Department of Mechanical Engineering

Cost-optimal renovation of residential, educational and office buildings in Finnish climate toward nearly zero-energy buildings

Tuomo Niemelä

Aalto University

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Cost-optimal renovation of residential, educational and office buildings in Finnish climate toward nearly zero-energy buildings

Tuomo Niemelä

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Abstract

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Abstract

Cost-effective renovation of existing buildings is a challenging and important task to significantly reduce the environmental impact of the built environment. Determining cost-effective renovation concepts for buildings inevitably leads to a multi-dimensional optimization problem because cost-effectiveness and energy efficiency are conflicting objectives with each other. The building owners are interested in solid renovation concepts that reduce the operating costs of the building but also deliver a reasonable return on investment and a reasonable payback period.

The main objective of this thesis was to study and determine the cost-optimal renovation concepts for the common Finnish building types that also have a significant energy efficiency improvement and environmental impact reduction potential. The studied building types were typical brick apartment buildings, concrete large panel apartment buildings, educational buildings, and office buildings. The objective was to take all applicable energy efficiency improvement measures, including the modern heat pump and renewable energy production technologies, into account in the assessment of each building type. In addition to studying the economic viability of different renovation concepts, technical, functional, feasibility, and quality aspects, such as the indoor environment conditions and the productivity of occupants, were examined closely.

A common solution of the cost-optimal renovation concepts of all the studied building types was that the investments should be focused on renewable energy production technologies and on technical systems of the buildings instead of investing in major renovations of the building envelopes. Especially the modern heat pump systems delivered significant improvements in both the energy performance of the buildings and in the cost-effectiveness of the deep renovation in all the studied building types. The studied heat pump systems delivered better cost-effectiveness than the district heating system in all the studied building types. According to the study, it is not cost-efficient or recommended to improve the energy efficiency of the building envelope beyond the current national building regulations regarding the energy performance of new buildings.

According to the results, the minimum primary energy performance requirements of the current building regulations related to improving energy performance of buildings in deep renovations could be tightened by 10% for residential apartment buildings, 30% for educational buildings and 20% for office buildings, depending on the original condition of the building. The proposed national nearly zero-energy building requirements can be cost-effectively achieved in deep renovations. However, external financial support mechanisms and competitive financial solutions are essential factors and motivators to encourage the building owners to take the next step in deep renovations of buildings by lowering the economic risks related to the renovation.

Keywords cost-optimal renovation, cost-effectiveness, energy efficiency, renewable energy source, environmental performance, multi-objective optimization, thermal comfort

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Tiivistelmä

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Tiivistelmä

Olemassa olevan rakennuskannan kustannustehokas korjaaminen on haastava ja tärkeä tehtävä rakennetun ympäristön kasvihuonekaasupäästöjen vähentämiseksi. Kustannusoptimaalisten peruskorjauskonseptien määrittäminen johtaa väistämättä monitavoitteelliseen optimointi-ongelmaan, koska kustannus- ja energiatehokkuus ovat keskenään ristiriitaisia tavoitteita. Kiinteistönomistajat ovat kiinnostuneita selkeistä peruskorjauskonsepteista, joilla rakennusten käyttökustannuksia saadaan pienennettyä järkevällä takaisinmaksuajalla ja sijoitetun pääoman tuotolla.

Tämän väitöstutkimuksen päätavoitteena oli tutkia ja määrittää kustannusoptimaaliset peruskorjauskonseptit yleisimmille suomalaisille rakennustyypeille, joiden energiatehokkuuden parantamispotentiaalit ja ympäristövaikutusten pienentämispotentiaalit ovat suuria. Tutkitut rakennustyypit olivat 1960-luvun tiilimuuri- ja 1970-luvun betonielementtirakenteiset asuinkerrostalot, 1960- ja 1970-luvun opetusrakennukset sekä 1980-luvun toimistorakennukset. Tutkimuksen tavoitteena oli tarkastella kaikki tutkituille rakennustyypeille soveltuvat energiatehokkuuden parantamistoimenpiteet, mukaan lukien nykyaikaiset lämpöpumppu- ja uusiutuvan energian tuotantojärjestelmät. Peruskorjauskonseptien taloudellisen kannattavuuden lisäksi tutkimuksessa otettiin huomioon tutkittujen ratkaisuiden tekniset, toiminnalliset, toteutettavuus- ja laatunäkökulmat, kuten sisäympäristöolosuhteet sekä rakennusten käyttäjien tuottavuus ja tyytyväisyys.

Yhteinen tekijä kaikkien tutkittujen rakennustyyppien kustannusoptimaalisissa peruskorjauskonsepteissa oli se, että investoinnit kannattaa keskittää uusiutuviin energiantuotantojärjestelmiin sekä rakennusten taloteknisiin järjestelmiin sen sijaan, että investoitaisiin rakennusten ulkovaippojen massiivisiin peruskorjauksiin. Erityisesti nykyaikaisilla lämpöpumppujärjestelmillä saavutetaan merkittäviä parannuksia sekä rakennusten energiatehokkuudessa että peruskorjausten kustannustehokkuudessa. Lämpöpumppujärjestelmillä saavutettiin parempi kustannustehokkuus kuin kaukolämmöllä kaikissa tutkituissa rakennustyypeissä. Tutkimuksen perusteella rakennuksen ulkovaipan energiatehokkuutta ei ole kustannustehokasta eikä suositeltavaa parantaa tämän hetkisiä uudisrakentamisen energiatehokkuusvaatimusten vertailuarvoja paremmaksi.

Tutkimuksen tulosten perusteella tämän hetkisiä rakennusten peruskorjausten primäärienergiatehokkuusvaatimuksia voitaisiin tiukentaa 10 % asuinkerrostaloissa, 30 % opetusrakennuksissa ja 20 % toimistorakennuksissa. Ehdotetut uudisrakennusten lähes nollaenergiavaatimustasot voidaan saavuttaa kustannustehokkaasti myös peruskorjauksissa. Ulkopuoliset ja kilpailukykyiset rahoitusratkaisut ovat kuitenkin keskeisiä tekijöitä, jotta kiinteistönomistajat saadaan investoimaan peruskorjausratkaisuihin, joilla kiinteistöjen energiatehokkuutta saadaan merkittävästi parannettua.

Avainsanat kustannusoptimaalisuus, kustannustehokkuus, energiatehokkuus, uusiutuva energianlähde, ympäristötehokkuus, monitavoiteoptimointi, lämpöolosuhde

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On 17 December 2013 Professor Risto Kosonen sent me an email and told me that there is an open master's thesis position at the Aalto University's Laboratory of Heating, Ventilation, and Air Conditioning (HVAC). The topic of the thesis related to theoretical modeling and simulation of heat pump systems in future nearly zero-energy buildings. The topic sounded interesting and I accepted the position. At that time, I had no idea that the research would expand to a doctoral dissertation. Professor Kosonen was my supervisor and D.Sc. Juha Jokisalo was my instructor in the master's thesis and we have continued with the same team in this doctoral thesis.

I would like to express my deepest gratitude to my supervisor Professor Risto Kosonen and to my instructor D.Sc. Juha Jokisalo. We have formed an excellent and efficient team and it has been truly a pleasure and a privilege to work with both of you. Without your inspiring support and encouragement this dissertation would not have been possible. Professor Kosonen has an amazing ability to motivate students during the different phases of the research. I would like to give special thanks to my instructor Juha Jokisalo for the extremely constructive and professional feedback, invaluable advice and encouraging support during this thesis.

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I became a master's student and moved to Espoo from Rovaniemi in September 2012. I have to admit that the last five years have been intensive, but also extremely rewarding. Now it is time to move on and focus on new challenges, whatever they may be.

Espoo, December 2017
Tuomo Niemelä

Contents

List of Publications

This doctoral dissertation consists of a summary and of the following publications, which are referred to in the text by their numerals.

1. Niemelä, Tuomo; Kosonen, Risto; Jokisalo, Juha. 2017. Cost-effectiveness of energy performance renovation measures in Finnish brick apartment buildings. Elsevier Ltd. Energy and Buildings, vol. 137, pages 60–75. ISSN 0378-7788. http://dx.doi.org/10.1016/j.enbuild.2016.12.031.

2. Niemelä, Tuomo; Kosonen, Risto; Jokisalo, Juha. 2016. Cost-optimal energy performance renovation measures of educational buildings in cold climate. Elsevier Ltd. Applied Energy, vol. 183, pages 1005–1020. ISSN 0306-2619. http://dx.doi.org/10.1016/j.apenergy.2016.09.044.

3. Niemelä, Tuomo; Kosonen, Risto; Jokisalo, Juha. 2017. Energy performance and environmental impact analysis of cost-optimal renovation solutions of large panel apartment buildings in Finland. Elsevier Ltd. Sustainable Cities and Society, vol. 32, pages 9–30. ISSN 2210-6707. http://dx.doi.org/10.1016/j.scs.2017.02.017.

4. Niemelä, Tuomo; Levy, Karoliina; Kosonen, Risto; Jokisalo, Juha. 2017. Cost-optimal renovation solutions to maximize environmental performance, indoor thermal conditions and productivity of office buildings in cold climate. Elsevier Ltd. Sustainable Cities and Society, vol. 32, pages 417–434. ISSN 2210-6707. http://dx.doi.org/10.1016/j.scs.2017.04.009.

5. Niemelä, Tuomo; Manner, Mika; Laitinen, Ari; Sivula, Timo-Mikael; Jokisalo, Juha; Kosonen, Risto. 2018. Computational and experimental performance analysis of a novel method for heating of domestic hot water with a ground source heat pump system. Elsevier Ltd. Energy and Buildings, vol. 161, pages 22–40. ISSN 0378-7788. https://doi.org/10.1016/j.enbuild.2017.12.017.

6. Niemelä, Tuomo; Vuolle, Mika; Kosonen, Risto; Jokisalo, Juha; Salmi, Waltteri; Nisula, Markus. 2016. Dynamic simulation methods of heat pump systems as a part of dynamic energy simulation of buildings. Proceedings of the 3rd IBPSA-England Conference BSO 2016, Newcastle, United Kingdom, 12–14 September. IBPSA-England. Paper 1146. ISBN 978-0-7017-0258-8. http://www.ibpsa.org/proceedings/BSO2016/p1146.pdf.

Author's Contribution

Publication 1: "*Cost-effectiveness of energy performance renovation measures in Finnish brick apartment buildings*"

Tuomo Niemelä is the principal author of the paper. The principal author proposed the concept and methodology, collected the data, conducted the numerical simulations and optimization, analyzed the data, and wrote the paper. The co-authors commented on the paper and provided valuable suggestions to improve the paper.

Publication 2: "*Cost-optimal energy performance renovation measures of educational buildings in cold climate*"

Tuomo Niemelä is the principal author of the paper. The principal author proposed the concept and methodology, collected the data, conducted the numerical simulations and optimization, analyzed the data, and wrote the paper. The co-authors commented on the paper and provided valuable suggestions to improve the paper.

Publication 3: "*Energy performance and environmental impact analysis of cost-optimal renovation solutions of large panel apartment buildings in Finland*"

Tuomo Niemelä is the principal author of the paper. The principal author proposed the concept and methodology, collected the data, conducted the numerical simulations and optimization, analyzed the data, and wrote the paper. The co-authors commented on the paper and provided valuable suggestions to improve the paper.

Publication 4: "*Cost-optimal renovation solutions to maximize environmental performance, indoor thermal conditions and productivity of office buildings in cold climate*"

Tuomo Niemelä is the principal author of the paper. The principal author proposed the concept and methodology, collected the data, conducted the numerical simulations and optimization, analyzed the data, and wrote the paper. The co-authors commented on the paper and provided valuable suggestions to improve the paper.

Publication 5: "*Computational and experimental performance analysis of a novel method for heating of domestic hot water with a ground source heat pump system*"

Tuomo Niemelä is the principal author of the paper. The principal author conducted the computational analysis and numerical simulations. The second and the third author conducted the performance measurements related to the experimental analysis. The principal, second, and third authors conducted the analysis of the data and results. The principal author wrote the paper. The co-authors commented on the paper and provided valuable suggestions to improve the paper.

Publication 6: "*Dynamic simulation methods of heat pump systems as a part of dynamic energy simulation of buildings*"

Tuomo Niemelä is the principal author of the paper. The principal author proposed the concept and methodology, collected the data, conducted the numerical simulations and optimization, analyzed the data, and wrote the paper. The co-authors commented on the paper and provided valuable suggestions to improve the paper.

Abbreviations

A2WHP	air-to-water heat pump
AHU	air handling unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BR	basic refurbishment
BREEAM	Building Research Establishment Environmental Assessment Method
CHP	combined heat and power
clo	clothing index of occupants, thermal resistance of the clothing
COP	Coefficient of Performance
CPU	central processing unit
DCV	demand-controlled ventilation
DCW	domestic cold water
DE	delivered energy
DH	district heating
DHW	domestic hot water
EAHP	exhaust air heat pump
EPBD	Energy Performance of Buildings Directive
EPC	energy performance certificate
ESBO	Early Stage Building Optimization
FCIE	Finnish Classification of Indoor Environment
FiSIAQ	Finnish Society of Indoor Air Quality
GOS	global optimum solution
GSHP	ground source heat pump
HP	heat pump

HVAC	heating, ventilation, and air conditioning
IAQ	indoor air quality
IC	investment cost
IEA	International Energy Agency
IRR	internal rate of return
LCA	life-cycle assessment
LCC	life-cycle cost
LEED	Leadership in Energy and Environmental Design
MET	metabolic rate of occupants
MOBO	Multi-Objective Building Performance Optimization
MP	mutation probability
NBCF	National Building Code of Finland
NPV	net present value
nZEB	nearly zero-energy building
PDH	hours of people dissatisfied
PE	primary energy
PMV	predicted mean vote
PPD	predicted percentage of dissatisfied
PV	photovoltaics
RES	renewable energy source
ROI	return on investment
SBMOO	simulation-based multi-objective optimization
SBO	simulation-based optimization
SCOP	Seasonal Coefficient of Performance
SFP	specific fan power
SPF	Seasonal Performance Factor
STC	solar thermal collector
TRY	test reference year
USGBC	United States Green Building Council
VAT	value added tax

Nomenclature

A	difference between total profits and costs, the total net profit, €/a
A_{net}	heated net floor area of the building, m^2
ceil	a function that returns the next integer that is equal or greater to its parameter, -
$CO_{2,DE}$	CO_2 emissions of delivered energy consumption, kg
$CO_{2,materials}$	embodied CO_2 emissions of construction materials, kg
$CO_{2,total}$	total CO_2 emissions, kg
$CO_{2,transport}$	CO_2 emissions of transportation of the construction materials, kg
E_a	annual energy cost, €/a
E_i	annual delivered energy consumption of energy carrier i, kWh/a
$E_{primary}$	primary energy consumption of the building, kWh/(m^2 a)
f_i	primary energy weighting factor of energy carrier i, -
i	internal rate of return, internal interest rate, %/a
$I_{0,add.}$	additional investment cost of the renovation measures, €
$I_{0,tot}$	total investment cost, €
k_i	year from the start of the LCC calculation analysis, when a specific renewal measure is carried out, -
LCC_{15a}	net present value of the 15-year life-cycle cost of the building, €
LCC_{20a}	net present value of the 20-year life-cycle cost of the building, €
LCC_{25a}	net present value of the 25-year life-cycle cost of the building, €
MR_a	annual maintenance and repair cost of the renovation measures, €/a
n	life-cycle period of the LCC calculation analysis, a
n_1	number of possible values with first discrete variable, -
n_2	number of possible values with second discrete variable, -

n_c	number of continuous variables, -
n_x	number of possible values for last discrete variable, -
$Q_{condenser}$	heating energy produced by the condenser, kWh
Q_{DHW}	heating energy produced to the domestic hot water system, kWh
$Q_{elec.,HP+aux.}$	total electrical energy consumed by the heat pump system and auxiliary equipment, kWh
$Q_{heat,total}$	total heating energy produced by the heat pump system, kWh
$Q_{losses,storage}$	heat losses of the domestic hot water heat storage system, kWh
$Q_{superheat}$	heating energy produced by the superheater, kWh
r	real interest rate, %
r_e	escalated real interest rate, %
r_w	average annual increase in the total value of the work, %
R_M	renewal cost of the renovation measure, €
Res_{tot}	total residual value of the renovation measures, €
SPF_{total}	overall energy performance of the heat pump system, -
t_{lost}	sum of annual lost working hours due to productivity loss, h/a
Va_{work}	total value of the work, €/h

1. Introduction

1.1 Background

Buildings account for approximately 32–35% of global final energy consumption and approximately 20–25% of global greenhouse gas emissions (IEA, 2016; Lucon et al., 2014). In Finland, buildings currently account for up to 40% of the final energy consumption and up to 33% of the total greenhouse gas emissions (Statistics Finland, 2017a, 2017b). The Finnish figures correspond accurately to the average statistics of the European Union region where buildings account for 40% of the final energy consumption and approximately 36% of the total greenhouse gas emissions (European Commission, 2017).

Due to its significant energy consumption, the building sector plays a major role in restraining global climate change by reducing the final energy consumption and greenhouse gas emissions of buildings. Improving the energy efficiency of buildings and implementing renewable energy sources (RESs) in the energy production of buildings have become key objectives for regional and international energy policies. According to the recast Energy Performance of Buildings Directive (EPBD) (2010/31/EU), improved energy efficiency of buildings is maintaining good indoor climate and thermal comfort conditions with less energy use than before.

In Europe, the European Commission has implemented the recast EPBD (2010/31/EU), which requires all member states of the European Union to develop methods and guidelines for improving the energy performance of new buildings toward nearly zero-energy buildings (nZEBs). The main objectives of the EPBD are to significantly improve the primary energy (PE) performance of buildings and utilize RESs in the energy production of buildings (EPBD, 2010/31/EU).

A more detailed definition of requirements for nZEBs and methods to determine the energy performance of buildings are left to the member states. While more specific requirements of the EPBD mainly concern new buildings, the member states are also required to develop energy performance targets and energy efficiency improvement concepts for existing buildings (EPBD, 2010/31/EU). However, the EPBD (2010/31/EU) also states that technical, functional, and economical aspects should always be taken into account when the energy efficiency of buildings is improved in deep renovations.

The energy and carbon dioxide (CO_2) emissions savings potential of existing buildings is significant compared to the corresponding savings potential of new buildings (Balaras et al., 2005; Nemry et al., 2010). In addition, the existing building stock is renewed slowly, on average 1–2% per year, so it is important to determine cost-effective renovation concepts that also improve the energy performance of buildings (Balaras et al., 2005; Kuusk & Kalamees, 2015; Kuusk et al., 2017; Nemry et al., 2010). Recent studies carried out by Kuusk and Kalamees (2015) and Economidou et al. (2011) indicate that the existing residential building sector is the largest individual building sector in the European Union. According to Kuusk and Kalamees (2015) and Economidou et al. (2011), residential buildings account for approximately a 75% share of all existing buildings in Europe. Furthermore, over 50% of the residential buildings in Europe were built before 1970 (Birchall et al., 2014; Birchall et al., 2016). In Finland, residential buildings account for a 62% share of all existing buildings, as determined by total built floor area (Statistics Finland, 2017c). Approximately 31% of Finnish residential buildings were built before 1970 and 49% before 1980 (Statistics Finland, 2017c).

To reduce the environmental impact of the building sector, the popularity of RESs is increasing in the energy production of buildings. The recast EPBD (2010/31/EU) states that renewable energy production technologies should be extensively used to cover the PE demand of nZEBs and buildings with high energy performance. Recent studies conducted by Häkämies et al. (2014, 2015), Salata et al. (2017), and Moran et al. (2017) demonstrate that heat pump systems are one of the best applications to utilize RESs and improve the PE performance of buildings cost-effectively.

The popularity of heat pump installations is increasing in deep renovations of buildings because heat pump systems typically provide a cost-effective alternative to significantly improving the energy efficiency of residential and office buildings over the more conventional renovation measures related to improving the energy efficiency of the building envelope (Gustafsson et al., 2017; Salata et al., 2017). In addition to heat pump systems, solar photovoltaics (PV) and solar thermal harvesting technologies are developing at a fast pace, and they are also becoming cost-effective and recommended energy efficiency improvement measures to be considered in both new low-energy buildings and deep renovations of existing buildings (Gustafsson et al., 2017; Häkämies et al., 2015; Moran et al., 2017; Salata et al., 2017).

Cost-effective renovations of existing buildings are challenging and important tasks. Major research efforts have been put in internationally to determine economical and sustainable renovation concepts for different building types built during different eras. However, the main problem of previous studies and implementations is that they have mainly focused on individual and more conventional energy efficiency improvement measures and renovation concepts related to the building envelopes, technical systems of buildings, or different energy production technologies. Full-scale renovation studies have not been conducted previously, where all applicable energy efficiency improvement measures, including modern renewable energy production technologies, are studied simultaneously.

The previous studies have been carried out using more conventional research methods, where different measures and their effect on the overall energy performance of the studied buildings have been investigated by means of a limited number of predefined cases. Typically, the more conventional research methods applied in the previous studies include parametric-based analyses or individual simulation-based analyses, where different renovation and retrofitting alternatives are manually simulated and studied without the utilization of automated and highly efficient multi-objective optimization methods. In addition, the limited number of predefined cases, which is typically 5–30, is a major limiting factor in the manually performed analyses and research methods, when accuracy, reliability, effectiveness, and number of potential renovation alternatives are discussed. This creates a problem in larger and more detailed studies because the conventional research methods limit both the total number of studied measures that can be selected and the accuracy and reliability of the results when several measures and their economic feasibilities are studied simultaneously. The conventional research methods cannot guarantee the global cost-optimum solution of several simultaneous measures because there can easily be thousands or even millions of different renovation solution combinations, depending on the case.

Determining cost-optimal renovation concepts for different building types inevitably leads to a multi-dimensional optimization problem because cost-effectiveness and energy efficiency are conflicting objectives. When improving indoor environment conditions is also an objective of deep renovations, next generation research methods are required to solve the demanding multi-objective optimization task.

1.2 Research objectives and questions

The main objective of this thesis is to study and determine cost-optimal deep renovation concepts for the common Finnish building types that also have significant energy efficiency improvements and environmental impact reduction potential. All applicable energy efficiency improvement measures, including modern heat pump and renewable energy production technologies, are accounted for in the assessment of each building type. By studying all the applicable measures simultaneously instead of a limited number of predefined renovation cases, the global optimum renovation concepts can be determined. In addition to the economic viability of the studied renovation concepts, technical, functional, feasibility, and quality aspects are also accounted for and examined closely. The studied building types are:

- Typical brick-structured apartment buildings built in the 1960s (Publication 1)
- Typical brick-structured educational buildings built during the 1960s and 1970s (Publication 2)
- Typical large panel-structured apartment buildings built during the first half of the 1970s (Publication 3)
- Typical office buildings built in the 1980s (Publication 4).

The first national building regulations related to the energy efficiency of buildings came into force in 1976. However, approximately 40–50% of the Finnish building stock has been built before 1976, meaning that there is a substantial number of buildings with significant energy-saving potential included in the building stock. Furthermore, most of the buildings built before the 1980s already require deep renovations and retrofitting measures. The need for deep renovations is estimated to exponentially increase soon because the total value of renovation debt of the Finnish building stock is estimated to be €30 billion–€50 billion in 2016, which is almost as high as the €54 billion total budget of the Finnish government (Finnish Government, 2016; Soimakallio et al., 2017).

A key objective of this thesis is to study, develop, and validate the current dynamic simulation methods used for simulating complex energy systems. As the heat pump and other renewable energy production systems are increasing their popularity, validated accuracy and reliability of the used simulation methods play an essential role in optimum dimensioning of the systems and in ensuring optimum operation of the systems. The study reported in Publication 6 focused on developing a functional calibration methodology for dynamic simulation of different heat pump systems as a part of dynamic energy simulation of buildings.

Another essential objective of this thesis is to develop and assess the performance of novel heat pump applications for use in future low-emission and high-performance buildings equipped with smart control systems. The study reported in Publication 5 aimed at developing a novel methodology for energy efficient heating of domestic hot water (DHW) with a geothermal heat pump system.

The objectives of this thesis can be further developed into six main research questions:

1. What are the cost-optimal renovation concepts for different building types, and what measures should be applied to maximize the cost-effectiveness, energy performance, and environmental impact reduction potential in deep renovations?
2. What types of renewable energy production technologies should be applied, if any, and how should they be dimensioned in deep renovations where more restrictions and challenges are typically included in the installation of the technology than in new buildings?
3. How should the maintenance and energy performance improvement renovations be scheduled and combined, and how can significant benefits be obtained by combining them?
4. What are the main differences between the cost-optimal renovation concepts, and how significant is the difference if the economic viability analysis is carried out to minimize the PE consumption, actual delivered energy consumption, or total environmental impact (CO_2 emissions) of the building?
5. Can the proposed national nZEB energy performance requirements be achieved cost-effectively in deep renovations?

6. How accurate are the current energy performance simulation methods, especially the simulation methods of heat pump systems compared to the verified performance of actual installed systems in both standardized test conditions and real dynamic operating conditions, and can they be reliably used to predict the performance and operation of modern energy efficient heat pump systems in building performance analyses?

1.3 Novelty of research

This thesis is based on the new contributions to the original publications carried out during the author's doctoral study period. The new contributions to original Publication 1 can be divided into two main aspects. The first aspect is to provide cost-optimal renovation concepts for Finnish brick apartment building owners that are also functional and technically feasible to be conducted in deep renovations of brick apartment buildings. The second aspect is to demonstrate a novel methodology, the simulation-based multi-objective optimization (SBMOO) analysis, for renovation and refurbishment of buildings where all applicable renovations and retrofitting measures are taken into account and studied simultaneously. Previous studies utilizing the SBMOO method have mainly focused on cost-optimal construction of new high-performance buildings, such as net zero-energy buildings or zero-carbon buildings. In Publication 1, the cost-optimal renovation concepts that meet different energy performance criteria were determined from over 2 billion potential renovation measure combinations by using the SBMOO analysis.

The new contribution to original Publication 2 is to provide cost-optimal renovation concepts for Finnish educational buildings built during the 1960s and 1970s. While the initial setting of the research is similar to Publication 1, renovation of educational buildings differs from renovation of residential apartment buildings because the usage, occupancy, HVAC systems, and indoor environment requirements of the two building types are significantly different. The research presented in the original Publication 2 provides new insights for renovations of educational buildings. Previous studies have not come up with cost-optimal solutions to renovate existing educational buildings located in cold climate conditions to nZEBs, while improving or maintaining excellent indoor climate conditions at the same time. The main reason for this is that the previous studies have typically been limited to the more commonly carried out renovation measures.

