PI control with demand detection and a variable temperature setpoint depending on room function with night-setback (variable) and extreme setback when the zone is not occupied	VAV based on demand and with a variable supply air temperature setpoint with setback for when the house is not occupied	Automatic control with dimming following a day/night schedule, sweeping extinction signal and automatic off-switch when enough daylight is present and/or when the room is not occupied	*As class B*

5.5.1 Heating Control Strategies

The heaters were controlled with a standard PI controller and schedules, similarly to the first approach. Compensation of the setpoint based on outdoor temperature and based on room function was taken into account, see *Figure 5.22*, where class D is represented in the color black, class C in green, class B in purple and class A in brown.

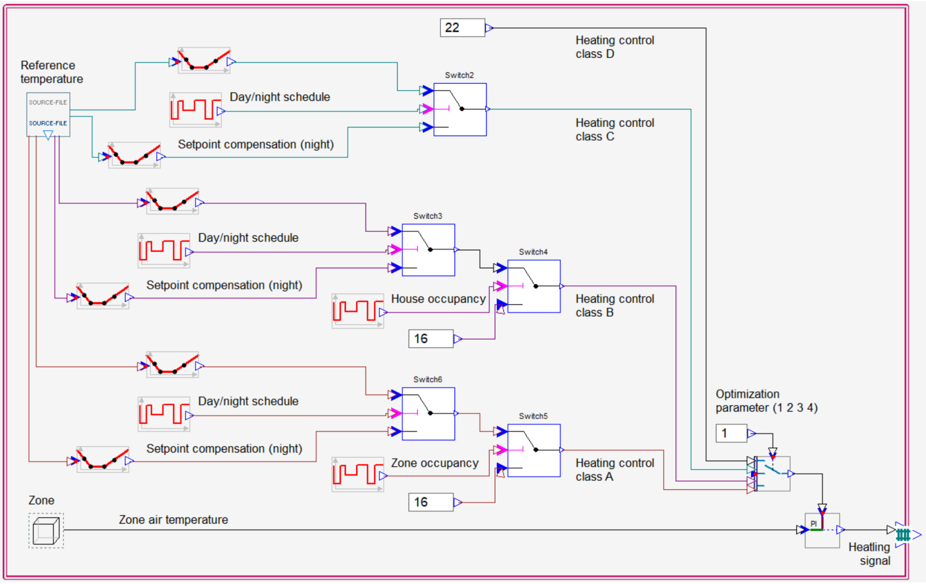


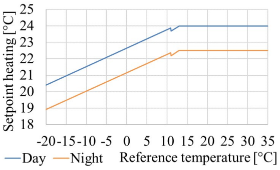
FIGURE 5.22. Control strategies for heating used in approach II.

The constant temperature setpoint in class D was 22°C, the normalized value in NS 3031 [49]. The variable temperature setpoints followed the neutral comfort temperature curves defined by Peeters et al. [45], but flattened out when they reached 22°C (24°C for bathrooms), see *§ 5.5.1*. The night setback temperature setpoints were constant at 19°C in class D, and variable following the 10% PPD lower limit of the adaptive comfort criteria in class C, B and A. Night was defined as from 23:00h to 04:30h on weekdays and from 23:00h to 07:30h on weekends (1.5 hour reheating time). In class B and A, there was occupancy and demand detection, respectively. This was modeled as an extreme temperature setback (16°C) when the house was not occupied (class B) or when the room was not occupied (class A). *Table 5.11* summarizes the adaptive temperature setpoints for the room functions used in strategies C to A. Due to the variation in setpoints depending on room function, three control strategies were created in IDA ICE. These were linked together in a graphical script to ensure that all heaters were controlled following the same BACS class definition.

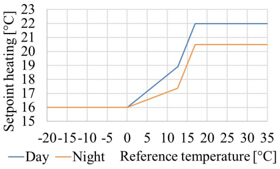
It should be noted that there is no mention of outdoor compensated temperature setpoints in EN 15232. This method was chosen to define variable setpoints so that thermal comfort could be assessed as by the method described by Peeters et al. [45].

Table 5.11. Heating temperature setpoints for day, night and extreme setback used in approach II, derived from adaptive comfort criteria [45].

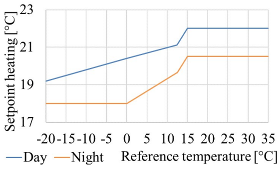
Room function	Day setpoint	Night setpoint
Bedrooms, $T_{set,bed}$	if $T_{ref} < 17$°C then $T_{bed,n}$ °C, else 22°C	$max(16, T_{set,bed} - 1.5)°C$
Bathrooms, $T_{set,bath}$	if $T_{ref} < 13$°C then $T_{bath,n}$ °C, else 24°C	$max(18, T_{set,bath} - 1.5)°C$
Other rooms, $T_{set,other}$	if $T_{ref} < 15$°C then $T_{other,n}$ °C, else 22°C	$max(18, T_{set,other} - 1.5)°C$
Extreme setback, $T_{set,ext}$	16°C	16°C



(A) Heating setpoint for bathrooms.



(B) Heating setpoint for bedrooms.



(C) Heating setpoint for other rooms.

5.5.2 Ventilation Control Strategies

Ventilation control consists of many parameters and was divided into two control strategies: air flow rate control (*Figure 5.24*) and air supply temperature control (*Figure 5.25*). In the figures, class D is represented in the color black, class C in green, class B in purple and class A in brown. These two strategies were linked together in IDA ICE using a graphical script to ensure they would be controlled as the same BACS class. The air flow rate in class D is constant at the required air flow rate for occupied rooms ("maximum"). In class C and B, the air flow rate was reduced to the minimum flow rate when no occupants were present in the house. In class A, the air flow rate was reduced to halfway between the maximum and minimum when the room was not occupied, and to the minimum when there was no occupant present in the house. The maximum and minimum ventilation air flow rates are listed in *Table 5.4*.

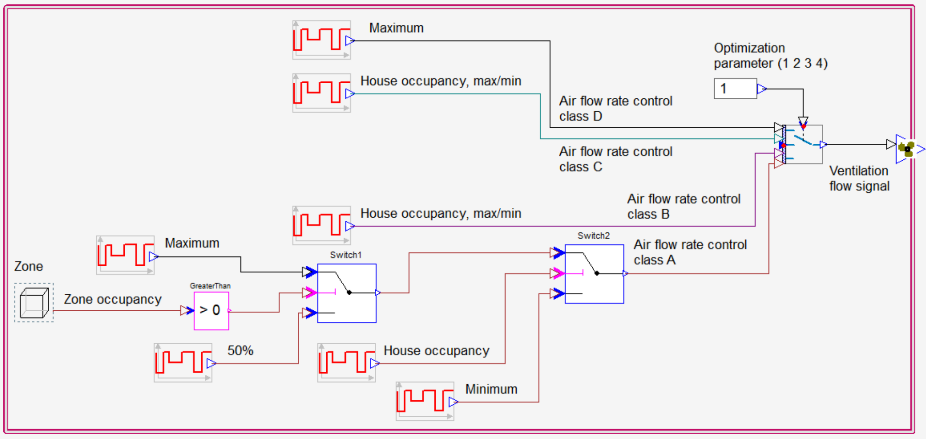


FIGURE 5.24. Control strategies for air flow rate used in approach II.

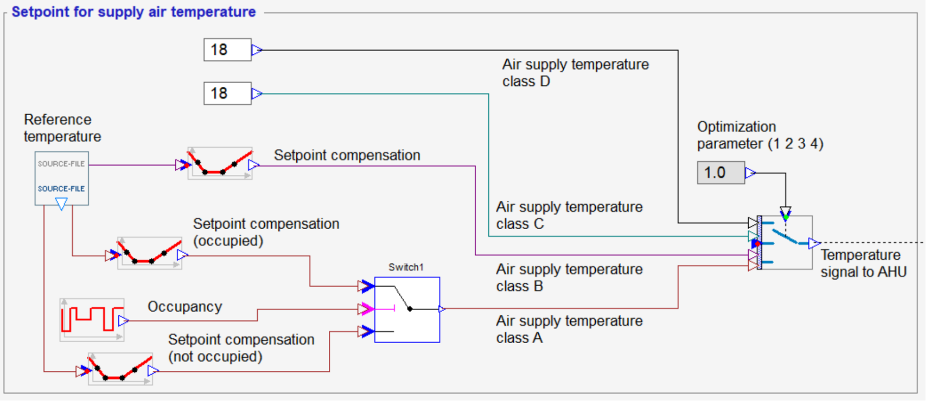


FIGURE 5.25. Control strategies for supply air temperature used in approach II.

The temperature setpoints for the supply air are summarized in *Table 5.12* and illustrated in *Figure 5.26*. In class D and C, the temperature setpoint was constant at 18°C. In class B, the temperature setpoint was compensated for the reference outdoor temperature (see *Equation 2.3*). The adaptive setpoint had the same slope as the heating setpoints between a supply air temperature of 16°C and 18°C. In class A, the setpoint was lowered by 2°C when the house was not occupied. When the house was occupied, the temperature setpoint for the supply air was as in class B.

Table 5.12. Supply air temperature setpoints in the four automation strategies used in approach II.

Strategy	Temperature setpoint	Rule
Class D and C	18°C	–
Class B and A, occupied	16°C	when $T_{ref} < 13°C$
	$0.333 \cdot T_{ref} + 11.667$ °C	when $13°C \leq T_{ref} < 19°C$
	18°C	when $T_{ref} \geq 19°C$
Class A, not occupied	14°C	when $T_{ref} < 13°C$
	$0.333 \cdot T_{ref} + 9.667$ °C	when $13°C \leq T_{ref} < 19°C$
	16°C	when $T_{ref} \geq 19°C$

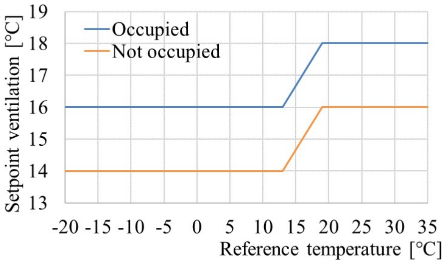


Figure 5.26. Variable ventilation setpoint.

5.5.3 Lighting Control Strategies

These strategies were modeled as illustrated by *Figure 5.27*, where class D and C are shown in green, class B in purple and class A in brown. For manual control in class D and C, a schedule was assumed that follows the occupancy in the room, i.e. the lights were switched on when an occupant was present. In class B, the same schedule was followed, and a sweeping extinction signal was added that switched off all lights between 23:00 and 06:00. In addition, the lights were switched off when the illuminance level exceeded 200 lux. In class A, the lights were switched on and off according to presence of occupants and the lights were dimmed and ultimately switched off when enough daylight was present. Daylight levels were measured in IDA ICE at first occupant level (assumed at 0,6 m above the floor). The occupants were placed in the center of the rooms in the model. The value of 200 lux was chosen as this represents a typical minimum illuminance level in homes.

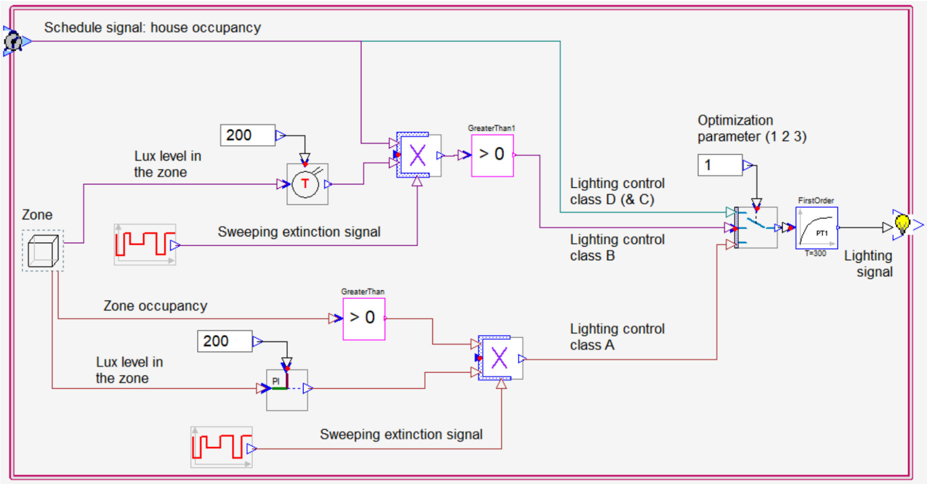


FIGURE 5.27. Control strategies for lighting used in approach II.

5.5.4 Blind Control Strategies

Because of modelling restrictions in IDA ICE, only two blind control strategies were created: a strategy with manual control, representing class D and C, and a strategy with automatic control, representing class B and A. This is illustrated in *Figure 5.28*, where class D and C are shown in green and class B and A in brown. It was assumed that all windows, except basement windows, had external blinds.

To represent manual control, several assumptions were made concerning occupant behavior. It was assumed that an occupant does not regulate the blinds constantly, therefore a time delay of one hour was introduced. It was also assumed that an occupant has to be present in the room to control the blinds. Blinds were only lowered when the indoor operative temperature exceeded 24°C, which is the normalized setpoint for cooling given in NS 3031 [49]. Finally, an additional constraint was added saying that the outdoor temperature should be higher than 15°C, so that passive solar gains during the winter were maximized. The control strategy was also tested without this constraint and with lower temperature setpoints (i.e. 10°C and 12°C), but it was found that it did not affect overheating while the energy consumption increased. Overheating was not a problem when the outdoor temperature was below 15°C and lowering blinds on cold days caused an increased space heating demand.

Automatic control was presented by adding a sensor that measured incoming solar radiation. The blinds were automatically lowered when the solar radiation exceeded 200 W/m^2. This setpoint was chosen because it is used as boundary condition in EN 15232 [25]. In this control strategy, the constraint concerning outdoor temperature was also added to maximize the use of winter passive solar gains.

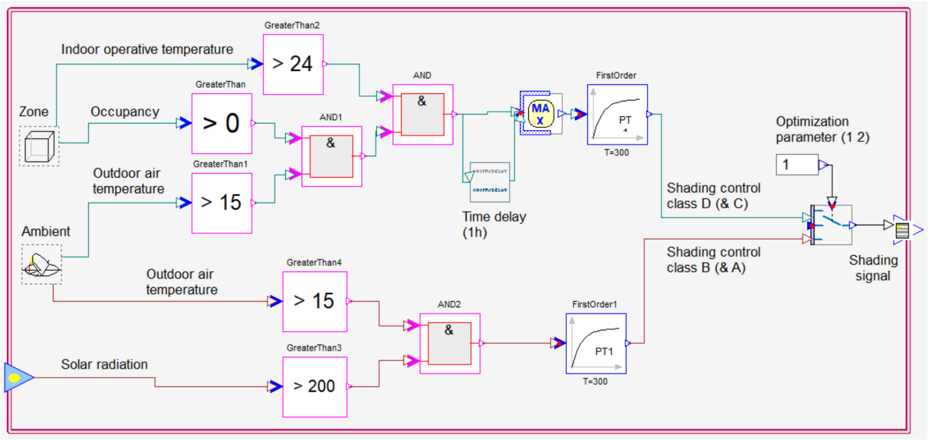


FIGURE 5.28. Control strategies for blinds used in approach II.

5.5.5 Window Opening behavior

The window control strategy from approach I was adjusted and extra constraints were added to minimize heat losses. It was assumed that windows closed automatically to minimize energy losses and avoid excessive heating. Therefore, the time delay component was removed. The occupancy pattern was adjusted, so that windows could also open at night. This significantly improved the air quality, especially in the bedrooms, and allowed for night flush cooling. The updated occupancy pattern is shown in *Figure 5.30*.

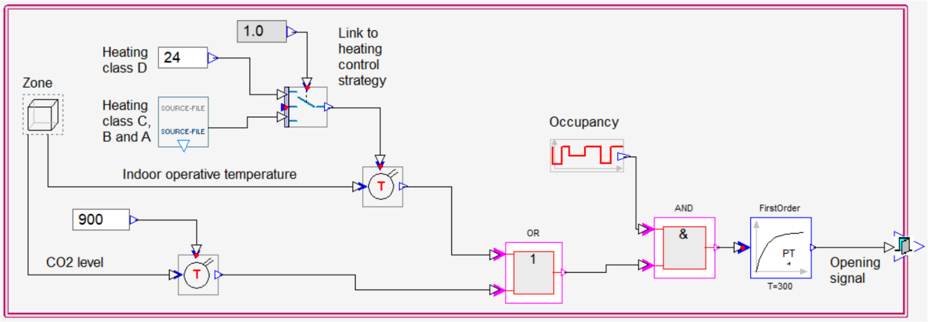


FIGURE 5.29. Control strategy for window opening behavior used in approach II.

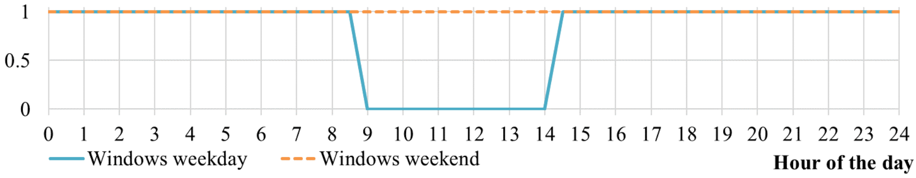


FIGURE 5.30. Occupancy schedule for window opening behavior used in approach II.

The temperature setpoints are summarized in *Table 5.13* and illustrated in *Figure 5.31*. In heating strategy D, windows were opened when the indoor operative temperature exceeded 24°C. In heating strategies C to A, windows were opened when the indoor operative temperature exceeded the 10% PPD upper limit defined by Peeters et al. [45]. The temperature deadband was 3°C, so that the window closed before the temperature dropped below the heating setpoint. In this way, simultaneous window opening and heating was avoided. The CO_2 setpoint was set to 900 ppm with a deadband of 200 ppm.

TABLE 5.13. Temperature setpoints for opening and closing windows used in approach II.

Heating class and room function	**Heating setpoint**	**Window temperature setpoint**
Heating level D, all rooms	22°C	24°C
Heating level C-A, bedrooms	$T_{n,bed}$ (*Equations 2.4* to *2.7*)	$min(26, T_{n,bed} + 3.5) - 1.5°C$
Heating level C-A, bathrooms	$T_{n,bath}$ (*Equations 2.8* and *2.9*)	$(T_{n,bath} + 3.5) - 1.5°C$
Heating level C-A, other rooms	$T_{n,other}$ (*Equations 2.10* and *2.11*)	$(T_{n,other} + 3.5) - 1.5°C$

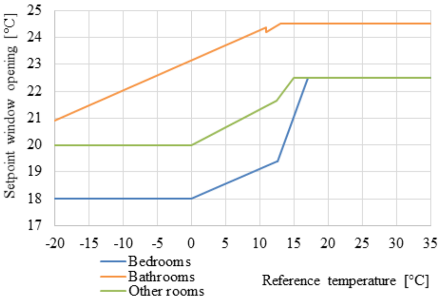


FIGURE 5.31. Variable window opening setpoints.

To illustrate the effect of the changed window opening behavior on the energy consumption and indoor comfort, results from the control validation simulation model, described in *§ 6.2*, were compared. In this model, the energy performance characteristics were set to the minimum energy criteria in TEK17. All control strategies were set to class D (no automation) and only window opening behavior was adjusted. The relevant energy performance results are shown in *Table 5.14*. There was a significant decrease of the space heating consumption and a slight decrease in the energy consumption of the ventilation system in approach II. This may seem counter intuitive at first, as windows could be opened at night, resulting in more possible opening hours. However, the time constraint was removed in approach II so that windows did not stay open for a minimum period of 30 minutes. The setpoint for opening windows was also increased, to increase the deadband between heating and cooling through opening windows. This resulted in a decreased energy consumption. This illustrates that window opening control significantly impacts the energy consumption and that setpoints have to be chosen carefully.

In the case study models before retrofitting, windows were opened quite often in approach I and II, mostly triggered by the CO_2 setpoint. This resulted in a significant increase of the energy consumption. After retrofitting and installing a balanced ventilation system, windows were mainly opened to provide natural cooling as the ventilation system ensured acceptable CO_2 levels. The increase of energy consumption in a TEK17 scenario with window opening behavior (approach II) was only 4-5% compared to the same building without window opening behavior.

Analysis of the thermal comfort in the living room showed that there was no difference between the two window opening behaviors (i.e. both work equally well as cooling strategies). The CO_2 levels in the living room and one bedroom were compared. The number of yearly hours where the CO_2 level exceeded 1000 ppm in the bedroom was 1938 hours for approach I and 810 hours for approach II. For the living room, this was 6 hours for approach I and 53 hours for approach II. All hours where the CO_2 level exceeded 1000 ppm were occupied hours. The large improvement for bedrooms can be explained by the occupancy schedule adjustment in approach II. In approach I windows were always closed at night, whereas they could be opened during the night in approach II. It was not clear why the air quality in the living room worsened from approach I to II.

TABLE 5.14. Energy performance results from implementing two window opening behavior control strategies.

	Approach I	**Approach II**	**Savings from I to II**
Space heating [kWh/m^2 year]	111.7	84.4	24%
AHU heating and fans [kWh/m^2 year]	2.2	2.1	5%
Total energy consumption [kWh/m^2 year]	176.1	148.6	16%

5.6 Short Conclusions

The following was concluded from this analysis:

- To evaluate the impact of BACS, occupancy schedules should mimic typical behavior as opposed to the normalized occupancy schedule that assumes an occupant is always present.
- Window opening behavior significantly impacted the energy consumption.
- The BACS descriptions in EN 15232 can be interpreted in different ways.
- There is no template for modelling advanced control strategies and it can be done in different ways.

6 | Impact of Building Automation

This chapter answers research question 4: *What is the effect of building automation control strategies on the energy consumption and thermal comfort of the reference buildings?*. This research question was the main topic of paper B and was also investigated in paper C.

6.1 Control strategies following approaches I and II

The impact of the four BACS classes in combination with four levels of retrofitting on the potential energy savings, indoor comfort, and cost-effectiveness was investigated for the single-family house simulation model. Two methods were used to calculate the potential energy savings: the simple factor method as described in EN 15 232 [25] and a detailed calculation method using building performance simulations. Thermal comfort was assessed following EN 16798 [43] and the cost-effectiveness was assessed with the discount payback period (DPP) method. In the paper that presents these results (paper B), control strategies according to approach I were implemented (described in *Section § 5.4*). Later, the parametric analysis was repeated with the control strategies from approach II. The relevant results from both approaches are presented here.

6.1.1 Model Input and Assumptions

The simulation model of the single-family house followed the description given in *Chapter 5*. The occupancy patterns and schedules for equipment and lighting were as described in *Section § 5.2.3*. The following assumptions were made, in addition to the assumptions in *Section* 5.3:

- Only HVAC, energy systems and appliances that were present before retrofitting were automated and upgraded, i.e. no additional HVAC or energy systems were introduced.
- Automation of the blinds were outside the scope.

- The model before retrofitting had halogen lighting, which was replaced by LED lighting after retrofitting.