The new contribution to original Publication 3 is to provide cost-optimal renovation concepts for Finnish prefabricated concrete large panel apartment building owners. The concrete large panel apartment buildings built in the 1970s are the most common apartment building type in Finland and in many other European countries. The study provides a novel and extensive research perspective, as the cost-optimal renovation concepts are determined individually for two different renovation scenarios. The first scenario provides cost-optimal renovation concepts to maximize the PE performance of the building and to provide cost-effective renovation concepts to meet the proposed national nearly zero-energy apartment building requirements. The second scenario provides cost-optimal renovation concepts to maximize the environmental impact reduction potential of the studied building type in deep renovations. The study included in the original Publication 3 implements the multi-objective optimization analysis in an environmental life-cycle assessment (LCA) of deep renovation of buildings for the first time. In the analysis, the entire CO_2 emissions assessment is conducted using optimization, whereas in previous studies, the CO_2 emissions assessments have been carried out manually using a fixed design solution or a limited number of predefined design solutions.

The new contribution to original Publication 4 is to provide cost-optimal renovation concepts for Finnish office building owners. The research included in the original Publication 4 includes two aspects. The first aspect is to provide cost-optimal renovation concepts for building owners who are also responsible for both the salaries of the employees and the operating costs of the building, such as a government organization. The second aspect is to provide cost-optimal renovation concepts for building owners who are not responsible for the salaries of the building users but are responsible for the operating costs of the building, such as a private or public organization that rents office spaces. The multi-objective optimization method is applied in the study to optimize up to three conflicting objectives, such as economic indicators (LCC, return on investment), energy and environmental performance, and the thermal comfort conditions, simultaneously. The research method is applied in deep renovations of existing office buildings for the first time, and it is also used to determine the optimum combination of renovation measures and HVAC system set points to maximize the indoor thermal conditions and the productivity of the building users with minimum energy consumption and construction costs. Finally, the study reported in the original Publication 4 provides a useful and effective methodology to assess the overall performance of deep renovations of office buildings, which can also be applied to other climate conditions and techno-economic environments.

In general, the new contributions of original Publications 1–4 are that they determined the cost-optimal and especially the global optimum renovation concepts for each studied building type for the first time by using a sophisticated and highly efficient SBMOO method as the main research method. In addition, the results of the individual case studies can be generalized for deep renovations of residential apartment and educational and office buildings located in cold climate conditions and in similar techno-economic environments, such as Scandinavia.

The new contribution to original Publication 5 is to provide a novel methodology developed for energy efficient heating of DHW with a ground source heat pump (GSHP) system without the need for auxiliary heating systems or supporting renewable energy production systems. The performance of the developed methodology is studied and validated by computational and experimental performance analyses and by conducting on-site field studies in existing apartment buildings located in the cold climate of Finland. In addition to the novel methodology, original Publication 5 developed a dynamic simulation model as a result of the computational validation analysis to simulate the performance and operation of a GSHP system utilizing the developed DHW heating methodology. While the novel methodology was originally developed for GSHP systems, it can also be used with other heat pump systems, such as air-to-water, exhaust air, and hybrid heat pump systems.

The new contribution to original Publication 6 is the validation methodology of dynamic simulation models of heat pump systems. The novel calibration methodology developed in the original Publication 6 can be used to accurately calibrate the energy performance and operation of different heat pump simulation models to correspond to the energy performance and operation of actual heat pump units and systems. The developed calibration methodology was successfully validated in the study reported in the original Publication 6, and it was also utilized in all the other individual studies reported in original Publications 1–5. In addition, the developed calibration and validation methodology will also be implemented in the next versions of the IDA Indoor Climate and Energy (IDA ICE) simulation software by Equa Simulation Ab.

1.4 Structure of the thesis

This thesis consists of six appended peer-reviewed research papers and a summary. This summary consists of an introduction, literature review, methods, results, discussion, and conclusions. The summary links the individual research papers together and discusses how the papers contribute to the research questions of this thesis. The summary also presents the mutual conclusions of the research, which are derived from the contributions of the individual research papers.

The introduction presents the background, research objectives, and research questions. The second part consists of a compact literature review, where a summary of previous research related to the thesis topic is presented. The methods section presents the main research methodology used in this thesis. The methods section also describes the initial research setting of the appended research papers. The results section presents the main results of the individual research papers. The discussion presents the findings and new contributions of the papers. Evaluation of the research as a whole and suggestions for future research are also discussed. Finally, the conclusions section presents the main conclusions of the research.

The first three research questions are addressed in Publications 1–4. The second research question is also discussed in Publication 5. The fourth research question is addressed in Publications 3–4. The fifth research question is discussed in Publications 1–4, and the sixth research question is addressed and discussed in detail in Publications 5–6.

2. Review of literature

2.1 Renovation of residential apartment buildings

Previous studies conducted by Balaras et al. (2000, 2005), Bonakdar et al. (2014), Csoknyai et al. (2016), Kuusk et al. (2017), and Paiho et al. (2013) have concluded that brick and concrete large panel-structured residential apartment buildings built between the 1960s and 1990s are among the most common residential building types and the most common apartment building types with a significant energy savings potential in many European countries. In Finland, apartment buildings built during the 1960s and 1970s account for the largest share of the apartment building stock. The concrete large panel-structured apartment buildings built during the 1970s account for a 24% share of the Finnish residential apartment buildings, which is the largest individual share (Statistics Finland, 2017c). The brick-structured apartment buildings built during the 1960s account for a 16% share of the apartment building stock, which is the second-largest individual share (Statistics Finland, 2017c).

The studies conducted by Balaras et al. (2000, 2005), Bonakdar et al. (2014), Csoknyai et al. (2016), Kuusk et al. (2017), and Paiho et al. (2013) demonstrate that the characteristics and technical specifications of the apartment building stock are relatively similar in many European countries located in cold climate regions, such as in the Scandinavian countries, Estonia, northern Russia, and many eastern European countries.

A common conclusion of the aforementioned studies is that the apartment buildings built in the 1960s and 1970s are now requiring major renovation measures for both the building envelope and the technical systems of the buildings. However, recent studies conducted by Kuusk and Kalamees (2015), Kuusk et al. (2014, 2017), and Bonakdar et al. (2014) indicate that regardless of the tightened member-state-specific energy performance requirements and the European Union 2020 targets to reduce both energy consumption and greenhouse gas emissions, apartment building owners are typically motivated to carry out major energy efficiency improvement measures in deep renovations only to achieve energy cost savings with a reasonable investment payback period. It is obvious that renovation concepts with low or even negative return on investment are difficult to justify for apartment building owners, regardless of the improvements in energy efficiency or the reduction in greenhouse gas emissions.

Several studies have been conducted during the last two decades by Kuusk et al. (2014), Koiv and Toode (2001), Martinot (1997), Matrosov (2000), and Paiho et al. (2012) where the economic viability of deep renovations and the energy savings potential of brick and concrete large panel-structured apartment buildings located in cold climate conditions have been studied. The results of these studies indicate that there are many measures that can be applied to brick apartment buildings in deep renovations, depending on the type and the energy performance target level of the renovation. Typically, individual measures, such as additional thermal insulation of external walls, replacement of windows, or renovation of the ventilation system, are applied, but recent studies conducted by Kuusk et al. (2014, 2017) and Kuusk and Kalamees (2015) indicate that larger renovation packages, including multiple measures, are also economically feasible when they are correctly selected and dimensioned and when they are combined with the mandatory large-scale maintenance renovations.

The condition of the outer concrete layer of the panel elements determines the minimum maintenance need in concrete panel-structured apartment buildings. If the outer concrete layer is highly carbonated, this results in the corrosion of the reinforcement structures due to neutralization of concrete, and in this case, the outer concrete layer is typically demolished along with the original thermal insulation, and new thermal insulation and outer layers are installed. Additional thermal insulation is often not applied, and it is also not economically viable in typical situations where the outer concrete layer does not have to be demolished. The research perspective to determine the cost-optimum combination of renovation measures is different in situations where the outer concrete layer and the original thermal insulation are demolished and renewed. In addition, the selected solutions must be technically feasible and functional (e.g., moisture behavior in external walls with thick thermal insulation layers and various climate conditions, which are essential aspects that must also be accounted for in the design phase of deep renovations in addition to the economic and energy saving aspects).

Paiho et al. (2013, 2014, 2015), Csoknyai et al. (2016), Kuusk and Kalamees (2015), and Bonakdar et al. (2014) conclude that an essential aspect of economically viable renovation solutions is to combine the energy performance improvement measures with the mandatory maintenance repairs. The studies have also concluded that innovative motivation mechanisms are needed to encourage the apartment building owners to conduct deep renovations, where the energy performance of apartment buildings is improved further than the cost-optimum level, possibly toward nearly zero-energy apartment buildings. In addition, the findings of the studies indicate that the energy production systems of residential apartment buildings located in cold climates have a significant impact on the environmental impact reduction potential and on the overall energy efficiency of the existing apartment building stock.

However, the aforementioned studies have mainly focused on individual renovation measures or renovation packages regarding the building envelope, the ventilation systems of the buildings, and individual renewable energy production systems, such as solar thermal collector (STC) or PV-panel systems. Furthermore, the literature review related to cost-efficient renovations of apartment buildings indicates that various cost-effective main heating system alternatives, such as applicable modern heat pump systems with cost-optimum dimensioning, have not been extensively studied previously, and further research is needed to determine and compare the economic viability of different main heating system concepts to the economic viability of the more conventional individual renovation measures related to the energy performance of the building envelope and building services systems, which have been studied in detail in several recent studies (Bonakdar et al., 2014; Csoknyai et al., 2016; Kuusk & Kalamees, 2015; Paiho et al., 2013, 2014, 2015).

When modern heat pump systems and other RESs are compared to additional thermal insulation of external walls and roofs, replacement of windows, renovation of the ventilation system, and other more commonly applied renovation measures, there are typically millions of potential renovation combinations. Determining the global optimum renovation concepts for different main heating systems that can be applied in existing residential apartment buildings, from both the energy performance improvement and overall environmental impact reduction perspectives, is impossible without using a modern and sophisticated research method, such as an SBMOO analysis.

2.2 Renovation of educational buildings

Raatikainen et al. (2016), Desideri et al. (2012), Dall'O' and Sarto (2013), Hong et al. (2013), Kameda et al. (2007), Corgnati et al. (2007), Wargocki and Wyon (2007), Daisey et al. (2003), and Lee et al. (2012) have conducted studies related to the learning and productivity of students and teachers, indoor climate conditions, and energy efficiency of schools and educational buildings. The common findings of these studies indicate that there is a strong connection between the productivity, learning performance, and indoor climate conditions, including both thermal comfort conditions and indoor air quality (IAQ). Recent studies conducted by Bakó-Biró et al. (2012) and Haverinen-Shaughnessy et al. (2011) demonstrate that the IAQ is highly determined by the ventilation rates applied in educational buildings during operating times.

Studies conducted by Alfano et al. (2010), Gameiro da Silva et al. (2013), and Bernardo and Dias Pereira (2014) indicate that it is often relatively difficult to maintain excellent indoor climate conditions energy efficiently and cost-effectively in educational buildings because indoor climate conditions and energy efficiency have conflicting objectives. This creates a problem in both designing new educational buildings and renovating existing educational buildings because the primary objective of deep renovations of educational buildings is typically to improve the indoor climate conditions in addition to improving the energy performance of the buildings (Alfano et al., 2010; Bernardo & Dias Pereira, 2014; Gameiro da Silva et al., 2013).

The aforementioned studies demonstrate that it is essential to provide high-quality indoor environment conditions in educational buildings, which should be the priority in deep renovations of educational buildings. High energy performance should never be achieved at the expense of indoor environment conditions. In addition, the literature review indicates that existing educational buildings often require significant renovation measures for the HVAC and lighting systems, especially for the ventilation system, to improve the indoor environment conditions and maximize the learning performance of students.

While a relatively significant amount of research efforts has been put in to determine cost-effective low-energy, nearly zero-energy, and net zero-energy design concepts for new educational buildings, the literature review indicates that there is still a limited number of studies where the cost-effectiveness of modern renewable energy production technologies has been extensively studied in renovations of existing educational buildings located in cold climate regions.

The literature review indicates that, in general, educational buildings built before the 1980s are now requiring major renovation measures for both the building envelope and the building services systems. The current situation is similar in Finland, as approximately 68% of Finnish educational buildings were built before 1980 (Statistics Finland, 2017c).

2.3 Renovation of office buildings

The specific delivered and PE consumptions of office buildings are one of the highest compared to other building types (Juan et al., 2010). According to Juan et al. (2010), improving both the energy performance and indoor climate conditions in existing office buildings cost-effectively is challenging, and an increasing number of globally operating organizations have been investing substantial resources in sustainable building renovation processes over the last two decades. Studies conducted by Juan et al. (2010), Doukas et al. (2009), and Çakmanus (2007) demonstrate that various integrated decision support systems have been developed to assess the condition of existing office buildings and to determine recommendable renovation actions, where renovation costs, building quality, and environmental aspects are taken into account.

The property owners are clearly interested in solid renovation measures and deep renovation concepts to maximize the return on investment (ROI), decrease the annual operating costs, and improve the value of office buildings (Doukas et al., 2009; Çakmanus, 2007; Juan et al., 2010). In addition, improving the indoor climate conditions during operating times of office buildings enhances work efficiency (Seppänen et al., 2006a, 2006b).

Ihara et al. (2015), Griego et al. (2015), Gruber et al. (2015), Krstić-Furundžić and Kosić (2016), and Fasi and Budaiwi (2015) have studied the effects of different facade and building envelope solutions on the energy performance and indoor climate conditions of office buildings and concluded that effective solar shading solutions can cost-effectively improve both the energy performance and indoor thermal conditions of office buildings. However, the majority of previous studies have focused on measures applied in office buildings located in hot or intermediate climates, where the dimensioning and operation of cooling systems is one of the essential factors in office buildings in regards to energy performance, indoor climate conditions, and performance of workers (Fasi & Budaiwi, 2015; Gou et al., 2012; Gruber et al., 2015; Krstić-furundžić & Kosić, 2016; Ornetzeder et al., 2016; Ucci & Yu, 2014).

Typically, improved indoor climate conditions lead to increased energy consumption in office buildings. It is challenging to improve the energy performance and decrease the environmental impact of buildings toward low-energy and nZEBs while providing productive and comfortable indoor climate conditions (Fasi & Budaiwi, 2015; Ornetzeder et al., 2016; Ucci & Yu, 2014). Previous studies conducted by Ornetzeder et al. (2016), Ucci and Yu (2014), and Gou et al. (2012) indicate that the effects of low-carbon and high energy performance office building designs and technologies on the indoor environment quality are still relatively unknown and require further validation. Their studies also demonstrate that the popularity of different environmental classifications, such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM) (BREEAM, 2017; USGBC, 2017), have increased in deep renovations of office buildings. Major property owners want to certify their buildings to increase the value of the buildings. However, studies carried out by Ornetzeder et al. (2016) and Gou et al. (2012) indicate that the users of high energy performance office buildings with a high-level environmental certification have not experienced higher-rated indoor climate conditions and satisfaction than users of more conventional office buildings.

Multiple studies related to the productivity loss of workers due to unfavorable or poor IAQ and thermal comfort conditions have been conducted to determine the cost implication of productivity loss in office buildings (Fisk & Rosenfeld, 1997; Kosonen & Tan, 2004a, 2004b; Skåret, 1992; Wargocki et al., 1999, 2000; Woods, 1989; Wyon, 1996). The findings demonstrate that, depending on the techno-economic environment, the financial impact of productivity loss due to reduced work efficiency can be 10–100 times greater than the operating costs of an office building. This means that improving the indoor climate conditions through renovations of existing office buildings is essential and economically viable, especially if the building owner is the same organization that is paying the salaries of the employees, such as a government office or equivalent organization.

Typically, the objectives related to the indoor climate conditions of a renovation can be different between a building owner who is not responsible for the salaries of the employees, and a building owner who is paying the salaries in addition to the operating costs of the building (Kosonen & Tan, 2004a, 2004b). In general, the objective of renovations in tenant-occupied office buildings is to provide an acceptable indoor environment for occupants but not necessarily to maximize the thermal comfort and IAQ conditions (Kosonen & Tan, 2004a, 2004b; Skåret, 1992; Woods, 1989). Furthermore, the ideal target of renovations in owner-occupied office buildings is to determine cost-optimal compromise solutions to improve both the thermal comfort and IAQ conditions to maximize the productivity of workers and also to minimize the investment and life-cycle costs (LCCs) of the renovations (Kosonen & Tan, 2004a, 2004b; Skåret, 1992; Woods, 1989). In addition, both types of building owners have an increasing interest in reducing the carbon footprint of their buildings by investing in RESs and in measures that reduce the environmental impact of the buildings.

The ideal situation is to determine cost-effective renovation packages for both types of building owners to deliver optimal combinations of measures to meet the different objectives with as high an ROI as possible.

Previous studies conducted by Kosonen and Tan (2004a, 2004b), Wyon et al. (1975), and Wyon (1996) have demonstrated the economic impact of productivity loss due to decreased performance of workers and have suggested measures and design principles, such as airflow rates and individual microclimate controls, to improve the indoor environment conditions and minimize the productivity loss. However, these measures and design principles are conventionally applied to new office buildings, and they are typically extremely difficult, expensive, impractical, and often impossible to implement in renovations of existing office buildings because of space constraints. Furthermore, there are millions of different renovation package combinations that can be selected when deep renovations of office buildings are conducted. This makes it impossible to determine the global optimum combination of measures by using the conventional parametric-based analysis methods. In addition, the building ownership aspects (owner-user and tenant) have not been addressed in previous studies focusing on renovations of office buildings.

The findings and conclusions of the previous studies demonstrate that cost-effective renovations of office buildings, where the indoor environment conditions are also improved simultaneously, are challenging tasks, as cost-effectiveness, indoor climate conditions, and energy efficiency are all conflicting objectives, which results in a multi-objective optimization problem.

2.4 Development of renewable energy production technologies

The recast EPBD (2010/31/EU) requires that all new buildings must be nZEBs by the end of 2020. The EPBD requires nZEBs to be buildings with high energy performance and that RESs are effectively utilized to cover the PE demand of nZEBs (EPBD, 2010/31/EU). According to Häkämies et al. (2014, 2015), Salata et al. (2017), and Moran et al. (2017), heat pump systems, especially GSHP systems, are one of the best applications to utilize RESs and improve the PE performance of buildings cost-effectively, depending on the member-state-specific PE weighting factors.

In addition to the modern heat pump technologies, solar-based thermal and electricity production systems have developed at a fast pace and increased their popularity significantly over the last decade. Numerous studies have concluded that especially the solar-based PV systems are a cost-effective and recommended technology to utilize on-site renewable energy, improve the energy performance of buildings, and reduce both the LCCs and the total environmental impact of buildings (Asaee et al., 2017a; Camilo et al., 2017; El Gindi et al., 2017; Martins, 2017; Sagani et al., 2017; Sampaio & González, 2017; Weida et al., 2016). In addition, the techno-economic feasibility of the PV technology is constantly developing, as the efficiency of PV panels improves at a relatively fast pace and the construction costs of PV-panel systems are also decreasing at the same time.

The popularity of solar thermal energy production systems has increased over the last decade. According to Chen et al. (2011), Wang et al. (2012), Youssef et al. (2017), and Fraga et al. (2017), a solar thermal harvesting system is recommended to be used for heating DHW of buildings, and even more economic benefits can be achieved by combining the STC system with a geothermal heat pump system. In addition, Asaee et al. (2017b), Wang et al. (2017), and Fraga et al. (2017) conclude that an integrated and optimally dimensioned STC system is a good measure to improve the energy performance of a GSHP system during the heating season in residential buildings located in cold climate conditions. In a solar assisted heat pump (SAHP) application operating in cold climate conditions, the heat collected from the STCs is utilized in the borehole or ground heat source system during the heating season by increasing the brine inlet temperature of the GSHP system. During the summertime, the STCs are used to produce the DHW directly because the temperature level of the collectors is sufficient for heating DHW.

However, there are also several limitations related to the SAHP technology, especially in large high-rise residential apartment buildings because the roof area of the building might not be sufficient for optimum dimensioning of STCs. In addition, a large solar thermal system requires large accumulator or heat storage volume, resulting in increased technical space requirements. While the STC system improves the overall energy efficiency of buildings, it might not be a cost-optimum energy performance improvement measure in multi-family apartment buildings located in cold climate conditions if the main heating system of the building is a ground source, air-to-water, or exhaust air heat pump system. The main reason for this is that the efficiency of the heat pump system reduces the overall economic viability of the solar thermal system significantly when the initial investment cost of the solar thermal system and the total heating energy produced by the system are taken into account.

According to the literature review, modern on-site RESs, such as STCs and different heat pump systems, are often used for heating DHW. Heating DHW accounts for a significant share of the overall energy consumption in residential buildings. According to a study conducted by Yao and Steemers (2005), up to 20% of the overall domestic energy is used for DHW purposes in the United Kingdom. According to Geudens (2015), the DHW consumption of residential buildings accounts for as high as 73% of the total DHW consumption. A literature review conducted by Ahmed et al. (2015) indicated that the DHW consumption of occupants fluctuates significantly from country to country, but an average consumption is typically 30–70 L/person/day. A recent study conducted by Nykvist (2012) provided similar findings. According to Nykvist (2012), the average DHW consumption of Swedish residential apartment buildings is 58 L/person/day. Ahmed et al. (2015) also concluded that the season of the year affects the DHW consumption rate so that more DHW is consumed during the wintertime and less during the summertime. According to Ahmed et al. (2015), the specific DHW consumption of smaller apartments with 1–2 occupants is approximately 1.5 times higher than the specific DHW consumption of larger apartments in Finnish residential apartment buildings.

In many European countries, a significant share of the population lives in multi-family apartment buildings, where heating DHW can account for more than 50% of the overall heating energy demand of the building, depending on the age, size, location, and energy performance of the building (FInZEB, 2015; Häkämies et al., 2015; Kuusk et al., 2014; Kuusk & Kalamees, 2015; Paiho et al., 2013). In Nordic countries, the average DHW consumption rate is approximately 35 L/person/day with the highest consumption rate occurring in Finland (43 L/person/day) and the lowest occurring in Denmark (20 L/person/day) (Ahmed et al., 2015). For comparison, Swan et al. (2011) have determined that the average DHW consumption of typical Canadian households is approximately 67 L/person/day. This indicates that energy efficient heating of DHW has a significant impact on the overall energy performance of future nearly zero-energy apartment buildings, where the energy efficiencies of the building envelope and technical systems of the building are already maximized or at a high level.

Several studies conducted by Zhou et al. (2016), Omer (2008), Blum et al. (2010), Zhai et al. (2011), Self et al. (2013), and Geng et al. (2013) have investigated the performance, energy savings potential, and operation of GSHP systems in different climate conditions and concluded that the GSHP system is typically a highly efficient energy production technology in many different applications and building types when cost-effectiveness, energy efficiency, and environmental impact aspects are taken into account. While the technology development of the GSHP systems has improved the energy performance, operational characteristics, reliability, and controllability of the systems, the overall energy efficiency of a GSHP system is still highly dependent on the temperature levels of both the evaporator and the condenser. It has been concluded in numerous previous studies that energy efficient heating of DHW is a major challenge related to the performance of the GSHP systems, especially in cold climate conditions because the temperature requirement of DHW is typically 55–60°C to prevent legionella growth (Bakirci, 2010; Häkämies et al., 2015; Magraner et al., 2010; Peng et al., 2014; Zhou et al., 2016). The coefficient of performance (COP) of conventional GSHP systems is typically in the range of 2.2–3.0 when DHW with the aforementioned temperature requirement of 55–60°C is produced and the inlet temperature of domestic cold water (DCW) is 5–10°C.

The literature review related to different heat pump applications in energy efficient nZEBs and deeply renovated residential buildings indicates that cost-efficient, operational, and implementable applications are required to improve the energy efficiency of DHW heating with heat pump systems because the heating of DHW accounts for a significant share of the overall energy consumption in new, deeply renovated, and future nearly zero-energy residential buildings. The literature review also indicates that there is a limited number of studies related to investigating and improving the efficiency of heat pump system applications operating in multi-family residential buildings. In addition, a majority of the previous studies have focused on studying solar-assisted GSHP applications, which may not be the cost-optimal GSHP system application in many of the apartment building cases because of the main limitations related to the solar thermal systems, such as the limited roof area in large high-rise apartment buildings and increased technical space requirements for installation of accumulators or heat storages.

The literature review demonstrates that there is a limited number of studies related to the utilization of modern heat pump and other renewable energy production technologies as a part of deep renovation of buildings, where the economic viability and energy performance of the novel energy production technologies are integrated with the more traditional renovation measures related to the building envelope and other technical systems of the building.

2.5 Development of simulation and modeling methods

The performance and versatility requirements of simulation tools are rapidly increasing, as the development of energy systems and renewable energy production technologies requires that reliable and validated simulation methods are needed to simulate the performance and operation of on-site RESs and complex hybrid energy systems. Since the adoption and implementation of the recast EPBD (2010/31/EU), on-site renewable energy production systems and their utilization in the energy production of buildings must be studied more closely to reduce delivered PE consumption. Simulation tools have to cope with these new demands and requirements, and a suitable method must be selected to take the on-site renewable energy production systems into account in the economic and feasibility analyses.

According to a recent study conducted by Häkämies et al. (2015), the more simplifications that are used in the simulation of complex energy systems, the more inaccurate and unreliable the results of the simulation will be when the energy performance requirements of the EPBD (2010/31/EU) and the simulation of on-site renewable and hybrid energy systems are discussed.

A general problem with the currently used dynamic simulation tools is that the energy performance and operation of different heat pump systems and other renewable energy production systems are difficult to simulate accurately and fully dynamically as a part of the dynamic energy simulation of buildings. The main reason for this is that the simulation tools are typically used only to simulate the net energy demand of buildings and to study and verify the indoor climate conditions. More detailed, versatile, and validated simulation methods are required to simulate the more complex on-site energy production technologies in addition to the net energy demands of buildings.

While there are several dynamic simulation programs on the market, such as TRNSYS, EnergyPlus, and IDA Indoor Climate and Energy (IDA ICE), which can be used to simulate the on-site renewable energy production systems as a part of the dynamic energy simulation of buildings, the general conclusion at the moment is that the currently used simulation methods require further testing and validation to correspond to the modern rapidly developing energy systems (Häkämies et al., 2015; Migoni et al., 2016; Salvalai, 2012; Tozzi Jr. & Ho Jo, 2017).