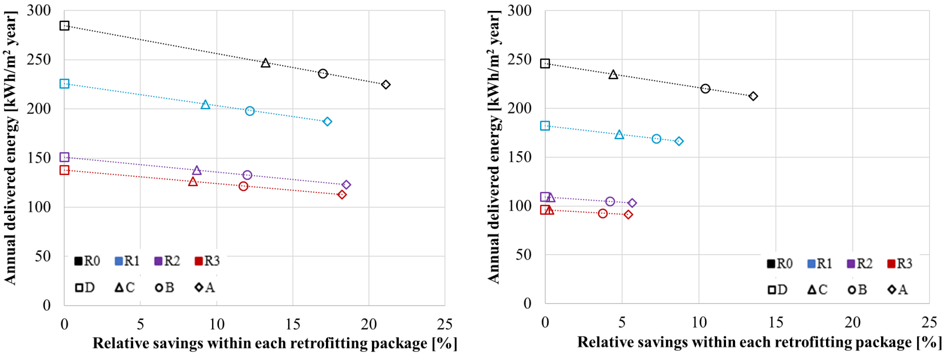
Four levels of retrofitting (R0–3) were defined and are presented in *Table 6.1*. The reference level, R0, is the building without retrofitting. The values assumed were taken from NS 3031 [49] that presents typical energy performance characteristics for constructions based on the built year, i.e. 1969–1985. These values take into account deterioration and building errors and are therefore worse than the technical requirements for buildings and constructions and typical values of that period. The other three retrofitting levels (R1–3) are renovation packages. In all retrofitting packages, a balanced ventilation with 80% heat recovery was installed. In the minimum package, R1, only the windows were replaced. When windows are changed, it is expected that the airtightness improves. However, there is a limited number of studies on the impact of replacing windows on the airtightness of the whole building, which makes it difficult to predict the improvement. The method proposed by Ridley et al. [97] was used to estimate the improved airtightness. It can also be expected that the thermal bridges around the perimeter of the windows are minimized, though this was not calculated. In the moderate package, R2, the house was fully upgraded to TEK17, following the component method [39]. In the ambitious package, the building was upgraded based on the Norwegian criteria for passive houses [40]. The energy performance characteristics for each retrofitting package are presented in *Table 6.1*.

TABLE 6.1. Energy performance characteristics of the four renovation packages.

	R0 – no renovation	**R1 – minimum**	**R2 – moderate**	**R3 – major**
U-value basement wall [W/m^{2}K]	1.0	1.0	0.18	0.10
U-value basement floor [W/m^{2}K]	0.5	0.5	0.10	0.08
U-value timber frame wall [W/m^{2}K]	0.6	0.6	0.18	0.10
U-value roof (loft insulation) [W/m^{2}K]	0.6	0.6	0.13	0.08
U-value windows [W/m^{2}K]	2.8	1.2	0.8	0.8
Air leakage at 50 Pa [h^{-1}]	6.0	1.4	0.6	0.6
Norm. thermal bridge value [W/m^{2}K]	0.07	0.07	0.05	0.03
SFP [kW/(m^3/s)]	2.0	1.5	1.5	1.5
Heat recovery [%]	0	80	80	80
Ventilation system	Mech. exhaust	Balanced	Balanced	Balanced

6.1.2 Energy Performance Assessment

Figure 6.1 shows the impact of BACS on the energy performance of the single-family house. The results from the model with control strategies following approach I is shown on the left and the results from the model with control strategies following approach II is shown on the right. The figure shows the savings from upgrading BACS within each retrofitting scenario. The second approach of control strategies shows a lower original energy consumption, due to the adjusted window opening strategy. The slopes of the trendlines indicate that the impact of BACS decreased when the original energy consumption (i.e. class D) was lower. Significantly more energy was saved from implementing BACS using the control strategies from approach I compared to approach II. Approach I was validated for the setpoints used in the model and approach II was validated for adaptive setpoints for heating and ventilation. However, the same setpoints from approach I were also used with approach II, i.e. only the control itself was changed, not the setpoints. This could be a reason why the savings were lower using approach II.

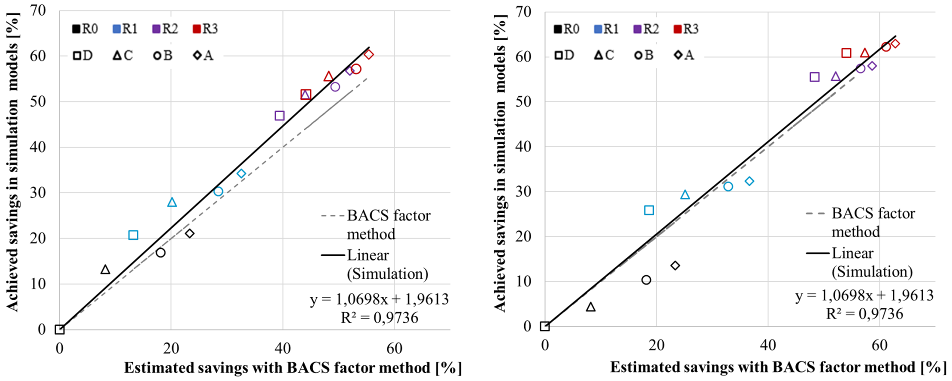


(A) Control strategies and setpoints following approach I.

(B) Control strategies following approach II, with setpoints following approach I.

FIGURE 6.1. Impact of upgrading building automation control strategies on the energy consumption for four levels of retrofitting.

The maximum energy saving potential that was achieved with a combination of retrofitting the building envelope and BACS was 60% for approach I and 63% for approach II, as is illustrated by *Figure 6.2*. In approach II the spread between the BACS classes within each retrofitting package was smaller, i.e. there were less energy savings from implementing BACS. In some cases, BACS upgrades achieved the same or more energy savings as building envelope upgrades, for example in approach I models R0,A and R1,D and models R2,A and R3,D. This effect was not visible in approach II.



(A) Control strategies and setpoints following approach I.

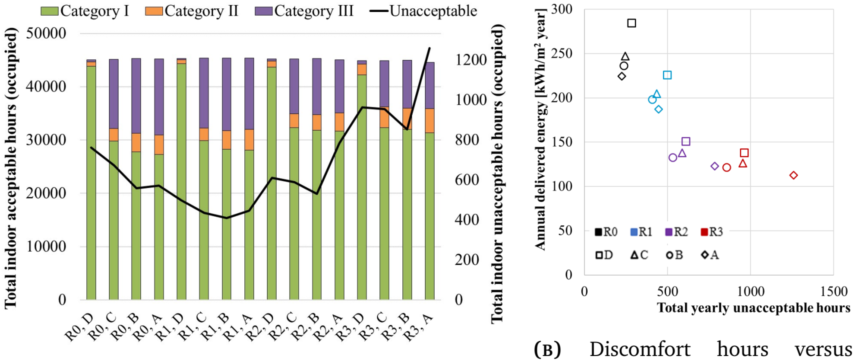
(B) Control strategies following approach II, with setpoints following approach I.

FIGURE 6.2. Total achieved energy savings and correlation between the detailed calculation method and simple factor method for estimating energy savings from BACS.

6.1.3 Thermal Comfort Assessment

Thermal comfort was assessed according to EN 16798 for buildings without mechanical cooling, and is presented in *Figure 6.3* and *Figure 6.4*. The bar charts (*Figure 6.3a* and *Figure 6.4a*) display the total number of annual occupied hours, summed for 13 zones, in the four comfort categories. The unacceptable hours were mostly a result of overheating. Both figures illustrate that the overheating hours decreased when the windows were replaced (R1), but increased when the house was retrofitted to a higher standard (R2 and R3). This was due to a combination of better envelope insulation, significantly increased air tightness and, for class C, B and A, reduced ventilation rates during parts of the day. It was not investigated which parameter(s) had the most impact on this increase. As no active cooling system was installed, it can be concluded that the window opening strategy was no longer sufficient after retrofitting. From the total number of unacceptable hours it becomes clear that the window opening strategy in approach II was more efficient for providing cooling. The decrease of number of hours in category I and II was due to the lowered setpoints for heating in the bedrooms. However, these setpoints are acceptable in Norwegian households. Therefore, it would be better to assess the thermal comfort with criteria that take this into account.

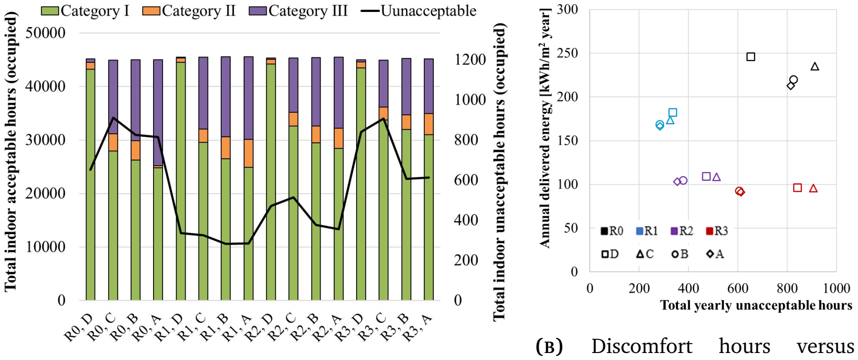
The scatter diagrams (*Figure 6.3b* and *Figure 6.4b*) show the annual discomfort hours versus the annual energy consumption. The number of unacceptable hours increased for every retrofitting package in approach I. In approach II, the thermal comfort improved for retrofitting packages R1 and R2, but was the same as the original situation in package R3. In approach II, thermal comfort improved in class B and A. This was not the case in approach I. The system design of the control strategies in approach I was less effective for improving thermal comfort, though the energy consumption was reduced.



(A) Thermal comfort assessment.

(B) Discomfort hours versus annual energy consumption.

FIGURE 6.3. Thermal comfort assessment according to the method described in EN 16798 for control strategies and setpoints following approach I.



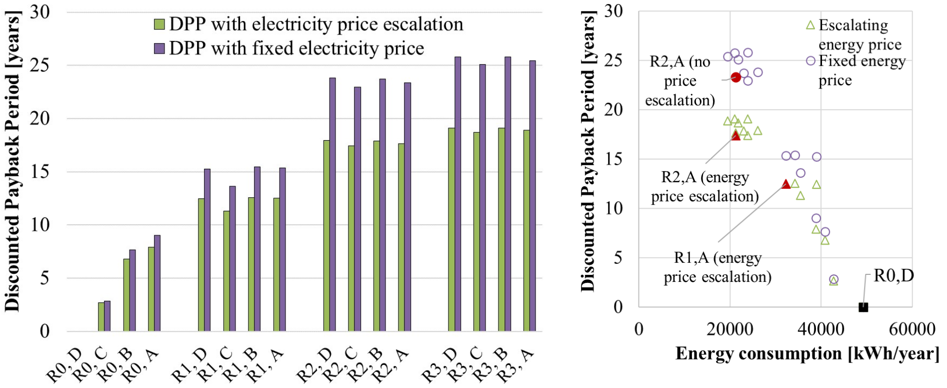
(A) Thermal comfort assessment.

(B) Discomfort hours versus annual energy consumption.

FIGURE 6.4. Thermal comfort assessment according to the method described in EN 16798 for control strategies following approach II with setpoints following approach I.

6.1.4 Economic Assessment

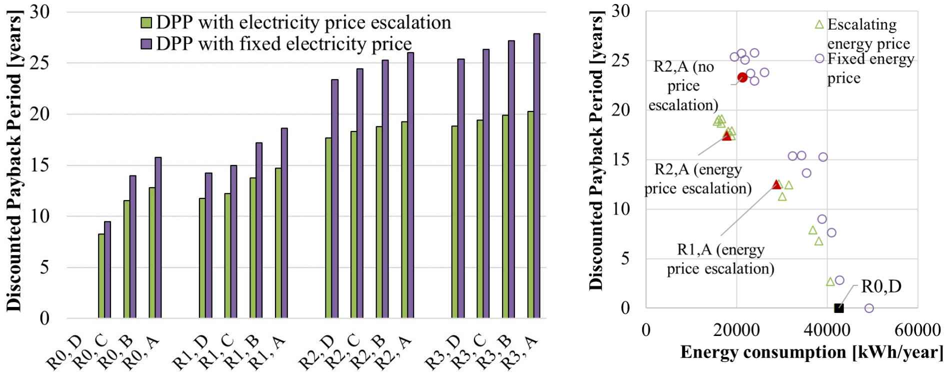
Figure 6.5 and *Figure 6.6* show economic assessment. The bar charts (*Figure 6.5a* and *Figure 6.6a*) show the discounted payback period (DPP) in years for each scenario, where it was assumed that there were no cost in the scenario without retrofitting. Two results are displayed: one taking into account a price escalation of electricity and one with a fixed electricity price. The DPP was lower when a price escalation was assumed, as the energy savings will save more money. The DPP for approach I was shorter than for approach II because the energy savings in approach I were higher, i.e. the investment cost were earned back faster. The DPP for packages R2 and R3 was similar for both approaches. The scatter diagrams (*Figure 6.5b* and *Figure 6.6b*) show that in both cases retrofitting to a lower level (i.e. R1 or R2) with full BACS upgrades (i.e. class A) was the most cost-effective. In all cases, the investment cost were earned back within 30 years.



(A) Discounted payback period.

(B) Discounted payback period versus annual energy consumption.

Figure 6.5. Economic assessment for control strategies and setpoints following approach I.



(B) Discounted payback period versus annual energy consumption.

(A) Discounted payback period.

Figure 6.6. Economic assessment for control strategies according to approach II with setpoints following approach I.

6.2 Control strategies following approach II

The impact of individual BACS strategies and the BACS classes on the potential energy savings, indoor comfort, and cost-effectiveness was investigated for the single-family house and the representative apartments. The impact of individual strategies was investigated as in some cases it might not be feasible or profitable to upgrade all systems to the same BACS level, i.e. high-performance BACS may not always pay off in terms of energy and/or cost for residential buildings in cold climates. Thermal comfort was assessed using the adaptive temperature criteria from Peeters et al. [45]. The cost-effectiveness was assessed using the difference in life cycle cost (dLCC).

6.2.1 Model Input and Assumptions

Validation was done through parametric runs in IDA ICE, where the control strategies were changed one by one to evaluate the impact of individual strategies. In addition, the impact of improving all control strategies to classes C, B and A was evaluated. The control strategies were tested in both building models, and with two different space heating sources: direct electricity, and direct electricity combined with an air source heat pump (ASHP). This resulted in 4 parametric runs with 13 variations each. The following boundaries were given for the models, in addition to or instead of the assumptions made in *Section* 5.3:

- The thermal properties of the building envelope, thermal bridges and airtightness were as the minimum energy criteria in TEK17 (see *Table 2.9*).
- The equipment and lighting schedules and loads were taken from NS 3031 [49].
- The occupancy schedule followed a typical pattern that was adjusted to the normalized yearly load, as described in *Section § 5.2.3*, to see the impact of occupancy and demand controlled strategies.
- The type of lighting (halogen) was not changed after retrofitting.

6.2.2 Energy Performance Assessment

Figure 6.7 shows the impact of upgrading BACS on the energy consumption of the four cases. More energy savings were achieved for the cases with direct electricity than for the cases with an ASHP and direct electric heaters. This could indicate that the settings of the ASHP were not optimal. The total savings that were achieved from upgrading BACS class D to A were similar to the results presented in *Section § 6.1*.

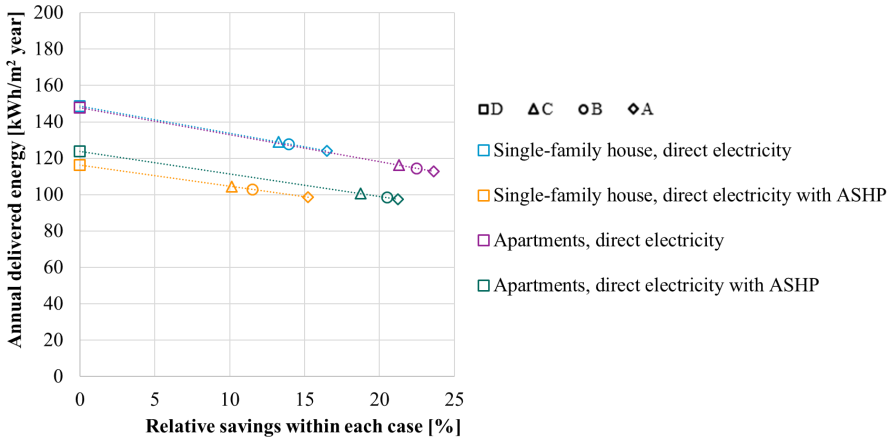


FIGURE 6.7. Impact of upgrading building automation control strategies on four different cases using control strategies and setpoints according to approach II.

More detailed results from the parametric study are presented for both buildings with space heating provided by direct electricity (*Table 6.2*) and with an air source heat pump (ASHP) in the living room, supplied by direct electrical heaters in the rest of the house (*Table 6.3*). The energy consumption of the case study without automated control strategies is shown in the first row ("Model D"). The other rows show the relative energy savings achieved by implementing more advanced BACS. A positive value indicates a higher energy consumption than the reference case and a negative value indicates energy savings. The cells in **bold** indicate an energy decrease of total energy consumption of more than 5%. This equals energy savings of more than 1000 kWh per year for the single-family house and more than 850 kWh per year for the representative apartments combined.

TABLE 6.2. Energy savings achieved by implementing BACS in a single-family house and apartment block with direct electricity as a space heating source.

	Single-family house				**Representative apartments**			
	Space heating	**AHU heating and fans**	**Lighting**	**Total**	**Space heating**	**AHU heating and fans**	**Lighting**	**Total**
Model D [kWh/m^2 year]	84.4	10.7	11.4	148.6	79.0	15.0	11.4	147.8
BACS strategy		*Relative increase or decrease in energy consumption [%]*						
Heating, C	–22	+6	–	**–12**	–38	+5	–	**–20**
Heating, B	–24	+9	–	**–13**	–38	+7	–	**–19**
Heating, A	–28	+23	–	**–14**	–39	+9	–	**–20**
Ventilation, C	–	–14	–	–1	+2	–15	–	–
Ventilation, B	+5	–26	–	+1	+10	–34	–	+2
Ventilation, A	+6	–35	–	+1	+10	–34	–	+1
Lighting, B	+2	–	–35	–2	–	–	–35	–3
Lighting, A	+4	+1	–61	–2	+2	+1	–55	–3
Blinds, B	+1	–	–	–	–	–1	–	–
Complete, C	–21	–9	–	**–13**	–38	–10	–	**–21**
Complete, B	–14	–23	–36	**–14**	–31	–30	–39	**–23**
Complete, A	–14	–28	–61	**–16**	–31	–31	–60	**–24**

TABLE 6.3. Energy savings achieved by implementing BACS in a single-family house and apartment block with direct electricity and an air source heat pump as space heating sources.

	Single-family house				Representative apartments			
	Space heating	**AHU heating and fans**	**Lighting**	**Total**	**Space heating**	**AHU heating and fans**	**Lighting**	**Total**
Model D [kWh/m^2 year]	48.7	14.1	11.4	116.3	52.9	17.2	11.4	123.9
BACS strategy		*Relative increase or decrease in energy consumption [%]*						
Heating, C	–21	–1	–	**–9**	–40	+2	–	**–17**
Heating, B	–20	–	–	**–8**	–37	+3	–	**–15**
Heating, A	–26	+9	–	**–10**	–38	+4	–	**–16**
Ventilation, C	–1	–11	–	–2	+1	–13	–	–
Ventilation, B	+6	–18	–	–	+7	–29	–	+2
Ventilation, A	+4	–22	–	–1	+8	–29	–	+1
Lighting, B	+1	+1	–35	–3	–2	–	–35	–4
Lighting, A	+5	+2	–61	–4	+1	+1	–55	–5
Blinds, B	–	–1	–	–	–	–1	–	–
Complete, C	–21	–12	–	**–10**	–40	–12	–	**–19**
Complete, B	–13	–22	–36	**–12**	–30	–29	–39	**–21**
Complete, A	–15	–23	–61	**–15**	–28	–28	–60	**–21**

The results show that significant overall energy savings were achieved when implementing BACS. Energy savings of 10–24% were achieved when BACS was upgraded to a complete class (see rows “complete, (class)” and columns “total”), and savings of 9–20% were achieved when only the heating control strategy was upgraded (see row “heating, (class)” and columns “total”). The achieved energy savings were mostly due to upgrading the heating control strategies, but the highest savings were achieved when all control strategies were upgraded simultaneously (“complete, (class)”). For apartments, the achieved energy savings were 1.5–2 times higher than for single-family houses. It was concluded that BACS, especially heating control strategies, had a bigger impact on the energy consumption for more compact buildings. The energy use for domestic hot water (DHW) and equipment were not affected and are not presented separately in the table, but are included in the total energy consumption.

When heating control strategies were implemented, the energy use for space heating and the total energy consumption were reduced. Only the heating control strategies significantly impacted the total energy consumption, indicating that the heating strategies in cold climates were the most effective BACS to achieve energy savings. Especially in apartments, the choice of heating control strategy had a large effect on the energy consumption, though there were no significant differences between class C, B and A. When an ASHP was installed, the space heating demand did not necessarily decrease for more advanced levels (see rows “heating, (class)” and “complete, (class)” and columns “space heating” in Table 8). This is because the ASHP only heated up a limited volume due to closed doors and because the efficiency of the ASHP is much higher than of direct electricity (i.e., the space heating demand decreased with more advanced control, but not necessarily the total energy consumption).

When the heating demand covered by space heaters decreased (for example, due to night setbacks in more advanced BACS classes), the energy use attributed to air heating unit (AHU) and fans increased, as more AHU heating was required to ensure a comfortable temperature (see rows “heating, (class)” and “ventilation, level” and columns “space heating” and “AHU heating and fans”).

More advanced ventilation control strategies reduced the energy consumption and energy for AHU heating (see row “ventilation, (class)” and column “AHU heating and fans”). As a result, the energy use for space heating increased. However, the total energy consumption was not significantly affected. In the representative apartments, class B and A resulted in equal energy savings, while for the single-family house class A was the most energy-efficient.

The lighting control strategies mainly affected the energy consumption for lighting (see row “lighting, (class)” and column “lighting”). Though these savings were high, the total energy consumption decreased only slightly, because lighting only represents a small share of the total energy consumption. In addition, the heating demand increased due to lower internal heat gains.

When the blind strategies were implemented, there was no significant effect on the energy demand or energy consumption (see row “blind, (class)” and column “total”). This is because cold climates are heating dominated and in housing, no active cooling systems were installed. It is possible that the cooling demand was reduced, but this was not investigated. Instead, thermal comfort was investigated. As cooling was achieved through window opening behavior, it did not affect the energy consumption.

Though the energy for space heating increased when the energy for AHU heating and fans decreased and vice versa, both decreased when they were upgraded simultaneously (see row “complete, (class)” and columns “space heating” and “AHU heating and fans”). Most energy savings were achieved when multiple control strategies were combined, though the differences between classes C, B and A were small. Therefore, other criteria, such as cost or thermal comfort, could be used to decide which BACS class to choose.

6.2.3 Thermal Comfort Assessment

Thermal comfort was assessed in terms of indoor discomfort degree hours (occupied) as described in *Section § 3.5*. *Figure 6.8* shows the energy consumption versus the number of indoor discomfort degree hours (occupied) for each of the model versions. The discomfort degree hours were in most cases due to overheating. Only class B and A in the apartments with direct electricity as space heating source had undercooling of 2 and 28 discomfort degree hours, respectively. Overheating was a more critical issue for the representative apartments than for the single-family house. This is most likely because the apartments are more compact and have less heat losses through the envelope due to a smaller exterior surface area. Other reasons could be because they were located on the top floor and received more solar gains or because cooling through cross-ventilation was less effective compared to the single-family house.

Thermal comfort increased when more advanced BACS were implemented, though there was no direct positive effect from implementing advanced ventilation control. However, when ventilation control was combined with other control strategies, the thermal comfort improved significantly. The heating control strategies had the biggest impact on the thermal comfort in all four cases. Combining the BACS strategies (i.e. the complete class upgrade) resulted in the highest improvement of thermal comfort.

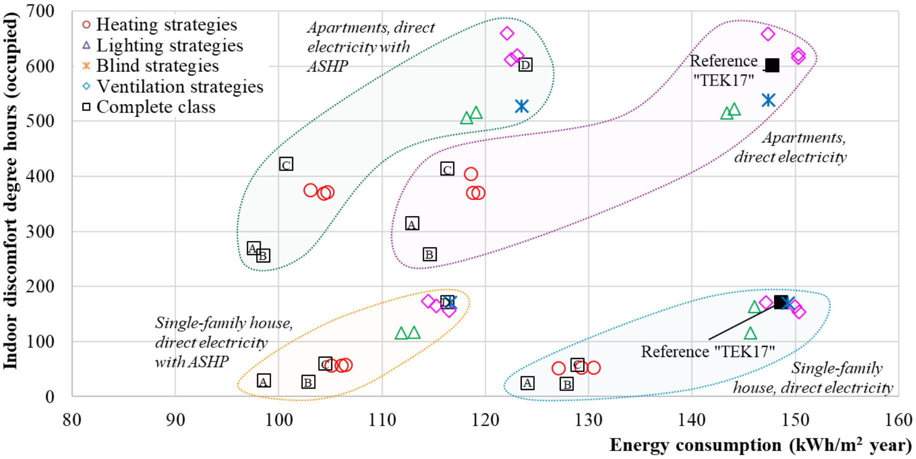
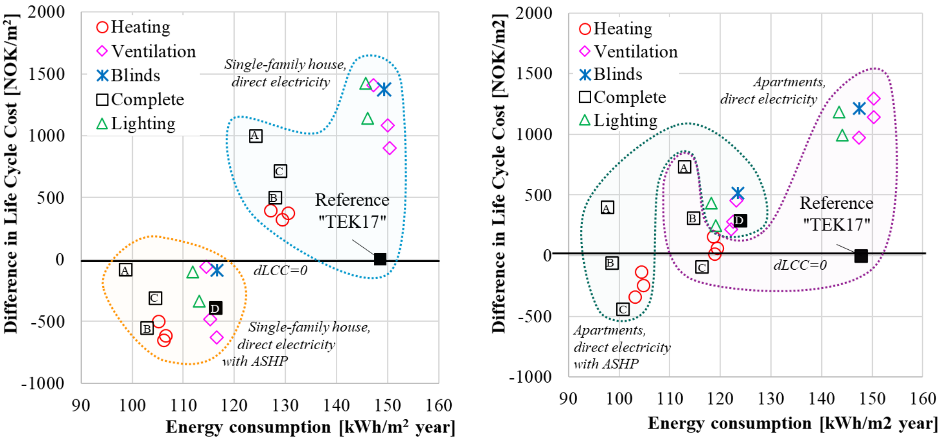


FIGURE 6.8. Results of the parametric analysis: indoor discomfort degree hours (occupied) versus annual energy consumption.

6.2.4 Economic Analysis

Figure 6.9 shows the profitability of individual BACS measures compared to model D without an ASHP. This was assessed using the difference in life cycle cost (dLCC). The profitability of the BACS measures improved when the achieved energy savings increased. For the single-family house, installing an ASHP was profitable regardless the automation class (orange shape). Without the ASHP (blue shape), no automation measures were profitable. For the apartments, upgrading all automation systems to class C was profitable without an ASHP (green shape). When the ASHP was installed (purple shape), upgrading the heating control systems and upgrading all systems to class C or B was profitable.



(A) Single-family house.

(B) Representative apartments.

FIGURE 6.9. Difference in life cycle cost (dLCC) versus annual energy consumption for control strategies implemented according to approach II.

6.3 Short Conclusions

The following was concluded from this analysis:

- Up to 24% energy savings were achieved from only implementing BACS, though the impact of the measures decreased when the original energy consumption was lower.
- Setpoints and modelling control strategies can significantly impact the energy consumption and achieved savings.
- Of the individual control strategies, only implementing more advanced heating control strategies resulted in significant energy savings. Combining all the BACS measures resulted in the highest energy savings.
- BACS, especially heating control strategies, had a bigger impact on the energy consumption when volume-to-surface ratio was higher, i.e. more compact buildings, such as apartments.
- As BACS measures are cheaper to implement than other energy retrofitting measures, such as retrofitting the building envelope or energy systems, it was most profitable to have a lower level of envelope retrofitting with a high performance BACS.
- It is critical to take into account thermal comfort in addition to energy savings when implementing BACS measures, as different control strategies and setpoints can significantly affect both. Not optimized settings can negatively affect the thermal comfort.

7 | Defining Optimal Retrofitting Packages

This chapter answers research question 5: *What are the optimal retrofitting packages for the reference buildings where building automation control systems are combined with building envelope and energy systems retrofitting?* and research question 6: *What is the cost-effectiveness of optimized retrofitting packages for the reference buildings where building automation control systems are combined with building envelope and energy systems retrofitting?*. These questions were the main topics of paper C.

7.1 Model Input and Assumptions

Optimal combinations of BACS, building envelope and energy systems retrofitting measures were defined for the two case study buildings. These were found through single-objective optimization of the energy consumption. The difference in life cycle cost (dLCC) and thermal comfort following the adaptive criteria defined by Peeters et al. [45] were assessed using post-processing algorithms. The following assumptions were made, in addition to the assumptions presented in *Section* 5.3:

- Typical window opening behavior (approach II) was implemented.
- The control strategies from approach II were used.
- Settings for the control strategies were not optimized.
- The type of lighting (halogen) was not changed after retrofitting.

Table 7.1 presents the design variables for optimization. The building envelope design variables were chosen so that the lower limit of the range fulfilled the minimum energy performance requirements of TEK17 [39]. The alternative method criteria were used to define the lower limit when minimum requirements were not specified. The upper limits were based on the recommendations and criteria for

Norwegian passive houses [40]. The insulation thickness corresponding to the upper and lower limit U-values was calculated. It was assumed that the timber frame construction with mineral wool had a combined thermal conductivity of λ=0.044 W/mK. See *Table 5.10* for the description of the BACS classes.

TABLE 7.1. Solution space with the optimization design variables.

	Design variable	**Single-family house**			**Representative apartments**		
		Options range	**Step size**	**Nr. of steps**	**Options range**	**Step size**	**Nr. of steps**
Building envelope	Insulation thickness external walls [m]	0.2…0.4	0.05	5	0.2…0.4	0.05	5
	Insulation thickness roof [m]	0.25…0.4	0.05	4	0.2…0.4	0.05	5
	Insulation thickness basement walls [m]	0.15…0.3	0.05	4	–	–	–
	Insulation thickness basement floor [m]	0.1…0.35	0.05	6	–	–	–
	Infiltration rate [h^{-1}]	0.6…1.0	–[1]	–[1]	0.6…1.0	–[1]	–[1]
	Normalized thermal bridge value [W/m^{2}K]	0.03…0.05	–[1]	–[1]	0.05…0.07	–[1]	–[1]
		Options		**Nr. of options**	**Options**		**Nr. of options**
	Windows (t=0.7, g=0.5)	1.2 W/m^{2}K 0.8 W/m^{2}K		2	1.2 W/m^{2}K 0.8 W/m^{2}K		2
Automation classes	Heating control	Class D Class C Class B Class A		4	Class D Class C Class B Class A		4
	Ventilation control	Class D Class C Class B Class A		4	Class D Class C Class B Class A		4
	Lighting control	Class D & C Class B Class A		3	Class D & C Class B Class A		3
	Blind control	Class D & C Class B & A		2	Class D & C Class B & A		2
	Possible combinations			92160			4800

[1] The infiltration rate and normalized thermal bridge value are a function of the insulation levels, where these values improved when the insulation levels increased.

Figures 7.1 and *7.2* are detailed building sections that illustrate the lower and upper limits of the building envelope retrofitting design variables. The vapour barrier is marked in red, the wind barrier in blue, the existing thermal insulation in grey and the additional thermal insulation in yellow. Most existing thermal bridges were significantly reduced by adding exterior insulation. There are still thermal bridges around the balconies of the apartment block, though a thermal break was added. To completely avoid the thermal bridges in this location, it is better to move the building envelope so that the original balconies become part of the interior. Insulation of the floors was not investigated for the apartment block, but the range values from the single-family house were used for this illustration.

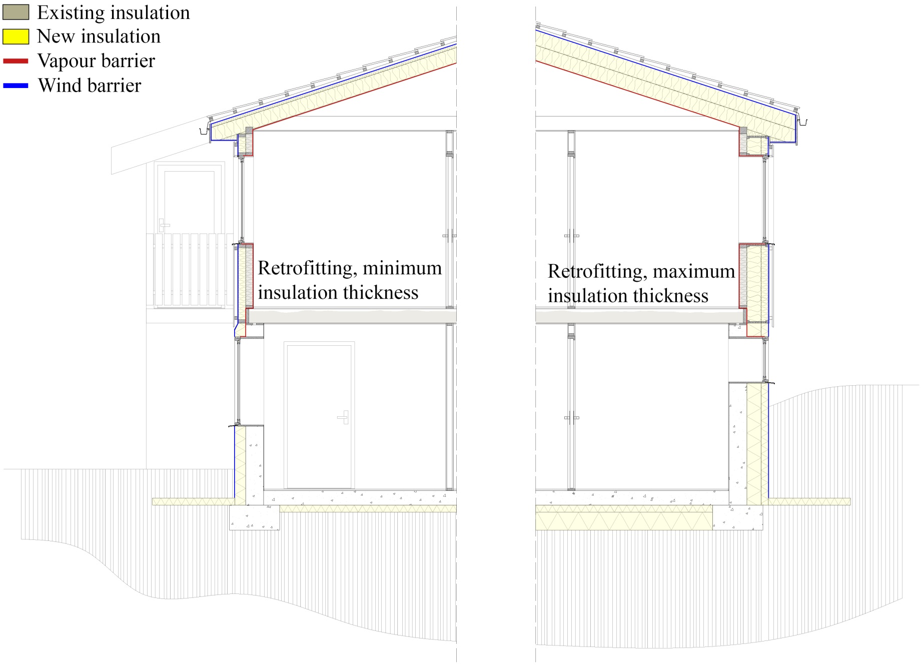


FIGURE 7.1. Section of the retrofitted single-family house with the insulation layer, wind barrier and vapour barrier marked. The left side of the figure represents retrofitting with the minimum insulation thickness as presented in *Table 7.1* and the right side of the figure represents retrofitting with the maximum insulation thickness.

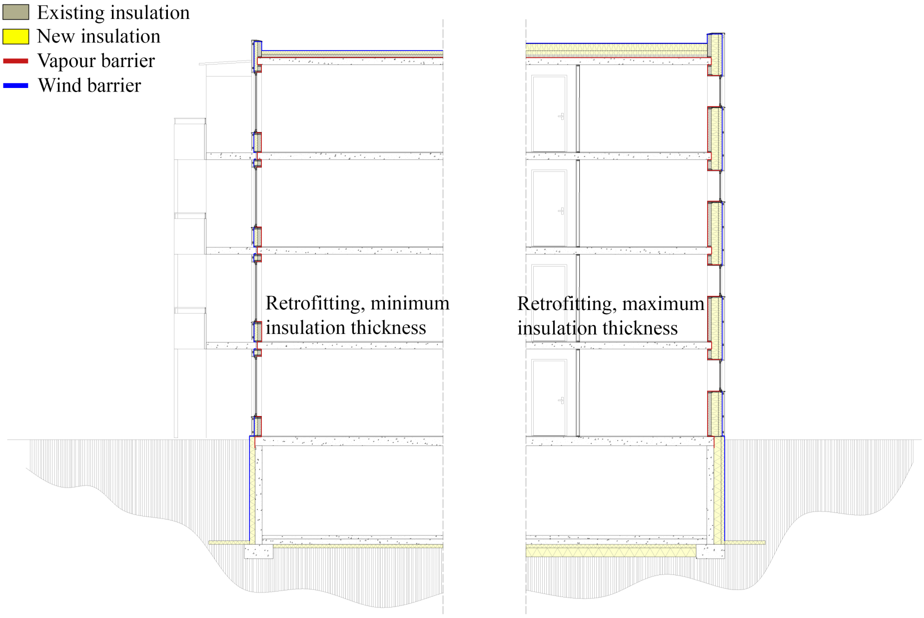


FIGURE 7.2. Section of the retrofitted apartment block with the insulation layer, wind barrier and vapour barrier marked. The left side of the figure represents retrofitting with the minimum insulation thickness as presented in *Table 7.1* and the right side of the figure represents retrofitting with the maximum insulation thickness.

7.2 Investment Cost

Tables 7.2 to *7.4* show the investment costs for the different retrofitting measures. The total cost for the building envelope, excluding windows, were calculated with a graphical script in IDA ICE that multiplied the total exterior surface area of each component with the price depending on the insulation thickness. The costs for windows, the ASHP and the automation measures were added to the building envelope cost with a post-processing algorithm in Excel. It was assumed that the automation measures and the heat pump were replaced once within the calculation period of 30 years. It is expected that the lifetime of the building envelope retrofitting measures, including windows, is equal to or exceeds 30 years.

TABLE 7.2. Investment cost for the building envelope retrofitting measures for the single-family house (SF) and the apartments (AP), taken from Norsk Prisbok [54].

	Total	**Cost [NOK/m^2]**
Additional external wall insulation, SF & AP (original 10 cm)	20 cm	1164
Including: removing the original cladding, adding a wind barrier, adding mineral wool insulation (variable thickness) and timber-frame, adding cladding	25 cm	1271
	30 cm	1553
	35 cm	1701
	40 cm	1777
Additional insulation sloped roof, SF (original 15 cm)	25 cm	2006
Including: removing roof cladding and loft insulation, adding mineral wool insulation (variable thickness) and timber-frame to the sloped roof, adding wind and vapour barriers, adding cladding	30 cm	2087
	35 cm	2155
	40 cm	2218
Additional insulation flat roof, AP (original 10 cm)	20 cm	673
Including: demolition of the roof cladding and insulation, adding EPS insulation (variable thickness), adding new cladding	25 cm	753
	30 cm	841
	35 cm	906
	40 cm	970
Additional insulation basement walls, SF (original 0 cm)	15 cm	645
Including: digging out mass, adding EPS insulation (variable thickness)	20 cm	843
	25 cm	952
	30 cm	1061
Additional insulation basement floor, SF (original 0 cm)	10 cm	2552
Including: demolition of flooring and concrete floor, digging out mass, adding EPS insulation (variable thickness), adding new concrete floor and flooring	15 cm	2665
	20 cm	2710
	25 cm	2823
	30 cm	2868
	35 cm	2980

TABLE 7.3. Investment cost for the automation control systems retrofitting measures for the single-family house (SF) and the apartments (AP), taken from Norsk Prisbok [54].

	Options	Cost [NOK]
Overall automation, SF	–	7048
Overall automation, apartments	–	10114
Heating control, SF	Class C	24133
Including: smart heaters, sensors	Class B	25319
	Class A	41927
Heating control, AP	Class C	21726
Including: smart heaters, sensors	Class B	24099
	Class A	34775
Ventilation control, SF	Class D	84260
Including: balanced ventilation system, sensors	Class C	121104
	Class B	123140
	Class A	140934
Ventilation control, AP	Class D	75566
Including: balanced ventilation system, sensors	Class C	75566
	Class B	79637
	Class A	92686
Lighting control, SF	Class B	18972
Including: sensors	Class A	45026
Lighting control, AP	Class B	13913
Including: sensors	Class A	33019
Blind control, SF	Class B	24595
Including: motorized blinds, sensors		
Blind control, AP	Class B	20780
Including: motorized blinds, sensors		

TABLE 7.4. Investment cost for window retrofitting and installation of an air source heat pump for the single-family house (SF) and the apartments (AP), taken from Norsk Prisbok [54].

	Options	Cost [NOK]
Windows replacement, SF (original U=2.8 W/m^{2}K)	U=1.2 W/m^{2}K	196847
Including: removing old windows, placing new windows	U=1.2 W/m^{2}K	226337
Windows replacement, AP (original U=2.8 W/m^{2}K)	U=1.2 W/m^{2}K	83103
Including: removing old windows, placing new windows	U=1.2 W/m^{2}K	98329
Air source heat pump	–	22000
Toshiba Shorai 25 including installation		

The cost for automation include the installation of sensors and other equipment in the houses. *Table 7.5* gives an overview of which sensors and equipment was required for each of the automation classes and where they were placed. For central placement, only one sensor per dwelling unit was required. When the sensors were placed in each room, storage rooms were excluded. This resulted in 15 sensors for the single-family house, 5 sensors for the corner apartment and 6 sensors for the middle apartment. The cost for overall automation were calculated based on the heated floor area, excluding storage rooms. This was 153 m^2 for the single-family house and 138 m^2 for the apartments, i.e. 53 m^2 for the corner apartment and 85 m^2 for the middle apartment.

TABLE 7.5. Sensors and equipment required by the automation control systems.

BACS function	Class	Type of sensor or equipment	Placement
Heating	D	Normal heaters	In each room
	C	Smart heaters	In each room
		Weather sensor	Central
	B	Smart heaters	In each room
		Weather sensor	Central
		Occupancy sensor	Central
	A	Smart heaters	In each room
		Weather sensor	Central
		Occupancy sensor	In each room
Ventilation	D	Balanced ventilation (CAV)	Central
	C	Balanced ventilation (VAV)	Central
	B	Balanced ventilation (VAV)	Central
		Weather sensor	Central
		Temperature sensor	Central
	A	Balanced ventilation (VAV)	Central
		Weather sensor	Central
		Temperature sensor	Central
		Occupancy sensor	In each room
Lighting	B	Daylight sensor	In each room
	A	Daylight sensor	In each room
		Occupancy sensor	In each room
Blinds	B	Motorized blinds	In each room
		Solar radiation sensor	In each room

7.3 Energy Performance Assessment and Economic Assessment

Figure 7.3 shows the energy consumption of the optimization process with the associated dLCC, compared to the original reference model, for each combination. The optimal solutions are marked on the pareto fronts. The achieved energy savings were 32–57% for the single-family house and 17–46% for the representative apartments. Installing an ASHP was the most effective retrofitting measure for reducing the energy consumption. In many cases, the savings from installing an ASHP were larger than energy savings from retrofitting the building envelope and control strategies. It is expected that the effect of installing an ASHP will be even larger when internal doors are opened. However, this can be challenging for maintaining temperature setpoints based on room function. Therefore, internal doors were kept closed.

The associated dLCC shows a difference in profitability for the single-family house and the representative apartments. Because of high investment cost and the low energy price for electricity, i.e. a long period to earn back invested cost through energy savings, no solutions were profitable after 30 years (dLCC>0). When no ASHP was installed, the optimal retrofitting solutions for the apartments were more profitable than for the single-family house. As apartments have a smaller exterior surface area in relation to the heated floor area, i.e. are more compact, it is cheaper to retrofit the building envelope and improve the energy efficiency. The apartments had a smaller exterior surface area in relation to the heated floor area, i.e. were more compact buildings. More compact buildings require less investment cost for retrofitting of the building envelope to improve the energy efficiency. The total investment cost were 956,000–1,500,000 NOK for the single-family house and 468,000–835,000 NOK for the apartments. Retrofitting of the building envelope and energy systems accounted for 64–85% and 46–70%, respectively. When an ASHP was installed, the profitability of the single-family house and the apartments was similar. The higher investment cost for retrofitting the building envelope of the single-family house outweighed the higher energy savings, resulting in more profitable solutions. The comparable probabilities of the retrofitting solutions for the apartments with and without an ASHP indicate that achieved energy savings from installing an ASHP were similar to the reduced operational cost.

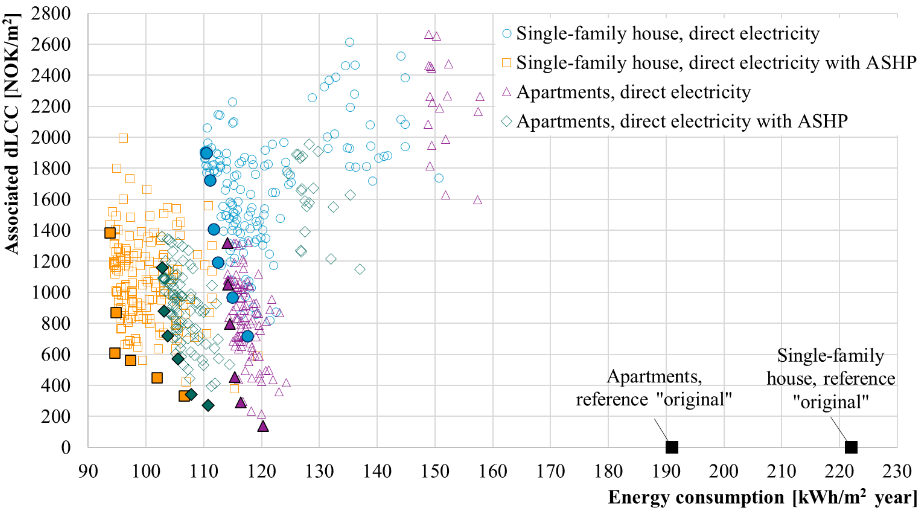


FIGURE 7.3. Results of the single-objective optimization runs: energy consumption versus the associated difference in life cycle cost, with the optimal retrofitting combinations marked on the pareto fronts..

The results from the representative apartments were used to estimate the energy savings and profitability after retrofitting for the whole apartment block (see 7.4). The following assumptions were made: the energy consumption for the whole block was 8% higher than the energy consumption for the representative apartments; and no retrofitting was done to the ground floor. The investment costs were calculated from the total area of exterior envelope and the total number of windows. The cost for automation was a function of the heated floor area. The optimal solutions for the whole apartment building were similar to those from the representative apartments, but they were more profitable. This is because the ratio of exterior surface area to heated floor area decreases when the whole building is considered as opposed to two top floor apartments, thus decreasing the investment cost per heated floor area. It should be noted that these results are heavily derived from the results of the representative apartments and is only an estimation for the whole apartment.

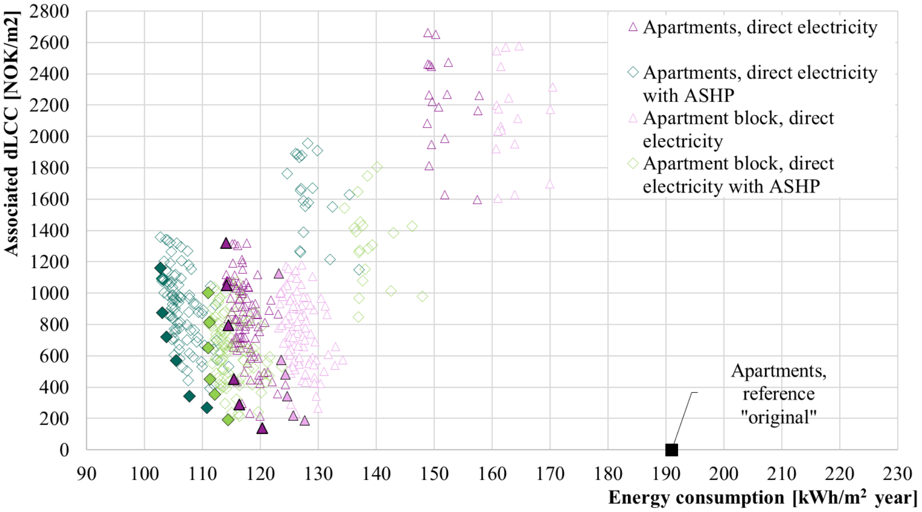


FIGURE 7.4. Results of the single-objective optimization runs: energy consumption versus the associated difference in life cycle cost estimated for the apartment block, with the optimal retrofitting combinations marked on the pareto fronts.

Tables 7.6 to *7.9* show the design variables of the optimal retrofitting combinations marked on the pareto fronts. *Tables 7.10* and *7.11* show the design variables of the estimated optimal retrofitting combinations for the whole apartment block. The optimal combinations include for each case the combination with the lowest energy consumption and the combination with the lowest associated dLCC. The lowest energy consumption (bottom row of each table) was achieved when the envelope was retrofitted (almost) to the upper limits of the design variable range and when the heating and lighting control strategies were upgraded to class A.

High-performance roof and external wall components, i.e. with low U-values, were essential for high energy savings. The thermal properties of the windows, basement walls and floor had less impact on the energy-saving potential than those of the external walls and roof, though all were retrofitted to at least the minimum level of energy performance requirements in TEK17. The U-value of the windows was not crucial for the apartments, but most optimal retrofitting combinations of the single-family house used the window option with the lowest U-value.