Typically, parametric-based estimations and different fitting curve-based simulation methods have been used to integrate the dynamic simulation of a heat pump system to the dynamic energy simulation of buildings. Salvalai (2012) has conducted a detailed analysis of a parameter estimation study of a water-to-water heat pump model implemented in the earlier versions of the IDA ICE software to simulate the performance of modern GSHP systems. In the study, Salvalai (2012) also validated the studied heat pump model by using experimental data. The study demonstrates how difficult and laborious an accurate dynamic simulation of heat pump systems was just a few years ago and why new, accurate, validated, and usable simulation methods are required to simulate the onsite renewable energy production systems as a part of the dynamic energy simulation of buildings. Furthermore, the simulation and calibration method developed by Salvalai (2012) is already out of date and required significant user-applied input data and performance maps.

Investigations and calibration of heat pump simulation models have also been studied recently. Villarino et al. (2017) conducted a study, where an experimental and modeling analysis of an office building HVAC system based in a ground-coupled heat pump and radiant floor was carried out. The studied energy simulation environment was EnergyPlus (Villarino et al., 2017). The results of the study demonstrated very good agreement between the simulated office building model, including the GSHP system and the experimental analysis, which consisted of energy performance measurements from the actual case office building and the corresponding HVAC and GSHP systems (Villarino et al., 2017). Heat pump and energy simulation model calibrations were studied and developed by Mustafaraj et al. (2014). The study included a two-level calibration methodology, where the operation and performance of the simulated water-to-water heat pump model was improved in two consecutive calibration stages. The results of the simulations were compared to measured performance data of an actual heat pump system operating in a selected case building. The final results of the heat pump model calibrations included a relatively good agreement between the simulated and measured heat pump systems, but Mustafaraj et al. (2014) conclude that future research work is definitely required to further improve both the accuracy of the calibration process and the usability of the EnergyPlus simulation environment in dynamic simulations of modern heat pump systems.

Cacabelos et al. (2017) determined a functional and efficient calibration methodology of heat pump simulation models using the TRNSYS energy simulation environment. The developed methodology utilizes a multi-stage model calibration method, which improves the accuracy of the calibration process and reduces the calibration time of the heat pump system (Cacabelos et al., 2017). The results of the study showed promising accuracy and effectiveness for the developed methodology when both the performance and realistic operation of the calibrated heat pump simulation model are discussed (Cacabelos et al., 2017).

Successful calibration methodologies of heat pump systems were investigated and determined in the studies conducted by Cacabelos et al. (2015), Chaudhary et al. (2016), and Yun and Song (2017). Cacabelos et al. (2015) studied the calibration of heat pump simulation models, among other energy simulation parameters and variables, utilizing the TRNSYS simulation environment. Chaudhary et al. (2016) studied the evaluation of autotune calibration against manual calibration of building energy models in the EnergyPlus v7.0 simulation environment. The study conducted by Chaudhary et al. (2016) included a dual-capacity air source heat pump model with a variable-speed blower. Yun and Song (2017) studied the development of an automatic calibration method of a variable refrigerant flow energy model for the design of energy efficient buildings utilizing the EnergyPlus simulation environment. The results of the studies showed good agreement between the calibrated heat pump simulation models and the measured performance of the corresponding tested heat pump systems (Cacabelos et al., 2015; Chaudhary et al., 2016; Yun & Song, 2017). However, all three studies also indicated the need for future development of more efficient and automated calibration methodologies to be used in the simulation model calibration of both high-performance heat pump units and entire heat pump systems, including the modeling of large borehole fields and heat storage tanks (Cacabelos et al., 2015; Chaudhary et al., 2016; Yun & Song, 2017).

Simulation of geothermal energy piles and boreholes and calibration of a GSHP simulation model in the IDA ICE simulation environment have been recently studied by Fadejev and Kurnitski (2015). Their study includes both the validation of the borehole simulation model and the calibration of a GSHP simulation model included in the IDA ICE simulation software. The conclusions presented by Fadejev and Kurnitski (2015) indicate that the IDA ICE simulation environment is an accurate simulation platform to be used in detailed GSHP system analyses and in the design and dimensioning of complete large-scale GSHP systems, including geothermal energy piles and boreholes. However, the major limitation included in their study is the validation of the calibrated heat pump simulation model in several operating conditions. Their study includes calibration parameters, where the performance of the simulated heat pump unit is calibrated to correspond to the performance of the selected manufacturer heat pump unit at four operating conditions, whereas a real heat pump unit typically operates at 6–10 operating conditions in actual dynamic case conditions. However, the study conducted by Fadejev and Kurnitski (2015) also demonstrates how complex and laborious a detailed calibration of heat pump simulation models according to actual manufacturer heat pump unit specifications is in the IDA ICE simulation environment. Their study also highlights the importance of determining functional, usable, accurate, and efficient calibration methods for more accurate and reliable simulation of the modern heat pump systems.

During the past decade, simulation-based optimization (SBO) analysis methods have increased their popularity significantly in building performance analyses (Nguyen et al., 2014). A recent study conducted by Nguyen et al. (2014) demonstrates that yearly scientific publications related to building performance optimization have doubled between 2009 and 2012 and increased by a multiplier of five between 2004 and 2012. According to Nguyen et al. (2014), in the building sector, the SBO analysis is mainly used to determine optimal building designs for net and nZEBs and to optimize multiple conflicting objectives, such as LCCs, indoor climate conditions, and energy efficiency simultaneously. In addition, the extensive literature review conducted by Nguyen et al. (2014) indicates that the SBO analysis is developing a popular, usable, and highly efficient research method to be used in the design and performance analyses of high-performance buildings.

Development and applicability of SBO was also extensively studied by Hamdy (2012). Hamdy (2012) concluded that an SBO approach can be effectively used for dimensioning optimal building envelopes and HVAC systems of buildings. According to Hamdy (2012), the simulation time is typically the limiting factor of the analysis, and significant efforts should be focused on developing methods to speed up the analysis to determine the optimal or close-to-optimal solutions.

2.6 Simulation-based optimization approach in renovations

The simulation-based optimization approach and its applications have been applied in several recent renovation studies. Asadi et al. (2014) developed an optimization model using a genetic algorithm and neural network. The model developed by Asadi et al. (2014) was tested by using it to provide the non-dominated solutions for a case study. In addition, the strengths and limitations of the proposed approach were reviewed and discussed in their study. A similar study was conducted by Wang et al. (2014), where a multi-objective optimization model was developed and studied for building retrofitting. The model developed by Wang et al. (2014) simultaneously maximizes energy savings and minimizes payback periods of different renovation and retrofitting alternatives. In addition, the model was applied for a case study to demonstrate the effectiveness of the model in obtaining cost-effective retrofitting plans over specific life-cycle periods.

Asadi et al. (2012a) studied a multi-objective optimization approach for building retrofit strategies by presenting a multi-objective optimization model to assess different renovation alternatives in the built environment. The model deals with multiple conflicting objectives and allows for simultaneous investigation of all applicable renovation combinations (Asadi et al., 2012a). A case study demonstrates the effectiveness of the approach in determining compromised solutions, but the results of the study also highlight the potential problems included in the methodology, such as a simplified energy simulation model used for improved computational performance, that should be addressed in the future development of the model (Asadi et al., 2012a). Antipova et al. (2014) studied a multi-objective optimization approach combined with a life-cycle assessment for retrofitting buildings. In general, Antipova et al. (2014) studied the utilization of a multi-objective optimization model for renovating buildings. Their study included renovation measures related to the building envelope and solar-based energy production technologies (Antipova et al., 2014). The optimized objectives included simultaneous minimization of cost and environmental performance of a semi-detached case building (Antipova et al., 2014). While the approach presented by Antipova et al. (2014) is somewhat simplified, it demonstrates the increasing requirement for effective and easy-to-use multi-objective optimization methodologies that can be applied in deep renovations of buildings.

The simulation-based optimization and multi-criteria decision-making approaches applied in renovations have been studied in detail by Rysanek and Choudhary (2013), Ascione et al. (2017a, 2017b), Kontokosta (2016), Menassa (2011), Kumbaroğlu and Madlener (2012), and Fan and Xia (2015). Rysanek and Choudhary (2013) presented a holistic optimization strategy for optimal building energy retrofits under technical and economic uncertainty. Ascione et al. (2017a) conducted a cost-optimal analysis by multi-objective optimization and artificial neural networks that can be used for assessment of cost-optimal renovation concepts of different buildings. In addition, the methodology presented by Ascione et al. (2017a) is feasible for performance analyses of several building types. Ascione et al. (2017b) applied the multi-objective optimization approach in a study that investigated the resilience of robust cost-optimal energy retrofits of buildings to global warming. The results of the study provided different optimal energy conservation measures, resilient building refurbishment solutions, and a new methodology for decision making among the sub-optimal renovation concepts.

Kontokosta (2016) studied the modeling of optimal energy renovation decisions and strategies in commercial office buildings. Menassa (2011) conducted a study where sustainable and cost-effective renovation solutions were evaluated in existing buildings under uncertainty. Kumbaroğlu and Madlener (2012) investigated economically optimal renovation investment options by developing a novel evaluation methodology for deep renovations of buildings that determines the cost-optimal set of renovation and retrofit measures. Fan and Xia (2015) presented a multi-objective optimization model specifically developed for building envelope retrofit planning. The model developed by Fan and Xia (2015) maximizes energy savings and economic viability of building envelope retrofit measures so that investment budget, thermal comfort, and life-cycle impact are also considered. A common conclusion of the previous studies conducted by Rysanek and Choudhary (2013), Ascione et al. (2017a, 2017b), Kontokosta (2016), Menassa (2011), Kumbaroğlu and Madlener (2012), and Fan and Xia (2015) is that advanced, easy-to-use, and efficient multi-objective optimization and multi-criteria decision-making methods are necessary to both design and carry out cost-effective and sustainable deep renovations of buildings and to significantly reduce the environmental impact of existing buildings simultaneously.

Shao et al. (2014) conducted a study where a simulation-based multi-objective optimization methodology was applied to determine optimal office building energy retrofit strategies. Shao et al. (2014) presented a model to support multi-criteria decisions for energy-performance-improving renovations. The model integrates human reasoning, individual requirement analysis, and multi-objective optimization for versatile design of deep renovations (Shao et al., 2014). The simulation-based multi-objective optimization analysis included a three-dimensional optimization problem where three conflicting objectives were optimized simultaneously using the NSGA-II genetic algorithm.

Penna et al. (2015) conducted a detailed study where simulation-based multi-objective optimization was applied to determine cost-optimal energy efficiency measures related to the building envelope and HVAC systems. Penna et al. (2015) used the NSGA-II genetic algorithm and the TRNSYS simulation environment to optimize energy savings, indoor thermal comfort conditions, and life-cycle costs over a 30-year life-cycle period. The results demonstrate that the applied methodology was efficient, and it was able to determine the optimal solutions among the three different and conflicting objectives (Penna et al., 2015).

A simulation-based analysis approach was studied by Hong et al. (2015), where a novel energy retrofit analysis toolkit was presented for deep renovations of commercial buildings. The commercial building energy saver developed by Hong et al. (2015) provides benchmarking, energy simulation model calibration, and model-based renovation assessment of different building types. The method presented by Hong et al. (2015) is simplified but effective methodology for energy-performance-improving analyses carried out in existing commercial buildings.

A specific decision support model for establishing the optimal energy retrofit strategies for existing multi-family residential buildings was studied by Hong et al. (2014). Their study presents a model that was developed to establish the optimal energy-efficiency-improving strategies for different buildings by using dynamic energy simulations. The optimal renovation strategy can be determined by conducting analyses, where the life-cycle cost and environmental performance of the renovation measures are selected as key performance indicators of the analysis (Hong et al., 2014). The decision support model developed by Hong et al. (2014) improves multi-criteria decision making in situations where the decision must be made among multiple conflicting objectives.

Lee et al. (2015) conducted an extensive review on available building performance analysis methods that can be effectively used to assess different renovation alternatives and to determine cost-optimal retrofit concepts. Lee et al. (2015) reviewed a total of 19 retrofit analysis toolkits and methods with different features, data requirements, and computing methods. Lee et al. (2015) concluded that many detailed dynamic simulation and analysis methods suffer from complexity, longer data input, and simulation run time, whereas many analysis methods were too simplified for accurate and reliable retrofit analyses. In general, Lee et al. (2015) stated that more effort should be put in to the development of existing, and also new, renovation assessment methods and toolkits in the future, as effective, accurate, and easy-to-use analysis toolkits can accelerate the implementation of energy-performance-improving measures.

An effective simulation-based analysis approach was also applied by Chidiac et al. (2011a) in their research, where a screening methodology was studied for implementing cost-effective energy-performance-improving measures in Canadian office buildings. Chidiac et al. (2011a) also used regression analyses to develop a model for estimating the energy consumption of office buildings characterized into different sets of archetypes. The developed methodology can be used to determine optimal combinations of energy retrofit measures and to plan both energy and environmental-performance-improving activities in existing office buildings. Dall'O' et al. (2012) presented a methodology for evaluating the potential energy savings of retrofitting large residential building stocks. The methodology developed by Dall'O' et al. (2012) provides an innovative approach for the analysis of energy-performance-improving measures carried out in deep renovations of residential buildings. In addition, the approach takes the actual techno-economic constraints of the implementation of feasible energy retrofit measures into account (Dall'O' et al., 2012).

A simulation-based multi-objective optimization approach was applied by Wu et al. (2017) to determine optimal building envelope and energy system solutions in a deep renovation of a residential community. Wu et al. (2017) concluded that simultaneous optimization of both the building envelope and energy system renovation solutions is necessary because the cost-optimal combination of renovation and energy system solutions changes with every renovation concept selected for the building. Therefore, the optimum selection of renovation alternatives is always a tradeoff between cost-effectiveness and energy efficiency, and it should always be determined according to the specific case conditions of the studied building or community (Wu et al., 2017). Wu et al. (2017) used mixed-integer linear programming optimization and the EnergyPlus simulation environment to carry out the multi-objective optimization analyses and concluded that the used combination of optimization and simulation methods was sufficient to deliver cost-optimal LCC-GHG emission tradeoffs for different renovation options.

Chidiac et al. (2011b) studied the effectiveness of single and multiple energy-performance-improving measures on the energy performance of existing office buildings by using a detailed simulation-based approach. Chidiac et al. (2011b) concluded that the selection of multiple retrofitting measures that are applied in deep renovations of buildings is essential to reduce the energy consumption and environmental impact of the existing building stock. Chidiac et al. (2011b) also concluded that a combination of energy retrofit measures that are carried out simultaneously is not as beneficial as the sum of individual retrofit measures. For this reason, more efficient simulation, modeling, and optimization methods are required to effectively determine the cost-optimal combinations of energy retrofit measures to be applied in deep renovations of different buildings (Chidiac et al., 2011b).

Asadi et al. (2012b) had similar findings and presented a simulation-based multi-objective optimization approach to deal with simultaneous investigations of multiple energy retrofit measures that can be applied in renovations of buildings. Asadi et al. (2012b) concluded that there are multiple competing objectives in deep renovations of buildings, such as cost-effectiveness and energy efficiency, that must be satisfied by selecting the optimum combination of renovation measures among a large number of potential alternatives. Asadi et al.

(2012b) presents that a proper selection of the optimization technique, and especially the optimization algorithm, is important and necessary for solving multi-dimensional optimization problems and that evolutionary multi-objective optimization algorithms are recommended for complex multi-criteria optimization analyses.

Mauro et al. (2015) presented a novel simulation-based large-scale uncertainty/sensitivity analysis approach for investigating the cost-effectiveness of energy retrofitting a specific building category. The methodology includes a combination of the EnergyPlus simulation environment and the MATLAB environment, and it is proposed to be used to determine cost-optimal renovation concepts of different building categories (Mauro et al., 2015). Mauro et al. (2015) suggest that the future development of the presented methodology should include a comparison between the developed simulation-based approach and a simulation-based multi-objective (Pareto) optimization approach to determine if the same renovation concepts can be obtained from both analyses.

Michael et al. (2017) presented a multi-objective optimization model that can be used to determine optimal retrofitting strategies of existing buildings to reduce both energy and water consumptions of the buildings. The multi-objective optimization model presented by Michael et al. (2017) has been specifically developed to take the LEED green building rating into account as one of the optimized objectives of the renovation. The mathematical optimization model also takes the economic indicators, including life-cycle cost and payback period, of the renovation into account (Michael et al., 2017). In future work, Michael et al. (2017) recommend that the energy simulation tool is utilized in simulation-based analyses of the renovated buildings to achieve improved accuracy and reliability.

Son and Kim (2016) studied and evaluated the performance of the NSGA-III genetic algorithm in a renovation case study of a public school building. The study focuses on the performance and accuracy of the NSGA-III algorithm more than on the cost-effective renovation and retrofit solutions of the studied school building (Son & Kim, 2016). However, the study presented by Son and Kim (2016) demonstrates promising advancements in the field of multi-objective optimization analyses applied to assess building performance because four individual and conflicting objectives were optimized simultaneously in the study. The future work carried out by Son and Kim (2016) includes comparisons and benchmarking of different optimization algorithms and strategies in order to determine the superior optimization algorithms for different multi-objective optimization problems, including 2–4 competing objectives that are all optimized simultaneously and occur in building retrofit planning.

Cetiner and Edis (2014) developed a method for assessing sustainability aspects of residential building renovations. The method utilizes dynamic energy simulations carried out with EnergyPlus and a simplified data processing tool, which can be used to process the data and select the feasible retrofitting alternatives that are required to be studied in the analysis (Cetiner & Edis, 2014). The method includes predefined building types that can be selected to assess the sustainability and cost-effectiveness aspects of specific buildings with their individual features (Cetiner & Edis, 2014). While the method does not include a detailed multi-objective optimization approach, it provides an efficient tool for building owners, building users, architects, and designers to evaluate different retrofitting options and to determine cost-effective renovation alternatives for their buildings (Cetiner & Edis, 2014).

Jafari and Valentin (2017) developed a novel simulation-based optimization and decision-making method for sustainable building energy retrofits. The method is based on a model, which provides the best energy retrofitting strategy for a specific building by taking the initial investment cost, energy and cost savings, life-cycle cost, and different uncertainties related to deep renovations of buildings into account (Jafari & Valentin, 2017). The method includes dynamic energy simulations using the eQuest simulation environment and optimizations carried out using the MATLAB optimization environment (Jafari & Valentin, 2017). While the presented model is a single-objective optimization model, it was successfully applied to determine the optimum renovation strategy in the selected residential case building that leads to the minimum life-cycle costs with a limited budget of the building owner that was selected as a constraint in the optimization analysis (Jafari & Valentin, 2017). The minimized objective of the optimization analysis was the future costs of the case building after the energy retrofit (Jafari & Valentin, 2017).

Roberti et al. (2017) developed a method for identifying the optimal renovation strategies for historic buildings. The method applies a simulation-based multi-objective optimization approach, where optimal renovation concepts are determined by taking comfort, energy, and conservation compatibility aspects into account (Roberti et al., 2017). The case study carried out included three optimized objectives, which were all optimized simultaneously using the NSGA-II genetic algorithm (Roberti et al., 2017). The simulation-based multi-objective optimization analysis carried out by Roberti et al. (2017) delivered over 1,200 Pareto-optimal solutions to meet the optimized three objectives with different weighting. Further data processing and weighting was performed to reduce the recommendable renovation solutions to seven final options for further decision making (Roberti et al., 2017). In addition, Roberti et al. (2017) concluded that the multi-objective optimization approach is an extremely efficient analysis method in demanding renovation projects, where multiple competing objectives are required to be optimized simultaneously. Roberti et al. (2017) also stated that the presented approach should be part of the integrated decision-making process between design teams and building owners to further improve the quality, cost-effectiveness, and energy efficiency of the selected renovation and retrofitting concepts.

Simulation-based multi-objective optimization approaches were also applied in renovation studies by Murray et al. (2014) and Fan and Xia (2017). Murray et al. (2014) applied a simulation-based optimization method by using a static energy modeling approach and a genetic optimization algorithm technique. The objective of the study conducted by Murray et al. (2014) was to develop and apply the multi-variable optimization approach in evaluation of cost-optimal energy retrofits of buildings. Fan and Xia (2017) applied the simulation-based multi-objective optimization approach to energy performance building envelope retrofitting design, where a rooftop PV system installation was also investigated. Fan and Xia (2017) utilized a genetic algorithm in their analysis and also discussed the optimization algorithm convergence and the potential limitations related to the optimization analysis. The main objective of the study conducted by Fan and Xia (2017) was to develop a multi-objective optimization model that can be used to design building envelope retrofitting plans and improve the energy performance of existing buildings with a given, and typically limited, budget of the building owners and investors.

Evins (2013) conducted an extensive review of computational optimization methods applied to sustainable building design. The review included a detailed summary of different optimization and analysis techniques applied to the design process of new buildings and deep renovations of existing buildings (Evins, 2013). The review also discusses future trends, and it demonstrates that the simulation-based multi-objective optimization analysis techniques have increased their popularity tremendously during the last decade and that the future trend seems similar (Evins, 2013).

3. Methods

3.1 Studied buildings

3.1.1 Residential apartment buildings

As the brick and concrete large panel-structured apartment buildings built during the 1960s (16% share) and 1970s (24% share) account for the largest individual shares of the Finnish apartment building stock, they were also studied in this thesis (Publications 1 and 3). A detailed survey was conducted before the analyses to determine typical features of the studied building types. Studied features included building sizes; technical and building services systems and their conditions, energy efficiencies, and conditions of the building envelopes; and energy consumption data. Based on the results of the surveys, suitable and representative case buildings were selected for the research. The main geometry and features of the studied apartment buildings are presented in Figures 1 and 2. Both of the studied case buildings represent typical residential apartment buildings built in the 1960s (Figure 1) and 1970s (Figure 2).

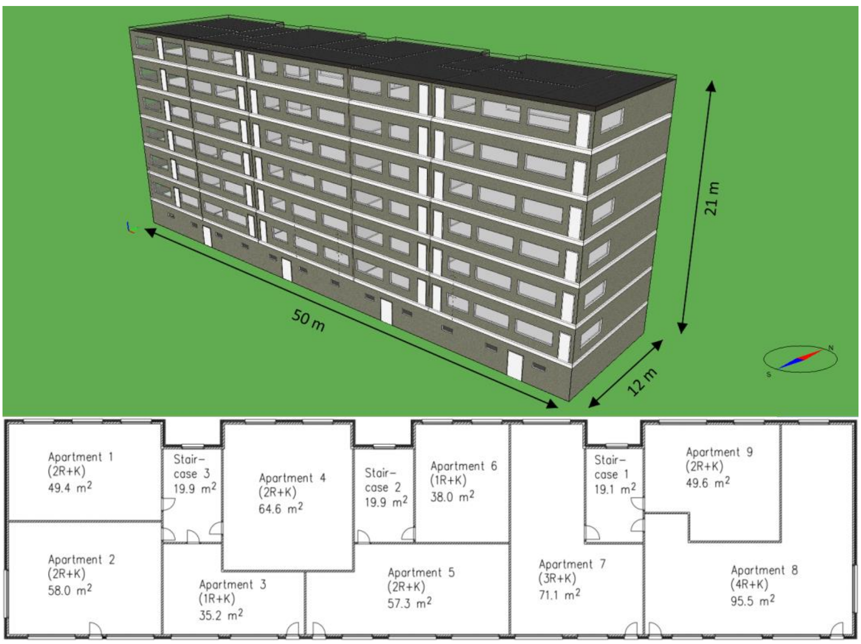

Figure 1. The main geometry of the studied brick apartment building (above) and the floor layout of the apartment floors (below), r = room, k = kitchen.

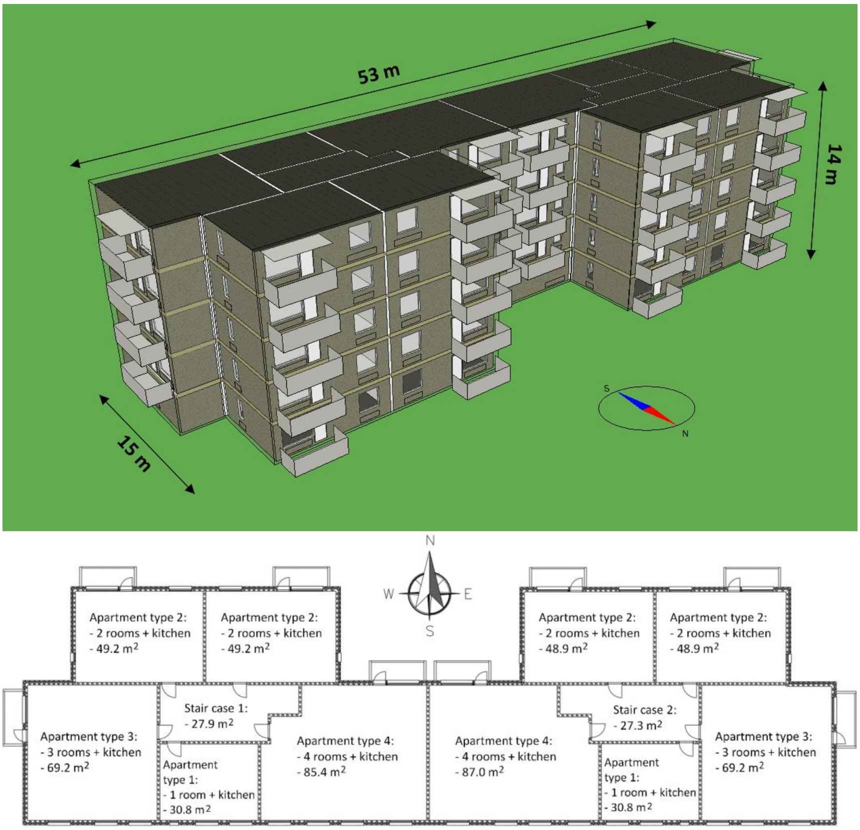

Figure 2. The main geometry of the studied concrete large panel apartment building (above) and the floor layout of the apartment floors (below).

The studied brick apartment building is located in Vantaa, and the studied concrete large panel apartment building is located in Kerava. The heated net floor areas of the buildings are 3,697 m^2 (brick-structured) and 2,898 m^2 (panel-structured). The heated volumes of the buildings are 10,497 m^3 (brick-structured) and 7,952 m^3 (panel-structured). Both of the studied apartment buildings are in their original condition before any renovations or retrofitting measures have been conducted. The main technical characteristics of the external structures before the renovation are presented in Table 1.

Table 1. The main technical characteristics of the external structures.

Structure	**Brick apartment building**	**Concrete large panel apartment building**
External walls, U-value [$W/m^2 K$]	0.60	0.55
Roof, U-value [$W/m^2 K$]	0.34	0.38
Base floor (connected to the ground), U-value [$W/m^2 K$]	0.40	0.44
Windows, U-value [$W/m^2 K$] / g-value (two-pane structure)	2.5 / 0.76	2.1 / 0.70
Integrated window shading	Blinds between panes	Blinds between panes
External doors, U-value [$W/m^2 K$]	1.41	2.2
Air tightness of the building envelope, the q_{50}-value [$m^3/(m^2 h)$]	6.0	6.0

The ventilation systems of both of the studied buildings are a mechanical exhaust air ventilation system without a heat recovery system, and the fans run continuously 24 hours per day. The heat distribution system of the buildings is a water-based radiator heating system with 80/50°C (brick) and 80/60°C (panel) dimensioning temperatures. The technical specifications and operation of the HVAC systems, internal heat gains, and occupancy of the buildings were accounted for according to the actual specifications of the case apartment buildings and according to the National Building Code of Finland (NBCF), part D3 (2012). More detailed specifications regarding the internal heat gains, airflow rates, and DHW consumptions of the studied apartment buildings are presented in the appended Publications 1 and 3.

In Publication 3, the deep renovation scenario of the concrete large panel apartment building was selected according to the survey conducted before the analysis. In the selected scenario, the outer concrete and thermal insulation layers of the original external wall structure are demolished because of carbonization and their poor condition, and new thermal insulation and outer structure layers are installed. This renovation scenario of external walls was determined to be the most popular renovation method for external walls in the Finnish concrete large panel apartment buildings when quality and longevity aspects of the renovations were discussed. The initial setting related to the renovation of the building envelope of the studied panel-structured apartment building is presented in Figures 3 and 4.

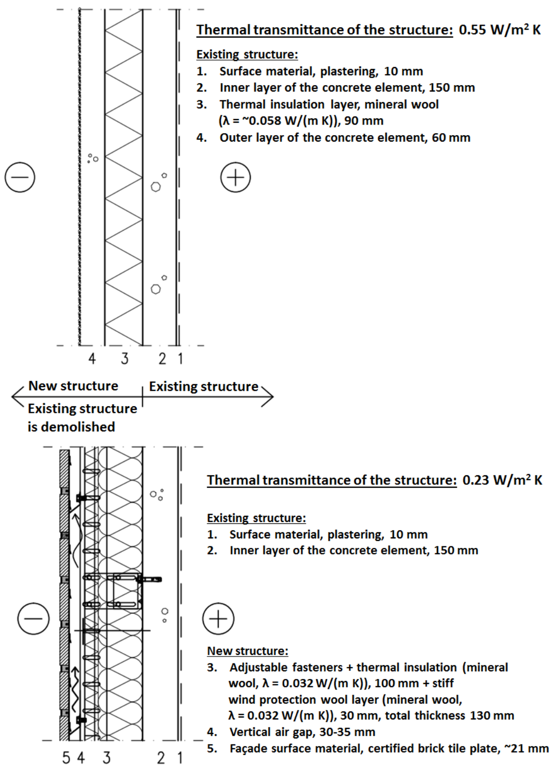

Figure 3. The structure details of original (above) and renovated (below) external walls, according to the selected renovation methods with the new and existing structure layers presented.

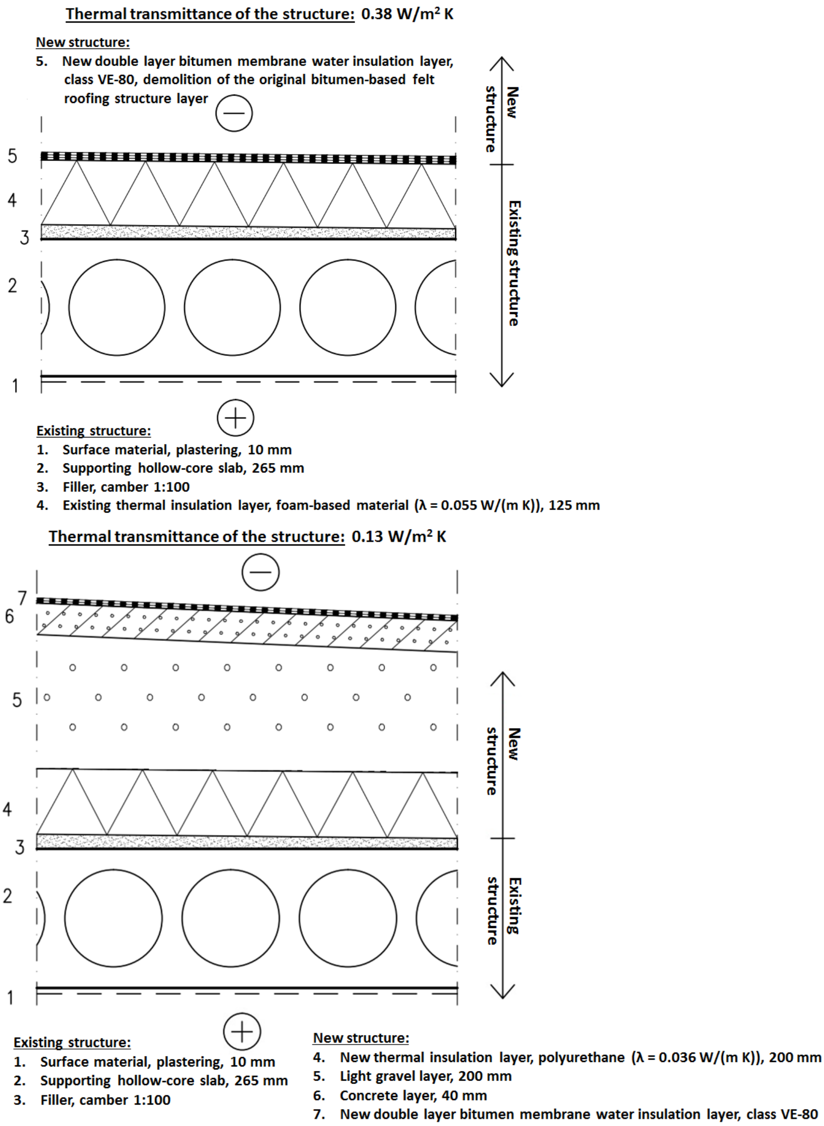

Figure 4. The structure details of the basic refurbishment (above) and renovated (below) roof with additional thermal insulation, according to the selected renovation methods with the new and existing structure layers presented.

3.1.2 Educational buildings

As the educational buildings built before 1980 account for a 68% share of the Finnish educational building stock, they were also studied in this thesis (Publication 2). As with the residential apartment buildings, a detailed survey was conducted before the analysis to determine typical features of the studied educational building types. The technical features of the buildings are typically significantly different between buildings built during different decades (e.g., in the 1940s or 1970s). The breakdown of Finnish educational buildings according to the construction year is presented in Figure 5.

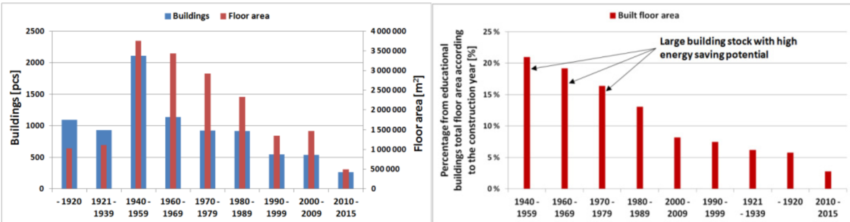

Figure 5. The number and floor area of the educational buildings (left) and the distribution of buildings by the total floor area according to the construction year (right) (Statistics Finland, 2017c).

Based on the survey results, a suitable and representative case building was selected for the research. As presented in Figure 5, educational buildings built between 1940 and 1980 account for the highest individual shares of the educational building stock. In addition, the technical features of the educational buildings built during the 1960s and 1970s are similar. For this reason, an educational building built during the late 1960s and early 1970s was selected as the studied case building. The studied educational building is located in the Lappeenranta University of Technology (LUT) campus area. The studied building represents the majority of the Finnish educational buildings built during 1960–1979 with good accuracy regarding exterior structures, HVAC, and other technical systems.

The LUT campus area is located in the suburban region of Lappeenranta, Finland. The main geometry of the studied building 1 is presented in Figure 6. In addition, Figure 7 presents the main floor layout and the total heated net floor areas of the seven buildings located in the campus area with the studied building highlighted. The studied building has five floors, which include an office; educational, meeting, and lecture rooms; and laboratory spaces on the first floor. Building 1 also includes an underground basement floor, which includes some technical, laboratory, and warehouse spaces.

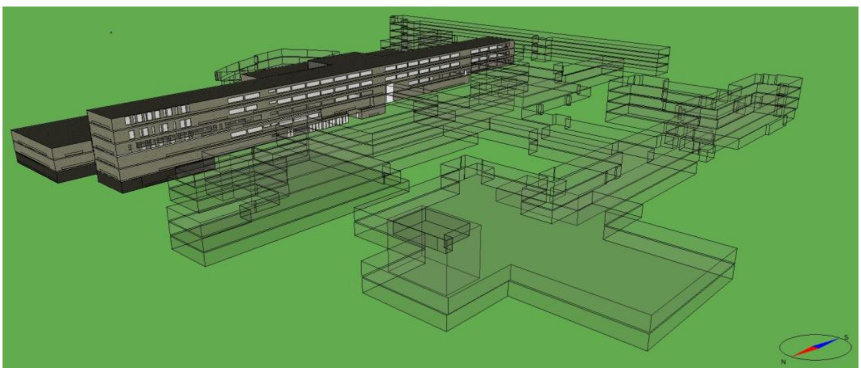

Figure 6. The main geometry of the studied building 1 (highlighted) as a part of the LUT campus area from the northwest.

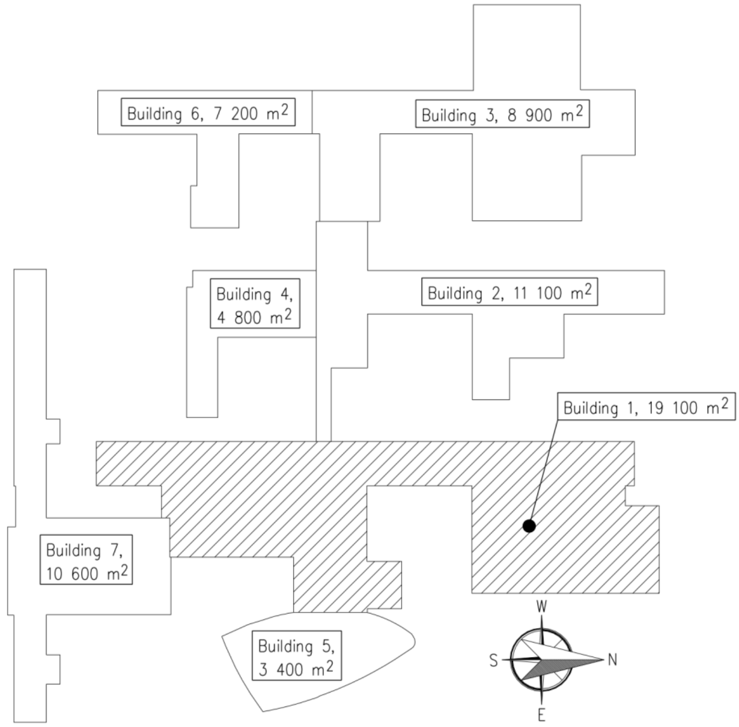

Figure 7. The main floor layout and the total floor areas of the seven buildings of LUT campus area with the studied building 1 highlighted.

The heated net floor area of the studied building is 19,100 m², and the heated volume of the building is 67,500 m³. The studied educational building is brick-structured, and it is in its original condition, before any renovations or retrofitting measures have been conducted. The main technical characteristics of the external structures before the renovation are presented in Table 2.

Table 2. The main technical characteristics of the external structures.

Structure	Studied building 1 of the LUT campus area
External walls, U-value [W/m² K]	0.54
Roof, U-value [W/m² K]	0.17
Base floor (connected to the ground), U-value [W/m² K]	0.43
Windows, U-value [W/m² K] / g-value (two-pane structure)	2.8 / 0.68
Integrated window shading	Blinds between panes
External doors, U-value [W/m² K]	1.39
Air tightness of the building envelope, the q_{50}-value [m³/(m² h)]	6.0

The ventilation system of the studied building is a mechanical supply and exhaust air ventilation system without a heat recovery system. The ventilation system operates from Monday to Friday between 7:00 a.m. and 5 p.m. with a 100% capacity and during other times with an average of 5% capacity according to the NBCF part D3 (2012). The heat distribution system of the building is a water-based radiator heating system with 80/60°C dimensioning temperatures. The technical specifications and operation of the HVAC systems, internal heat gains, and occupancy of the building were considered according to the actual specifications of the case building and according to the NBCF part D3 (2012). More detailed specifications regarding the internal heat gains, airflow rates, and DHW consumption of the studied educational building are presented in the appended Publication 2.

As demonstrated in the literature review in Sections 2.2 and 2.3, the indoor environment conditions have a significant impact on the learning performance of students and on the productivity of persons. For this reason, the indoor climate requirements—including indoor operative temperatures and their duration within the required values during winter and summer, IAQ, and acoustic requirements—after the renovation were selected according to the Finnish Classification of Indoor Environment (FCIE) 2008 class S2, which was determined and published by the Finnish Society of Indoor Air Quality (FiSIAQ) in 2008. This was a voluntary-based decision of the building owner, as the S2 class of the FCIE 2008 provides better indoor climate conditions than the minimum requirements of the current Finnish building regulations. To improve the indoor climate conditions of the studied educational building to the S2 class of the FCIE 2008 requires that the original ventilation system of the building has to be renovated and additional cooling must be installed in office and classroom spaces (FiSIAQ, 2008). Normally, the minimum measure related to the cooling system of the building is to equip the renovated air handling units (AHUs) with cooling coils for supply air cooling when the indoor climate conditions of the S2 class of the FCIE 2008 are targeted (FiSIAQ, 2008).

3.1.3 Office buildings

The objective of the office building study reported in Publication 4 was to determine the cost-optimal renovation concepts for typical office buildings located in cold climate regions. As with the residential apartment and educational buildings, a detailed survey was conducted before the analysis to determine typical features of different building types. An office building located in Lahti, Finland was selected as the studied case building. As presented in Figure 8, the studied office building stock accounts for the largest share of the Finnish office building stock, determined by both the total floor area and the number of individual buildings. In addition, the office buildings built in the late 1970s and in the 1980s require major renovation measures in the near future.

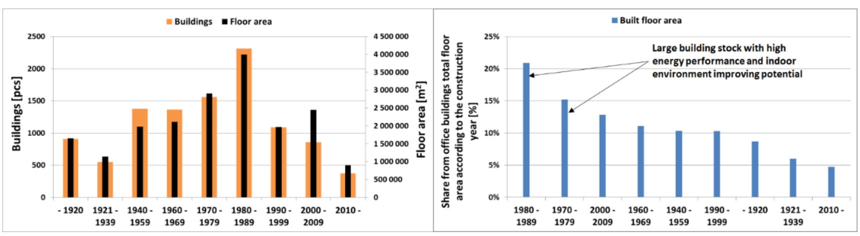

Figure 8. The total floor area and number of office buildings (left) and the breakdown of buildings by the total floor area according to the construction year (right) in Finland (Statistics Finland, 2017c).

The main geometry of the studied case building is presented in Figure 9. In addition, the layout of the main office floors is presented in Figure 10. The distribution of occupant groups on the main office floors used in the calculation of thermal comfort conditions is also presented in Figure 10. Each occupant group symbol represents a group of 25 occupants, resulting in a total of 225 occupants per floor when all nine groups are summed up. The layout of the office floors originally consisted of approximately 12–15 m² rooms, but it is modified to an open layout office in the deep renovation because the open layout office design is more popular and typically more practical in most modern office buildings because of higher space efficiency.

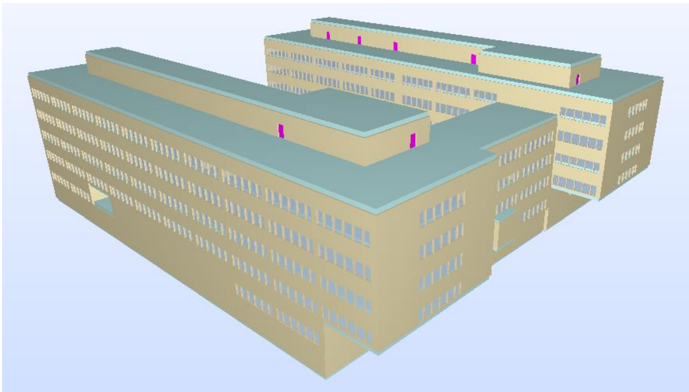

Figure 9. The main geometry of the studied office building.

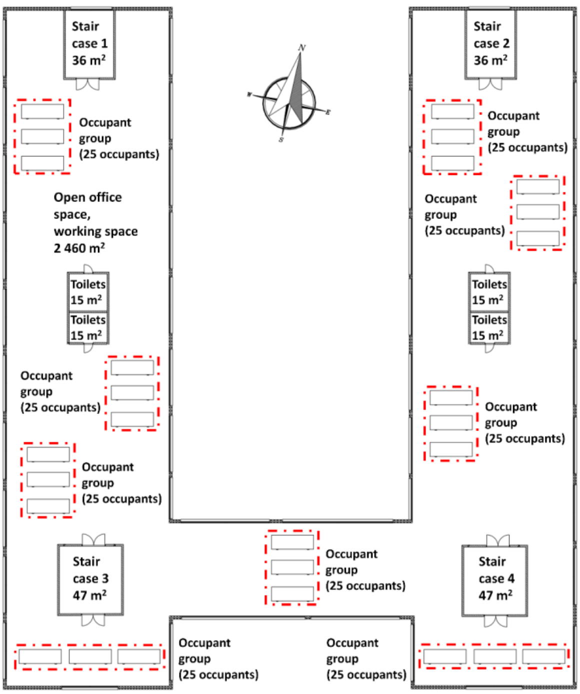

Figure 10. The layout of the main office floors and the distribution of occupants. The occupants are assumed to be sitting.

The studied building has a total of five floors, with the top four floors being open office floors (Figure 10) and the bottom floor being a combination of open office space and meeting rooms. The top-most floors are technical spaces including the AHUs of the building. The heated net floor area of the studied building is 13,400 m^2, and the heated volume of the building is 44,700 m^3. In the initial state of the study, the studied building is in its original condition before any renovations or retrofitting measures have been conducted. The main technical characteristics of the external structures before the renovation are presented in Table 3.

Table 3. The main technical characteristics of the external structures.

Structure	Studied office building
External walls, U-value [W/m^2 K]	0.35
Roof, U-value [W/m^2 K]	0.29
Base floor (connected to the ground), U-value [W/m^2 K]	0.40
Windows, U-value [W/m^2 K] / g-value (three-pane structure)	2.1 / 0.60
Integrated window shading	None
External doors, U-value [W/m^2 K]	1.40
Air tightness of the building envelope, the q_{50}-value [m^3/(m^2 h)]	6.0

The ventilation system of the studied building is a mechanical supply and exhaust air ventilation system without a heat recovery system. The ventilation system operates from Monday to Friday between 7 a.m. and 6 p.m. with a 100% capacity and during other times with a 15% capacity. The heat distribution system of the building is a water-based radiator heating system with 70/40°C dimensioning temperatures. The technical specifications and operation of the HVAC systems, internal heat gains, and occupancy of the building were considered according to the actual specifications of the case building and according to the NBCF part D3 (2012). More detailed specifications regarding the internal heat gains, airflow rates, and DHW consumption of the studied office building are presented in the appended Publication 4.

Due to the significant impact of the indoor environment conditions on the performance of workers, the indoor conditions were also considered in the renovation of the case office building. The renovated lighting system of the case building was designed to produce over 500 lx illuminance in working areas. Furthermore, the IAQ and indoor thermal conditions were also considered according to the voluntary-based FCIE 2008 class S2 (FiSIAQ, 2008). As described with the studied educational building in Section 3.1.2, the S2 class of the FCIE can be obtained with a centralized cooling system. Typically, cooling the supply air by using cooling coils in the AHUs is required as the minimum measure to reach the S2 class indoor climate criteria, depending on the specific case features. Figure 11 presents the room air temperature set point profile, the minimum and maximum limits for the operative temperature, and the maximum limit for the CO_2 concentration of indoor air in the occupied building for the S2 class of the FCIE 2008 (FiSIAQ, 2008).

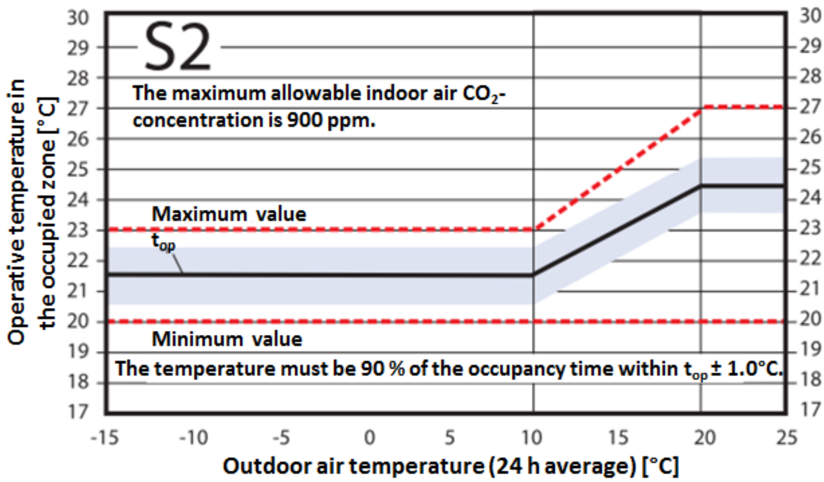

Figure 11. The room temperature set point profile, minimum and maximum limits for operative temperature, and the maximum limit for CO_2 concentration of indoor air during the occupied time according to the FCIE 2008 (FiSIAQ, 2008).

3.2 Studied renovation measures

3.2.1 Residential apartment buildings

The studies related to the renovations of residential apartment buildings (Publications 1 and 3) were conducted by taking all applicable renovations and retrofitting measures into account. In addition, the initial setting of the renovations was selected so that the buildings were undergoing deep renovations of building façades and roofs. By integrating different energy efficiency improvement measures into the major mandatory renovations of the buildings, the overall cost-effectiveness of the deep renovations improved. The studied renovations and retrofitting measures of both the brick and concrete large panel apartment buildings are presented in Table 4. For comparison, Table 4 also presents the potential measures that were not taken into account in the residential apartment building studies.

Studied measures include a combination of typical renovation measures, which have been studied before as individual renovation measures, as well as applicable heat pump systems and solar-based thermal and PV-production systems, which have also proved to be cost-effective energy performance improvement measures in several recent studies (Asaee et al., 2017a; El Gindi et al., 2017; Häkämies et al., 2015; Moran et al., 2017; Salata et al., 2017).

Table 4. Studied renovations and retrofitting measures of the residential apartment buildings.

Renovation measure	Brick apartment building	Concrete large panel apartment building
Basic refurbishment and additional thermal insulation of external walls	Yes	Yes
Basic refurbishment and additional thermal insulation of roof	Yes	Yes
Basic refurbishment and additional thermal insulation of base floor	No	No
Basic refurbishment and replacement of windows	Yes	Yes
Basic refurbishment and replacement of external doors	No	Yes
Renovation of the ventilation system, centralized	Yes	Yes
Renovation of the ventilation system, decentralized/distributed	No	Yes
Renovation of the heat distribution system (low-temperature radiators)	Yes	No
Renovation of the original district heating system (substation)	Yes	Yes
Installation of an air-to-water heat pump system	Yes	Yes
Installation of a GSHP system	Yes	Yes
Installation of an exhaust air heat pump system	Yes	Yes
Installation of a sewage water heat recovery system	No	No
Installation of an STC system	Yes	Yes
Installation of a PV-panel system	Yes	Yes
Installation of centralized or decentralized cooling system	No	No
Refurbishment or renovation of lighting system	No	No

3.2.2 Educational buildings

Suitable and applicable renovations and retrofitting measures were taken into account in the renovation study of the educational building (Publication 2). As with the residential apartment buildings, the initial setting of the renovation was selected so that the building is undergoing a deep renovation of building façades and the roof to improve the overall economic viability of the deep renovation. The investigated renovation and retrofitting measures of the studied educational building are presented in Table 5.

As with the residential apartment buildings, the studied measures include a combination of typical renovation measures, which have been studied before as individual renovation measures, as well as applicable on-site renewable energy production technologies. In addition to the energy performance improvement measures, renovation and retrofitting measures that improve the indoor environment conditions of the building were also closely studied.

Table 5. Studied renovation and retrofitting measures of the educational building.

Renovation measure	Studied building 1 of the LUT campus area
Basic refurbishment and additional thermal insulation of external walls	Yes
Basic refurbishment and additional thermal insulation of roof	Yes
Basic refurbishment and replacement of windows	Yes
Renovation of the centralized ventilation system (AHUs and ductwork)	Yes
Renovation of the heat distribution system (low-temperature radiators)	Yes
Renovation of the original district heating system (substation)	Yes
Installation of a GSHP system (used for combined heating and cooling operation)	Yes
Installation of an STC system	Yes
Installation of a PV-panel system	Yes
Installation of centralized cooling system with water chiller units	Yes
Installation of centralized room cooling system with radiant ceiling cooling panels	Yes
Refurbishment or renovation of lighting system	Yes

3.2.3 Office buildings

As the improvement of indoor environment conditions plays a significant role in deep renovations of office buildings, suitable and applicable renovations and retrofitting measures that also improve the indoor environment conditions of the building were considered in addition to the more common renovation measures related to improving the energy performance of office buildings (Publication 4). As with the residential apartment and educational buildings, the initial setting of the renovation was selected so that the energy efficiency and indoor environment improvement measures are integrated in a mandatory deep renovation process of the building envelope to maximize the overall cost-effectiveness of the deep renovation. The investigated renovation and retrofitting measures of the studied office building are presented in Table 6.

All applicable renovation and retrofitting measures, including applicable on-site renewable energy production systems, were considered in the office building study to determine the cost-optimal deep renovation concepts for office buildings located in cold climate conditions.

Table 6. Studied renovation and retrofitting measures of the office building.