The implemented heating control strategy had a significant impact on the energy consumption, resulting in a visible separation of the retrofitting solutions for three of the four cases (see *Figure 7.3*). For the apartments and the single-family house, upgrading the heating strategy to class C or better was essential to significantly reduce the energy consumption. The retrofitting combinations with class D heating control strategy had a higher energy consumption than the combinations with a class C or higher heating control and exactly the same other parameters. The difference was 8–23 kWh/m^2 year for the single-family house and 21–35 kWh/m^2 for the representative apartments.

Upgrading the lighting and heating control strategies to class A was essential to achieve a cost-effective low energy consumption for both building typologies. For the representative apartments, the solutions with the highest-energy savings also had class A of ventilation control strategies. The ventilation control strategies had less impact on the energy consumption of the single-family house. The impact of the blind control strategies did not significantly impact the energy consumption, and resulted in higher investment cost. The optimal solutions for the whole apartment block typically had more advanced automation measures. The most profitable solutions were characterized by a building envelope with a lower energy performance, though still fulfilling the minimum energy performance requirements of TEK17.

TABLE 7.6. Optimal retrofitting combinations for the single-family house with direct electricity.

Name	Energy [kWh/m^2 year]	dLCC [NOK/ m^2]	Insulation thickness				U-value glazing [W/m^{2}K]	Level of control strategies			
			Ext. wall	Roof	Basement wall	Floor		Heating	Ventilation	Lighting	Blinds
S-005	117.5	720	0.35	0.3	0.15	0.2	0.8	A	B	D	D
S-256	114.9	969	0.4	0.35	0.2	0.2	0.8	A	B	B	D
S-258	112.4	1196	0.4	0.4	0.2	0.3	0.8	A	B	A	D
S-226	111.7	1410	0.4	0.4	0.2	0.3	0.8	A	D	A	D
S-296	111.1	1722	0.4	0.4	0.2	0.2	0.8	A	C	A	D
S-307	110.4	1899	0.4	0.4	0.3	0.35	0.8	A	C	A	D

TABLE 7.7. Optimal retrofitting combinations for the single-family house with direct electricity and an air source heat pump.

Name	Energy [kWh/m^2 year]	dLCC [NOK/ m^2]	Insulation thickness				U-value glazing [W/m^{2}K]	Level of control strategies			
			Ext. wall	Roof	Basement wall	Floor		Heating	Ventilation	Lighting	Blinds
S-HP-035	106.6	332	0.25	0.4	0.2	0.25	1.2	B	D	D	D
S-HP-005	101.9	452	0.3	0.3	0.25	0.15	0.8	A	B	D	D
S-HP-190	97.3	562	0.35	0.35	0.25	0.25	0.8	A	B	B	D
S-HP-262	94.7	872	0.35	0.4	0.25	0.25	0.8	A	A	A	D
S-HP-257	94.6	611	0.4	0.4	0.2	0.3	0.8	A	B	A	D
S-HP-164	93.8	1383	0.4	0.4	0.2	0.3	0.8	A	C	A	D

Table 7.8. Optimal retrofitting combinations for the the representative apartments with direct electricity.

Name	Energy [kWh/m^2 year]	dLCC [NOK/ m^2]	Insulation thickness		U-value glazing [W/m^2K]	Level of control strategies			
			Ext. wall	Roof		Heating	Ventilation	Lighting	Blinds
A-100	120.3	139	0.4	0.3	1.2	B	C	D	D
A-235	116.4	290	0.4	0.4	1.2	C	B	B	D
A-042	115.4	454	0.35	0.4	1.2	C	C	B	B
A-046	114.5	795	0.4	0.4	0.8	A	C	A	D
A-160	114.2	1050	0.4	0.4	0.8	A	A	B	B
A-105	114.1	1319	0.4	0.4	0.8	A	A	A	B

Table 7.9. Optimal retrofitting combinations for the representative apartments with direct electricity and an air source heat pump.

Name	Energy [kWh/m^2 year]	dLCC [NOK/ m^2]	Insulation thickness		U-value glazing [W/m^2K]	Level of control strategies			
			Ext. wall	Roof		Heating	Ventilation	Lighting	Blinds
A-HP-102	110.8	269	0.4	0.3	1.2	B	C	D	D
A-HP-231	107.8	341	0.4	0.3	1.2	C	B	B	D
A-HP-042	105.5	570	0.35	0.4	1.2	C	C	B	B
A-HP-066	103.8	721	0.4	0.4	1.2	A	B	A	D
A-HP-227	103.1	877	0.4	0.4	1.2	A	A	A	D
A-HP-014	102.8	1159	0.4	0.4	1.2	A	A	A	B

Table 7.10. Optimal retrofitting combinations for the apartment block with direct electricity.

Name	Energy [kWh/m^2 year]	dLCC [NOK/ m^2]	Insulation thickness		U-value glazing [W/m^2K]	Level of control strategies			
			Ext. wall	Roof		Heating	Ventilation	Lighting	Blinds
AB-074	127.7	728	0.3	0.35	1.2	B	C	B	D
AB-235	125.7	754	0.4	0.4	1.2	C	B	B	D
AB-042	124.6	871	0.35	0.4	1.2	C	C	B	B
AB-066	124.3	1007	0.4	0.4	1.2	A	B	A	D
AB-230	123.6	1099	0.4	0.4	1.2	A	A	A	D
AB-105	123.2	1127	0.4	0.4	0.8	A	A	A	B

TABLE 7.11. Optimal retrofitting combinations for the apartment block with direct electricity and an air source heat pump.

Name	Energy [kWh/m^2 year]	dLCC [NOK/ m^2]	Insulation thickness		U-value glazing [W/m^{2}K]	Level of control strategies			
			Ext. wall	Roof		Heating	Ventilation	Lighting	Blinds
AB-HP-909	114.5	678	0.25	0.35	1.2	A	B	A	D
AB-HP-066	112.1	830	0.4	0.4	1.2	A	B	A	D
AB-HP-227	111.3	922	0.4	0.4	1.2	A	A	A	D
AB-HP-159	111.2	815	0.4	0.4	0.8	A	A	B	B
AB-HP-014	111.0	1123	0.4	0.4	1.2	A	A	A	B
AB-HP-107	111.0	1001	0.4	0.4	0.8	A	A	A	B

The energy consumption for the simulation-based optimization with TEK17 envelopes did not result in equal values to the results from the parametric analysis in *Section § 6.2*. This was due to the different internal gain schedules that were used. In the parametric analysis, standardized schedules for equipment and lighting were used, while typical schedules were used in the simulation-based optimization. The yearly energy use for both equipment and lighting loads were the same. Especially for lighting less energy savings were achieved when a typical schedule was used as opposed to the standardized schedule. The profitability of the simulation results of the simulation-based optimization and the parametric analysis can neither be compared as a different reference value was used.

7.4 Thermal Comfort Assessment

Figure 7.5 shows the thermal comfort of the optimal combinations as a function of the energy consumption. The occupied indoor discomfort degree hours (DDH) were significantly reduced after retrofitting. This was mostly a result of installing external blinds and more advanced BACS, as 98–100% of the DDH were caused by overheating. Undercooling as a result of heating strategies with temperature setback occurred almost solely when no occupants were present and was therefore not registered. This means that the size of the heaters and the reheating time of 1.5 hours were sufficient to ensure thermal comfort during occupied hours.

There were no significant differences in DDH between the optimal packages of each building. The living room of the corner apartment had more DDH than the living room on the upper floor of the single-family house. This may be caused by less heat losses due to a more compact build, or because cross-ventilation was less efficient. Overheating for both buildings can be decreased further by optimizing the window opening control strategies so that the window opening size is adapted to the outdoor temperature. For example, the openable area can be increased in the summer to maximize cooling by natural ventilation and decreased in the winter to avoid excessive heating. However, as thermal comfort was not the main focus, these issues were not further investigated.

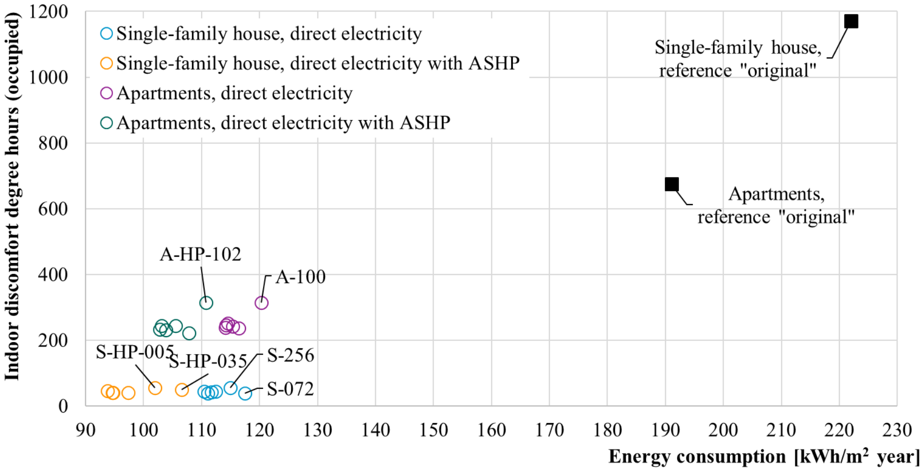


FIGURE 7.5. Discomfort degree hours of the optimal retrofitting combinations.

7.5 Short Conclusions

The following was concluded from this analysis:

- The achieved energy savings were 32–57% for the single-family house and 17–46% for the representative apartments.
- Installing an air source heat pump in addition to direct electricity as a space heating source was the most cost-effective retrofitting measure for both buildings.
- Upgrading the heating and lighting control strategies was essential for cost-effective retrofitting.
- It was cheaper to retrofit the building envelope and improve the energy efficiency of buildings with a higher volume-to-surface ratio, i.e. more compact buildings, such as apartments.
- Retrofitting the whole apartment block was more profitable than retrofitting only the top apartments.
- Thermal comfort improved significantly after retrofitting, though there were no significant differences between the retrofitting combinations.
- Apartments generally had more overheating degree hours than single-family houses, but this was not investigated further.

8 | Conclusion

Retrofitting residential buildings is crucial to decrease the energy consumption of the existing building stock. There has been a lot of focus on energy savings from retrofitting the building envelope and systems, and the focus on implementing smart technologies increases. However, there are few studies that evaluated the impact of building automation control systems (BACS) on the energy efficiency of residential buildings. The main objective of this thesis was to evaluate the impact of integrating BACS with building envelope retrofitting on the energy efficiency of two typical Norwegian houses. Six sub-questions were defined to answer the main research question. These questions focused on analyzing the existing building stock; defining and modelling reference buildings; evaluating the effect of BACS on the energy consumption; finding optimal retrofitting solutions that combined building envelope and energy systems retrofitting with implementing advanced BACS; and assessing the cost-effectiveness of the proposed retrofitting solutions.

A literature study was conducted to analyze the retrofitting status of the residential building stock in European cold climates. It was expanded with an analysis of the Norwegian building stock and its energy use. Several studies concluded that a large share of the existing building stock in Europe is not efficient and that most of the building stock consists of residential buildings. It was found that in Norway, residential buildings accounted for 11% of the total energy consumption and 32% of the electricity consumption. Detached single-family houses represented the largest share of floor area, and had the highest average energy consumption per heated floor area (196.8 kWh/m^2 year). Multi-dwelling buildings represented the second largest share of floor area, and had the lowest average energy consumption per heated floor area (153.9 kWh/m^2 year). These two buildings offer a large energy saving potential when retrofitted. Most of the literature on retrofitting dwellings focused on building envelope measures and energy systems. A third retrofitting measure of implementing advanced BACS was not studied often.

Based on the analysis of the residential building stock, building energy performance simulation models were created in IDA ICE for a typical detached single-family house and for an apartment block. These were validated by comparing the simulation results to typical references values, to provide a model that was representative for the building typology. Schedules for occupancy, lighting and equipment mimicked realistic behavior and were adjusted to fit the yearly normalized value.

During the process of defining and modelling the control strategies, it was concluded that the descriptions in EN 15232 can be interpreted in different ways. Two approaches with different system design and setpoints were used to illustrate this. Both approaches achieved energy savings up to 24% from implementing BACS. However, the energy savings were lower when the original energy consumption was lower. The achieved energy savings were also impacted by the choice of setpoints and modelling strategy. These should ideally be optimized for the simulation model, though this was not part of the thesis. The impact of individual BACS functions and complete BACS class upgrades were investigated. When BACS were upgraded as individual measures, only heating control strategies resulted in significant energy savings. Upgrading all BACS functions (i.e. heating, lighting, ventilation and shading control) to the same class resulted in the highest energy savings. Automation measures, especially heating control strategies, had a bigger impact on the energy consumption when volume-to-surface ratio was higher, i.e. more compact buildings, such as apartments.

As a final step of the work, optimal retrofitting packages for a typical detached single-family house and apartment block were defined. This was done through single-objective optimization in IDA ICE with GenOpt. Energy savings up to 57% were achieved for the single-family house, and up to 46% for the representative apartments. Installing an air source heat pump was the most cost-effective retrofitting measure in terms of energy savings. Implementing more advanced BACS measures accounted for up to 24% of the total energy savings. Upgrading the heating and lighting control strategies was essential for cost-effective retrofitting. Ventilation and blind control strategies did not significantly affect the energy consumption, but contributed to improving the thermal comfort. For more compact building shapes, it was cheaper to improve the energy efficiency through retrofitting. Assessment of the thermal comfort showed that the number of indoor discomfort degree hours significantly reduced after retrofitting, though there were no significant differences between the retrofitting combinations within a case.

To summarize and answer the main research question: *What is the impact of integrating building automation measures with envelope retrofitting on the energy efficiency of housing in cold climates?*, the following can be said. BACS can result in significant energy savings for residential buildings, though its impact is lower than the impact of traditional retrofitting measures, such as building envelope and energy systems retrofitting. The effectiveness of BACS depends highly on the design of the control strategies, the chosen setpoints and the building compactness. In general it can be said that if the primary goal is to minimize the energy consumption, an air source heat pump in combination with a high-performance building envelope and high-performance heating and lighting control strategies is the most cost-effective. For more profitable solutions or when a deep retrofit is not possible, high-performance BACS are an attractive retrofitting measure.

8.1 Scientific impact

To assess the scientific impact of this thesis, the work was compared to a selection of the most relevant of the reviewed case studies included in the literature review. On of the main conclusions from the literature review was that many studies focused on envelope retrofitting and retrofitting of HVAC systems and/or energy systems. Only few studies assessed the potential energy savings of BACS, and even fewer included case study buildings in a cold climate. This was identified as a research gap. Many studies included economic assessment, though only few included thermal comfort assessment. Analysing thermal comfort is crucial when BACS are implemented as they affect thermal comfort parameters. It requires as a simple assessment as a minimum to ensure that the system settings result in improved thermal comfort, in addition to improved energy performance.

Table 8.1 shows the topics related to energy retrofitting covered by the thesis and other relevant studies. These are presented in alphabetical order and are not arranged by relevance. All case study buildings were residential and in all cases the energy savings from upgrading an existing dwelling were investigated. The table illustrates the identified research gap in the existing literature as well as the similarities and differences between the thesis and other studies.The table also shows that this study partially covered the identified research gap.

Table 8.1. Similarities and differences between the thesis and other relevant studies [9]. Topics that were evaluated in detail are marked with *x*. Topics that were only partly explored (e.g. only one option is considered) are marked with *(x)*.

		Retrofitting measures			**Additional assessments**			
Study	**Cold climate**	**Envelope retrofitting**	**HVAC or energy systems retrofitting**	**BACS**	**Optimization**	**Economic assessment**	**Thermal comfort assessment**	**Sensitivity analysis**
Thesis	x	x	(x)	x	x	x	x	–
Hirvonen et al. [35]	x	x	x	–	x	x	–	–
Ippolito et al. [26]	–	–	–	x	–	x	–	–
La Fleur et al. [34]	x	(x)	–	–	x	x	–	x
Niemelä et al. [15]	x	x	x	–	x	x	–	x
Reda et al. [31]	x	–	x	x	–	–	x	–
Sanseverino et al. [29]	–	–	–	x	–	x	–	–

One element of the identified research gap that this study covered is the investigation of BACS as an energy saving retrofitting measure in combination with envelope retrofitting. Another element is that this study went beyond evaluating the energy saving potential and included optimization, economic assessment and thermal assessment.

An element of the research gap that remains is related to the limited options of some of the investigated measures and robustness of the results. Only one retrofitting option for energy systems was considered, as the results showed that the selected energy system has a significant impact on the energy consumption. One climate zone was selected, as opposed to a selection of cold climate zones. This was the case in most other studies as well, but limits the ability to generalize of the results.

Finally, several other parameters that impact the simulation results were identified throughout this study. These include, but are not limited to, occupancy behavior, BACS system settings and energy costs and tariffs. More detailed analysis and sensitivity (robustness) analysis is required to address these issues. Section *§ 8.3* discusses the limitations of this study and gives directions for future work based on these limitations, keeping in mind the research gap.

8.2 Broader impact

There is a clear shift in the building industry towards more sustainable buildings with a lower environmental impact. This shift requires innovative solutions for new buildings as well as for the renovation of existing buildings. This thesis investigated the potential of smart home technologies, which are increasingly more available on the market, to improve the energy efficiency of existing housing. The work showed that BACS can be seen as a new retrofitting measure that has become possible due to the development of more complex analysis software and advanced technologies for intelligent buildings.

BACS address the part of the amendment of 2018 of the Energy Performance of Buildings Directive (EPBD) that focuses on implementing smart technologies to improve the energy performance and the thermal and visual comfort of buildings increased. BACS are well-developed for commercial buildings but rarely used to their full potential in residential buildings. They can be attractive retrofitting measures, especially when the improvement of other energy performance requirements, such as the U-values of the building envelope, is limited due to, for example, space restrictions or financial constraints.

Smart home technologies, such as the BACS strategies described in this study, are a measure to decrease the energy use of the building (input) while maintaining, or in some cases improving, a comfortable environment (output). Improved energy efficiency is thus achieved by decreasing the input per output and in some cases, where a poor energy performance results in poor thermal comfort, also increasing the output per input. It was concluded that more advanced heating control strategies, such as night-setback temperature, significantly decreased the energy consumption. This is a convincing conclusion for housing in Norway, and other cold climates, where space heating in old, poorly insulated dwellings accounts for most of the energy consumption. With increasing cost of energy, this is also an attractive outcome in terms of monthly energy bills.

8.3 Future Work

Chapter 3 pointed out several limitations of this work. This section discusses those in more detail and gives some research directions for future work, based on the assumptions and results presented in *Chapters 5* to *7*. This section is divided into limitations related to modelling and limitations related to the methodology including post-processing assessments.

8.3.1 Modelling

There lies an uncertainty in defining reference buildings and validating the simulation models with typical averaged values instead of with measured data. This was done so that the results could be generalized and applied to a large group of dwellings, rather than creating a model fitted to one particular building. Because of this, the results can only be adopted as optimal solutions for residential buildings that fit the assumptions: correct building typology and geometry, located in the climate of Trondheim (or similar) and with no previous retrofitting carried out. There is no guarantee that the presented optimal retrofitting solutions will be the most optimal retrofitting solutions for other buildings that do not fit the brief. Some assumptions, such as climate, orientation and state of the building, are case specific and can influence the results in terms of energy saving potential and profitability. In addition, there are factors such as occupancy behaviour and lifestyle, that will impact the outcome.

Case study buildings

While selecting two representative case study buildings, it was discovered that there are many variations to these building typologies. Catalogue house designs, such as the selected typologies, are often adjusted to the site location. This could impact parameters such as the orientation, surroundings, sheltering, exterior surface area in contact with the ground. It is expected that variations in sheltering and exterior surface area in contact with the ground have a limited impact when the heated floor area is the same. Orientation and shading from the surroundings could have a significant impact on the results, due to the variation in solar heat gains

Two representative apartments were modeled instead of the whole apartment block. This was done to minimize the computational time needed to run the simulations. Because of this, the results are only valid for these two apartments. The optimization results were used to estimate the energy savings and profitably of retrofitting the whole apartment building. Retrofitting of the ground floor was not taken into account. The results were heavily derived from the optimization results of the representative apartments. For more correct optimal packages for the whole apartment block, the simulation model should be adapted so that the included apartments represent the whole building better (i.e. including apartments on the ground floor and middle floor).

Climate

All simulations were performed using climate data for Trondheim. Due to the large variation of climate zones in Norway (and other cold climate countries), it is not possible to assume the outcome of the study for the whole of Norway. It would be interesting to select several climate zones, ranging from mildest to harshest, to evaluate the impact of climate on the results. It is not unlikely that optimal retrofitting solutions in terms of energy and profitability differ between buildings located in the south of Norway and those located in the North. Climate zone could be a scenario in a robustness assessment.

State of the building

It was assumed that no retrofitting was carried out previously, though it is highly unlikely that a house from this built period has not undergone any type of building envelope retrofitting. Dwellings older than 20-30 years are often partly retrofitted (e.g. new windows are installed) due to the expired technical lifetime of components. A reference case that includes some retrofitting instead of no retrofitting will result in different optimal combinations of retrofitting solutions. More research is needed to assess the effect of varying assumptions on the state of the building. Several scenarios of varying levels of retrofitting could be part of a robustness assessment.

Building automation control strategies

As mentioned before, the setpoints of the BACS influence the effectiveness of the measures. In this study, setpoints were assumed at the start of the analysis and adjusted according to preliminary validation results. However, setpoints were not optimized. Future research should focus on optimizing the BACS settings for each building typology and investigating the effect of not-optimal settings on the energy savings. Furthermore, not all BACS functions were taken into account. Cooling functions were excluded as there are typically no active cooling systems installed in residential buildings. Domestic hot water functions were excluded as well, though there is a potential to optimize the heating of hot water to shift and/or reduce peak loads. Advanced control of water-borne heating systems was not investigated, though this is relevant for residential buildings connected to district heating.

It can be expected that grid rent tariffs will be introduced with varying energy prices based on the time of day and season. The impact of BACS on the profitability will significantly increase because of this, as advanced control of heating (and cooling), ventilation, lighting, domestic hot water, and other functions such as charging electric vehicles, can take grid rent tariffs into account to minimize the energy cost. This could be investigated in future work.

Occupant behavior

Occupancy behavior (schedules) was modelled based on schedules presented in a Norwegian study on the energy use in residential buildings and did not take into account different user profiles or lifestyles. The occupancy behavior in the window opening strategies and in the blind control strategies was simplified occupant behavior. The energy use and the effectiveness of BACS is significantly impacted by occupancy behavior. For more robust results, the occupant behaviour should be investigated more. Different user profiles for various lifestyles could be included as scenarios in a robustness assessment. A component could be added to the control strategy that takes into account more dynamic occupant behavior. For example, outdoor temperature compensated behavior when opening windows. This could be investigated in future work.

Plausibility of the assumptions

Many assumptions were made to define the scope of the study. As mentioned earlier, some of these assumptions can have a large impact on the results. The plausibility of some of the assumptions is briefly discussed below.

Though cost-effective retrofitting solutions were found, some of the proposed optimal building envelope retrofitting might not be realistic. All insulation was added on the exterior side of the construction. However, it might not be desirable or feasible to add insulation to the exterior side, for example for the ground floor. It would require removing the original concrete floor and lowering the masses below the floor to place the insulation. For heritage buildings or buildings close to other buildings, it could be difficult to add exterior insulation to the walls and/or roof. Therefore, the proposed optimized results might not be suitable for every house in the investigated housing typologies.

As part of assessing the energy saving potential of BACS, highly advanced control strategies were introduced to the residential buildings. Many of these are typically not a common feature in housing. Control based on demand might not result in large energy savings depending on the lifestyle. There are commonly only small variations in typical occupancy behavior and number of occupants within a household. This kind of strategy is more suitable for commercial buildings with high variations in number of occupants. It is likely that only the advanced control strategies that have a direct positive effect on the energy consumption (and/or thermal comfort), such as heating control strategies, are attractive measures for residential buildings.