Renovation measure	Studied office building
Basic refurbishment and additional thermal insulation of external walls	Yes
Basic refurbishment and additional thermal insulation of roof	Yes
Basic refurbishment and replacement of windows	Yes
Installation of integrated window shading solution (blinds between the inner panes of windows)	Yes
Renovation of the centralized ventilation system, replacement of the original AHUs with high efficiency heat recovery system and cooling coils	Yes
Renovation of the centralized ventilation system, installation of demand-controlled ventilation (DCV) system to office and equivalent spaces	Yes
Renovation of the original district heating system (substation)	Yes
Installation of a GSHP system (used for combined heating and cooling operation)	Yes
Installation of a PV-panel system	Yes
Installation of centralized cooling system with water chiller units	Yes
Installation of centralized room cooling system with radiant ceiling cooling panels	Yes
Refurbishment or renovation of lighting system	Yes
Control type of renovated lighting system	Yes

3.3 Cost data

The cost data used in the studies reported in Publications 1–4 were mainly determined by groups of recognized Finnish experts specialized in the cost accounting of buildings. The cost data of different measures were specifically determined for each of the studied buildings using case-specific cost estimations, where factors such as the location and age of the building, general condition of the technical systems and the building envelope, and the overall extent of the renovation were compiled. In addition, case-specific constraints, such as technical space requirements for new and renovated technical systems, and individual features were also detailed in the cost estimates. The installation costs were included in the construction and investment cost estimates of different measures in each case study.

Cost data of relevant recent studies related to refurbishment of existing apartment, educational, and office buildings were utilized in addition to the more detailed and specific cost estimations determined by groups of experts. Furthermore, cost estimates and technical expertise of different system manufacturers, such as heat pumps, ventilation equipment, and solar energy system manufacturers, were also utilized to an appropriate extent.

Essential and relevant maintenance and renewal costs related to the studied renovation measures were detailed in each case study. Relevant maintenance costs included costs for the annual maintenance of different heat pumps, district heating and solar-based energy production systems, and replacement of filters in the AHUs. Relevant renewal costs included costs for replacing compressors in the heat pump units, replacing PV panels or STCs, replacing the lighting system, renewing the district heating substation, and basic refurbishing of windows and external walls.

The Finnish value added tax (VAT) was included in the cost estimates of the brick apartment building study (Publication 1) but excluded from the cost estimates of the other renovation studies (Publications 2–4). In addition, the residual value of different renovation measures was included in the economic calculations of the brick apartment building study but excluded from the economic calculations of the other renovation studies. The residual values of different measures (Publication 1) were determined according to the common technical service life cycles of the measures and systems.

Table 7 presents a summary of the cost data and different cost aspects that were utilized in the economic calculations of each individual case study. More detailed case-specific cost data are presented in the appended Publications 1–4.

Table 7. Summary of the cost data and cost aspects utilized in the case studies.

Economic calculation parameter	Brick apartment building	Concrete large panel apartment building	Educational building	Office building
Construction and investment costs of studied measures, including installation costs	Yes	Yes	Yes	Yes
Maintenance costs of the technical systems and building envelope	Yes	Yes	Yes	Yes
Renewal costs of the technical systems and building envelope	Yes	Yes	Yes	Yes
Energy costs, according to the building's location-specific energy prices	Yes	Yes	Yes	Yes
Residual value of renovation and retrofitting measures	Yes	No	No	No
Life-cycle period used in the economic calculations	25 years	30 years	20 years	15 years
Finnish VAT (24%) included in the cost data	Yes	No	No	No

3.4 Finnish climate conditions and weather data

The updated Köppen-Geiger climate classification categorizes Finland in the cold climate zone (D) (Peel et al., 2007). Finland is divided into four separate climate zones (I–IV) according to the NBCF part D3 (2012) for energy performance and heating power demand calculations of buildings. In this country-specific classification, Vantaa (brick apartment building), Kerava (concrete large panel apartment building), and Lahti (office building) are located in zone I, which is the southern-most climate zone in Finland. Lappeenranta (educational building) is located in the eastern part of Finland in zone II. The Finnish climate zones (I–IV) are presented in Figure 12.

The NBCF part D3 (2012) requires that the PE consumption of the energy performance certificates (EPCs) must always be calculated by using the updated climate zone I (Helsinki-Vantaa test reference year, TRY2012) weather data to make the energy performance of different buildings located in different regions comparable. The TRY2012 weather data include all the essential energy calculation parameters, such as hourly outdoor temperature, relative humidity, wind direction, and velocity and solar radiation for three Finnish climate zones (I, III, and IV). The updated weather data of the TRY2012 correspond to the current climate conditions of the zones (see Figure 12).

The TRY2012 climate data of zone I are also used for climate zone II because Kalamees et al. (2012) determined that the weather conditions of climate zone I describe the weather conditions of zone II accurately enough. The annual average temperature of the Helsinki-Vantaa area is +5.6°C, and the average degree day number (at an indoor temperature of 17.0°C, S17) is 3,952 Kd (Kalamees et al., 2012; NBCF part D3, 2012). These updated test reference year weather data of zone I were used in the dynamic energy simulations conducted in Publications 1–4. The weather data of zone I were also used in the detailed calibration methodology developed in the study reported in Publication 6. A more detailed description of the updated test reference year weather data are presented in the original study carried out by Kalamees et al. (2012). The annual outdoor air temperature of zone I (Helsinki-Vantaa) is presented in Figure 13.

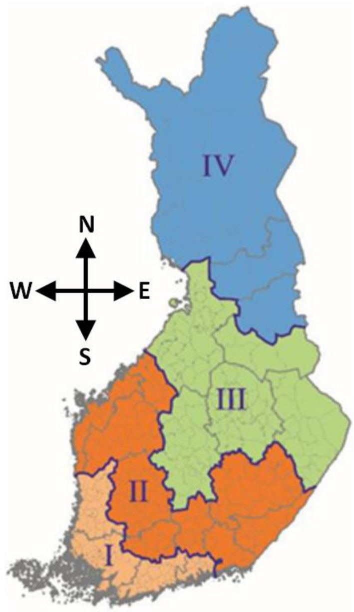

Figure 12. Finnish climate zones (I–IV) for energy performance calculations of buildings (NBCF part D3, 2012). Hourly weather data of climate zone I are used in the energy simulations of the case studies.

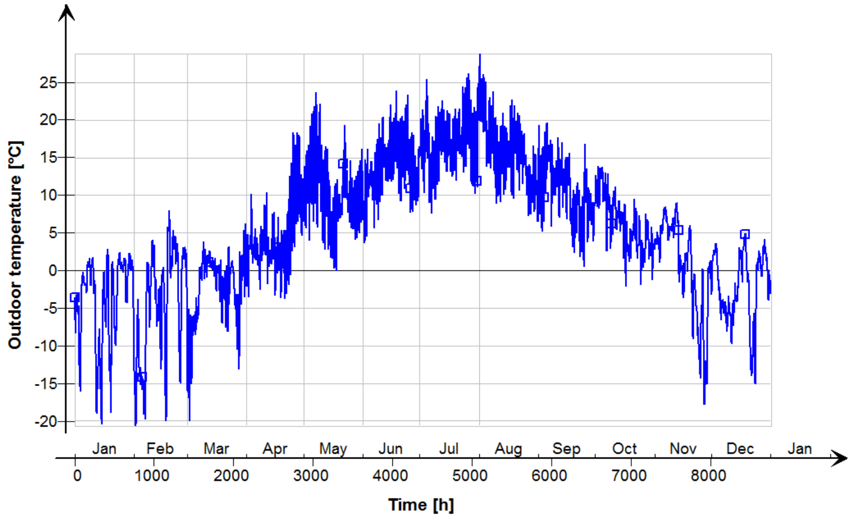

Figure 13. Annual outdoor temperature of the TRY2012 in climate zone I (Helsinki-Vantaa).

3.5 Research methods

3.5.1 Introduction

SBMOO was used as the main research method in this thesis because of the complexity of the analyses conducted and the large number of renovation measures investigated in the case studies reported in Publications 1–4. The recent development of simulation and optimization methods presented in the literature review demonstrates that the SBO analysis is superior to the more conventional parametric-based analysis methods when many individual energy efficiency improvement measures are studied and when there are multiple conflicting objectives, such as energy performance and cost-effectiveness, that must be maximized or minimized simultaneously.

The SBO analysis is not limited to the number of predefined cases or to the total number of individual simulations in building performance studies when suitable simulation and optimization methods are used. In addition to the more detailed and automated processing of data by utilizing advanced optimization algorithms, an SBO analysis always includes hundreds or even thousands of individual simulation cases, improving the reliability and accuracy of the analysis significantly compared to the parametric-based analyses, which are typically conducted manually. Furthermore, global optimum solutions cannot be determined by using conventional parametric-based research methods in building performance studies where many different measures are studied simultaneously.

SBO analysis was utilized in the study reported in Publication 6 where a novel methodology was developed to calibrate simulation models of heat pump systems to correspond to the performance data of actual heat pump systems. The developed methodology improves the reliability and accuracy of dynamic energy simulations, including heat pump systems, and reduces the number of numerical errors occurring during the simulations. The SBO analysis was utilized in determining the optimum calibration parameters for different heat pump models. The analysis improved the effectiveness of the calibration procedure significantly by automating the entire calibration process. Utilizing the SBO analysis in the calibration process also improved the reliability of the simulated heat pump models by reducing the number of the aforementioned numerical errors occurring during the simulations.

In the study reported in Publication 5, a novel method was developed for energy efficient heating of DHW with a GSHP system. Research methods used in the study included laboratory measurements conducted in the experimental analysis of the study, on-site field measurements conducted in the studied case building, and dynamic energy simulations conducted in the computational analysis of the study. The study reported in Publication 5 did not include any optimization analyses, but it included a calibration analysis of the studied heat pump simulation model using the methodology developed in Publication 6. The calibration analysis was carried out to calibrate the performance data of the simulated heat pump model to correspond to the measured performance data of the studied heat pump unit.

3.5.2 Simulation method

Dynamic energy simulations conducted in the studies reported in Publications 1–6 were carried out using IDA Indoor Climate and Energy (ICE) versions 4.6 and 4.7 simulation software. IDA ICE's performance, accuracy, and reliability as a dynamic simulation tool have been validated and proved in numerous previous studies conducted by Sahlin (1996), Björsell et al. (1999), Moinard and Guyon (1999), Travesi et al. (2001), Achermann and Zweifel (2003), Kropf and Zweifel (2001), and Loutzenhiser et al. (2007). The validation studies include tests against measurements and several independent inter-model comparisons. The accuracy of IDA ICE has been compared to other established dynamic simulation tools used in energy performance and indoor climate simulations of buildings. In addition to fully dynamic energy simulations, IDA ICE can be used to perform various indoor climate and thermal comfort simulations.

The performance of the studied heat pump and solar-based energy production systems was simulated by using the Early Stage Building Optimization (ESBO) plant model integrated in the latest versions of IDA ICE. Different on-site renewable energy production technologies, such as heat pump systems, micro-combined-heat-and-power (CHP) plants, wind turbines, and solar-based thermal and electricity production systems, can be simulated as part of dynamic energy and indoor comfort simulations of buildings by applying the ESBO plant model extension, resulting in more versatile and detailed building performance analyses, including the dimensioning of on-site RESs.

3.5.3 Optimization method

Studies related to building performance optimization have increased significantly over the last years, and new optimization methods have been constantly developed (Delgarm et al., 2016; Harish et al., 2016; Lu et al., 2015; Nguyen et al., 2014; Palonen et al., 2013; Salata et al., 2016). The optimization method used in the SBO analyses conducted in the studies reported in Publications 1–4 and 6 was the Multi-Objective Building Performance Optimization (MOBO), version 0.3b.

MOBO is optimization software that was developed by Aalto University and VTT Technical Research Centre of Finland in 2010–2015 for building performance optimization (Palonen et al., 2013). MOBO can be combined with many different simulation platforms, and it can solve one- and multi-dimensional optimization problems (Nguyen et al., 2014; Palonen et al., 2013). MOBO includes multiple types of optimization algorithms to be used in various optimization problems (Palonen et al., 2013). A graphical user interface is used to feed the input data to MOBO. It is also possible to carry out parallel simulation with MOBO to increase the effectiveness and reduce the simulation time of the SBO analysis (Palonen et al., 2013). According to Nguyen et al. (2014), recent studies indicate that the SBO analysis is an effective method to determine the optimal solutions in multi-objective building performance analyses.

MOBO includes a total of seven different optimization algorithms that can be used in building performance analyses, depending on the specifications of the analysis. The Pareto-Archive NSGA-II genetic algorithm was used in all the multi-objective optimization analyses of the studies reported in Publications 1–4 and 6. The Pareto-Archive NSGA-II algorithm is an advanced and further developed version of the regular NSGA-II genetic algorithm, and it has been specifically developed to solve multi-dimensional optimization problems. The Pareto-Archive NSGA-II algorithm was selected for the SBO analyses of the thesis because it was determined to be the best and most efficient optimization algorithm included in MOBO that can be used to solve the multi-objective optimization tasks included in the thesis.

MOBO is benchmarked to different kinds of building performance optimization problems, and its performance has been tested with good success in previous studies related to building performance optimization analyses (Nguyen et al., 2014; Palonen et al., 2013). Despite being a new optimization tool, MOBO has already established a position as a popular optimization engine used in multi-objective building performance optimization analyses (Nguyen et al., 2014).

3.5.4 Selection of optimization algorithm parameters

The Pareto-Archive NSGA-II genetic algorithm was used in all the multi-objective optimization analyses of the thesis (Publications 1–4 and 6). As the utilized optimization algorithm is a genetic algorithm, correct selection of algorithm parameters according to the optimization problem is an essential factor in achieving optimal results from the analyses. Four different parameter values must be determined with the selected Pareto-Archive NSGA-II genetic algorithm. In addition, the parameter values should always be determined according to the specific optimization problem of the analysis. The optimization parameter values that must be determined for each analysis are:

- Population size
- Number of generations
- Mutation probability
- Crossover probability.

The total number of simulations is determined by the selection of population size and number of generations. Currently, the computational time is the major limiting factor in the SBO analyses carried out by using the IDA ICE simulation environment. Therefore, a detailed SBO analysis is often a small compromise between the computational efficiency and accuracy of the results. Experience is required from the user conducting the analysis in setting up the SBO analysis, including the optimization problem and the energy simulation model, so that the analysis can be carried out as efficiently as possible with minimum computational effort but also as accurately as possible.

In the development of MOBO, a significant amount of work has been put in by the developer to provide useful and easy-to-use features regarding the selection of optimization algorithm parameter values according to the features of specific optimization problems. The GUI of MOBO (version 0.3b) provides hints to select the optimization algorithm parameter values according to the specifications of the optimization problem derived for the SBO analysis in MOBO. The mutation probability (MP), used in the SBO analyses reported in Publications 1–4 and 6, is calculated by Equation (1).

$$\mathrm{MP} = \frac{1}{\left(10 \times n_c + ceil\left(log_2(n_1)\right) + ceil\left(log_2(n_2)\right) +, \ldots, + ceil\left(log_2(n_x)\right)\right)} \tag{1}$$

where: n_c is the number of continuous variables; n_1 is the number of possible values with first discrete variable; n_2 is the number of possible values with second discrete variable; n_x is the number of possible values for last discrete variable; and *ceil* is a function that returns the next integer that is equal or greater to its parameter. According to the developer, all MP values that are in the range [MP,2MP] should work well when algorithm convergence is discussed. The number of continuous and discrete variables, and the number of possible values for each discrete variable, are presented in original Publications 1–4. In the study reported in Publication 6, only continuous variables, a total of 6, were used in the SBO analysis. The MP used in the analysis was calculated by Equation (1) in each of the studies reported in Publications 1–4 and 6.

A parameter value of 0.9 was used for the crossover probability in all of the SBO analyses. The developer of MOBO suggests that a value in the range [0.8,1] should be selected for the crossover probability parameter when algorithm convergence is discussed. After discussing with the developer in more detail, it was determined that a parameter value of 0.85–0.9 should be selected for the crossover probability parameter in the SBO analyses conducted in the thesis. After further consideration and testing, the parameter value 0.9 was determined to be a good value for the optimization analyses of the thesis when algorithm convergence is discussed.

The population size was selected according to the optimization problem studied and according to the total number of CPUs included in the computers used to carry out the SBO analyses. As mentioned above, the computational time of the SBO analysis is the major limiting factor in the more detailed SBO studies conducted using the IDA ICE simulation environment. For this reason, the selection of the population size and the number of generations must be carefully determined so that the calculation time of the analysis is reasonable but also so that the results obtained from the analysis are optimal or close to optimal. As MOBO supports parallel computing, the number of CPUs included in the computers used to carry out the analyses has a significant impact on the overall calculation time of the analyses.

The SBO analyses of the study reported in Publication 1 were carried out by using computers with 8–12 CPUs. The SBO analyses of the studies reported in Publications 2–4 were carried out by using computers with 32–48 CPUs. The SBO analyses of the study reported in Publication 6 were carried out by using a computer with 8 CPUs. The population size was selected to meet the number of CPUs in each analysis so that it could be divided by the number of CPUs utilized in the optimization. For example, if the computer used in the optimization had 32 CPUs, a population size of 32 was selected for the optimization analysis. Population sizes with even numbers were always used in the SBO analyses of the thesis.

The number of generations used in optimization analyses of the thesis were selected so that a sufficient number of simulations was conducted in each analysis and also so that optimal or close-to-optimal solutions could be determined. In reality, the number of generations was always a compromise selection between the calculation time and the accuracy of the analysis because SBO analyses with approximately 500–2,400 simulations were determined to be reasonable when calculation time of the analyses is discussed. However, the final selection of the optimization algorithm parameters was always discussed with the developer of MOBO before each SBO analysis to determine that the selected algorithm parameters were appropriate to be used in the studied analysis in terms of efficiency, accuracy, and algorithm convergence.

In the study reported in Publication 1, the computational performance of computers was a limiting factor regarding calculation time. In the studies reported in Publications 2–4, computers with higher calculation capacity and more CPUs were used, which improved the efficiency and decreased the calculation times of the SBO analyses significantly. For comparison, it took approximately one week to carry out one SBO analysis (450–600 simulations) in the study reported in Publication 1, whereas it took approximately two days to carry out a similar analysis in the studies reported in Publications 2–4. In the study reported in Publication 6, the SBO analyses carried out in the study were so simple and fast to carry out that the calculation time was only approximately 15–20 minutes per analysis. The optimization algorithm parameter values for each SBO analysis carried out in the thesis are presented in Table 8.

Table 8. Optimization algorithm parameter values used in the SBO analyses of the thesis.

SBO analysis	Population size	Number of generations	Mutation probability	Crossover probability
Publication 1:				
- A2WHP system optimization	8	64	0.032	0.9
- DH system optimization	8	57	0.032	0.9
- EAHP system optimization	8	57	0.025	0.9
- GSHP system optimization	12	50	0.032	0.9
- Sensitivity analysis, GSHP system	8	64	0.032	0.9
Publication 2:				
- DH system optimization	48	12	0.04	0.9
- GSHP system optimization	32	14	0.04	0.9
Publication 3:				
- A2WHP system optimization	28	30	0.029	0.9
- DH system optimization	28	30	0.029	0.9
- EAHP system optimization	28	30	0.031	0.9
- GSHP system optimization	28	30	0.029	0.9
Publication 4:				
- Analysis 1: DH system concept	30	50	0.038	0.9
- Analysis 2: GSHP system concept	30	50	0.028	0.9
- Analysis 3: DH system concept	30	50	0.038	0.9
- Analysis 4: GSHP system concept	30	30	0.028	0.9
- Analysis 5: Thermal comfort conditions	30	80	0.023	0.9
Publication 6:				
- All heat pump calibration analyses (all analyses included six continuous variables that were optimized)	32	30	0.017	0.9

The optimization algorithm parameter values presented in Table 8 were determined to provide sufficient compromise between calculation time and accuracy of the analyses. They were carefully selected for each analysis after extensive consideration and discussion with the developer of MOBO. While some of the obtained solutions may in fact be close-to-optimal solutions due to the relatively low number of simulations, they are definitely very close to the global optimum achievable by a larger number of generations and simulations.

In general, the expertise of Matti Palonen, the developer of MOBO, was utilized in the selection of the optimization algorithm parameter values in all SBO analyses carried out in the thesis. The parameter values were determined and selected in each analysis so that they deliver both high accuracy and fast computational time. In addition, the recent research conducted by Hamdy (2012) was extensively utilized in the selection of both the optimization algorithm (the Pareto-Archive NSGA-II algorithm) and the optimization algorithm parameter values used in the SBO analyses of the thesis.

3.5.5 Operation of SBO

The main components and their relationships for the SBO analysis are presented in Figure 14. In addition, the operation principle of the SBO analysis, with the simulation and optimization methods used in the case studies of the thesis, is presented in Figure 15.

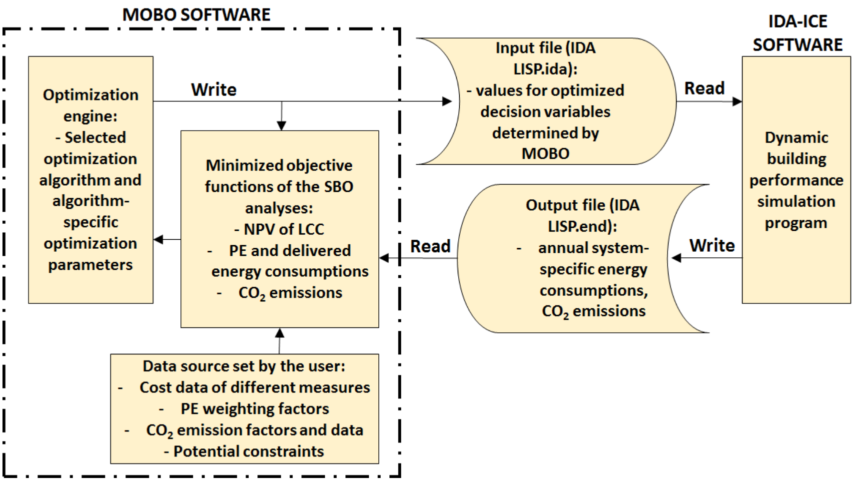

Figure 14. The main components and their relationships in the SBO analysis.

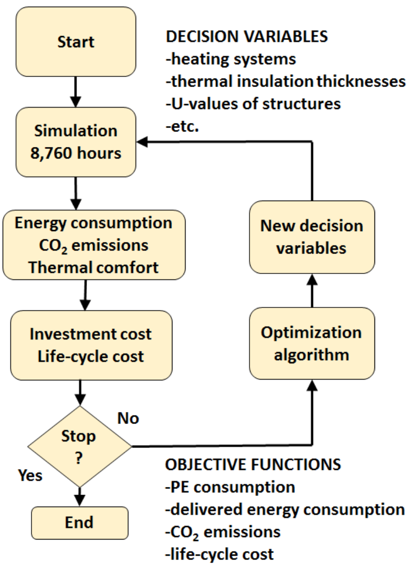

Figure 15. The operation principle of the SBO analysis.

3.5.6 Calculation of energy performance

PE consumption

According to the recast EPBD (2010/31/EU), the energy efficiency classifications of the EPCs are defined according to the PE consumption of buildings. Furthermore, the energy performance requirements of nZEBs are defined according to the PE consumption by using the guidelines of the recast EPBD. To calculate the total PE consumption, weighting factors of different energy carriers are needed. The PE weighting factors of different energy carriers are typically country-specific, and they are determined by each member state, depending on the energy production infrastructure and other features related to the energy consumption of buildings (EPBD, 2010/31/EU).

In Finland, the total PE consumption includes the use of heating energy for space, ventilation, and DHW heating; electricity used by lighting, household appliances, and technical systems, including all auxiliary equipment, such as pumps and fans; and the energy, cooling, and/or electricity used by the cooling systems of the building. In addition, the efficiencies of the energy production systems are included when the total PE consumption is calculated.

However, the total PE consumption of buildings is always calculated according to the NBCF part D3 (2012) by using standardized usage profiles and internal heat gains of different building types, such as residential, educational, and office buildings, in Finland. The indoor air temperature set points are fixed in the calculation of the PE consumption (e.g., the indoor air temperature set point for heating is 21°C and for cooling is 25°C in office and educational buildings) (NBCF part D3, 2012). A more detailed description of the PE consumption calculation process is presented in the NBCF part D3 (2012) and part D5 (2012). The total PE consumption of a building, according to the NBCF part D3 (2012), is calculated by Equation (2).

$$E_{primary,D3(2012)} = \frac{\sum_i (E_i \cdot f_i)}{A_{net}} \quad (2)$$

where: E_i is the annual delivered energy of energy carrier i (district heating, electricity, and renewable and fossil fuels used for energy production of the building and district cooling), kWh/a; f_i is the PE weighting factor of energy carrier i, -; A_{net} is the heated net floor area of the building, m^2 (NBCF part D3, 2012). The currently used PE weighting factors for different energy carriers in Finland are (NBCF part D3, 2012):

- Electricity 1.7
- District heating 0.7
- District cooling 0.4
- Fossil fuels 1.0
- Renewable fuels 0.5.

However, while the aforementioned PE factors are currently in use in Finland, the final PE factors proposed to be used in the calculation of PE consumption and in the definition of energy efficiency requirements of nZEBs are currently under revision by the Finnish Ministry of the Environment. The proposed final PE weighting factors to be used in the calculation of PE consumption are:

- Electricity 1.2
- District heating 0.5
- District cooling 0.28
- Fossil fuels 1.0 (same as the currently used weighting factor)
- Renewable fuels 0.5 (same as the currently used weighting factor).

The effect of the lower PE weighting factors on the cost-optimal renovation solutions was studied in Publication 3. The maximum PE consumption limits of nZEBs for different building types are also going to decrease in the same proportion, according to the new proposed PE weighting factor values. In an additional sensitivity analysis carried out in Publication 3, different PE weighting factors are used to compare the cost-optimum combination of renovation measures between an analysis conducted by using the current higher national PE weighting factors and an analysis conducted by using the proposed lower PE weighting factors.

Delivered target energy consumption
The delivered target energy consumption is calculated without the energy-carrier-specific PE factors. Unlike the calculation of the PE consumption using standardized usage profiles and internal heat gains, estimated actual usage profiles and internal heat gains are used in the calculation of the delivered target energy consumption. No standardized building type-specific internal heat gains or usage profiles are used, as the calculation is always based on the estimated actual use and occupancy of the building. In addition, actual indoor air temperature set points can be used for both heating and cooling buildings. The temperature set points can be selected according to the estimated actual use of the building—for example, to represent typical indoor climate temperature set points used in modern office buildings to provide high-quality thermal comfort conditions.

Calculation of the delivered target energy consumption represents the actual use of the building better than the calculation of the PE consumption, which is nevertheless used to determine the energy performance ratings of the EPCs and the requirements of the nZEBs. The individual specifications and preferences (e.g., the effect of holidays on the occupancy of the building users) of the building can be more accurately used in the calculation of the delivered target energy consumption.