In addition to this, the practical side of installing advanced BACS should be mentioned. More advanced control strategies require additional sensors and upgrades to technical systems. For example to upgrade a ventilation system with constant supply air temperature and air flow rates to variable setpoints and air flow rates. This requires more components to the ventilation system and in some cases more ducting. In retrofitting projects, the existing geometry and available floor height could be constrictions for more advanced BACS. Another example is demand detection. This requires a sensor, e.g. a CO_2 sensor, in each room which needs to be connected through wiring or by a wireless network to the main system. It could be challenging to place and connect all required components of the energy management system in an existing building, especially when no internal retrofitting is done. Installing BACS also requires proper user interaction and, to some extent, technical understanding of the system. This is a challenge as well.

8.3.2 Methodology and post-processing assessments

This study concluded that there is a significant potential for saving energy in existing buildings through retrofitting. Ideally, the choice of retrofitting measures is based on achieved energy savings as well as cost. This requires optimization based energy performance simulations. Defining optimal retrofitting solutions is a challenging task as these measures should save energy, improve the indoor climate, and be cost-effective. The results are influenced by the choice of method, but also by assumptions.

Robustness

Due to uncertainty of assumptions, there is often a deviation between the simulated energy performance and the actual energy performance, also in retrofitting cases. One solution to minimize the performance gap is by using robust retrofitting measures. A robust building performs as it was designed under various scenarios. In order to assess the robustness of the optimal retrofitting packages, scenarios that illustrate uncertainties such as occupancy behavior and climate, including climate change, should be selected. Some concrete examples have been mentioned earlier.

Optimization

Optimization was done with a single-objective optimization of the energy consumption. Associated difference in life cycle cost (dLCC) were calculated during post-processing to assess the profitability of each retrofitting combination. A multi-objective optimization can optimize energy consumption and dLCC simultaneously, to find cost-effective solutions. Since cost are a vital aspect of construction projects, it is recommended that future work focuses on multi-objective optimization as opposed to single-objective optimization.

Thermal comfort and economic assessment

The assessment of thermal comfort and cost was simplified as these were not primary objectives of the thesis. For a full and more detailed thermal comfort analysis, more rooms should be considered instead of one representative room per house. The economic analysis was simplified by neglecting maintenance cost and using a fixed energy price with price escalation. It is expected that different grid rent tariffs will be introduced with energy prices varying based on the time of day and season. With the introduction of such grid rent tariffs, the importance of smart control systems and peak load shifting increases. Therefore, this could be included in future work.

Database

This study could be continued to develop a database with robust, optimal retrofitting solutions for various typologies of Norwegian residential buildings in different climate zones. The uncertainty of the previously mentioned parameters should be taken into account.

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Appendices

Paper A - Retrofitting towards energy efficient homes in European cold climates - a review

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CORRECTION

Correction to: Retrofitting towards energy-efficient homes in European cold climates: a review

Laurina C. Felius · Fredrik Dessen ·
Bozena Dorota Hrynyszyn

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The original version of this paper was unfortunately published with an error in Fig. 3. The published figure includes excess layers, which negatively affect the readability of the figure. The correct figure is displayed below. The authors apologize for this error.

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Paper B - The impact of building automation control systems as retrofitting measures on the energy efficiency of a typical Norwegian single-family house

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The impact of building automation control systems as retrofitting measures on the energy efficiency of a typical Norwegian single-family house

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The impact of building automation control systems as retrofitting measures on the energy efficiency of a typical Norwegian single-family house

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Abstract. In this study, the energy savings and cost-effectiveness of building automation measures in a retrofitting context are evaluated for a Norwegian single-family house. In addition, two methods for calculating savings from implementing building automation control systems (BACS) are compared: energy performance simulation and the BACS factor method proposed in EN 15232. Four retrofitting packages and four automation levels are combined to create 16 model versions. This study shows that BACS can increase energy savings and improve indoor comfort when implemented as a retrofitting measure. However, the relative impact on energy savings of building automation decreases when the delivered energy is lower. In addition, the impact of building automation on the energy savings is low compared to the effect of retrofitting the building envelope. When only BACS are implemented, savings up to 21% can be achieved, but when an integrated solution is implemented savings up to 60% can be achieved. Finally, some directions for future work are suggested.

1. Introduction

Buildings consume a large share of the total energy consumption in Europe, mostly due to an inefficient existing building stock [1]. As residential buildings represent around 75% of the existing buildings, it can be concluded that retrofitting offers a significant energy saving potential [2]. The building stock situation in Norway is similar, though it is characterized by its reliance on electricity as the main energy source in residential buildings [3, 4]. A way to improve the energy efficiency of existing buildings, though not often done, is by implementing building automation control systems (BACS). BACS can reduce the operational energy use while maintaining a comfortable indoor climate as highlighted in previous work [5], but system settings can have a significant effect on the achieved energy savings [6]. The system can also reduce peak loads and overall energy costs. This is increasingly important in Norway, as a new grid rent tariff will be introduced by the end of 2020 [7]. If the typical consumption pattern is not changed, it will result in higher energy costs for the consumer [8, 9].

Standard EN 15232 [10] focuses on building automation control (BAC) and technical building management (TBM) functions that can improve the energy performance of a building. The BAC functions are divided into heating, cooling, ventilation, hot water, lighting and blind control; the

TBM functions focus on data monitoring and diagnosis. Four efficiency levels are introduced in the standard based on the implemented functions (see table 1) [10]. These labels are not related to energy performance labels [11], though both are defined by delivered energy. To quickly estimate the effect of BAC and TBM functions on the energy performance of a building, the BACS factor method can be used as presented in EN 15232. Efficiency factors for different building categories are divided into thermal and electrical energy. Thermal energy includes energy used for heating, cooling and domestic hot water. Electrical energy includes auxiliary energy and energy used for lighting. The energy use of appliances is not taken into account. By multiplying the efficiency factors with its associated delivered energy, the expected energy savings are estimated. The efficiency factors assume that the current standard of BACS is level C. However, for this case study it was assumed that there is no automation present (level D). The overall efficiency factors for housing are listed in table 1.

Table 1. BACS levels with corresponding thermal and electrical efficiency factors to estimate the energy savings from implementing BACS and TBM functions [10]

	Thermal	Elecrical
Level D: no automation	1.10	1.08
Level C: standard BAC for new buildings	1.00	1.00
Level B: advanced BAC with some TBM functions	0.88	0.93
Level A: high-performance BAC and TBM functions	0.81	0.92

Several studies discussed the expected outcome from upgrading BACS in residential buildings and concluded that significant energy savings can be achieved [12, 13, 14, 15]. However, the number of studies investigating the effect of BACS in a residential context is limited and does not focus on cold climates. Therefore, the aim of this study is to evaluate the potential of BACS as an energy saving measure for a typical Norwegian house. Previous work highlighted that the effect on the total energy consumption is low compared to savings that can be achieved by upgrading the building envelope [5, 16]. Therefore, four BACS packages are assessed in combination with four retrofitting packages, resulting in 16 models. The packages are based on standards and are not optimized for this building. In the BACS packages, not all functions listed in EN 15232 are included. The combinations of measures are evaluated in terms of energy savings, indoor comfort and cost-effectiveness. In addition, the soundness of the BACS factor method is evaluated by comparing estimated energy savings calculated with this method to the simulation results.

2. Case study model

The case study (see figure 1) is a typical Norwegian single-family house as described by Thyholt et al. [17]. The external walls and roof are a timber-frame construction and the walls of the lower floor are constructed with LECA blocks. The ground floor is a concrete slab on grade with no to little insulation. This housing type is located throughout Norway, but for this study the climate of Trondheim, Værnes was used. The house was built according to the building code of 1969. However, higher U-values are used in the simulation model to take into account that the insulation may have worsened over the years due to deterioration. An overview of the electrical loads and internal gains in the house is given in table 2.

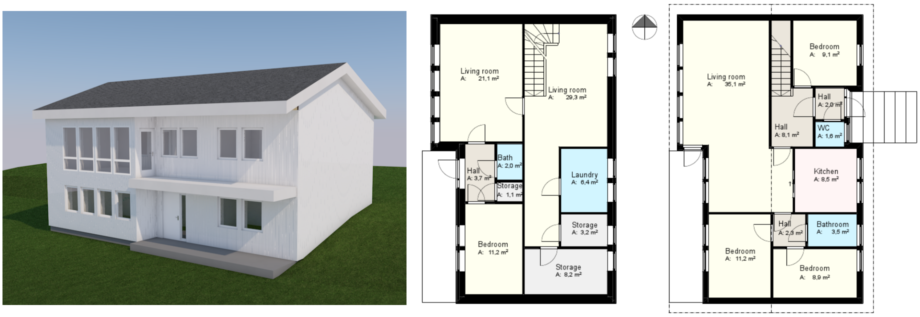

Figure 1. Layout and appearance of a typical single-family house, mostly built in the 70s and early 80s, with an area of ca. 170 m^2. The east half of the lower floor is partly submerged.

Table 2. Electrical loads and internal gains in the case study. The lighting load in the retrofitting packages, after upgrading to LED, is given in brackets.

	Equipment	Room	Area [m^2]	Lighting [Watt]	Heating [watt]
Kitchen	Freezer, fridge, oven, microwave, kettle, small cooking, dishwasher		8.5	2 x 46 (10)	1000
Living room	Television, TV receiver, HiFi, clock, personal computer	LR 1	35.0	3 x 46 (10)	3800
		LR 2	21.0	3 x 46 (10)	2000
		LR 3	26.6	3 x 46 (10)	1500
Bedroom	Clock, cordless phone	BE 1&2	11.2	46 (10)	1000
		BE 3&4	9.1	46 (10)	1000
Bathroom		BA 1	3.5	46 (10)	500
		BA 2	1.9	30 (6)	250
		WC	1.5	30 (6)	250
Laundry	Iron, vacuum cleaner, washing machine, dryer		6.4	46 (10)	500
Hall		H 1	5.3	2 x 30 (6)	600
		H 2	3.6	30 (6)	250
		H 3	2.3	30 (6)	250

2.1. Simulation model

The case study building was modeled in IDA-ICE [18]. The aim of this study required a model where all rooms were modeled as individual zones to study the effects of BACS (i.e. individual room control and setpoints). The simulation model was validated by comparing the model with standardized input values and occupancy behaviour [19] to reference values [20, 21]. Occupancy behaviour and distribution of internal gains were adjusted to fit a more realistic scenario. Occupancy schedules were derived from Nord et al. [22], the schedules for lighting and equipment were taken from open-source models by Richardson et al. [23, 24] and the schedule for DHW was taken from Ahmed et al. [25]. These models were adapted to the case study and location.

The effect of four building automation levels was evaluated for four retrofitting packages, resulting in 16 model versions. The retrofitting packages are based on standards and are not optimized for the building type. The first package (R0) is the building in its current state, without any renovation. Standard values for old buildings as presented in NS 3031 [19] are used. In package R1 (minimum retrofitting) only the windows are improved. As a result, it is expected that the airtightness improves and that thermal bridges around the windows are reduced. To estimate the improvement of airtightness, the method of Ridley et al. [26] was used. In package R2 (moderate retrofitting) the house is upgraded to TEK 17, the current minimum energy requirements in Norway [27]. Package R3 (major retrofitting) is based on the building envelope criteria from the Norwegian passive house standard [28]. The improvements to the energy performance characteristics are listed in table 3. In packages R1-3 it is necessary to upgrade the ventilation system to ensure proper air quality. Additionally, all lights were replaced by LED lights in R1-3.

Table 3. Energy performance characteristics in the four renovation packages.

	R0 - no renovation [19]	R1 - minimum	R2 [27] - moderate	R3 - major [28]
U-value basement wall [W/m^{2}K]	1.0	1.0	0.18	0.10
U-value basement floor [W/m^{2}K]	0.5	0.5	0.10	0.08
U-value timber frame wall [W/m^{2}K]	0.6	0.6	0.18	0.10
U-value roof (loft insulation) [W/m^{2}K]	0.6	0.6	0.13	0.08
U-value windows [W/m^{2}K]	2.8	1.2	0.8	0.8
Air leakage at 50 Pa [h^{-1}]	6.0	1.4	0.6	0.6
Norm. thermal bridge value [W/m^{2}K]	0.07	0.07	0.05	0.03
SFP [kW/(m^3/s)]	2.0	1.5	1.5	1.5
Heat recovery [%]	0	80	80	80
Ventilation system	Mech. exhaust	Balanced	Balanced	Balanced

The heating system consists of electric radiators and was sized according to the heating demand of the building. The heating capacity includes the additional reheating capacity needed to increase room temperatures from night to day setpoint within one hour, as required in some of the BACS scenarios. Though this house typically has a fireplace, it is assumed that it is not used. There are five occupants that use the whole house apart from the storage rooms (i.e. no heaters and no internal gains). Internal and external blinds and window opening control are added as fixed occupant behaviour to avoid overheating and to provide fresh air. Windows are opened when the operative temperature exceeds a setpoint given by the running mean outdoor temperature or if the CO_2 levels are higher than 1000 ppm. The blinds go down when the indoor temperature exceeds 23.5 °C. These control strategies are only applied when at least one occupant is at home.

2.2. Building Automation Control

Automation levels D, C, B and A were implemented in R0-3 based on their description in EN 15232 [10]. Only HVAC systems and equipment that were already present in level D were automated. An overview of the input parameters is given in table 4. As the standard describes the type of control but does not give specific input parameters, several assumptions were made.

- The heating temperature setpoints in level D are reference values [19]. The setpoints in level C, B and A are based on survey data, taken from [29].

- Ventilation air flow rates are based on minimum requirements from TEK17 [27].
- The supply air temperature setpoint, when variable, is increasing with the outdoor temperature as it is mainly used to provide fresh air [30, 31].
- The day/night schedule is based on NS 3031 [19].
- Automation of the domestic hot water system and blinds were outside the scope.
- There is no active cooling system and therefore automation of cooling was irrelevant.

Table 4. Settings for the BACS and TBM functions for levels A, B, C and D.

Heating control	D [°C]	C [°C]	B [°C] day / night	A [°C] occ. / not occ.
Living	22.0	21.5	21.5 / 19.0	21.5 / 19.0
Bedroom	22.0	19.0	19.0 / 19.0	19.0 / 19.0
Bathroom	22.0	23.0	23.0 / 19.0	23.0 / 19.0
Supply air temperature	D [°C]	C and B [°C]		A [°C]
All rooms	18.0	16.0-21.0, depending on T_{out}		16.0-21.0, depending on $T_{in,op}$
Air flow rate	D [L/s m^2]	C and B [L/s m^2] day / night		A [L/s m^2] occ. / not occ.
Living (+)	CAV, 0.33[1]	0.33 / 0.19		0.33 / 0.19
Bedroom (+)	CAV, 0.80[1]	0.19 / 0.80		0.80 / 0.19
Kitchen (-)	CAV, 1.20[1]	3.50 / 1.20		3.50 / 1.20
Laundry (-)	CAV, 1.60	3.20 / 1.60		3.20 / 1.60
Bathroom (-)	CAV, 4.40	8.70 / 4.40		8.70 / 4.40
Toilet (-)	CAV, 6.30	6.30 / 6.30		6.30 / 6.30
Lighting control	D and C		B	A
All rooms	Manual on/off		Manual on/off with day/night schedule and daylight control	Automatic presence detection with daylight control

[1] In the baseline scenario (R0,D) the supply air is provided by natural ventilation.

3. Energy performance

The delivered energy (see equation 1) and indoor climate (i.e. temperature and CO_2 levels) were assessed to evaluate the energy performance of the 16 model versions. There was no energy production on site and all energy was delivered by electricity ($\eta = 1$).

$$\text{Delivered energy} = \sum \frac{E_{\text{demand,energy source}}}{\eta_{\text{energy source}}} - E_{\text{produced,on site}} \qquad (1)$$

The results from the energy performance simulations are shown in Figures 2 and 3. Figure 2 shows the effect of BACS integrated with building envelope retrofitting on the energy savings. The lines represent different retrofitting packages and the symbols represent the BACS levels from D (left) to A (right). The graph shows the savings from the integrated solutions compared to the retrofitting scenario without BACS. Up to 21% energy savings were achieved only by implementing BACS (see figure 2). The slopes of the trendlines indicate that the effect of automation measures relatively decreases when the delivered energy before implementing automation is lower (i.e. level D in packages R1-3). This is consistent with results of other studies [6, 13]. The figure indicates that a similar annual energy consumption can be achieved in R0,A as in R1,D and similar in R2,A as in R3,D.

Figure 3 compares the simulation results with the estimated savings from the BACS factor method and shows the relation between them. Integrating BACS with envelope retrofitting can save up to 60% energy compared to the existing situation. The graph indicates that for this type of housing in the studied climate, the BACS factor method underestimated the energy saving potential of BACS (i.e. the achieved savings are higher than estimated). The savings for detached housing in Trondheim can be estimated by applying a correction factor of: *1.9613 + 1.0698 * BACS factor estimation*. This is the correction factor for the overall savings, though it would be more precise to find the correction factors for thermal and electrical energy.

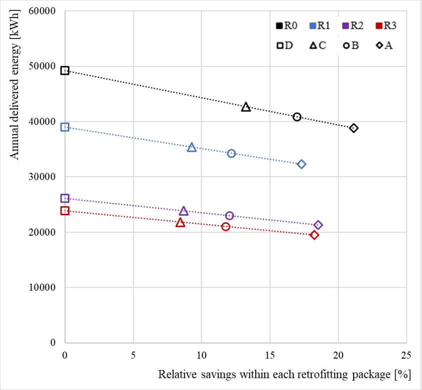

Figure 2. The effect [%] of upgrading building automation measures on the delivered energy in terms of energy savings for different levels of renovation.

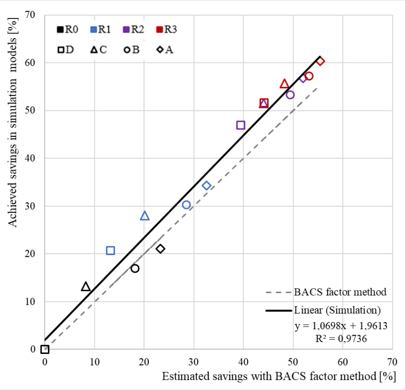

Figure 3. Correlation between the simulation results and estimated energy savings according to the BACS factor method.

3.1. Indoor comfort

Many parameters impact indoor comfort, but in this study only the thermal comfort based on overheating hours and indoor air quality in terms of CO_2 levels were evaluated. The thermal comfort analysis based on EN 15251 [32] showed that the number of unacceptable hours decreased in R0 and R1 when automation is upgraded, but increased when the house is retrofitted to a higher level (R2 and R3) (see figure 4). For all cases (R0-3) the unacceptable hours were mostly due to overheating. As there was no active cooling system installed, it indicates the assumed window opening behaviour no longer provided sufficient free cooling after retrofitting. In addition, the supply air temperature can be high during the summer (equals outdoor temperature). In the automation packages C-A there were less hours in the best category (category I) due to changed setpoints (i.e. night setback). However, this setpoint is accepted in Norwegian households and therefore the indoor temperature should be assessed with adaptive comfort criteria instead. More detailed analysis showed that the indoor temperature increased after retrofitting and became more stable. CO_2 levels improved significantly after renovation, and the best results were achieved with automation level A, because the ventilation is based on demand.

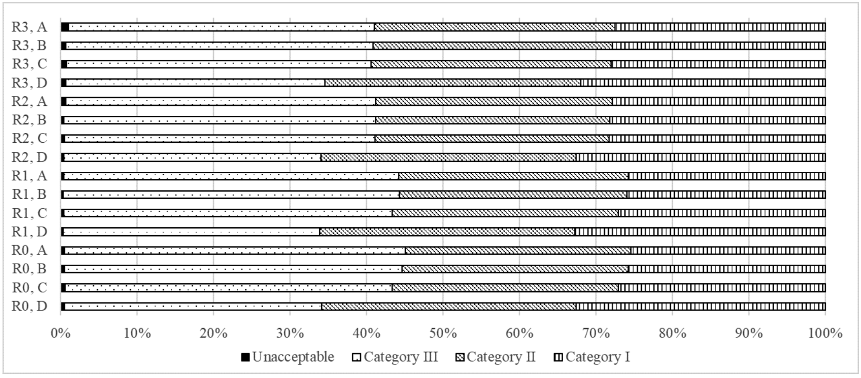

Figure 4. Total occupied hours [%] per comfort criteria as given in EN 15251 [32].

4. Costs and payback period analysis

Discounted payback period (DPP) as given in equation 2 was used to preliminary assess the profitability of the model versions. This method gives the number of years to break even by comparing the yearly energy savings with the initial investment, taking into account the time value of money.

$$\text{Discounted payback period} = \frac{ln[(1 - \frac{dIC}{ES*e} * r)^{-1}]}{ln[1 + r]} \qquad (2)$$

where dIC is the difference in investment cost between the model version and the original in NOK, ES is the energy savings in kWh per year, e is the energy price in NOK/kWh and r is the real interest rate, as calculated in [33]. The interest rate was assumed to be 3.0% because of the low nominal interest on housing loans, the inflation rate was set to 0.03% and the energy price for electricity including taxes and grid rent was 1.23 NOK/kWh with a yearly price escalation assumed at 3.15% [34]. The investment costs including removal of old elements were taken from Norsk Prisbok [35] and were divided into retrofitting and automation packages (see table 5). Maintenance, replacement and recycling costs were not taken into account.

Table 5. Investment costs in NOK for the retrofitting and BACS packages.

	dIC		dIC	Included in BACS
R0	-	Level D	34 387	CAV system
R1	174 401	Level C	76 126	VAV system, weather sensor, general home automation and thermostat controllers
R2	736 891	Level B	134 967	As R1 + daylight sensors and room control units
R3	893 266	Level A	174 735	As R2 + occupancy sensors and temperature sensors

Figure 5 shows the discounted payback period in years for a fixed energy price and with an energy price escalation. As mentioned earlier, the energy savings achieved in R0,A were similar to R1,D and those achieved in R2,A were similar to R3,D. However, the payback period for a higher level of retrofitting was longer. This means that if the focus is only on saving energy, it is more profitable combine a lower level of renovation with the highest level of automation (see figure 6). Though more energy savings are achieved when upgrading to a higher level of building automation, the payback period does not significantly shorten. This is due to higher investment cost for achieving a higher level of automation.

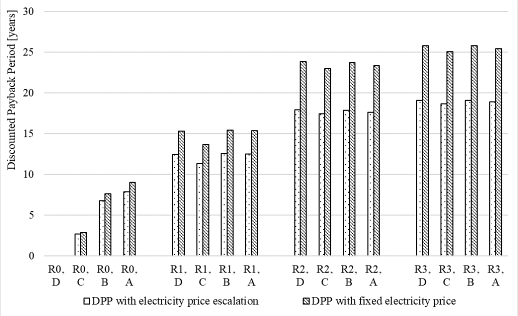

Figure 5. Discounted Payback Period (DPP) for the model versions, both with and without energy price escalation.

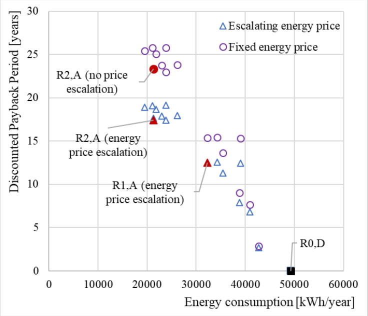

Figure 6. Correlation between the total energy consumption and discounted payback period.