Typically, the selection of economically viable renovation solutions should always be based on the delivered target energy consumption calculated according to the estimated actual use of a building. No decisions should be made by solely calculating the standardized PE consumption without studying the effects of the energy performance improvement measures on the delivered target energy consumption. However, the economic viability of different energy efficiency improvement measures must be estimated and determined according to the PE consumption of the building, and the energy efficiency classifications of the EPC and the energy performance requirements of nZEBs are defined based on the PE consumption of buildings.

3.5.7 Energy performance requirements of buildings

The buildings are categorized to different energy performance classes according to their PE consumption (EPBD, 2010/31/EU). Table 9 presents the different energy performance classes of different building types used in Finland (Ministry of the Environment, 2013a).

Table 9. The energy performance classes of different building types according to the total PE consumption (Ministry of the Environment, 2013a).

Building type	Energy efficiency rating and PE consumption [$kWh_E/m^2,a$]						
	A	B	C	D	E	F	G
Detached houses	*Energy efficiency ratings are based on the heated net floor area of the house.*						
Row and linked houses	*≤ 80*	*81-110*	*111-150*	*151-210*	*211-340*	*341-410*	*411 ≤*
Apartment buildings	*≤ 75*	*76-110*	*101-130*	*131-160*	*161-190*	*191-240*	*241 ≤*
Office buildings	*≤ 80*	*81-120*	*121-170*	*171-200*	*201-240*	*241-300*	*301 ≤*
Commercial buildings	*≤ 90*	*91-170*	*171-240*	*241-280*	*281-340*	*341-390*	*391 ≤*
Boarding houses	*≤ 90*	*91-170*	*171-240*	*241-280*	*281-340*	*341-450*	*451 ≤*
Educational buildings and kindergartens	*≤ 90*	*91-130*	*131-170*	*171-230*	*231-300*	*301-360*	*361 ≤*
Sports facilities[1]	*≤ 90*	*91-130*	*131-170*	*171-190*	*191-240*	*241-280*	*281 ≤*
Hospitals	*≤ 150*	*151-350*	*351-450*	*451-550*	*551-650*	*651-800*	*801 ≤*

[1] *Swimming and ice hockey arenas not included.*

The preliminary Finnish nZEB requirements for new buildings have been defined by the FInZEB project, which was completed in February 2015 (FInZEB, 2015). As a result of the FInZEB project, a preliminary proposal was made for a cost-effective and reasonable nZEB level for different building types. The nZEB energy performance definition of different building types was defined by the total PE consumption of the building type. The energy performance requirements for nZEBs were revised after the new lower PE weighting factors were proposed (Ministry of the Environment, 2017). The revised nZEB requirements will be implemented in the revised national building regulations coming into force in the beginning of 2018 (Ministry of the Environment, 2017). The preliminary and new proposed PE consumption requirements of nZEBs for different building types are presented in Table 10.

Table 10. The preliminary and new proposed energy performance requirements for nZEBs (FInZEB, 2015; Ministry of the Environment, 2017).

Building type	PE consumption, preliminary nZEB requirements (higher PE factors) [$kWh_E/m^2,a$]	PE consumption, revised nZEB requirements (lower PE factors) [$kWh_E/m^2,a$]
Detached houses, heated net floor area 50–150 m^2	*$A_{net} < 120\ m^2$: 204* *$120\ m^2 \le A_{net} \le 150\ m^2$: 372 - 1.4 x A_{net}*	*200 - 0.6 x A_{net}*
Detached houses, heated net floor area 150–600 m^2	*173 - 0.07 x A_{net}*	*116 - 0.04 x A_{net}*
Detached houses, heated net floor area over 600 m^2	*130*	*92*
Row and linked houses	*150*	*105*
Apartment buildings	*116*	*90*
Office buildings	*90*	*100*
Commercial buildings	*143*	*135*
Boarding houses	*182*	*160*
Educational buildings and kindergartens	*104 (educational buildings)* *107 (kindergartens)*	*100*
Sports facilities[1]	*115*	*100*
Hospitals	*418*	*320*

[1] *Swimming and ice hockey arenas not included.*

The same energy efficiency and nZEB classifications were applied to both new and existing buildings in Finland, even though the nZEB requirements set by the recast EPBD (2010/31/EU) only currently concern new buildings. The same energy performance target levels are applied to existing buildings if the objective of a deep renovation is to renovate an existing building to an nZEB.

In Finland, improving energy performance in deep renovations is mandatory, and it is also regulated by the authorities (Ministry of the Environment, 2013b). The decree on improving energy performance in renovations (4/2013) presents three alternative methods to improve energy efficiency in renovations, which are (Ministry of the Environment, 2013b):

1. Improving the energy efficiency of the building envelope by installing additional thermal insulation to external walls and the roof and by replacing the original windows with new windows
2. Decreasing the calculated delivered energy consumption of the building in standard use without energy-carrier-specific PE factors below a required reference level
3. Decreasing the total PE consumption of the building below a required, building type-specific level.

The third method is selected as the minimum energy performance requirement level of the renovation measures in all the case studies reported in Publications 1–4. According to the decree 4/2013 (Ministry of the Environment, 2013b), the minimum requirement level for existing apartment buildings is 0.85 x the initial total PE consumption of the building (a 15% reduction) when no energy performance improvement measures have been conducted. The corresponding minimum requirement level for existing educational buildings is 0.80 x the initial total PE consumption of the building (a 20% reduction) and for existing office buildings is 0.70 x the initial total PE consumption of the building (a 30% reduction) (Ministry of the Environment, 2013b). For the studied case buildings, the minimum requirement levels of the decree that must be achieved after the renovation measures are conducted are:

- Brick apartment building: 0.85 x 165 kWh/(m^2,a) = 140 kWh/(m^2,a)
- Concrete large panel apartment building: 0.85 x 186 kWh/(m^2,a) = 158 kWh/(m^2,a)
- Educational building: 0.80 x 220 kWh/(m^2,a) = 176 kWh/(m^2,a)
- Office building: 0.70 x 218 kWh/(m^2,a) = 153 kWh/(m^2,a).

3.5.8 Assessment of productivity loss

The economic impact of productivity loss caused by unfavorable indoor thermal conditions was investigated in the office building study reported in Publication 4. Several studies conducted by Kosonen and Tan (2004a, 2004b), Wyon et al. (1975), and Wyon (1996) have developed models to predict the productivity loss of workers and the possible economic impacts of unfavorable or poor indoor climate and thermal conditions. It is essential to notice that the productivity loss and the optimal indoor thermal conditions are highly connected to the perceived thermal comfort conditions, and they are typically predicted using the whole body thermal sensation indices, such as the predicted mean vote (PMV) and the predicted percentage of dissatisfied (PPD), which represent the average thermal sensation of a person in specific indoor thermal conditions. Furthermore, the same level of thermal comfort and productivity can be obtained by many different combinations of clothing and indoor thermal conditions (Kosonen & Tan, 2004a, 2004b; Wyon et al., 1975; Wyon, 1996). Typically, there is always at least a 5% dissatisfaction to indoor climate conditions among building users, regardless of the actual indoor climate conditions of the building (Kosonen & Tan, 2004a, 2004b; Wyon et al., 1975; Wyon, 1996). The PPD index is calculated by Equation (3).

$$PPD = 100 - 95e^{[-(0.03353PMV^4 + 0.2179PMV^2)]} \quad (3)$$

where: *PPD* is the predicted percentage of dissatisfied and *PMV* is the predicted mean vote (Fanger, 1970). The PMV index is calculated according to the Fanger's thermal comfort model, and it is affected by factors such as clothing (clo-index) and the metabolic rate (MET-index) of occupants, air temperature, mean radiant temperature, air velocity, and the relative humidity (RH) of air (Fanger, 1970). Perceived air quality, pollution loads, ventilation efficiency, lighting conditions, and acoustics privacy affect the productivity and the potential productivity loss of occupants in office buildings (Kosonen & Tan, 2004a, 2004b).

Because a similar PMV index and thus similar productivity loss can be achieved by many different combinations of thermal comfort factors, some simplifications and assumptions have to be made in indoor climate conditions and productivity loss analyses (Kosonen & Tan, 2004a, 2004b). The basic assumptions related to the thermal comfort factors used in the office building study reported in Publication 4 are as follows:

- Air velocity in the occupied zone is 0.15 m/s
- The room air is fully mixed
- Metabolic rate of occupants is 1.2 MET (represents average office work)
- Clothing of occupants is 0.85 ± 0.25 clo; clothing of occupants is automatically adapted between the following limits to obtain comfort:
  - PMV index -1: occupants wear maximum clothing (1.10)
  - PMV index +1: occupants wear minimum clothing (0.60)
- The radiant temperatures of different spaces, room air temperatures, and RH of indoor air throughout the year are calculated in the hourly based dynamic energy simulation.

Wyon (1996) has determined that the productivity loss according to the PMV index is different for thinking- than typing-related tasks, estimating that the productivity loss is higher in typing-related tasks when the PMV index increases from its optimal value of -0.21. For this reason, Wyon (2000) has developed a simplified method to estimate the overall productivity loss from workers resulting from too high or too low operative temperatures (over- or underheating) in the occupied zone of a room space. In this simplified model, productivity is not lost on average for operative temperatures between 20°C and 25°C when it is assumed that occupants can affect the indoor thermal comfort sensation by adding or removing clothing to adapt to the thermal conditions according to the perceived thermal comfort. When the operative temperature is below 20°C or above 25°C, the overall productivity loss is assumed to be 2%/°C (e.g., 8% at an average operative temperature of 29°C and 10% at an average operative temperature of 30°C) (Wyon, 2000). The relative reduction in performance of building users according to the indoor temperature in office buildings has been presented in a meta-analysis conducted by Seppänen et al. (2006b), resulting in similar conclusions.

The simplified model derived by Wyon (2000) was selected to determine the productivity loss caused by unfavorable indoor thermal comfort conditions in the office building study reported in Publication 4. The productivity loss was assessed according to the thermal comfort conditions of the studied office building because the effect of factors such as lighting conditions and ventilation efficiency on the productivity loss were assumed to be constant and thus relatively low when the productivity loss caused by these factors was discussed (Kosonen & Tan, 2004a, 2004b; Wyon et al., 1975; Wyon, 1996). The illuminance of the renovated lighting system is over 500 lx in working areas, and an average outdoor airflow rate of the ventilation system is approximately 24 dm^3/s/person.

The economic impact of the productivity loss was calculated by using the average salary data of government office workers to form an integrated analysis where the monetary impact of the productivity loss can be combined with the LCC analysis of deep renovation of the case office building. In addition to the direct salary expenses of workers, the side costs, such as the social security costs and other indirectly related salary expenses, were included in the economic calculations. However, the potential overhead factors related to the salaries of employees of commercial companies were excluded from the analysis.

The average monthly direct salary of a Finnish government official is €3,550/month (in 2014), which is approximately €23.3/h with an average of 152.5 working hours per month (Ministry of Finance, 2014, 2015; Statistics Finland, 2016). The side costs of government official salaries were approximately 61–62% in Finland during 2012–2015 (Ministry of Finance, 2015). This means that the total salary expenses for the employer are approximately €23.3/h x 1.62 = €38/h (Ministry of Finance, 2014, 2015; Statistics Finland, 2016).

The hourly-based cost of €38/h was used as the value of the lost work due to unfavorable indoor thermal comfort conditions in the LCC analysis of the office building study reported in Publication 4.

Additional analyses were carried out in Publication 4 to determine the cost-optimal measures to maximize the productivity of occupants. The main purpose of the additional analyses was to determine the global optimum measures to maximize the productivity of building users and compare the measures with the results of the principal analyses where the main objective was to determine the global cost-optimum overall solutions. The additional analyses were conducted because the optimal measures to maximize the productivity were not necessarily the same as the measures to deliver the cost-optimum overall solutions. The results and developed models of previous studies were used to predict the productivity loss caused by different thermal factors (Kosonen & Tan, 2004a, 2004b). The limitations caused by the technical space requirements (suspended ceilings and vertical ventilation shafts) were also taken into account, and it was determined that increasing the airflow rate of the original ventilation system over 3.0

$dm^3/(s,m^2)$ was not possible, which typically is the case in the renovations of the majority of existing office buildings. This limitation of the airflow rate of the ventilation system was selected as a constraint parameter in the additional analyses carried out to maximize the indoor thermal conditions.

The total hours of people dissatisfied (PDH) was selected as an indicator to represent the quality of the indoor thermal conditions in the additional analyses. The total PDH (dissatisfied hours/occupant per year) is the sum of all the annual individual PPD calculation results (e.g., nine individual PPD calculation locations including 25 occupants in each location in Figure 10) of all occupied room spaces during the operating time of the building. As the total PDH index of the building includes all the individual PPD calculation results of the occupied zones, it can be reliably used as an accurate average index to compare overall indoor thermal comfort between different design and renovation alternatives. The PDH index will always be at least 5% of the total occupant hours of the building [see Equation (3)], regardless of the actual conditions (Kosonen & Tan, 2004a, 2004b). The distribution of occupant groups in an office floor that was used to determine the average annual PMV and PPD indices for the studied case office building was shown in Figure 10. Each occupant group location shown in Figure 10 consists of 25 sitting occupants, which equals a total of 225 occupants per office floor.

3.5.9 Assessment of environmental impact

The environmental impact of renovations was assessed in detail in the studies reported in Publications 3 and 4. The environmental impact was assessed according to the CO_2 emissions of the investigated case buildings in both of the studies. Publication 3 included a detailed environmental impact analysis, where the overall environmental impact of a deep renovation of concrete large panel apartment buildings was studied. Publication 4 utilized the results and conclusions of Publication 3 and applied a more specific research perspective to assess the environmental impact of deep renovations of office buildings located in cold climate conditions.

As the literature review demonstrates, the operation period of a building is dominant over the construction and demolition periods, when the total CO_2 emissions and overall environmental impact of buildings are discussed. Several recent studies related to investigating the energy, material, and emission efficiency of existing concrete-structured apartment buildings located in cold climate conditions have concluded that the energy efficiency, delivered energy consumption, and energy production systems of existing apartment buildings are the key factors to minimize the total CO_2 emissions (Nemry et al., 2010; Paiho et al., 2013, 2014). Studies conducted by Nemry et al. (2010) and Paiho et al. (2013, 2014) conclude that the CO_2 reduction potential of the factors related to the energy performance of buildings is significant compared to the CO_2 reduction potential of construction materials related to the building envelope and infrastructure.

Both studies reported in Publications 3 and 4 made use of the key findings of the previous studies and literature and implemented an appropriately practical analysis perspective by neglecting factors that have little or no effect on the overall environmental impact of the deep renovation. All the CO_2 emissions determined in the studies were based on actual CO_2 emissions—not the CO_2 equivalent emissions. After considering different alternative methods to be used in the CO_2 emissions assessments, it was determined that by using the described actual CO_2 emissions data instead of the CO_2 equivalent data, the results of the case studies were more universal and could be used for comparison better in future studies related to the assessment of CO_2 emissions of multi-family residential and office buildings located in different climate conditions and techno-economic environments.

In the concrete large panel apartment building study, CO_2 emissions of construction materials, transportation of the materials to the construction site, and CO_2 emissions of delivered energy consumption according to different energy carriers were included in the assessment of the environmental impact. The total CO_2 emissions generated from the construction materials used in the deep renovation of the case apartment building, from the transportation of the construction materials to the construction site and from the delivered energy consumption of different energy carriers during the selected 30-year life-cycle period, are calculated by Equation (4).

$$CO_{2,total} = \sum CO_{2,materials} + \sum CO_{2,transport.} + \sum CO_{2,DE} \quad (4)$$

where: $\Sigma CO_{2,materials}$ is the overall embodied CO_2 emissions of construction materials, depending on the selected renovation measures related to the building envelope and building services systems, kg; $\Sigma CO_{2,transport.}$ is the overall CO_2 emissions of transportation of the construction materials to the construction site, kg; $\Sigma CO_{2,DE}$ is the overall CO_2 emissions of delivered energy consumption according to different energy carriers (electrical energy and district heating), kg.

The embodied CO_2 emissions of the construction materials and the CO_2 emissions of transportation of the construction materials were determined by using the 360optimi software developed by Bionova Oy (Bionova Oy, 2016). The 360optimi software includes local material databases to be used for more accurate and detailed emissions impact analyses (Bionova Oy, 2016). Local Finnish construction material emissions data were used in the environmental impact analysis of the concrete large panel apartment building. A detailed description of the embodied CO_2 emissions of construction materials and the CO_2 emissions of transportation of the materials to the construction site used in the study are presented in the appended Publication 3.

The CO_2 emissions of different energy carriers were determined by using the delivered energy consumption of the studied case apartment building. The dynamic energy simulations, which were carried out to determine the delivered energy consumption of the building, were conducted according to the estimated actual use of the case building described in Section 3.5.6 to provide estimations of CO_2 emissions generated from delivered energy consumption as accurately as possible. The CO_2 emissions of energy carriers used in the apartment building case study (Publication 3) were (Motiva Oy, 2016):

- The average CO_2 emissions factor for district heating energy produced by CHP production is currently 183 kgCO_2/MWh in Finland. The emissions factor of district heating is an average value of the last three years.
- The average emissions factor for electrical energy is currently 209 kgCO_2/MWh in Finland. The emissions factor of electrical energy is an average value of the last five years.

In the office building study (Publication 4), the CO_2 emissions caused by the delivered energy consumption of the building were determined to be dominant over the embodied CO_2 emissions of the construction materials and the transportation of the materials to the construction site, forming over 80% of the total CO_2 emissions. For this reason, the system boundary of the study was selected so that the environmental impact analysis was focused on studying the renovation measures that cost-effectively reduce the delivered energy consumption of the case office building because it was determined to be the most important aspect to significantly reduce the overall environmental impact and carbon footprint of the studied office building stock toward low-carbon office buildings.

The CO_2 emissions factors of different energy carriers were selected according to the average Finnish emissions factors presented above with the concrete large panel apartment building (183 kgCO_2/MWh for district heating and 209 kgCO_2/MWh for electricity) (Motiva Oy, 2016).

3.5.10 Economic calculations

The minimum net present value (NPV) of LCC was used to assess the economic viability of different renovation measures in all the studies reported in Publications 1–4. The annual maintenance repairs and renewals of different measures were used to prevent decay of the buildings and to prevent the increase of renovation debt. The life-cycle periods of the calculations in different case studies were selected according to Table 7. The global NPV of LCC of the brick apartment building (Publication 1) was calculated by Equation (5).

$$LCC_{25a} = \sum I_{0,tot} + \sum MR_a \times \frac{1-(1+r)^{-n}}{r} + \sum R_M \times \frac{1}{(1+r)^{k_i}} + \sum E_a \times \frac{1-(1+r_e)^{-n}}{r_e} - \sum Res_{tot} \quad (5)$$

where: LCC_{25a} is the NPV of the LCC of the building during the 25-year life-cycle period, €; $\Sigma I_{o,tot}$ is the total investment cost of the renovation measures, €; r is the real interest rate; n is the life-cycle period of the LCC calculation analysis, a; MR_a is the annual maintenance and repair cost of the renovation measures, €/a; r_e is the escalated real interest rate; E_a is the annual energy cost, €/a; k_i is the year from the start, when the renewal is carried out; R_M is the renewal cost of the renovation measure, €; ΣRes_{tot} is the total residual value of the renovation measures, €.

The total renewal cost consists of the sum of individual renewal costs of different renovation measures, such as replacing compressors in heat pump units or renewing STCs. The total residual value is the sum of residual values of individual renovation measures, and the total investment cost is the sum of individual investment costs of different renovation measures.

In the educational building study (Publication 2), the global NPV of LCC was calculated by Equation (6).

$$LCC_{20a} = \sum I_{0,tot} + \sum MR_a \times \frac{1-(1+r)^{-n}}{r} + \sum R_M \times \frac{1}{(1+r)^{k_i}} + \sum E_a \times \frac{1-(1+r_e)^{-n}}{r_e} \qquad (6)$$

where different LCC calculation parameters are the same as described with Equation (5). The difference between Equations (5) and (6) is that Equation (6) does not include the calculation of residual value as a part of LCC because the residual value was not included in the analysis of the educational building (see Table 7).

In the concrete large panel apartment building study (Publication 3), the global NPV of LCC was calculated by Equation (6), but the life-cycle period of the calculation was 30 years.

In the office building study (Publication 4), the global NPV of LCC was calculated by Equation (7).

$$LCC_{15a} = \sum I_{0,tot} + \sum MR_a \times \frac{1-(1+r)^{-n}}{r} + \sum R_M \times \frac{1}{(1+r)^{k_i}} + \sum E_a \times \frac{1-(1+r_e)^{-n}}{r_e} + \sum t_{lost} Va_{work} \times \frac{1-(1+r_w)^{-n}}{r_w} \qquad (7)$$

where: LCC_{15a} is the NPV of the LCC over the 15-year life-cycle period, €; $\Sigma I_{o,total}$ is the total investment cost of the renovation measures, €; ΣMR_a is the total annual repair and maintenance cost of the renovation measures, €/a; ΣR_M is the total renewal cost related to the renovation measures, €; ΣE_a is the total annual energy cost of the case building, €/a; r is the real interest rate selected for the LCC analysis; r_e is the escalated real interest rate selected for the LCC analysis, including an estimated energy price escalation rate in the future; n is the selected life-cycle period (15 a), a; k_i is the time step (year) from the start of the life-cycle period when a specific renewal measure is conducted; Σt_{lost} is the sum of annual lost working hours due to productivity loss caused by unfavorable indoor climate conditions, h/a; Va_{work} is the total value of the work, €/h; r_w is the estimated average annual increase in the total value of the work in the future.

In the office building study (Publication 4), the internal rate of return (IRR) method (ROI, internal interest rate) was studied to determine the measures truly delivering the best return on the investments in addition to delivering low LCCs. The IRR achieved by the renovation measure investments was calculated by Equation (8).

$$i = \frac{1-(1+i)^{-n}}{\frac{I_{0,add.}}{A}} \qquad (8)$$

where: i is the IRR achieved by the renovation investments, %/a; A is the difference of total profits and costs compared to a specific reference solution, the total net profit, €/a; $I_{o,add.}$ is the additional investment cost of the renovation measures compared to a specific reference solution, €; n is the selected life-cycle period (15 a), a. The solution of Equation (8) requires iteration procedure. However, the iteration procedure is relatively simple, and the iteration typically converges quickly. In some rare cases, there is no solution to Equation (8), and the internal interest rate i cannot be determined. Sometimes Equation (8) can be solved by using two different values of internal interest rate i, where the other value is negative. In this case, the negative solution can be dismissed and the positive solution is used as the internal interest rate.

The IRR method was also used in the concrete large panel apartment building study (Publication 3) where the method was used to determine the actual rate of return achieved by the renovation measures in addition to the calculation of the global LCC. Table 11 presents a summary of the LCC calculation parameters used in the individual case studies reported in Publications 1–4.

Table 11. Summary of the LCC calculation parameters used in the case studies.

LCC calculation parameter	Brick apartment building	Concrete large panel apartment building	Educational building	Office building
Real interest rate [%]	3.0	3.0	4.4	4.0
Escalation rate of energy prices [%/a]	+2.0	+2.0	+2.0	+2.0
Residual value of the renovation measures related to the building envelope [% from the investment]	37.5%	-	-	-
Residual value of the renovation measures related to the heat pump systems [% from the investment]	50%	-	-	-
Residual value of the renovation measures related to the district heating system [% from the investment]	60%	-	-	-
Residual value of the renovation measures related to the ventilation system [% from the investment]	32.5%	-	-	-
Residual value of the renovation measures related to the solar energy systems [% from the investment]	0% (PV) 75% (STC)	-	-	-
Average annual increase in the total value of the work [%/a]	-	-	-	+2.0
Sensitivity analyses with different LCC calculation parameters conducted	Yes	Yes	Yes	Yes

As presented in Table 11, different real interest rates were used in different building types. The real interest rates used in the case studies were selected according to interest rate levels that are typically used in the economic and LCC calculations of the studied building types. Typically, the expected ROI achieved by deep renovations, including energy efficiency improvement measures, is higher among major property owners than among conventional apartment owners. This aspect was realized by selecting the real interest rates used in the economic calculations of the studied building types according to the typical expected ROIs of the corresponding building owners.

3.5.11 Laboratory measurements and on-site field studies

The study reported in Publication 5 included laboratory measurements and on-site field studies in existing buildings. The performance of a novel method developed for energy efficient heating of DHW with a GSHP system was tested and validated by using specifically arranged laboratory measurements. The performance of the developed GSHP system was compared to the performance of a conventionally used GSHP system application.

The developed configuration of a GSHP system utilizing the novel step-based heating method of DHW is presented in Figure 16. The main challenge related to the step-based heating of DHW is the temperature requirement of DHW. To maximize the energy efficiency improvement benefits of the developed method, the heating of DHW should be started from the inlet temperature of DCW, which is typically 5–10°C, depending on both the season of the year and the location of the building. However, 55°C DHW should be available to occupants at the same time, and it is challenging to meet both criteria simultaneously. For this reason, additional heat storage tanks and more advanced control of the heating process are required (see Figure 16).

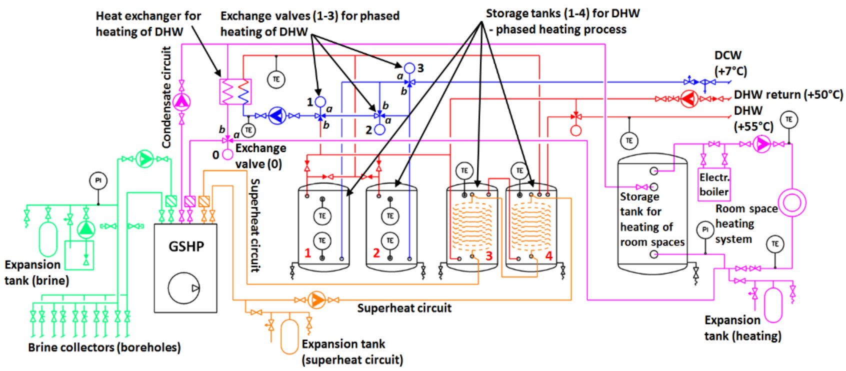

Figure 16. Configuration of a GSHP system equipped with step-based heating of DHW, refrigerant superheat exchanger, and variable condensing operation.