5. Limitations and future work

Not all BACS functions were taken into account because the focus was on those functions that have the most significant impact on energy savings. In addition, this study did not focus on optimizing the setpoints for the different levels of automation. As choosing the setpoint can significantly influence the energy consumption, it may be that higher savings can be achieved when setpoints are optimized. Retrofitting packages R1-3 were not optimized for this building type, and it was not considered how they are implemented. Therefore, they may not be realistic options. In addition, the study focused on electricity as a heating source, but these houses commonly have a fireplace and in retrofitting packages it is common to install an air source heat pump. Future work should focus on optimizing both retrofitting and BACS packages for this building type and should include several heating sources. Only two parameters were chosen to evaluate the indoor climate. Other parameters, such as number of undercooling and overheating hours and humidity levels, should be evaluated as well. The cost of replacement, maintenance and recycling were outside the scope. Therefore, the actual payback period will be longer than presented. When these costs are taken into account, it is more precise to perform a life cycle cost analysis instead. Future work should also focus on different grid rent tariffs to calculate the energy costs instead of a fixed energy price. Though the results look promising, they can only be concluded for a single-family house in the climate of Trondheim. Results may be different for other housing typologies and for other micro-climates in Norway, which should be investigated more.

6. Conclusion

The effect of building automation in combination with retrofitting packages was evaluated for a Norwegian detached house. The study showed that implementing building automation control systems can result in energy savings up to 21% compared to no automation, regardless the renovation level. However, these savings are rather low compared to those that can be achieved by retrofitting the building envelope. By integrating BACS and building envelope renovation, energy savings up to 60% can be achieved. The results indicated that achieved energy savings from retrofitting to a lower level and upgrading BACS are similar to when the building is retrofitted to a higher level without improving BACS. The former option had a shorter payback period, though more studies and optimization of the packages are needed assess the full effect of automation on costs, energy and indoor climate.

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Paper C - Upgrading the smartness of retrofitting packages towards energy-efficient residential buildings in cold climate countries – two case studies

buildings

Article

Upgrading the Smartness of Retrofitting Packages towards Energy-Efficient Residential Buildings in Cold Climate Countries: Two Case Studies

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Abstract: Improving the energy efficiency of existing buildings by implementing building automation control strategies (BACS) besides building envelope and energy system retrofitting has been recommended by the Energy Performance of Buildings Directive (EPBD) 2018. This paper investigated this recommendation by conducting a simulation-based optimization to explore cost-effective retrofitting combinations of building envelope, energy systems and BACS measures in-line with automation standard EN 15232. Two cases (i.e., a typical single-family house and apartment block) were modeled and simulated using IDA Indoor Climate and Energy (IDA-ICE). The built-in optimization tool, GenOpt, was used to minimize energy consumption as the single objective function. The associated difference in life cycle cost, compared to the reference design, was calculated for each optimization iteration. Thermal comfort of the optimized solutions was assessed to verify the thermal comfort acceptability. Installing an air source heat pump had a greater energy-saving potential than reducing heat losses through the building envelope. Implementing BACS achieved cost-effective energy savings up to 24%. Energy savings up to 57% were estimated when BACS was combined with the other retrofitting measures. Particularly for compact buildings, where the potential of reducing heat losses through the envelope is limited, the impact of BACS increased. BACS also improved the thermal comfort.

Keywords: smart retrofitting; residential buildings; building automation control strategies; energy optimization; energy efficiency

1. Introduction

One of the key strategies towards an energy-efficient building stock is retrofitting, especially of residential buildings, which have a considerable energy-saving potential. Effective retrofitting measures and achieved savings are climate-specific, and this paper concentrates on retrofitting the residential building stock in cold climate countries, i.e., Norway. Most of the literature on cold climate retrofitting of dwellings focuses on improving the energy efficiency through retrofitting the building envelope and energy systems, as pointed out by Felius et al. [1].

1.1. Building Automation Control Systems

Another category of retrofitting measures that has potential to decrease the energy consumption, though less often mentioned, is building automation control systems (BACS). BACS can lead to a

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reduction of the operational energy by optimizing the energy use for heating, lighting, ventilation, domestic hot water and blind systems, while, at the same time, maintaining a comfortable indoor climate. The Energy Performance of Buildings Directive (EPBD) amendment of 2018 [2] increased the focus on implementing smart technologies to improve the energy performance and the thermal and visual comfort of buildings. BACS are well-developed for commercial buildings but rarely used to their full potential in residential buildings. BACS can be attractive retrofitting measures, especially when the other energy performance requirements, such as the exterior wall U-value, cannot be improved due to, for example, space restrictions or financial constraints.

Several studies assessed the potential energy savings from BACS for residential buildings in Italy [3–5] and Spain [6] and concluded that implementing BACS improved the energy performance of a detached dwelling by one energy class. However, only a few studies have assessed the impact of BACS on the energy consumption using detailed building performance simulation models. Reda et al. [7] investigated the effect of ICT-driven intelligent solutions for heating and ventilation control in an apartment building through energy simulations in IDA-ICE. They concluded that the energy demand was significantly reduced in buildings with mechanical ventilation, especially in a cold climate. When implementing heating, ventilation and air conditioning (HVAC) control that switched off when windows opened, the energy demand was not affected significantly. Felius et al. [8] assessed the impact of retrofitting the building envelope combined with BACS on the energy consumption of a detached house using energy simulations in IDA-ICE. They found that BACS significantly decreased the energy consumption, though it was less effective than building envelope retrofitting. Combining building envelope retrofitting and BACS upgrades resulted in the highest energy savings.

There is still limited literature available on the impact of BACS on the energy consumption of retrofitting (and new-built) residential projects in cold climates. Therefore, this paper focuses on the energy-saving potential of BACS in combination with other retrofitting measures.

1.2. Simulation-Based Optimization

Simulation tools are highly useful in evaluating the impact of retrofitting measures on the energy performance. This can be a difficult and time-consuming task and is often not performed for smaller projects. Therefore, this paper presents optimal retrofitting packages for typical housing typologies, as opposed to an individual case approach, so that many buildings can benefit from the results, to a certain extent. Finding optimal solutions is typically done by adjusting design variables that affect the energy consumption until the objective function(s) is (are) minimized. This can be done through parametric runs, though it is extremely time-consuming to model every possibility, especially when advanced control strategies are implemented. To improve the time efficiency, automatic simulation-based optimization can be used to find the optimal combinations for a set of given parameters as opposed to running all possible combinations.

In this paper, the simulation tool IDA-ICE (version 4.8) with the built-in optimization tool GenOpt is used to perform a single-objective optimization. This combination, where GenOpt was externally linked to IDA-ICE, was successfully verified by Hasan et al. [9] by comparing the optimization results to a brute-force search method.

Many other combinations of simulation and optimization tools can be used, as the selection of the tools should be adapted to the research objective. Hirvonen et al. [10] used multi-objective optimization with IDA-ICE and the Pareto-Archive NSGA-II genetic algorithm in MOBO software to minimize the life cycle cost and CO_2 emissions for energy retrofitting of four typical Finnish apartment buildings. The same methodology was used by Niemelä et al. [11] to minimize the net present value of the life cycle cost and the primary energy consumption for retrofitting a typical Finnish apartment building. Both studies defined U-values of the building envelope and various heating systems as their design variables. Tokarik and Richman [12] identified cost-effective design solutions for future improvements to a house located in Toronto using EnergyPlus and a NSGA-II algorithm in jEPlus +

EA. La Fleur et al. [13] used the optimization tool OPERA-MILP to identify the optimal life cycle cost for energy retrofitting measures for a Swedish multi-family building.

The number of optimization studies for retrofit cases in cold climates is limited, though several studies performed optimizations for the design of residential buildings. Hamdy et al. [14] proposed a multi-objective optimization approach, based on a genetic algorithm, and combined it with IDA-ICE to minimize the life cycle cost (LCC) and primary energy considering a large-scale solution space for the building envelope and HVAC systems of a Finnish single-family house. The same case study building was used in a study by Hamdy and Mauro [15] that used multi-objective optimization to minimize the CO_2 emissions and the discounted payback time.

1.3. Research Objectives

The objective of our current study was to define optimal packages for building envelope retrofitting in combination with building automation control strategies for two typical Norwegian dwellings. The primary focus was to analyze the improvement of energy consumption. In addition, the cost-effectiveness and thermal comfort acceptability were assessed. After validating the building models and control strategies, optimal solutions were found through single-objective optimization of the energy consumption in IDA-ICE with GenOpt. Profitability and feasibility were investigated by assessing the difference in life cycle cost and thermal comfort. These results are presented for each building typology, i.e., a single-family house and an apartment block.

2. Materials and Methods

Figure 1 shows the steps of our methodology for finding optimal retrofitting packages with minimum energy consumption and acceptable levels of thermal comfort and cost-effectiveness. In the first step, the case study is defined, modeled, and validated. In the second step, strategies for control of the heating, ventilation, lighting and blind systems are defined and validated. In the third step, the solution space and objective function are set. In the fourth step, the optimization algorithm is executed for minimizing the predefined objective function. In the fifth step, the associated functions such as thermal comfort level and difference in LCC are evaluated for assessing the feasibility of the optimized solutions.

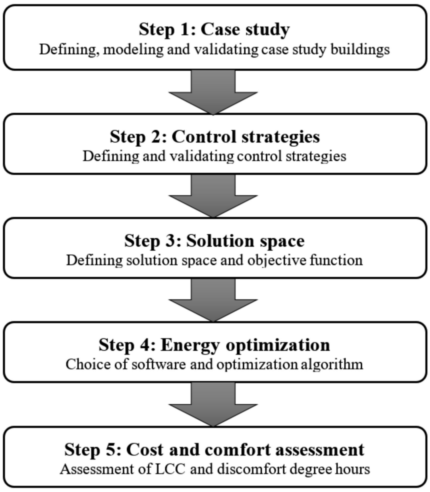

Figure 1. Proposed research methodology. LCC: life cycle cost.

2.1. Reference Buildings

The Norwegian residential building stock is divided into three groups: single-family houses (57%), apartment blocks (22%) and other small houses (21%) [16]. This last group consists of many different typologies and was not considered in the research. Two typical cases of a single-family house and an apartment block were selected to be studied, illustrated in Figure 2. The majority of these dwellings were built in the 1960s to 1990s, with a peak in the 1970s [17]. Two reference models were used for each case study: one representing the buildings before retrofitting (reference "original") and one representing the buildings fulfilling minimum energy requirements to evaluate the impact of BACS strategies (reference "TEK 17"). The relevant energy performance characteristics are presented in Table 1. The assumed building envelope characteristics used for the reference models before retrofitting were based on typical values. When no typical values were given, the values from the building code of 1969 or recommended input values from NS 3031 [18] were used.

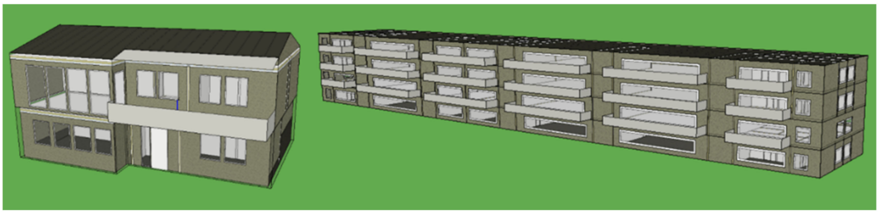

Figure 2. Models of the single-family house (**left**) and apartment block (**right**), created in IDA-ICE.

The reference cases were heated with direct electric heaters, placed in each room, and had mechanical exhaust ventilation in the kitchen and bathrooms. No cooling systems were considered, as Norwegian houses typically have no cooling systems installed. The electrical loads for each room function were as described in Table A1 [19].

Table 1. Input parameters for the energy performance characteristics of the reference models.

Parameter	**Reference "Original": Reference Models Built between 1969 and 1985 before Retrofitting**	**Reference "TEK 17": Reference Models according to the Minimum Energy Performance Requirements [1] in TEK 17 [20]**
U-value external wall (W/(m^{2}K))	0.38 [2]	0.22
U-value roof (W/(m^{2}K))	0.20 [2]	0.18
U-value basement wall (W/(m^{2}K))	0.81 [3]	0.22
U-value basement floor (W/(m^{2}K))	0.36 [2]	0.18
U-value windows (W/(m^{2}K))	2.8 [4]	1.2
Infiltration rate (h^{-1})	4.0 [4]	1.5
Normalized thermal bridge value (W/(m^{2}K))	0.07/0.13 [4]	–
Specific fan power (kW/(m^{3}s))	2.0 [4]	–

[1] These requirements are in addition to a requirement for maximum delivered energy. [2] Typical values for residential buildings built in 1971–1980 [16]. [3] Minimum requirements for walls belowground given in 1969–1985 [21]. [4] Recommended input values for single-family houses and apartments, respectively, built in 1969–1985 [18].

2.1.1. Case Study 1

The single-family house has an area of 173 m^2, divided over two floors, of which the lower floor is a partial basement. An east-west orientation was assumed, though the orientation can vary. The main living room, kitchen, bathroom and three bedrooms are located on the upper floor (see Figure 3). The lower floor has an extra living room, bathroom, bedroom, laundry room and storage rooms. The external walls and roof are timber frame constructions with 10 and 15 cm of mineral wool, respectively. The external walls of the lower floor, further referred to as basement walls, are constructed of expanded clay pellet blocks without insulation. The floor is a concrete slab on grade (not insulated).

Figure 3. Floor plans of the single-family house.

2.1.2. Case Study 2

The apartment block has four floors with a modular floorplan. The blocks can have a varying number of units and orientations. It was assumed that the building had 12 apartments per floor with west-oriented balconies. There are two types of apartments: corner apartments with one bedroom (54 m^2) and center apartments with two or three bedrooms (72–85 m^2) (see Figure 4). The external walls on the long side are timber frame walls, and the external walls on the short side are load-bearing concrete walls, both insulated with 10-cm mineral wool. The floor is a concrete slab on grade (not insulated). The roof is a concrete construction with 10-cm expanded polystyrene (EPS). Only two representative apartments on the top floor were modeled, surrounded by a building body representing the rest of the building: one corner apartment (54 m^2) and one center apartment (85 m^2); see Figure 4. This was done to reduce the computational time, which significantly increased due to the implementation of advanced room control strategies. The two apartments with the highest heating and cooling demands, due to high envelope heat losses and high solar heat gains, were selected.

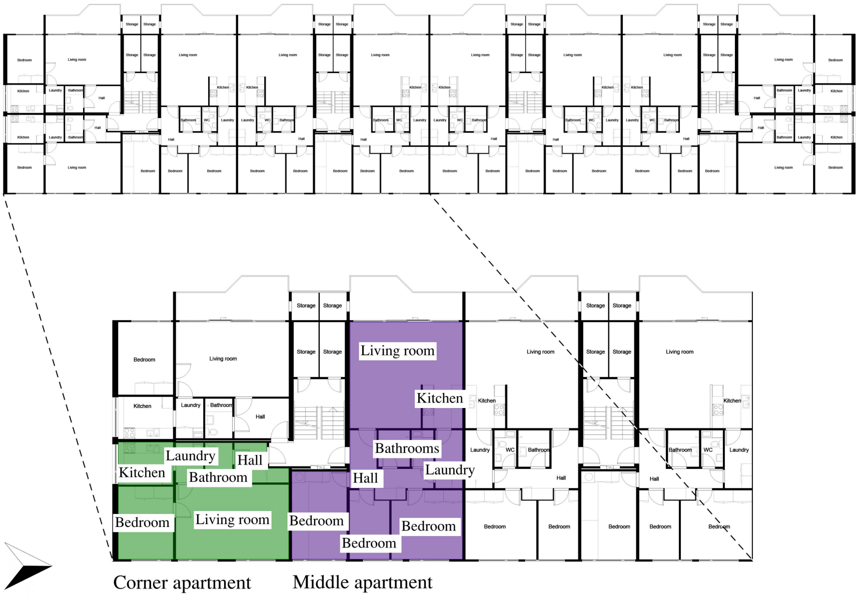

Figure 4. Floor plan of the apartment block.

2.2. *Building Energy Performance Modeling*

The reference buildings were modeled over a one-year period with a time step of one hour using the dynamic multi-zone building performance simulation tool IDA-ICE [22]. Each room function was modeled as an individual zone, and adjacent rooms with the same function were merged to minimize the computational time. Typical schedules for occupancy were implemented (illustrated in Figure 5), adapted from schedules used in a Norwegian study [23]. The occupancy patterns were converted from step schedules to linear schedules to reduce the computational time of the simulations. Two open-source models were used to calculate hourly lighting loads [24] and equipment loads [25]. The hourly schedules were adapted to fit the annual Norwegian normalized values [18]. All internal doors were kept closed to study the thermal comfort at each thermal zone separately. Both cases were placed in the climate of Trondheim, Værnes, Norway.

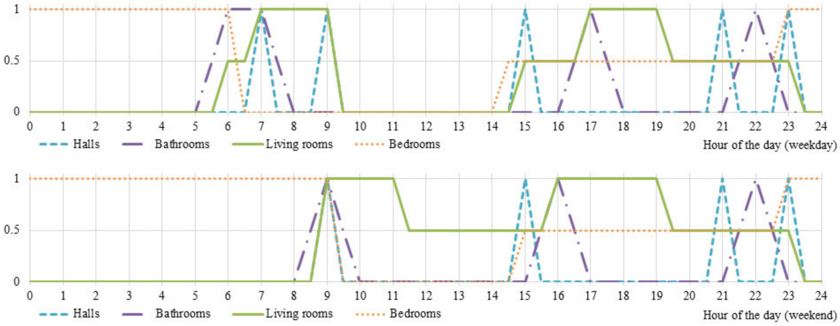

Figure 5. Occupancy patterns on weekdays (**top**) and weekends (**bottom**) for each room function.

Window-opening behavior was implemented to consider its significant impact on the thermal comfort and energy consumption. Window opening in dwellings is strongly influenced by the indoor temperature, solar radiation and the CO_2 level in the room [26]. In this paper, window opening was modeled by creating a macro in IDA-ICE to provide fresh air and/or cooling; see Figure 6. It was assumed that the windows closed automatically before the temperature dropped below the heating setpoint to minimize energy losses and avoid extra heating (see Figure A1). Windows were opened when the indoor operative temperature exceeded a predefined setpoint, 3.5 °C higher than the heating setpoint (deadband = 3 °C), or when the CO_2 level exceeded 1000 ppm (deadband = 200 ppm), though only when an occupant was present in the house. This resulted in windows opening quite often, causing an increased energy consumption. The window-opening behavior was the same in all retrofitting cases.

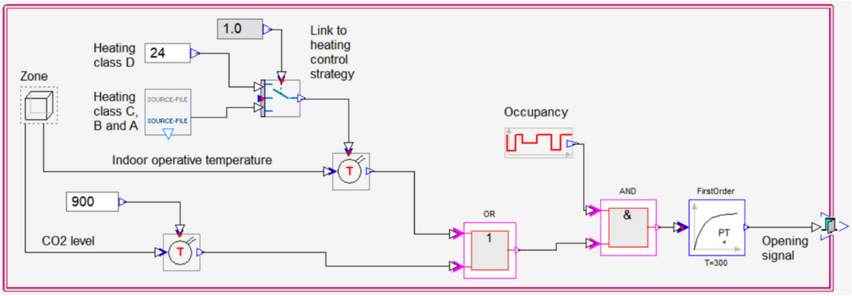

Figure 6. Macro for window-opening behavior created in IDA-ICE.

2.2.1. Model Validation

The representativeness of the simulation models was evaluated in two steps. First, models with a high validity were created using typical and normalized input data (see Table 1). Then, the output of the models (i.e., the simulation results) were compared with theoretical data. Both reference "original" models were simulated twice: with standardized (normative) internal gain loads from NS 3031 [18] and with typical internal gain loads. It is expected that the energy consumption will be below average when NS 3031 input is used, while the energy consumption is expected to be above average when typical internal gains and window-opening behavior are used. As the case studies are representative for a group of buildings, the results were compared to average data from statistics and typical values from other studies [16,27]. They were validated with a direct electrical heating system. The validations results are presented in Section 3.1.

2.2.2. Reference BACS Strategies

Using parametric runs in IDA-ICE, control strategies were changed one by one in the reference "TEK 17" models. In this way, the impact of each individual strategy on the energy use for systems and on the total energy consumption was evaluated, thereby validating the modeled controls and setpoints (i.e., each improved class should decrease the energy use). The validation results are presented in Section 3.2.

Normative loads for equipment and lighting were used [18]. Occupancy patterns and window-opening behavior were implemented, as described in Section 2.2. Space heating was provided by direct electric heaters, and a balanced ventilation system with 80% heat recovery was implemented after retrofitting. Halogen lights bulbs were used before and after retrofitting. Switching to LED lights was not considered so that the effect of control strategies could be compared. In some cases, an air source heat pump (ASHP) was installed in the living room of each dwelling. The complete BACS levels were evaluated as well, where strategies for heating, lighting, ventilation and blinds were set to the same level (C, B or A). The BACS strategy definitions were in-line with the automation standard EN 15232 [28] and are summarized in Table 2. Control of domestic hot water systems and cooling systems were out of the scope.

Table 2. Definition and setpoints for the building automation control strategies (BACS), based on the descriptions in EN 15232 [28].

Class	Heating Control	Ventilation Control	Lighting Control	Blind Control
D	Proportional–integral (PI) control with a constant temperature setpoint (22 °C)	Constant air volume (CAV) with a constant supply air temperature setpoint (18 °C)	Manual on/off lighting control	Manual control
C	Proportional–integral (PI) control with a variable temperature setpoint depending on room function with night setback (variable)	Variable air volume (VAV) with day/nighttime schedule and a constant supply air temperature setpoint (18 °C)	As level D	As level D
B	Proportional–integral (PI) control with occupancy detection and a variable temperature setpoint depending on room function with night setback (variable) and extreme setback (16 °C) when the house is not occupied	Variable air volume (VAV) with a day/nighttime schedule and a variable supply air temperature setpoint (16–18 °C)	Automatic on/off control with a day/night schedule, sweeping extinction signal (23:00–06:00) and automatic off-switch when enough daylight (>200 lux) is present	Automatic control based on incoming solar radiation (active when >200 W/m^2)
A	Proportional–integral (PI) control with demand detection and a variable temperature setpoint depending on room function with night setback (variable) and extreme setback (16 °C) when the zone is not occupied	Variable air volume (VAV) based on demand and with a variable supply air temperature setpoint (16–18 °C) with setback for when the house is not occupied (14–16 °C)	Automatic control with dimming following a day/night schedule, sweeping extinction signal = (23:00–06:00) and automatic off-switch when enough daylight (>200 lux) is present and/or when the room is not occupied	As level B

The normalized heating setpoint of 22 °C was used in class D [18]. The temperature setpoints in class C and higher were assumed variable and followed the neutral adaptive thermal comfort curves defined by Peeters et al. [29]. The curves are a function of the reference temperature (Equation (1)). These criteria are more realistic for residential buildings than the adaptive comfort criteria given in EN 16798 [30]. The maximum potential of the control strategies, i.e., the maximum energy savings that can be achieved, was evaluated by choosing extreme setpoints for when the house/room is not occupied. The adaptive heating setpoints are illustrated in Figures A2–A4 in Appendix C.

The air flow rates were taken from TEK 17 [20], which specifies the minimum air flow rates for each room function and for not occupied rooms in dwellings. The air supply temperature was constant at 18 °C in classes D and C. In classes B and A, the temperature setpoint varied between 16–18 °C during occupied hours and between 14–16 °C during not occupied hours (see Figure A5 in Appendix C).

$$T_{ref} = \frac{T_{ed} + 0.8 \times T_{ed-1} + 0.4 \times T_{ed-2} + 0.2 \times T_{ed-3}}{2.4} \tag{1}$$

where T_{ref} is the reference external temperature in degrees Celsius, T_{ed} is the arithmetic average of today's maximum and minimum temperature in degrees Celsius and T_{ed-i} is the arithmetic average of the maximum and minimum temperature of the ith previous day in degrees Celsius.

The manual control of lighting (class D and C) was modeled to follow the occupancy schedule for each room function. In classes B and A, the lights were switched off and dimmed, respectively, when the horizontal daylight illuminance level at the first occupant level exceeded 200 lux. This value was taken from EN 15232 [28].

Manual control of the blinds (classes D and C) was modeled as a function of the indoor operative temperature and room occupancy. In classes B and A, blinds were activated when the solar radiation exceeded 200 W/m^2 [28]. In all classes, blinds were only lowered when the outdoor temperature exceeded 15 °C to maximize solar heat gains during the heating season.

2.2.3. Objective Function and Solution Space

The total annual energy consumption was defined as a single-objective function. The objective function was minimized by finding optimal combinations of the discrete and continuous design variables given in Table 3. The values for the thermal envelope were chosen so that the lower limit of the range fulfilled the minimum energy performance requirements from TEK 17 [20]. When no values were specified, the TEK 17 energy-saving requirements were used to define the lower limit. The upper limits were based on the energy performance criteria for Norwegian passive houses [31]. These values are summarized in Table 4. U-value calculations were done to define the thickness of insulation required to achieve the upper and lower limits. It was assumed that the insulation was placed in a timber frame construction. This component had a combined thermal conductivity of λ = 0.044 W/mK. The insulation ranges include the original insulation thickness. The BACS options represent the four automation levels presented in Table 2.

Table 3. Solution space with the design variables for the optimization process.

	Design Variable	**Single-Family House**			**Apartment Block**		
		Options Range	**Step Size**	**Nr. of Steps**	**Options Range**	**Step Size**	**Nr. of Steps**
Building Envelope options	Insulation thickness external walls (m)	0.2 … 0.4	0.05	5	0.2 … 0.4	0.05	5
	Insulation thickness roof (m)	0.25 … 0.4	0.05	4	0.2 … 0.4	0.05	5
	Insulation thickness basement walls (m)	0.15 … 0.3	0.05	4	–	–	–
	Insulation thickness basement floor (m)	0.1 … 0.35	0.05	6	–	–	–
	Infiltration rate (h^{-1})	0.6 … 1.5	–[1]	–[1]	0.6 … 1.5	–[1]	–[1]
	Normalized thermal bridge value (W/(m^{2}K))	0.03 … 0.05	–[1]	–[1]	0.05 … 0.07	–[1]	–[1]
	-	Options		Nr. of options	Options		Nr. of options
	Windows (t = 0.7, g = 0.5)	U = 1.2 W/(m^{2}K) U = 0.8 W/(m^{2}K)		2	U = 1.2 W/(m^{2}K) U = 0.8 W/(m^{2}K)		2
Automation levels	Heating control	Level D Level C Level B Level A		4	Level D Level C Level B Level A		4
	Ventilation control	Level D Level C Level B Level A		4	Level D Level C Level B Level A		4
	Lighting control	Level D (and C) Level B Level A		3	Level D (and C) Level B Level A		3
	Solar shading control	Level D (and C) Level B (and A)		2	Level D (and C) Level B (and A)		2
	Total possible combinations			115,200			4800

[1] The normalized thermal bridge value and the infiltration rate were a function of the insulation levels. These values improved when the insulation levels increased.

Table 4. Reference values for upper and lower limits of the continuous variables.

Parameter	TEK 17 Minimum Energy Performance Requirements [20]	TEK 17 Energy-Saving Requirements [20]	Norwegian Passive House Criteria [31]
U-value external wall (W/(m^{2}K))	≤0.22	≤0.18	0.10–0.12 [1]
U-value roof (W/(m^{2}K))	≤0.18	≤0.13	0.08–0.09 [1]
U-value basement wall (W/(m^{2}K))	≤0.22	≤0.18	0.10–0.12 [1]
U-value basement floor (W/(m^{2}K))	≤0.18	≤0.10	0.08 [1]
U-value windows (W/(m^{2}K))	≤1.2	≤0.8	≤0.8
Infiltration rate (h^{-1})	≤1.5	≤0.6	≤0.6
Normalized thermal bridge value (W/(m^{2}K))	–	≤0.05/0.07	0.03
Specific fan power (kW/(m^{3}s))	–	≤1.5	≤1.5
Ventilation heat recovery (%)	–	≥ 80	≥ 80

[1] Recommended U-values for building components, not minimum requirements.

2.2.4. Simulation-Based Optimization

GenOpt [32], a built-in IDA ICE, was used to automate the simulation-based optimization process. GenOpt calls IDA-ICE and calculates the objective function for a given combination of design variables. The design variables are changed in each iteration until the objective function is minimized. GenOpt can use various algorithms, and in this case, a generalized pattern search particle swarm optimization in combination with the Hookes Jeeves algorithm was used. This hybrid algorithm first performs a particle swarm optimization for the design variables and then continues with the Hookes Jeeves algorithm to refine the continuous design variables [9]. The markers lined with black in Figure 7 illustrate when the design variable refining process started.

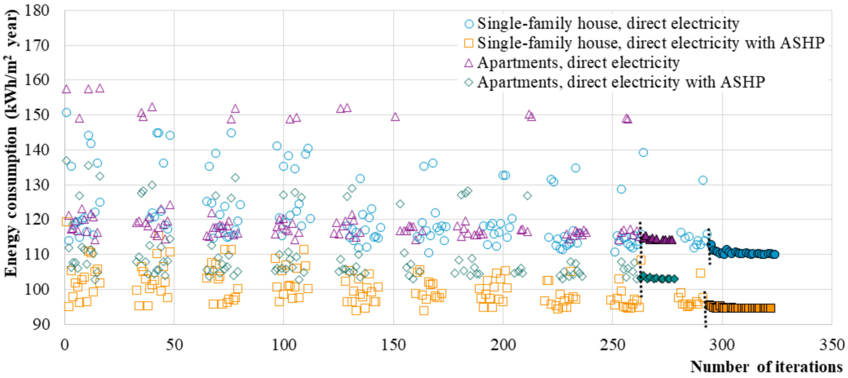

Figure 7. Minimization of the objective function in the simulation-based optimization (i.e., IDA ICE plus GenOpt).

2.3. Discussion-Based Decision-Making

The associated difference in life cycle cost (*dLCC*), compared to the reference design, and thermal comfort were calculated for each optimization iteration. This was done using a postprocessing algorithm in Excel.

2.3.1. Difference in Life Cycle Cost Analysis

The economic feasibility of the retrofitting packages was evaluated by calculating the *dLCC* between the reference model and each retrofitted model, following the methodology introduced by Hamdy et al. [33]. The selection of a reference model impacts the results, and only results with the same reference can be compared. It was assumed that the maintenance costs were equal in each scenario and that no replacement was needed for the building envelope measures within the calculation period of 30 years. The automation measures and the heat pump were replaced once within the calculation period. As a result, the *dLCC* was simplified to Equation (2). A negative *dLCC* indicates that the combination of retrofitting measures is more profitable than the reference case (*dLCC* = 0). Results with a negative *dLCC* are further defined as "profitable" and results with a positive *dLCC* as "not profitable". The profitability is in all cases compared to the reference case, i.e., no retrofitting.

$$dLCC = dIC + dOC \tag{2}$$

where *dIC* is the difference in investment cost in NOK, and *dOC* is the difference in operational cost in NOK. The difference in investment cost is calculated by summing the cost for each retrofitting measure, as shown in Equation (3).

$$dIC = \sum_{j=1}^{8} IC_j \tag{3}$$

The difference in operational cost of the total annual energy consumption between the reference model and each retrofitted model is calculated according to Equation (4).

$$dOC = a \times e_p \times dE_j \tag{4}$$

$$a = \frac{1 - (1 + r_e)^{-n}}{r_e} \tag{5}$$

$$r = \frac{i - f}{1 + f} \tag{6}$$

$$r_e = \frac{r - e_p}{1 + e_p} \tag{7}$$

where a is the discount factor, calculated according to Equation (5), e_p is the energy price for electricity, dE_j is the difference in energy consumption, r is the real interest rate, r_e is the real interest rate including the escalation of the energy price, i is the nominal interest rate, f is the inflation rate and e_p is the energy price for electricity. The interest rate was set to 3%, the inflation rate was set to 2.1% and the energy price was set to 1.23 NOK/kWh, with an annual price escalation of 3.15% [19]. All costs were taken from Norsk Prisbok [34] and were price-corrected from February 2019 to December 2019. The investment costs included material and labor costs and the cost for removing the old components of the building envelope. A more detailed description of the included cost can be found in Tables A2–A5. Value-added tax and costs for waste disposal were excluded. The total investment cost was converted from Norwegian Crowns to Euro using the average exchange rate over 2019, i.e., € 1.0 equals 9.85 NOK. The investment cost can be found in the Appendix C.

2.3.2. Thermal Comfort Assessment

To evaluate the thermal comfort, the total number of occupied indoor discomfort degree hours (DDH) was calculated for a one-hour time step according to Equations (8) and (9). The operative temperature, T_{op}, was compared to the upper and lower limits. The limits were defined as the temperature where the percentage of people dissatisfied (PPD) was 20% [29]. These are presented in Table 5, where $T_{x,u}$ is the upper limit, $T_{x,l}$ is the lower limit and $T_{x,n}$ is the neutral comfort temperature. Thermal comfort was assessed for the room with the most overheating hours, i.e., the living room in the corner apartment facing east and the living room on the upper floor of the single-family house facing west. These rooms also have the most heat losses and solar heat gains.

$$Undercooling: \ DDH = \sum\nolimits_{i=1}^{8760} T_{x,l} - T_{op} \ when \ T_{op} < T_{x,l} \quad (8)$$

$$Overheating: \ DDH = \sum\nolimits_{i=1}^{8760} T_{op} - T_{x,u} \ when \ T_{op} > T_{x,u} \quad (9)$$

Table 5. Lower and upper limits for evaluating the thermal comfort [29]. PPD: percentage of people dissatisfied.

Room	**Lower Limit (PPD = 20%)**	**Upper Limit (PPD = 20%)**
Bedrooms	$T_{bed,l} = \max\left(16,\ T_{bed,n} - 2.1\right)$	$T_{bed,u} = \min\left(26,\ T_{bed,n} + 4.9\right)$
Bathrooms, living rooms and other rooms	$T_{other,l} = \max\left(18,\ T_{other,n} - 2.1\right)$	$T_{other,u} = T_{other,n} + 4.9$

3. Results and Discussion

3.1. *Validation of the Reference "Original" Building Models*

Table 6 shows the energy performance simulation results in comparison to reference values for the single-family house and representative apartments, respectively. The energy consumption for domestic hot water (DHW) was the same in all cases, i.e., 25.0 kWh/m^2 year, as the control of the DHW systems was not considered in this paper. The whole apartment block was only simulated with NS 3031 input values, which resulted in a total energy consumption of 149.8 kWh/m^2 year, i.e., 8% higher than for the representative apartments. As expected, the energy consumption when using NS 3031 input was lower than the average, while the energy consumption when using typical internal gains and window-opening behavior was higher than the average. There was no reference value for space heating and auxiliary energy (HVAC aux). However, as the other energy consumption parameters and the total energy consumption are acceptable compared to the reference values, it was concluded that the energy use for space heating and auxiliary energy were acceptable.

Table 6. Validation of the single-family house model (SF) and representative apartments (AP) before retrofitting. HVAC: heating, ventilation and air conditioning.

Energy	**-**	**NS 3031**	**Typical**	**NS 3031 Reference Values**	**Typical Reference Values [1]**	**Statistical Reference Values [2]**
Space heating (kWh/m^2 year)	SF	118.0	160.4	-	-	-
	AP	76.9	129.8			
HVAC aux (kWh/m^2 year)	SF	7.6	7.6	-	-	-
	AP	7.1	7.1			
Lighting (kWh/m^2 year)	SF	11.4	11.9	11.4 [18]	-	-
	AP	11.5	11.7			

Table 6. *Cont.*

Energy	**-**	**NS 3031**	**Typical**	**NS 3031 Reference Values**	**Typical Reference Values** [1]	**Statistical Reference Values** [2]
Equipment (kWh/m^2 year)	SF	17.4	17.7	17.5 [18]	-	-
	AP	17.5	17.6			
Total energy consumption (kWh/m^2 year)	SF	179.0	222.1	-	225	196.8
	AP	137.9	191.1	-	165–190	153.9

[1] The typical value is 165 kWh/m^2 year for apartment blocks built in 1970–1980 and 190 kWh/m^2 year for apartment blocks built before 1970 [16]. [2] Estimated statistical reference based on statistics of the energy consumption for each built year and the energy consumption for each housing typology, weighed for the number of houses in each typology and built year [35].

3.2. Validation of the Reference "TEK 17" Models with BACS Control Strategies

The results from the parametric study are presented for the cases with space heating provided by direct electrical heating in the whole house (Table 7) and with an air ASHP in the living room, supplied by direct electrical heaters in the rest of the house (Table 8). The energy consumption of the case study with no automated control strategies is shown in the first row ("Model D"). The other rows show the relative energy consumption compared to model D achieved by implementing more advanced BACS. Text marked in bold indicates a significant decrease in energy consumption, i.e., more than a 5% decrease.

Table 7. Energy savings achieved by implementing BACS in a single-family house and apartment block with direct electricity as a space-heating source.

Direct Electricity	**Single-Family House**				**Representative Apartments**			
	Space Heating	**AHU Heating and Fans**	**Lighting**	**Total**	**Space Heating**	**AHU Heating and Fans**	**Lighting**	**Total**
Model D (kWh/m^2)	84.4	10.7	11.4	148.6	79.0	15.0	11.4	147.8
	Energy consumption compared to model D							
Heating, level C	78%	106%	100%	88%	62%	105%	100%	80%
Heating, level B	76%	109%	100%	87%	62%	107%	100%	81%
Heating, level A	72%	123%	100%	86%	61%	109%	100%	80%
Ventilation, level C	100%	86%	100%	99%	102%	85%	100%	100%
Ventilation, level B	105%	74%	100%	101%	110%	66%	100%	102%
Ventilation, level A	106%	65%	100%	101%	110%	66%	100%	102%
Lighting, level B	102%	100%	65%	98%	100%	100%	65%	97%
Lighting, level A	105%	101%	39%	98%	102%	101%	45%	97%
Blinds, level A	101%	100%	100%	100%	99%	100%	100%	100%
Complete level C	79%	91%	100%	87%	62%	90%	100%	79%
Complete level B	86%	77%	64%	86%	69%	70%	61%	78%
Complete level A	86%	72%	39%	84%	70%	71%	40%	76%

Table 8. Energy savings achieved by implementing BACS in a single-family house and apartment block with direct electricity and an air source heat pump as space-heating sources.

Direct Electricity with an Air Source Heat Pump	Single-Family House				Representative Apartments			
	Space Heating	**AHU Heating and Fans**	**Lighting**	**Total**	**Space Heating**	**AHU Heating and Fans**	**Lighting**	**Total**
Model D (kWh/m^2)	48.7	14.1	11.4	116.3	52.9	17.2	11.4	123.9
	Energy consumption compared to model D							
Heating, level C	79%	99%	100%	91%	60%	102%	100%	83%
Heating, level B	80%	100%	100%	92%	63%	103%	100%	85%
Heating, level A	74%	109%	100%	90%	62%	104%	100%	84%
Ventilation, level C	99%	89%	100%	98%	101%	87%	100%	99%
Ventilation, level B	106%	82%	100%	100%	107%	71%	100%	99%
Ventilation, level A	104%	78%	100%	99%	108%	71%	100%	99%
Lighting, level B	101%	101%	65%	97%	98%	100%	65%	96%
Lighting, level A	105%	102%	39%	96%	101%	101%	45%	95%
Blinds, level A	100%	100%	100%	100%	99%	100%	100%	100%
Complete level C	79%	88%	100%	90%	60%	88%	100%	81%
Complete level B	87%	78%	64%	88%	70%	71%	61%	79%
Complete level A	85%	77%	39%	85%	72%	72%	40%	79%

Energy savings of 10–24% were achieved when BACS was upgraded to a complete class (see rows “complete level” and columns “total”), and savings of 9–20% were achieved when only the heating control strategy was upgraded (see row “heating, level” and column “total”). The achieved energy savings were mostly due to upgrading the heating control strategies, but the highest savings were achieved when all control strategies were upgraded simultaneously (“complete level”).

The total achieved energy savings were 1.5−2 times higher for apartments than for the single-family house (see row “complete level” and column “total”). The control strategies, especially for heating, had a bigger impact on the energy consumption when the heated floor area in relation to the exterior envelope area increased, i.e., more compact buildings, such as apartments. The energy savings for the single-family house were similar to the results from our previous paper [19].

When the heating demand covered by space heaters decreased (for example, due to night setbacks in more advanced BACS classes), the energy use attributed to air heating unit (AHU) and fans increased, as more AHU heating was required to ensure a comfortable temperature (see rows “heating, level” and “ventilation, level” and columns “space heating” and “AHU heating and fans”). The opposite happened when a control strategy with a lower temperature setpoint for the supply air was implemented. When ventilation and heating strategies were upgraded simultaneously (“complete level”), the energy use for AHU heating and fans and for space heating decreased (see row “complete level” and columns “space heating” and “AHU heating and fans”).

When an ASHP was installed, the space heating demand did not necessarily decrease for more advanced levels (see rows “heating, level” and “complete level” and column “space heating” in Table 8). This is because the ASHP only heated up a limited volume due to closed doors and because the efficiency of the ASHP is much higher than of direct electricity (i.e., the space heating demand decreased but not necessarily the total energy consumption).

The lighting control strategies significantly decreased the energy consumption for lighting (see row “lighting, level” and column “lighting”). However, the total energy consumption decreased minimally, as the heating demand increased due to lower internal heat gains (see row “lighting, level” and column “total”). Control of the blinds did not affect the energy consumption. This is most likely because no active cooling systems are installed (see row “blind, level” and column “total”). The cooling demand may be reduced, but it was not investigated, as there are no cooling systems installed. Instead, the thermal comfort was investigated.

Figure 8 shows the number of total occupied indoor discomfort degree hours in the living room compared to the energy consumption. The DDH were mostly overheating hours, except for heating classes B and A in the apartment with direct electricity (2 and 38 DDH of undercooling, respectively). The heating strategies, especially temperature setback, had the biggest impact on the reducing the DDH and energy consumption. The latter is not surprising, as space heating accounted for most of the energy consumption (see Table 6).

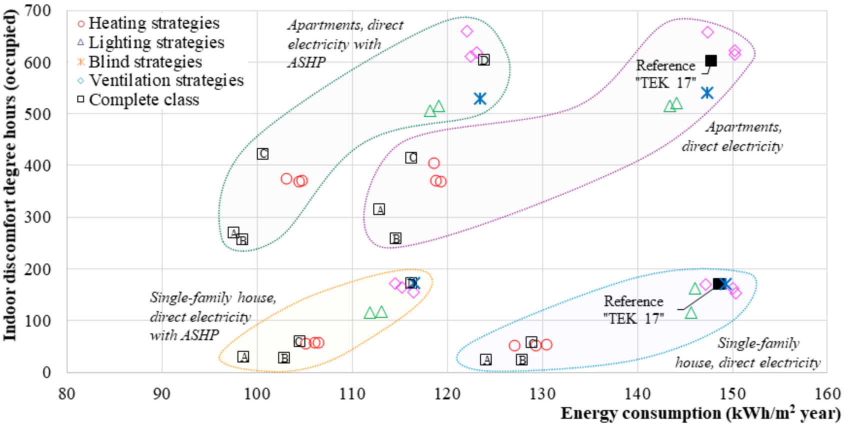

Figure 8. Parametric analysis results—indoor discomfort degree hours (occupied) versus energy consumption. ASHP: air source heat pump.

Overheating was a bigger issue in the living rooms of the representative apartments than in the living room of the single-family house. This was most likely because of less heat losses through the envelope due to a smaller exterior surface area.

Thermal comfort increased when more advanced automation strategies were implemented, though ventilation had no positive effect. When all control strategies were upgraded simultaneously (“complete level”), there was a significant improvement to the thermal comfort. Combining the BACS strategies resulted in the highest decrease of thermal discomfort.

Figure 9a,b shows the profitability of individual BACS measures. The dLCC was calculated in relation to the reference “TEK 17” models (class D) without an ASHP. The profitability of measures improved when the achieved energy savings increased. The figure shows that, for the single-family house, installing an ASHP was profitable regardless of the automation class. Without the ASHP, no automation measures were profitable. For the apartments, upgrading all automation systems to class C was profitable without an ASHP. When the ASHP was installed, upgrading the heating control systems and upgrading all systems to classes C or B was profitable.

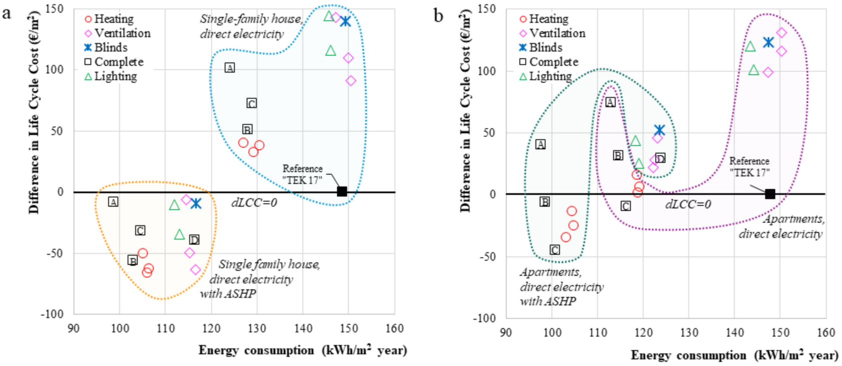

Figure 9. Parametric analysis results: difference in life cycle cost (dLCC) versus the energy consumption of building automation control strategies (BACS) (**a**) in a single-family house and (**b**) in representative apartments.

3.3. Simulation-Based Optimization and Economic Assessment

Figure 10 shows the results from the optimization with the dLCC, compared to the reference "original" model, as a function of the energy consumption. The optimal solutions are marked on the pareto fronts. The total energy savings were 32–57% for the single-family house and 17–46% for the representative apartments. Installing an ASHP significantly impacted the energy consumption. In many cases, this impact was larger than what a combination of envelope retrofitting and control strategies achieved. It is expected that the effect of installing an ASHP is larger when internal doors are opened.

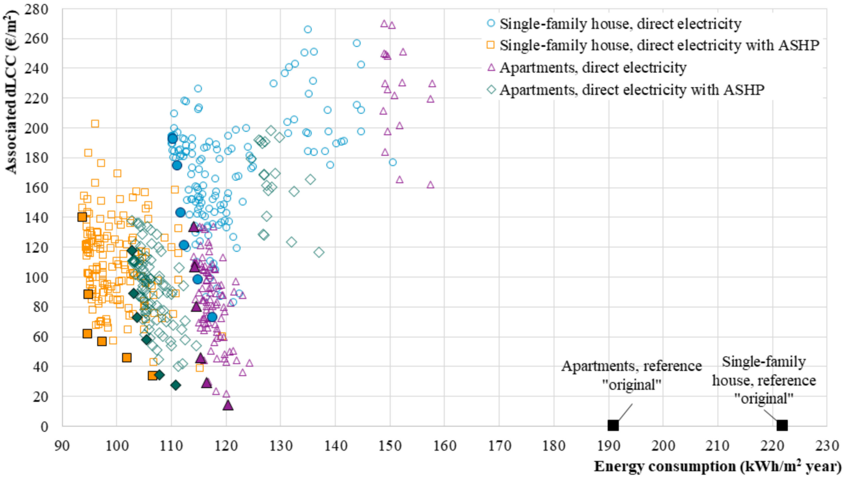

Figure 10. Results of single-objective optimization runs: energy consumption versus the associated difference in life cycle cost, where the optimal retrofitting combinations are marked on the pareto fronts.

Due to the high investment cost and the low energy price for electricity, i.e., a long period to earn back invested cost through energy savings, no solutions were profitable after 30 years (dLCC > 0). When no ASHP was installed, the optimal retrofitting solutions for the apartments were more profitable than for the single-family house. As apartments have a smaller exterior surface area in relation to the heated floor area, i.e., are more compact, it is cheaper to retrofit the building envelope and improve the energy efficiency. However, when an ASHP was installed, the profitability of the single-family house and the apartments was similar. The higher investment costs for retrofitting the building envelope of the single-family house were outweighed by higher energy savings, resulting in more profitable solutions. The probabilities of the retrofitting solutions for the apartments with and without an ASHP indicated that achieved energy savings from installing an ASHP were similar to the reduced operational costs.