The operation principle of the GSHP system utilizing the step-based heating of DHW is as follows (Figure 16):

- The GSHP system starts to heat tank 1, which is at the temperature of DCW (7°C) in the beginning of the heating process. Exchange valves 1–3 are controlled as follows: valve 1: connection *a* is open and *b* is closed, valve 2: connection *a* is closed and *b* is open, valve 3: connection *a* is closed and *b* is open. The temperature of tank 2 is approximately 50–55°C, the temperature of tank 3 is approximately 55–60°C, and the temperature of tank 4 is approximately 60–67°C. Tanks 2–4 are connected in series and used to deliver DHW to occupants during the heating process of tank 1.
- Tank 1 is gradually heated from the initial temperature of 7°C to the target temperature of 50–55°C using exchange valve 0 (connection *a* is closed and *b* is open) and the heat exchanger. The GSHP system is equipped with a variable condensing operation, and the DHW is heated using the step-based heating process with 7–8 steps (see Figure 1 presented in the appended Publication 5 for a thermodynamic principle of a five-step heating process) because the temperature increase

of DHW is approximately 7°C in each step. When the condensing temperature is high enough, the superheat circuit is started and the superheat energy is discharged to tanks 3 and 4, according to the temperature levels of both the superheat and tanks 3–4. The superheat circuit in tanks 3 and 4 is connected in series using heating coils so that tank 4 is heated first and tank 3 is heated second.

- Tanks 2–4 are discharged during the heating process of tank 1 by delivering DHW to occupants. When the temperature of tank 2 has decreased to the temperature of DCW (7°C), the heating of DHW is switched to tank 2, and the heating process is started from the beginning as with tank 1. The control of exchange valves 1–3 is switched as follows: valve 1: connection *a* is open and *b* is closed, valve 2: connection *a* is open and *b* is closed, valve 3: connection *a* is open and *b* is closed. During the discharge period of tank 2, tank 1 is heated to the target temperature of 50–55°C.
- During the discharge of tank 2, the temperature of the tank is decreased from the initial temperature of 50–55°C to the temperature of DCW (7°C). However, the required temperature of DHW is maintained at all times because the temperatures of tanks 3 and 4 are higher (55–60°C for tank 3 and 60–67°C for tank 4), and tanks 2 (or tank 1 when the heating process is switched), 3, and 4 are connected in series. In addition, the superheat received from heating tank 1 is also used to heat tanks 3 and 4 during the discharge period of tank 2, when the temperature level of the superheat circuit is high enough.

A more detailed description of the operation principle of the developed GSHP system concept is presented in the appended Publication 5. While the operation of the phased heating of DHW requires more control equipment than the conventional GSHP system, the smart control strategy is well implementable using conventional building management software. According to the previous on-site field studies conducted in existing buildings by the authors, the capacity of the superheat is approximately 10–15% of the nominal capacity of the heat pump unit (e.g., 5–7 kW with a 50 kW GSHP unit). Previous field measurements also demonstrate that as high as 90–95°C outlet temperatures are achievable from the superheat circuit when the outlet temperature of the condenser is 57–60°C.

The energy performance of the studied GSHP systems was assessed by conducting measurements related to the energy efficiency of the systems in the DHW heating process. The space heating was excluded from the measurements. In addition, the heating of a DHW circulation system was also excluded from the testing setup. The installation principles of both the conventional and the developed heat pump system concepts are presented in Figure 17. The presented installation configurations were used in the measurements of the experimental analysis of the study reported in Publication 5. In addition, the main components and measurements related to the testing procedure are also presented in Figure 17.

The energy performance of the heat pump systems was assessed by measuring the total heating energy produced and the total electrical energy consumed by the systems and by using the following definition (Equation 9) of the Seasonal Performance Factor (SPF), which is derived from the calculation of Seasonal Coefficient of Performance (SCOP), according to the EN 14825 (2016) standard.

$$SPF_{total} = \frac{Q_{heat,total}}{Q_{elec.,HP+aux.}} \tag{9}$$

where: $Q_{heat,total}$ is the total heating energy produced by the heat pump system during the measurement period, including condensate and superheat, kWh; $Q_{elec.,HP+aux.}$ is the total electrical energy consumed by the heat pump system and auxiliary equipment, such as circulation pumps and control equipment, kWh. However, the auxiliary heating systems, such as electrical heating coils or backup heaters, were not included in the calculation of the SPF, as they were not included in the testing setup (see Figure 17). In the measurements of the study (Publication 5), the SPF presents the overall performance of the studied heat pump applications in heating DHW.

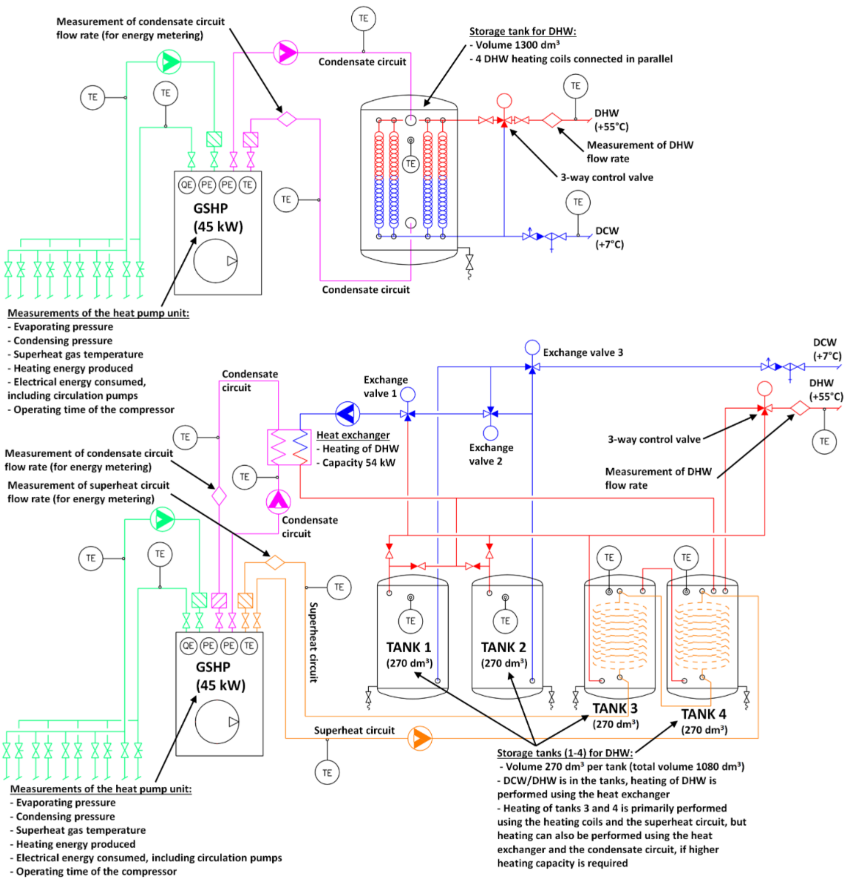

Figure 17. The installation principles used in the energy efficiency measurements of both the conventional heat pump system (above) and the developed heat pump system application utilizing the step-based heating of DHW (below).

The laboratory measurements were conducted at the heat pump measurement and test facilities of Finnish heat pump manufacturer Gebwell Oy. The tested heat pump unit was a Gebwell Taurus 90, which has two scroll-type compressors, electronic expansion valve, and a total heating capacity of 90 kW (Gebwell Oy, 2017). According to the manufacturer, the COP values [measured according to the EN 14511 (2013a, 2013b) standard] of the tested heat pump unit are 4.5 (0/35°C) and 3.2 (0/50°C) (Gebwell Oy, 2017). Only one of the two compressors was used in the test measurements, resulting in a 45 kW nominal heating power output of DHW, because this scenario was determined to better represent the actual average operating conditions of the tested heat pump unit, when monitored operation of installed GSHP systems is discussed.

While the testing procedure and measurement arrangements (Figure 17) do not accurately meet the requirements of part 2 (test conditions) and part 3 (test methods) of the EN 14511 (2013a, 2013b) standard, the results of the measurements give accurate information about the performance of both systems in dynamic operating conditions. In addition, the measurement results of both studied systems are comparable with each other, which was the main objective of the experimental analysis. All the measurement sensors and equipment used in the laboratory measurements of the experimental analysis were calibrated before the performance tests. The recording resolutions of energy meters were 10 kWh for produced condensate and superheat energies and 1 kWh for consumed electrical energy. The measurements included a total of three 16-hour measurement cycles for both studied heat pump applications. The selected measurement cycle was determined to represent an average daily DHW consumption profile of typical Finnish residential apartment buildings.

The daily DHW consumption was selected according to the power output of the tested heat pump unit to represent a typical application, where the heat pump unit would operate in actual case apartment buildings. The tested heat pump unit is normally used in applications where the number of apartments is approximately 50. The average number of occupants was assumed to be 1.5 occupants per apartment, resulting in a total of 75 occupants. The specific DHW consumption of an occupant was assumed to be 56 dm^3/occupant/day, which shows good agreement with the recent DHW consumption-related studies and results in a 4,200 dm^3 total daily consumption of DHW (Ahmed et al., 2015; Geudens, 2015; Swan et al., 2011). The DHW consumption profile used in the laboratory measurements is presented in Table 12. The profile was determined to represent an average DHW consumption profile of a Finnish apartment building. The supply temperature requirement of DHW was selected to be 55°C in the measurements according to the current Finnish building regulations. The inlet temperature of DCW varied according to the time of the day, but an average DCW inlet temperature was approximately 7.5°C in the laboratory measurements.

Table 12. The daily consumption profile of DHW used in the laboratory measurements.

Number of consumption cycle	Time of day	Duration of consumption cycle [s]	Flow rate [dm³/s]	Total flow rate of consumption cycle [dm³]
1	6:00	567	0.3	170
2	6:30	567	0.3	170
3	7:00	300	0.8	240
4	7:30	567	0.3	170
5	8:00	567	0.3	170
6	8:30	567	0.3	170
7	9:00	567	0.3	170
8	10:00	525	0.3	157.5
9	11:00	525	0.3	157.5
10	12:00	525	0.3	157.5
11	13:00	525	0.3	157.5
12	14:00	525	0.3	157.5
13	15:00	525	0.3	157.5
14	16:00	525	0.3	157.5
15	17:00	525	0.3	157.5
16	18:00	960	0.3	288
17	19:00	960	0.3	288
18	20:00	960	0.3	288
19	20:30	300	0.8	240
20	21:00	960	0.3	288
21	22:00	960	0.3	288
Total consumption of DHW [dm³]				***4,200***

The developed GSHP system concept utilizing the step-based heating process of DHW has been installed in over 40 Finnish multi-family apartment buildings since March 2016, when the concept was first introduced. The case buildings include both new and existing apartment buildings built during different decades. The energy efficiency and operation of the installed systems have been monitored in all the buildings. The field studies conducted in Publication 5 were carried out in new residential apartment buildings to better demonstrate the effectiveness of the developed concept.

The studied case apartment buildings consist of four individual apartment buildings located in Espoo, Finland. The total number of apartments included in the buildings is 140, and all of them are occupied. The average size of the apartments is approximately 40 m². The buildings were completed in December 2016, and they have been in use for approximately 6 months. The total heated floor area of the case buildings is 5,660 m², and the total heated volume is 16,600 m³. The site plan, main geometry, and features of the studied case apartment buildings are presented in Figure 18. In addition, the installation of the GSHP system setup is presented in Figure 19.

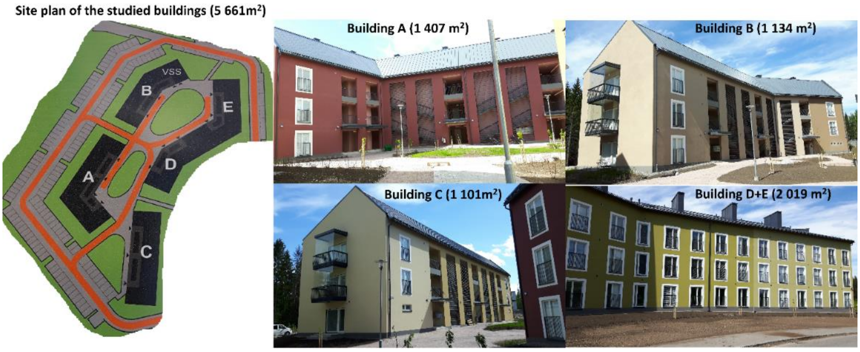

Figure 18. The site plan (left) and main geometry (right) of the studied apartment buildings.

Figure 19. The installation of the GSHP system setup, including two 90 kW GSHP units and two four-tank heat storage combinations for step-based heating of DHW. Phased charging and discharging of tanks 1 and 2 are controlled by three exchange valves (below left).

4. Results

4.1 Cost-optimal renovation concepts

4.1.1 Finnish brick apartment buildings

The results presented in this section include the main results of the brick apartment building study reported in Publication 1. A total of four SBO analyses were carried out in the original analysis of the study. The optimized concepts were the district heating system, the GSHP system, the exhaust air heat pump system, and the air-to-water heat pump system. Only the Pareto-optimal solutions of each optimization analysis are presented in the results. In addition, a few sensitivity analyses were carried out with the GSHP system to determine the effect of different economic calculation parameters and optimization method on the results and the recommendable renovation measures of the SBO analysis.

Figure 20 presents the cost-optimal energy performance improvement solutions in the studied brick apartment building. Figure 21 presents the investment cost of these solutions. The objective functions of the optimization analysis were the NPV of a 25-year LCC [Equation (5)] and the total PE consumption [Equation (2)] of the studied apartment building. The decision variables of the optimization analysis (see Table 4) for different main heating system concepts were the studied energy performance renovation measures. All the Pareto-optimal solutions of the studied main heating systems are also presented in Figures 20 and 21 to determine the cost-effectiveness of the renovation solutions to reach different energy performance criteria. The global optimum solution is the cost-optimal solution of the GSHP system.

A typical reference solution, where no energy performance improvement measures are carried out during the renovation, is also presented in Figures 20 and 21. In the selected reference solution, only the minimum renovation measures that are mandatory to be conducted to prevent decay of the building and to prevent increase in the renovation debt are carried out. The different energy performance classes of the EPC for new apartment buildings, proposed preliminary PE consumption for new nearly zero-energy apartment buildings, and the minimum energy performance target level in renovations are presented as references.

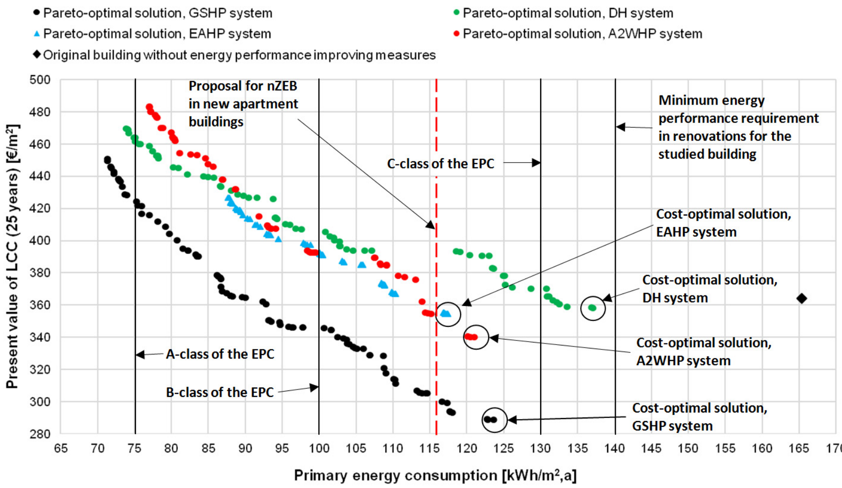

Figure 20. Cost-optimal energy performance improvement solutions for different main heating systems, present value of net LCC presented.

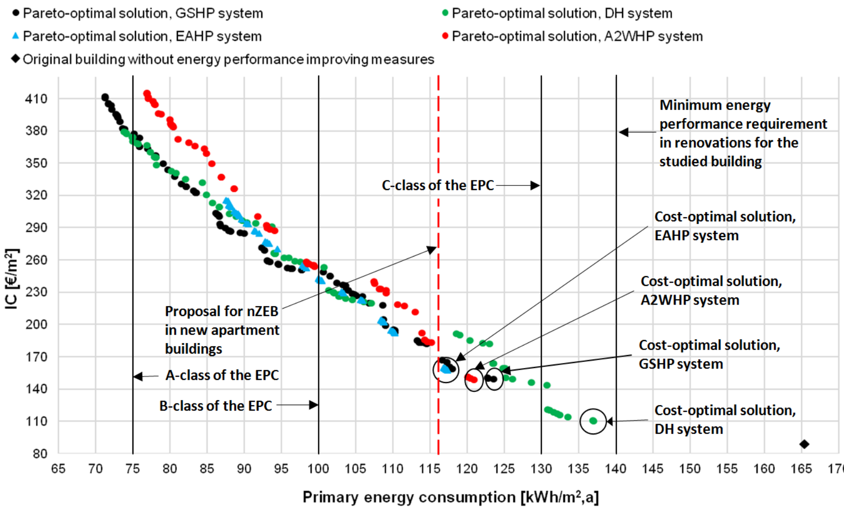

Figure 21. Cost-optimal energy performance improvement solutions for different main heating systems, investment cost presented.

The investment cost of the renovation measures is an important factor in the deep renovations of apartment buildings because the renovations are typically financed by loans (Häkkinen et al., 2012; Kuusk et al., 2014). The maximum amount of the loan is typically limited as is the maximum loan period. This means that the maximum investment cost of the renovation measures has to be carefully monitored, depending on the terms of the loan and on the energy performance target level of the renovation. Figure 21 presents the minimum investment cost to reach different energy performance target levels and helps to choose the loan terms and details according to the energy performance criteria of the renovation measures. The effect of the renovation measures on the energy performance of the studied building can be seen from the difference between the LCC of different solutions (Figure 20)—not from the difference between the investment costs of the solutions (Figure 21).

Table 13 presents the cost-effective energy performance improvement measures for the GSHP system concept, which was the global optimum main heating system concept in the studied apartment building. Table 13 includes the recommended measures of the studied decision variables depending on the energy performance target level. The recommended measures form a combination of energy performance improvement measures to meet different energy performance criteria (objective function 1) with the lowest LCCs (objective function 2) possible. As presented in Table 13, the recommended measures depend heavily on the energy performance target level of the renovation. Typically, the renovation concepts that meet the minimum requirement level or the cost-optimal level are selected because the investment cost of the measures to meet the higher classes of the EPC are relatively high (Häkkinen et al., 2012; Kuusk et al., 2014). The renovated heat distribution system presented in Table 13 means that the original high-temperature (80/50°C) water radiator heating system is renovated to the low-temperature radiator heating system with 45/35°C dimensioning temperatures.

Table 13. Cost-optimal renovation concepts with the GSHP to reach different energy performance criteria.

Energy class of the EPC, PE consumption [kWh/(m^2,a)]	**75 (A-class)**	**90**	**100 (B-class)**	**110**	**120**	**130 (C-class)**	**140 (min. requirement)**
NPV of LCC, 25 years [€/m^2]	428	366	346	318	294	289	289
Investment cost [€/m^2]	383	288	251	199	161	150	150
Power output of the heat pump system [kW]	70	73	70	150	130	94	94
Area of PV panels [m^2]	170	170	160	170	160	170	170
Area of STCs [m^2]	0	0	0	0	0	0	0
Additional thermal insulation of external walls [mm]	+150	0	0	0	0	0	0
Additional thermal insulation of roof [mm]	+350	+250	+150	+350	+400	+250	+250
Windows, U-value [W/m^{2}K]	1.0 (new)	1.0 (new)	2.5 (original)	1.0 (new)	2.5 (original)	2.5 (original)	2.5 (original)
Ventilation system of the building	Renovated	Renovated	Renovated	Original	Original	Original	Original
Heat distribution system of the building	Renovated	Renovated	Renovated	Renovated	Renovated	Renovated	Renovated

Several sensitivity analyses were carried out in the brick apartment building study reported in Publication 1. The main results of the essential sensitivity analyses are presented in Figure 22. The real interest rate of the economic calculations was 7.0% in the SBO analysis presented in Figure 22. The Pareto-optimal solutions of the original SBO analysis with the 3.0% real interest rate are also presented in Figure 22 for comparison. The sensitivity analyses of the study were only carried out for the GSHP system because it was the cost-optimal main heating system concept of the study. A more detailed description of all the sensitivity analyses carried out in the study are presented in the appended Publication 1. More Pareto-optimal solutions at the cost-optimal level can be determined with the higher real interest rate (see Figure 22). The main difference between these solutions is the cost-optimal dimensioning of the PV-panel system (170 m²/3.0%, 85 m²/7.0%) and the additional thermal insulation thickness of the roof (+250 mm/3.0%, +100 mm/7.0%), which have both been decreased from the recommended solutions of the original optimization analysis with the 3.0% real interest rate. In addition, the optimal dimensioning power output of the GSHP system is also slightly lower (94 kW/3.0%, 83 kW/7.0%) when the real interest rate of the LCC calculation is 7.0%.

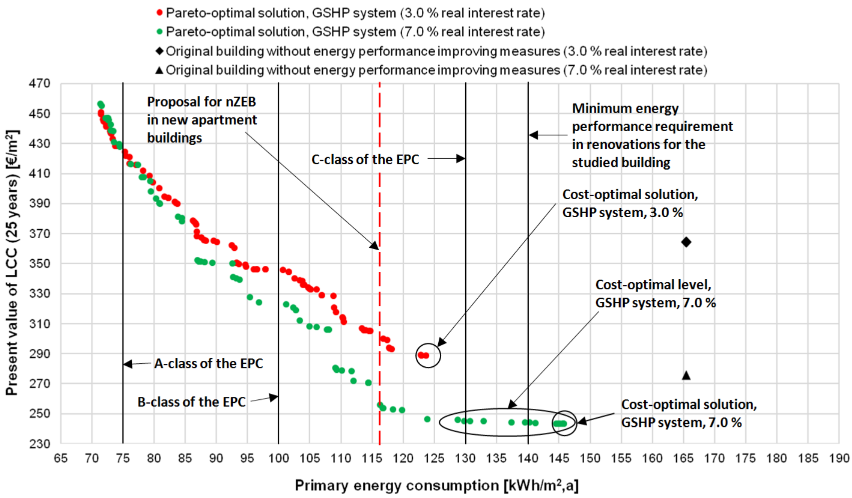

Figure 22. Cost-optimal energy performance improvement solutions for the GSHP system with different real interest rates of the LCC calculations, present value of net LCC presented.

4.1.2 Finnish concrete large panel apartment buildings

The results presented in this section include the main results of the concrete large panel apartment building study reported in Publication 3. Figure 23 and Table 14 present the cost-optimal renovation solutions to meet different energy efficiency criteria in terms of the PE performance of the studied building. Figure 23 presents the cost-optimal solutions using both the current and new proposed PE weighting factors described in Section 3.5.6. Table 14 presents the cost-optimal renovation concepts for the new proposed PE weighting factors. In addition, the nearly zero-energy apartment building PE consumption limits for both weighting factor scenarios are also presented in Figure 23. The PE consumption limits of different energy classes of the EPC are only shown for the analysis using the current PE weighting factors, as the PE consumption requirements of new energy classes of the EPC using the lower PE weighting factors have not been determined yet. The minimized objectives of the SBO analyses were the PE consumption, calculated according to Equation (2), and the NPV of the 30-year

LCC, calculated according to Equation (6). The IRR for the cost-optimal renovation concepts to meet different energy performance criteria is also presented in Table 14. The IRR is calculated for the cost-optimal solutions, which are compared to a selected reference solution, which is also shown in Figure 23. The presented IRRs are calculated without taking the escalation rates of energy prices into account for a simpler comparison of different solutions. If the escalation rates of the energy carrier prices were included, the IRRs of the solutions, including heat pump systems, would be even higher than the presented IRRs, where the escalation rates are not taken into account. The selected reference solution to which other solutions are compared includes the following renovations and retrofitting measures:

- The external walls are renovated according to Figure 3; the thermal transmittance of the new walls is 0.23 W/m^{2}K.
- The roof is renovated according to Figure 4; the thermal transmittance of the new roof is 0.13 W/m^{2}K.
- The original windows are replaced; the new windows have thermal transmittance of 0.8 W/m^{2}K and g-value of 0.49.
- The original external doors are replaced; the thermal transmittance of the new doors is 0.7 W/m^{2}K.
- The original district heating substation is renewed.
- The original ventilation system is not renovated, and no renewable energy production systems are installed.

In addition, the following reference solution (reference solution 2) was studied and compared to the selected reference solution described above to determine if it is cost-effective to maximize the energy performance of the building envelope in a deep renovation, where the initial setting of the renovation is similar as presented in Figures 3 and 4. The motivation to determine this renovation scenario is that the building envelope is renovated extensively because of its poor condition. The energy performance improvement measures related to the envelope can be cost-effectively combined with the mandatory maintenance, repair, and renewal measures, improving the general condition of the building envelope. The additional reference solution 2 includes the following renovation and retrofitting measures:

- The external walls are renovated so that the thermal transmittance of the new walls is 0.11 W/m^{2}K (280 mm insulation).
- The roof is renovated so that the thermal transmittance of the new roof is 0.07 W/m^{2}K (400 mm insulation).
- The original windows are replaced; the new windows have a thermal transmittance of 0.7 W/m^{2}K and g-value of 0.42.
- The original external doors are replaced; the thermal transmittance of the new doors is 0.7 W/m^{2}K.
- The original district heating substation is renewed.
- The original ventilation system is not renovated, and no renewable energy production systems are installed.