Low U-values of the walls and roof, better than the minimum energy performance requirements, were essential for high energy savings for both buildings (see Tables 9–12). The U-values of windows, basement walls and floors had less impact on the achieved energy savings than the U-values of the external walls and roof, though all were upgraded to fulfil at least the minimum energy performance requirements.

The choice of heating control strategy significantly affected the energy-saving potential, resulting in a visible separation of the retrofitting solutions for three of four cases. A heating control strategy of class C or better was essential to achieve significant energy savings. A detailed analysis showed that the models with class D heating control strategy had, for the single-family house, 8 to 23 kWh/m^2 higher energy consumption than models with the same envelope parameters and a class C or higher heating control strategy and 21 to 35 kWh/m^2 year higher for the representative apartments.

The results from the representative apartments were used to estimate the energy savings and profitability after retrofitting for the whole apartment block. The following assumptions were made: the energy consumption for the whole block was 8% higher than the energy consumption for the representative apartments (see Section 3.1), and no retrofitting was done to the ground floor. The investment costs were calculated from the total area of the exterior envelope and the total number of windows. The cost for automation was a function of the heated floor area. The optimal solutions for the whole apartment building were similar to those from the representative apartments, but they were more profitable (see Figure 11). This is because the ratio of exterior surface area to heated floor area decreases when the whole building is considered as opposed to two top floor apartments, thus decreasing the investment cost per heated floor area.

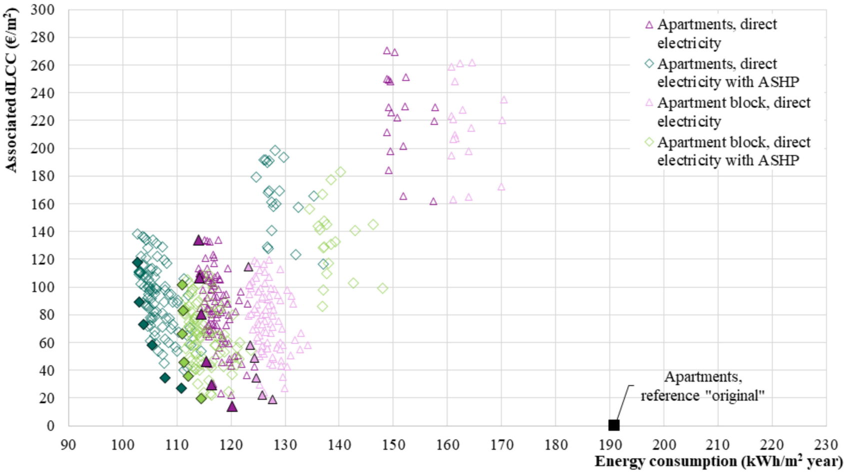

Figure 11. Results of the single-objective optimization runs: energy consumption versus the associated difference in life cycle cost estimated for the apartment block, with the optimal retrofitting combinations marked on the pareto fronts.

Table 9. Optimal combinations of envelope retrofitting and building automation control strategies for the single-family house with direct electricity. dLCC: difference in life cycle cost.

Name	Energy (kWh/m^2 Year)	dLCC (€/m^2)	Insulation Thickness (m)				U-Value Glazing (W/m^{2}K)	Control Strategies Class			
			External Wall	Roof	Basement Wall	Floor		Heating	Ventilation	Lighting	Blinds
S-005	117.5	73.1	0.35	0.3	0.15	0.2	0.8	A	B	D	D
S-256	114.9	98.4	0.4	0.35	0.2	0.2	0.8	A	B	B	D
S-258	112.4	121.4	0.4	0.4	0.2	0.3	0.8	A	B	A	D
S-226	111.7	143.1	0.4	0.4	0.2	0.3	0.8	A	D	A	D
S-296	111.1	174.8	0.4	0.4	0.2	0.2	0.8	A	C	A	D
S-307	110.4	192.8	0.4	0.4	0.3	0.35	0.8	A	C	A	D

Table 10. Optimal combinations of envelope retrofitting and building automation control strategies for the single-family house with direct electricity and an air source heat pump.

Name	Energy (kWh/m^2 Year)	dLCC (€/m^2)	Insulation Thickness (m)				U-Value Glazing (W/m^{2}K)	Control Strategies Class			
			External Wall	Roof	Basement Wall	Floor		Heating	Ventilation	Lighting	Blinds
S-HP-035	106.6	33.6	0.25	0.4	0.2	0.25	1.2	B	D	D	D
S-HP-005	101.9	45.9	0.3	0.3	0.25	0.15	0.8	A	B	D	D
S-HP-190	97.3	57.1	0.35	0.35	0.25	0.25	0.8	A	B	B	D
S-HP-262	94.7	88.6	0.35	0.4	0.25	0.25	0.8	A	A	A	D
S-HP-257	94.6	62.1	0.4	0.4	0.2	0.3	0.8	A	B	A	D
S-HP-164	93.8	140.4	0.4	0.4	0.2	0.3	0.8	A	C	A	D

Table 11. Optimal combinations of envelope retrofitting and building automation control strategies for the representative apartments with direct electricity.

Name	Energy (kWh/m^2 Year)	dLCC (€/m^2)	Insulation Thickness (m)		U-Value Glazing (W/m^{2}K)	Control Strategies Class			
			External Wall	Roof		Heating	Ventilation	Lighting	Blinds
A-100	120.3	14.1	0.4	0.3	1.2	B	C	D	D
A-235	116.4	29.4	0.4	0.4	1.2	C	B	B	D
A-042	115.4	46.1	0.35	0.4	1.2	C	C	B	B
A-046	114.5	80.7	0.4	0.4	0.8	A	C	A	D
A-160	114.2	106.6	0.4	0.4	0.8	A	A	B	B
A-105	114.1	133.9	0.4	0.4	0.8	A	A	A	B

Table 12. Optimal combinations of envelope retrofitting and building automation control strategies for the representative apartments with direct electricity and an air source heat pump.

Name	Energy (kWh/m^2 Year)	dLCC (€/m^2)	Insulation Thickness (m)		U-Value Glazing (W/m^{2}K)	Control Strategies Class			
			External Wall	Roof		Heating	Ventilation	Lighting	Blinds
A-HP-102	110.8	27.3	0.4	0.3	1.2	B	C	D	D
A-HP-231	107.8	34.6	0.4	0.3	1.2	C	B	B	D
A-HP-042	105.5	57.9	0.35	0.4	1.2	C	C	B	B
A-HP-066	103.8	73.2	0.4	0.4	1.2	A	B	A	D
A-HP-227	103.1	89.0	0.4	0.4	1.2	A	A	A	D
A-HP-014	102.8	117.7	0.4	0.4	1.2	A	A	A	B

Tables 9–12 show the building envelope and automation parameters of the optimal retrofitting packages (marked on the pareto fronts in Figure 10). The optimal solutions include the solution with the lowest energy consumption and the solution with the lowest associated dLCC. The lowest energy consumption (bottom row) was achieved when the building envelope was retrofitted (almost) to the upper limits (see Table 4) and when the heating and lighting control strategies were upgraded to class A. Upgrading the heating and lighting control strategies to class A was essential to achieve high energy savings. For the apartments, the solutions with the highest energy savings also required the ventilation control strategies to be upgraded to class A. This was less important for the single-family house. The impact of blind control strategies on the energy performance was not significant and resulted in higher investment costs. More profitable solutions had a building envelope with a lower energy performance, though still fulfilling the minimum energy performance requirements.

3.4. Thermal Comfort Assessment

The thermal comfort assessment in Figure 12 shows a significant decrease of DDH after retrofitting. Installing external blinds and using BACS had the highest impact, as all DDH were caused by overheating. Undercooling due to temperature setback occurred only when no occupants were present. No occupied undercooling hours were reported, meaning that the size of the heaters and implemented reheating time (i.e., 1.5 h) were sufficient to ensure a comfortable temperature during occupied hours. There were no significant differences in thermal discomfort between the optimal solutions. In general, the living room in the representative apartments had more discomfort degree hours than the living room in the single-family house.

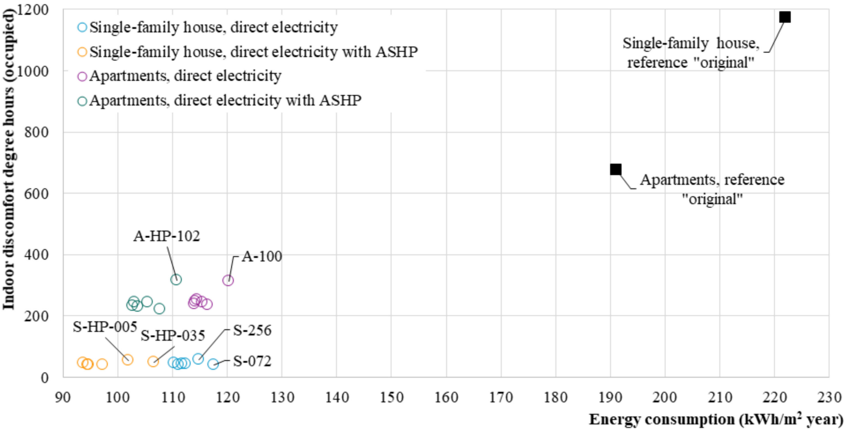

Figure 12. Discomfort degree hours of the optimal retrofitting combinations.

Overheating can be decreased further by implementing more advanced window-opening control strategies. For example, the openable area can be increased in the summer to maximize cooling by natural ventilation and decreased in the winter to avoid excessive heating. As overheating was not the primary focus of this paper, this was not further investigated. It should also be noted that, for a full thermal comfort analysis, all zones in the house should be considered.

3.5. Limitations and Further Works

This paper presents optimal solutions where the energy consumption was minimized through single-objective optimization. The profitability was calculated during postprocessing to define the cost-effective retrofitting solutions. The presented optimal solutions were therefore not optimized for the difference in life cycle cost. The calculation of the life cycle cost was simplified by not considering the maintenance cost. The energy price was assumed fixed, though it is expected that it will increase in the future and that different grid rent tariffs will be introduced, with energy prices varying during the day and season. With the introduction of such grid rent tariffs, the importance of smart control systems increases. The calculation period was set to 30 years, though no solutions were profitable after this period. The calculation period could be extended to 60 years, including the relevant replacement of components, such as windows, to evaluate the cost-effectiveness over the whole lifetime of the opaque envelope components. For defining cost-optimal retrofitting solutions, it is recommended that a multi-objective optimization is performed to optimize energy consumption and dLCC simultaneously.

Two representative apartments were modeled instead of the whole apartment block. This was done to minimize the computational time needed to run the simulations. Due to this, the results are only valid for these two apartments. The optimization results were used to estimate the energy savings and profitably of retrofitting the whole apartment building. Retrofitting of the ground floor was not taken into account. Corner and middle apartments on the ground floor and middle floor should be modeled as well so as to investigate the energy consumption, dLCC and thermal comfort after retrofitting for the whole block.

The simulation results are valid for the presented residential case studies and cannot be directly used for other building typologies. This paper aimed to propose retrofitting solutions for a housing typology as opposed to an individual case study building. The presented solutions can, to a certain extent, be adopted as optimal for other dwellings of the same typology. Some assumptions, such as climate, orientation and thermal performance of the building envelope, are case-specific. Especially the latter can impact the optimal results and profitability. In this paper, it was assumed that no retrofitting was done to the building. However, dwellings older than 20–30 years are often partly retrofitted (e.g., new windows are installed), and this will result in different optimal combinations of retrofitting solutions. More research is needed to assess the effect of varying assumptions.

Though cost-effective retrofitting solutions were found, some of the proposed building envelope retrofitting solutions might not be realistic. It was assumed that the insulation was added on the exterior side of the construction. However, it might not be desirable or feasible to add insulation to the exterior side, for example, for floors. It would require removing the original concrete floor to place the insulation below the floor. For heritage buildings or buildings close to other buildings, it could be difficult to add exterior insulation to the walls and/or roof. Therefore, the proposed optimized results might not be suitable for every house in the investigated housing typologies.

4. Conclusions

Optimal retrofitting packages that combine retrofitting of the envelope and energy systems with building automation control systems (BACS) were presented for two typical Norwegian dwellings: a single-family house and an apartment block. The reference models and BACS strategies were modeled and validated in IDA-ICE. The building envelope and automation parameters were optimized for energy consumption using GenOpt. The associated differences in life cycle cost and thermal comfort assessments were conducted using a post-processing algorithm in Excel. An air source heat pump, in combination with a high-performance building envelope and high-performance automation, was essential for cost-effective retrofitting. More profitable solutions had a building envelope with a lower energy performance, though still fulfilling the minimum energy performance requirements. Energy savings of 32–57% were achieved for the single-family house, and savings between 17–46% were achieved for the representative apartments. Upgrading BACS—in particular, the heating control strategies—accounted for up to 24% energy savings. Ventilation and blind control strategies did not significantly affect the energy consumption. When the potential of reducing heat losses through the envelope was limited, i.e., for more compact buildings with a low exterior surface area compared to heated floor area, the impact of BACS increased. A negative difference in life cycle cost was achieved faster for more compact buildings, as upgrading the BACS was significantly cheaper than building envelope retrofitting. The thermal comfort in the living room improved significantly after retrofitting, though no significant differences were identified between the optimal solutions. In general, the following can be concluded for residential buildings in cold climates: if the primary goal is to optimize the energy consumption (i.e., minimize it), an air source heat pump in combination with a high-performance building envelope and advanced heating and lighting control strategies is the most cost-effective solution. For more profitable solutions, or when a retrofit of the complete building envelope is not possible, high-performance BACS are an attractive retrofitting measure.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Electrical Loads and Installed Space Heating Power

Table A1. Electrical loads and installed space heating power for the single-family house (SF) and the apartments (AP) [19].

Room Function	Equipment	Case Study	Orientation	Area (m^2)	Lighting (W)	Heating (W)
Kitchens	Freezer, fridge, oven, microwave, kettle, small cooking, dishwasher	SF	E	8.5	46	1000
		AP	S	6.6	46	800
		AP	W	– [1]	–	–
Living rooms	Television, TV receiver, HiFi, clock, personal computer	SF	W	37.4	– [2]	3800
		SF	E&W	40.3	– [2]	3500
		AP	E	22.6	– [2]	800
		AP	W	33.0	– [2]	1200
Bedrooms	Clock, cordless phone	SF	E&W	20.4	2 × 46	2000
		SF	E	9.1	46	1000
		SF	W	11.2	46	1000
		AP	E	11.2	46	1200
		AP	E	35.1	3 × 46	3000
Bathrooms	–	SF	E	3.5	46	500
		SF	E	1.6	30	250
		SF	–	1.9	30	250
		AP	–	6.5	46	500
		AP	–	9.8	46	500
Laundry	Iron, vacuum cleaner, washing machine, dryer	SF	E	6.4	46	–
		AP	– [3]	– [3]	– [3]	–
		AP	– [3]	– [3]	– [3]	–
Halls	–	SF	E	7.4	46	500
		SF	W	4.8	30	250
		AP	–	6.5	30	500
		AP	–	7.4	30	500
Stairs	–	SF	–	2.5	30	–
Storage	–	SF	E	19.2	30	–

[1] There was no separate kitchen in the middle apartment. The equipment loads for the kitchen were added to the living room. [2] The lighting loads for living rooms were calculated using the model developed by Richardson et al. [24] and fit to the standardized yearly lighting load in NS 3031 [18]. [3] There was no laundry room in the apartments. The equipment loads for laundry were added to the bathroom.

Appendix B. Variable Temperature Setpoints

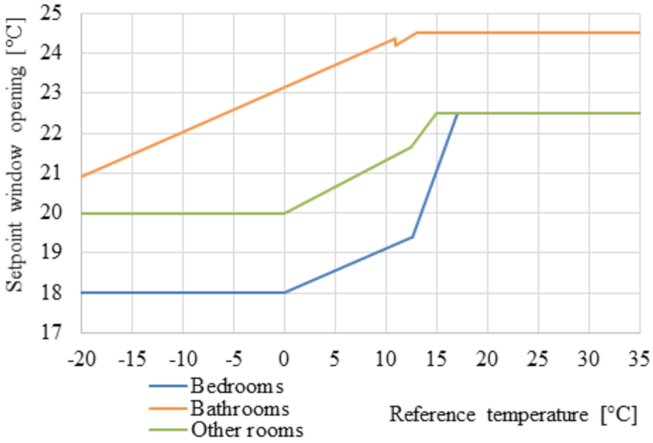

Figure A1. Adaptive temperature setpoints for opening the windows in the bedrooms, bathrooms and other rooms.

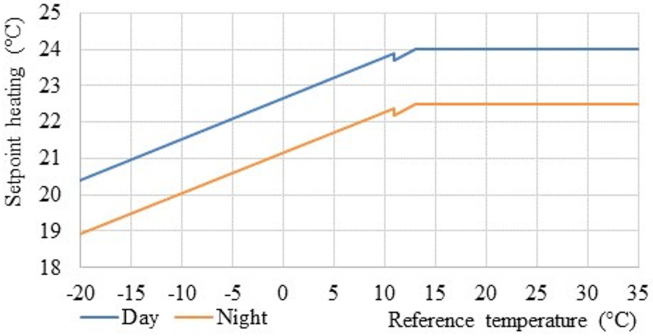

Figure A2. Adaptive heating temperature setpoints with night setback in the bathrooms.

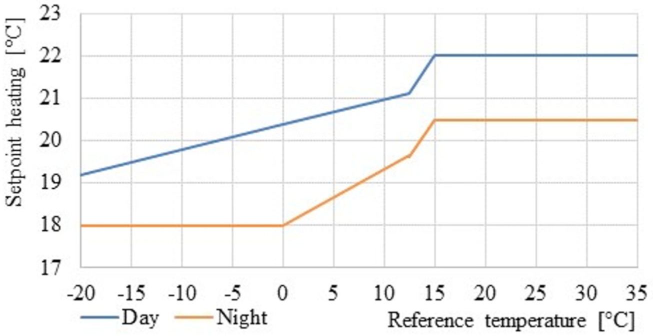

Figure A3. Adaptive heating temperature setpoints with night setback in the bedrooms.

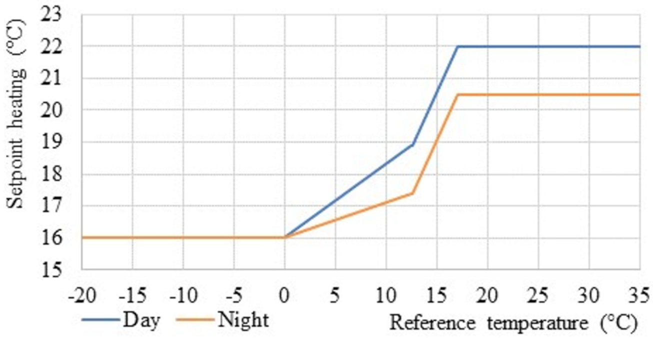

Figure A4. Adaptive heating temperature setpoints with night setback in the other rooms.

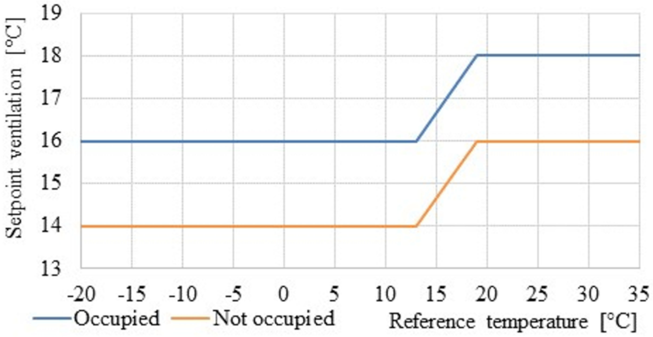

Figure A5. Variable air supply temperature setpoints with night setback.

Appendix C. Investment Cost

Table A2. Investment cost for the building envelope retrofitting measures.

Retrofitting Measure	Options	Cost (€/m^2)
Additional external wall insulation (original 10 cm) Including: removing the original cladding, adding a wind barrier, adding mineral wool insulation (variable thickness) and timber frame, adding cladding	10 + 10 cm	118.2
	10 + 15 cm	129.0
	10 + 20 cm	157.6
	10 + 25 cm	172.7
	10 + 30 cm	180.4
Additional insulation sloped roof, single-family house (original 10 cm) Including: demolition of the roof cladding, removing insulation from the loft, adding mineral wool insulation (variable thickness) and timber frame to the sloped roof, adding wind and vapor barriers, adding cladding	0 + 20 cm	193.9
	0 + 25 cm	203.7
	0 + 30 cm	211.8
	0 + 35 cm	218.8
	0 + 40 cm	225.1
Additional insulation flat roof, apartments (original 10 cm) Including: demolition of the roof cladding and insulation, adding expanded polystyrene (EPS) insulation (variable thickness), adding new cladding	10 + 10 cm	68.3
	10 + 15 cm	76.4
	10 + 20 cm	85.4
	10 + 25 cm	91.9
	10 + 30 cm	98.5

Table A2. *Cont.*

Retrofitting Measure	**Options**	**Cost (€/m^2)**
Additional insulation basement walls (original 0 cm) Including: digging out mass, adding EPS insulation (variable thickness)	0 + 15 cm	65.5
	0 + 20 cm	85.6
	0 + 25 cm	96.6
	0 + 30 cm	107.7
Additional insulation basement floor (original 0 cm) Including: demolition of flooring and concrete floor, digging out mass, adding EPS insulation (variable thickness), adding new concrete floor and flooring	0 + 10 cm	259.1
	0 + 15 cm	270.6
	0 + 20 cm	275.1
	0 + 25 cm	286.6
	0 + 30 cm	291.2
	0 + 35 cm	302.6

Table A3. Investment cost for the window retrofitting measures and air source heat pump.

Retrofitting Measure	**Options**	**Cost (€)**
Replacement of all windows, single-family house (original U = 2.8 W/m^2) Including: removing old windows, placing new windows	U = 1.2 W/m^2	19,984
	U = 0.8 W/m^2	22,978
Replacement of all windows, apartments (original U = 2.8 W/m^2) Including: removing old windows, placing new windows	U = 1.2 W/m^2	8437
	U = 0.8 W/m^2	9983
Air source heat pump, including installation	–	2234

Table A4. Investment cost for the building automation control systems retrofitting measures.

Automation Measure	**Options**	**Cost (€)**
Overall automation, single-family house	–	716
Overall automation, apartments	–	1027
Heating control, single-family house Including: smart heaters, sensors	Class C	2450
	Class B	2571
	Class A	3375
Heating control, apartments Including: smart heaters, sensors	Class C	2206
	Class B	2447
	Class A	3410
Ventilation control, single-family house Including: balanced ventilation system, sensors	Class D	8554
	Class C	12,295
	Class B	12,502
	Class A	12,678
Ventilation control, apartments Including: balanced ventilation system, sensors	Class D	7672
	Class C	7672
	Class B	8085
	Class A	8438
Lighting control, single-family house Including: sensors	Class B	1926
	Class A	4571

Table A4. *Cont.*

Automation Measure	Options	Cost (€)
Lighting control, apartments Including: sensors	Class B	1284
	Class A	3047
Blind control, single-family house Including: motorized blinds, sensors	Class B	2497
Blind control, apartments Including: motorized blinds, sensors	Class B	2110

Table A5. Sensors used for the different BACS strategies.

Control Strategy	Options	Sensors
Heating control	Class C	Weather sensor
	Class B	Weather sensor, occupancy sensor
	Class A	Weather sensor, motion sensor in every room
Ventilation control	Class C	-
	Class B	Weather sensor, temperature sensor
	Class A	Weather sensor, temperature sensor, motion sensor in every room
Lighting control	Class B	Daylight sensor in every room
	Class A	Daylight sensor in every room, motion sensor in every room
Blind control	Class B	Solar radiation sensor on every facade

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