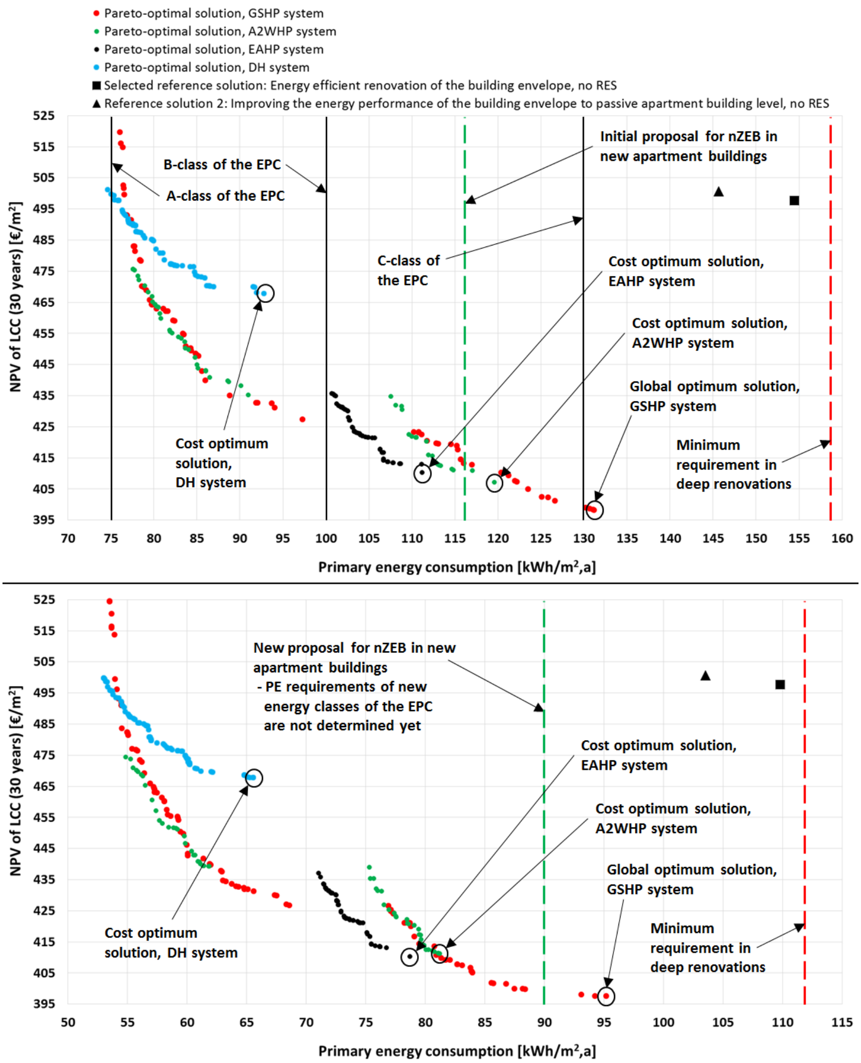

Figure 23. Cost-optimal renovation solutions in terms of PE consumption for different main heating systems using the current PE weighting factors (above) and new proposed weighting factors (below) in the analysis.

Table 14. Cost-optimal renovation concepts in terms of PE consumption to meet different energy efficiency criteria, new proposed PE weighting factors used in the analysis.

PE consumption [kWh/(m²,a)]	**55**	**60**	**70**	**80**	**90 (new proposal for nZEB**	**100**	**112, GOS[A] (min. requirement)**
Recommended main heating system	GSHP	GSHP	GSHP	EAHP	GSHP	GSHP	GSHP
NPV of LCC, 30 years [€/m²]	482	443	427	410	400	398	398
Investment cost [€/m²]	342	323	294	212	227	215	215
IRR [%/a]	1.1	3.5	5.3	36.2	18.1	32.3	32.3
Thermal insulation thickness of external walls [mm]	300	300	180	180	160	180	180
Additional thermal insulation of roof or BR[B] [mm]	+400	0, BR	0, BR	0, BR	0, BR	0, BR	0, BR
Replacement of windows or BR[B], U- and g-values [W/m²K]	Yes, 0.7, g 0.42	Yes, 0.8, g 0.49	Yes, 0.8, g 0.49	Yes, 0.8, g 0.49	Yes, 0.8, g 0.49	Yes, 1.0, g 0.50	Yes, 1.0, g 0.50
Replacement of external doors, U-value [W/m²K]	Yes, 1.0	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2
Area of PV panels [m²]	130	128	128	130	129	129	129
Area of STCs [m²]	0	0	0	0	0	0	0
Power output of the heat pump system [kW]	65	79	40	48	85	79	79
Individual renovation of the ventilation system of apartments	Yes, distributed	No	No	No	No	No	No
Individual renovation of the ventilation system of base floor spaces	Yes, distributed	No	No	No	Yes, distributed	No	No
Renovation of the entire ventilation system of the building to centralized system	No	Yes	Yes	No	No	No	No

[A] Global optimum solution

[B] Basic refurbishment

The cost-optimal renovation concepts were practically the same in both analyses using the lower and higher PE weighting factors as presented in Table 14.

The second analysis included in the concrete large panel apartment building study reported in Publication 3 was to minimize the overall environmental impact of the studied building. Figure 24 and Table 15 present the cost-optimal renovation solutions to meet different CO_2 emissions criteria using both moderate (2.0%/a) and high (4.5%/a) energy price escalation rate scenarios.

The presented CO_2 emissions include the embodied emissions of the construction materials, transportation of the materials to the construction site, and the CO_2 emissions caused by the delivered energy consumption according to the actual use of the studied apartment building. The minimized objectives of the SBO analyses were the total CO_2 emissions, calculated according to Equation (4), and the NPV of the 30-year LCC, calculated according to Equation (6). The IRR shown in Table 15 is calculated by comparing the presented cost-optimal renovation concept to the selected reference solution 1 described in the beginning of this section.

In addition, Figure 25 presents the breakdown of the total LCC and CO_2 emissions of both the global optimum renovation concept, highlighted in Figure 24 and described in Table 15, and the selected reference solution 1 in the moderate energy price escalation rate (2.0%/a) scenario. The global optimum solution presented in Figures 24 and 25 is achieved by selecting the GSHP system with a moderate dimensioning power output (approximately 66 kW; see Table 15) as the main heating system and by producing the auxiliary heating energy with electricity. The reference solution presented in Figures 24 and 25 is considered a baseline renovation concept, where the energy efficiency of the building envelope is improved to a good level using practical renovation measures that also meet the minimum requirements of the current national building regulations.

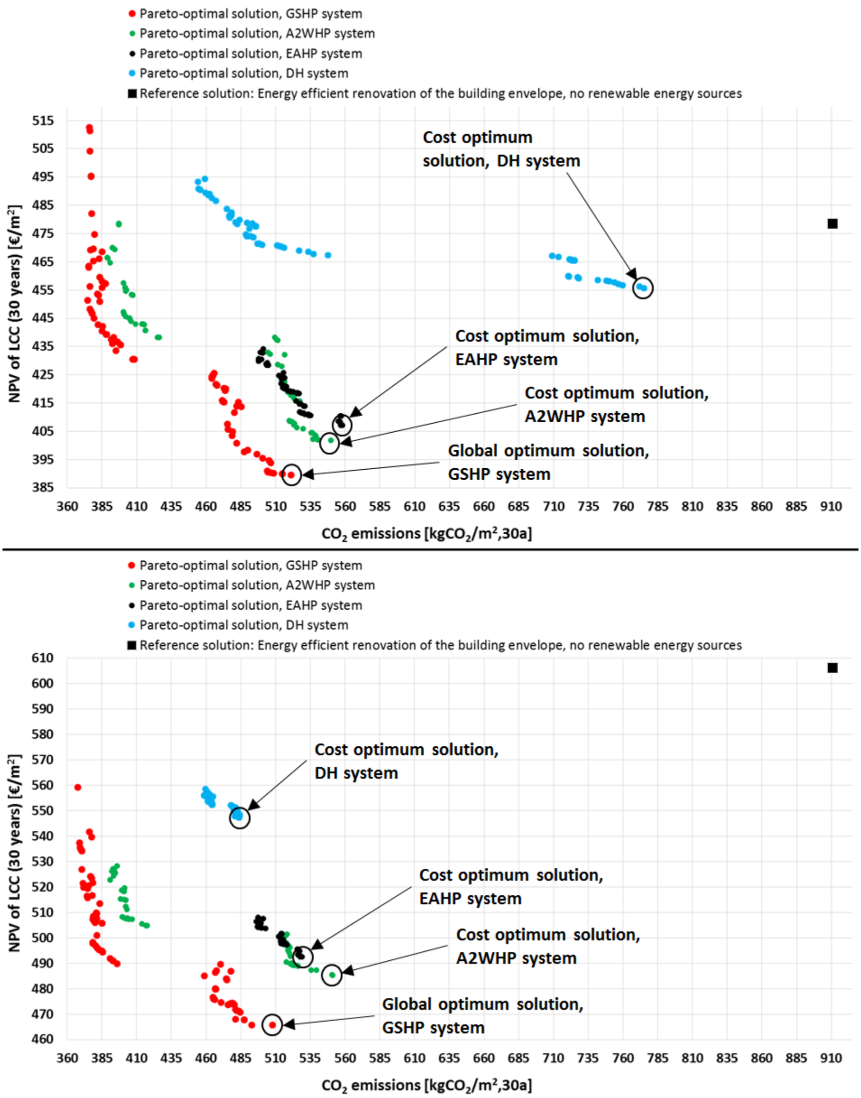

Figure 24. Cost-optimal renovation solutions in terms of CO_2 emissions for different main heating systems using a moderate (2.0%/a) energy price escalation scenario (above) and a high (4.5%/a) energy price escalation scenario (below) in the analysis.

Table 15. Cost-optimal renovation concepts in terms of CO_2 emissions to meet different CO_2 emissions criteria, moderate energy price escalation (2.0%/a) scenario.

Total CO_2 emissions [$kgCO_2/m^2$,30a]	**380**	**390**	**410**	**470**	**500**	**530, GOS[A]**	**560, GOS[A]**
Recommended main heating system	GSHP	GSHP	GSHP	GSHP	GSHP	GSHP	GSHP
NPV of LCC, 30 years [€/m²]	445	439	430	421	397	389	389
Investment cost [€/m²]	316	309	293	264	229	212	212
IRR [%/a]	2.6	3.1	4.0	5.8	14.7	37.4	37.4
Thermal insulation thickness of external walls [mm]	230	230	180	280	280	180	180
Additional thermal insulation of roof or BR[B] [mm]	0, BR	0, BR	0, BR	+250	0, BR	0, BR	0, BR
Replacement of windows or BR[B], U- and g-values [W/m²K]	Yes, 0.8, g 0.49	Yes, 0.8, g 0.49	Yes, 0.8, g 0.49	Yes, 0.8, g 0.49	Yes, 0.8, g 0.49	Yes, 0.8, g 0.49	Yes, 0.8, g 0.49
Replacement of external doors, U-value [W/m²K]	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2	No, 2.2
Area of PV panels [m²]	126	118	128	125	128	117	117
Area of STCs [m²]	0	0	0	0	0	0	0
Power output of the heat pump system [kW]	76	57	39	100	74	66	66
Individual renovation of the ventilation system of apartments	No	No	No	No	No	No	No
Individual renovation of the ventilation system of base floor spaces	No	No	No	Yes, distributed	No	No	No
Renovation of the entire ventilation system of the building to centralized system	Yes	Yes	Yes	No	No	No	No

[A] Global optimum solution

[B] Basic refurbishment

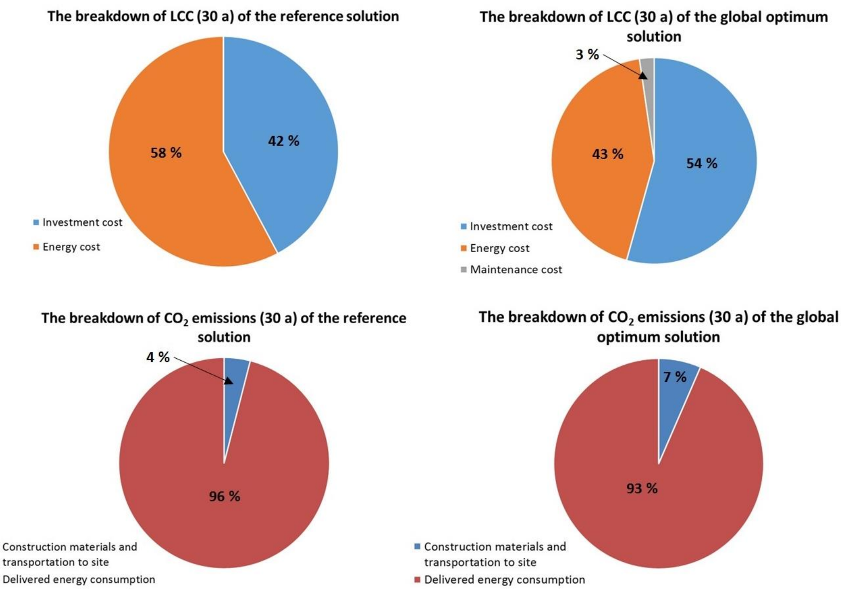

Figure 25. The breakdown of the LCC analysis (2.0%/a escalation rate) of the selected reference (top left) and the global optimum (top right) renovation concepts, and the breakdown of the total CO_2 emissions of the reference (bottom left) and the global optimum (bottom right) renovation concepts.

According to the SBO analyses conducted using both the moderate and high energy price escalation rate scenarios, no significant additional investments are needed when the global optimum renovation concepts of both energy price escalation rate analyses are compared. The main reason for this is that the GSHP system delivers excellent cost-effectiveness in an increasing energy price development scenario. However, the higher energy price escalation rate has a significant impact on the LCC of the reference solution, where the main heating system of the building is district heating. According to Figure 25, the CO_2 emissions caused by the delivered energy consumption are dominant over the transportation and embodied CO_2 emissions of the construction materials. In the higher energy price escalation rate scenario, the breakdown of both the LCC and the CO_2 emissions was similar to the breakdown of the LCC and CO_2 emissions of the moderate energy price escalation rate scenario. The share of the energy cost was approximately 9% higher, and the share of the investment cost approximately 9% lower. The breakdown of the total CO_2 emissions was basically identical in both energy price escalation rate scenarios.

4.1.3 Finnish educational buildings

The results presented in this section include the main results of the educational building study reported in Publication 2. The study included three individual SBO analyses. The SBO analyses were conducted with the district heating and GSHP main heating systems. In addition, several additional sensitivity analyses were carried out to determine the cost-effectiveness of the studied measures in different scenarios. The main results of the additional sensitivity analyses are also presented in this section along with the cost-optimal renovation concepts.

Figure 26 presents the Pareto-optimal solutions of the two most cost-effective individual SBO analyses along with the cost-optimal solutions. The optimized objective functions were the NPV of the 20-year LCC and the total PE consumption of the studied building. The solutions consist of different energy performance improvement measures (decision variables), depending on the energy performance target level of the renovation. The GSHP system concept provides the global optimum renovation concept. The current energy efficiency classes of the EPC for new educational buildings and the preliminary Finnish proposal for nearly zero-energy educational buildings are also presented in Figure 26.

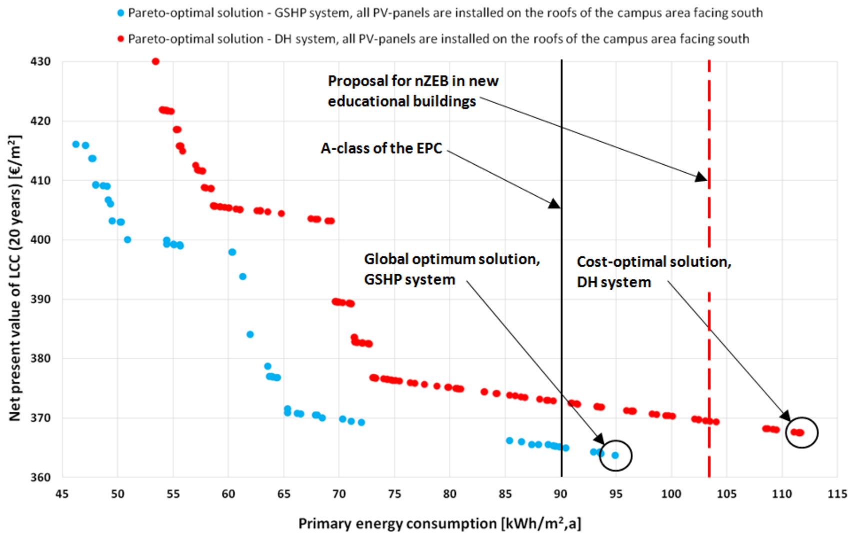

Figure 26. Cost-optimal energy performance renovation solutions, NPV of LCC for studied measures presented.

The preliminary Finnish nZEB PE consumption requirement for new educational buildings was the minimum energy performance target level of the deep renovation. One key aspect of the research was to study the cost-effectiveness of renovation measures to meet higher energy performance criteria than the preliminary proposed nZEB level.

The shape of the Pareto front in Figure 26 describes the selection of renovation measures applied in the SBO analysis. The solutions include more cost-effective measures near the cost-optimal solutions with both the district heating and GSHP systems. However, when the energy performance is improved further, more expensive measures must be applied to reach higher energy performance criteria. This can be seen in Figure 26, when the PE consumption of the studied building is reduced below 75 kWh/(m²,a) with the district heating system and below 65 kWh/(m²,a) with the GSHP system. When the PE consumption is reduced below the aforementioned figures, both the LCC and the total investment cost increase significantly, as heavier and fewer cost-effective measures are applied in the SBO analysis to reduce the PE consumption further. When the PE consumption of the building is reduced below approximately 60 kWh/(m²,a), even more significant investments have to be conducted, and the improvements in energy performance are low compared to the increase in both the LCC and investment cost.

Table 16 presents the recommended renovation measures according to the results of the SBO analysis for the GSHP system, which was the global optimum main heating system concept, to reach different energy performance target levels with the lowest 20-year LCC possible. In addition, the required minimum investment cost to reach the specific energy performance target level is also presented in Table 16. The GSHP system can be used for free cooling of the studied educational building by utilizing the borehole heat collector loops of the system, and this feature has also been taken into account in the analysis. The primary cooling method of room spaces of the studied building is the supply airflow rate of the ventilation system where the supply air is cooled in the AHUs of the building. According to the simulations, no room-specific cooling units are necessarily required to maintain the FCIE 2008 S2 class indoor climate conditions (FiSIAQ, 2008). To improve the indoor environment conditions and the IAQ of educational room spaces, the original ventilation system of the building is completely renovated because of its poor effectiveness and condition, so the investment cost of the ventilation system's renovation is a fixed and well justified cost included in every solution.

Table 16. Cost-optimal renovation concepts with the GSHP system to reach different energy performance criteria.

PE consumption [kWh/(m^2,a)]	**50**	**60**	**70**	**75**	**90 (A-class)**	**95**	**104 (preliminary proposal for nZEB)**
NPV of LCC, 20 years [€/m^2]	403	398	370	369	365	364	364
Investment cost [€/m^2]	324	312	266	263	246	241	241
Power output of the heat pump system [kW]	41	41	39	40	42	40	40
Area of PV panels [m^2]	3,200	2,720	2,950	2,670	1,600	840	840
Area of STCs [m^2]	0	0	0	0	0	0	0
Additional thermal insulation of external walls [mm]	+225	+75	0	0	0	0	0
Additional thermal insulation of roof [mm]	+200	+200	+200	+200	+200	+200	+200
Replacement of windows, U-value of windows [W/m^{2}K]	Yes, 1.0	Yes, 1.0	Yes, 1.0	Yes, 1.0	Yes, 1.0	Yes, 1.0	Yes, 1.0
Original ventilation system of the building	Renovated	Renovated	Renovated	Renovated	Renovated	Renovated	Renovated

The progress and logic of the SBO analysis can be seen in the selected renovation measures presented in Table 16. Measures with high cost-efficiency are selected at and near the cost-optimum level. As the energy performance is improved, measures with lower cost-efficiency are selected in addition to the measures with high cost-efficiency to reach higher energy performance criteria. The renovation measures are selected in the optimal order so that each energy performance target level is achieved as cost-effectively as possible.

According to Table 16, the proposed preliminary national nZEB target level can be achieved cost-effectively by renovating the original ventilation system of the building and by investing in a solar-based electricity production system with a relatively large area of PV panels. Additional thermal insulation of the roof (+200 mm) and new windows with U-value of 1.0 W/(m^{2}K) are cost-efficient and recommendable renovation measures at all energy performance target levels. According to the analysis, it is recommended to invest in the solar-based electricity production system with PV panels when lower PE consumption is pursued. According to the results, additional thermal insulation of external walls is the last energy performance improvement measure, when other more cost-effective measures have already been selected.

The utilization of STCs with the district heating system was also studied in one SBO analysis. However, according to the results of the analysis, the solar electricity system with PV panels proved to be a more cost-effective and recommendable measure than the STCs. In addition, due to the limited installation space on the roofs of the campus area, the recommended alternative is to use all the possible free roof area for the installation of PV panels.

Several sensitivity analyses were carried out in the study. Figure 27 presents the effect of different energy price escalation rate scenarios on the results of the SBO analysis. The higher the escalation rate of different energy carriers, the more significant the impact on the results of the LCC calculation.

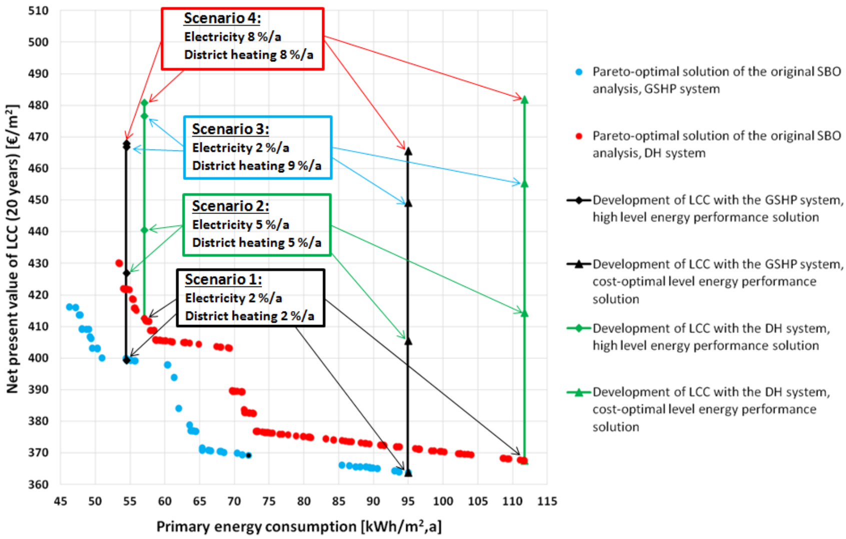

Figure 27. The effect of different energy price escalation rate scenarios on the results of the LCC calculation at different energy performance target levels.

4.1.4 Finnish office buildings

The results presented in this section include the main results of the office building study reported in Publication 4. The results of the study consist of the five individual SBMOO analyses presented in Table 17. Table 17 also presents the studied building type and the optimized objectives of each analysis. The extended LCC shown in Table 17 is an LCC analysis, where the productivity loss of workers caused by unfavorable indoor thermal comfort conditions was calculated and integrated into the conventional LCC analysis related to the renovation and retrofitting measures. The recommended and cost-optimal renovation concepts to reach different environmental impact criteria are presented for both the owner- and tenant-occupied office buildings, as the economic earning logic perspectives of the two office building types are different. In the owner-occupied office buildings, the building owner typically wants to achieve excellent indoor climate conditions to maximize the performance of employees, whereas in the tenant-occupied office buildings, the building owner typically wants to achieve acceptable indoor climate conditions cost-effectively but not necessarily to maximize the conditions.

Table 17. Studied SBMOO analyses.

Optimization analysis	Type of building	Minimized objectives and type of LCC calculation
1: CO_2 emissions of DE consumption, DH concept	Owner occupied	CO_2 emissions of DE consumption, NPV of 15-year LCC (extended), investment cost
2: CO_2 emissions of DE consumption, GSHP concept	Owner occupied	CO_2 emissions of DE consumption, NPV of 15-year LCC (extended), investment cost
3: CO_2 emissions of DE consumption, DH concept	Tenant occupied	CO_2 emissions of DE consumption, NPV of 15-year LCC (conventional)
4: CO_2 emissions of DE consumption, GSHP concept	Tenant occupied	CO_2 emissions of DE consumption, NPV of 15-year LCC (conventional)
5: Thermal comfort conditions, conventional airflow rate potential	-	Total PDH, investment cost, CO_2 emissions of DE consumption (no LCC calculation)

DE = delivered energy

PDH = occupant hours of dissatisfaction

Cases 1–2 in Table 17 were conducted to determine the cost-optimal renovation solutions for building owner-users. In this owner-occupied scenario, the building owner typically gets all the benefits from the improved indoor climate conditions and reduced productivity loss. Cases 3–4 in Table 17 were conducted to determine the cost-optimal solutions for building owners, who are not responsible for the salaries of the building users but who are responsible for the operating costs of the building. In this tenant-occupied scenario, the building owner typically does not get major benefits from the improved indoor climate conditions except by increasing the rent of the building. However, typically it is difficult to justify a sudden substantial increase in rent to tenants, even if major renovation measures are conducted to improve the indoor climate conditions.

Case 5 in Table 17 was conducted to determine the cost-optimal solutions to maximize the thermal comfort conditions of occupants. All essential factors affecting the productivity were considered, and the total occupant hours of dissatisfaction (PDH) were used to assess the thermal comfort conditions. However, to give a more realistic view on the measures that are possible to be practically conducted, appropriate constraints, such as maximum ventilation airflow rates that can be used in the studied building, were used in case 5.

Figures 28 and 29 present the cost-optimal solutions for owner-occupied office buildings. Three different but equally valuable objectives were minimized in the analyses (see Figures 28 and 29) to determine the cost-optimal solutions for building owners to make decisions. These aspects include initial investment costs, thermal comfort conditions, LCCs, low operating costs, and high environmental impact reduction potential. Figure 29 highlights the concept of Pareto-optimality and the Pareto-optimal solutions of a three-dimensional optimization problem, including three individual optimized objectives, which are conflicting with each other. The optimized objectives in the owner-occupied office building analysis were:

- The NPV of LCC over the 15-year discount period (minimized objective 1)
- The CO_2 emissions of the delivered energy consumption (minimized objective 2)

- The overall investment cost of the renovation measures (minimized objective 3).

The main objective of the analysis was to determine the cost-optimal renovation solutions from the building owner's or employer's point of view, where the objective is typically to provide excellent indoor climate conditions but still low operating costs, with measures as cost-efficient as possible to minimize the productivity loss and to maximize the energy performance.

Only the Pareto-optimal solutions of each optimization analysis are shown in Figures 28 and 29, as over 2,500 individual energy simulations were conducted to determine the Pareto-optimal solutions. To further clarify the analysis, certain main conclusions and logic of the solutions to meet the three optimized objectives are highlighted to make the interpretation of the results easier. The selected reference solution presented in Figures 28 and 29 consists only of the mandatory minimum renovation measures that must be conducted to prevent decay and to decrease the renovation debt of the building. The reference solution consists of:

- Basic refurbishment of the external walls with no additional thermal insulation installed; the renewal of the measure after 8 years is also included
- Basic refurbishment of the roof with no additional thermal insulation installed
- Basic refurbishment of the windows; no blinds installed
- Renewal of the original district heating substation; no GSHP system installed
- Renovation of the original lighting system to correspond to the modern lighting requirements; a fluorescent-based lighting system with a basic switch-based control system is installed; no automatic control system is installed; renewal of the fluorescent tubes after 8 years of operation
- No renewable energy production systems are installed.

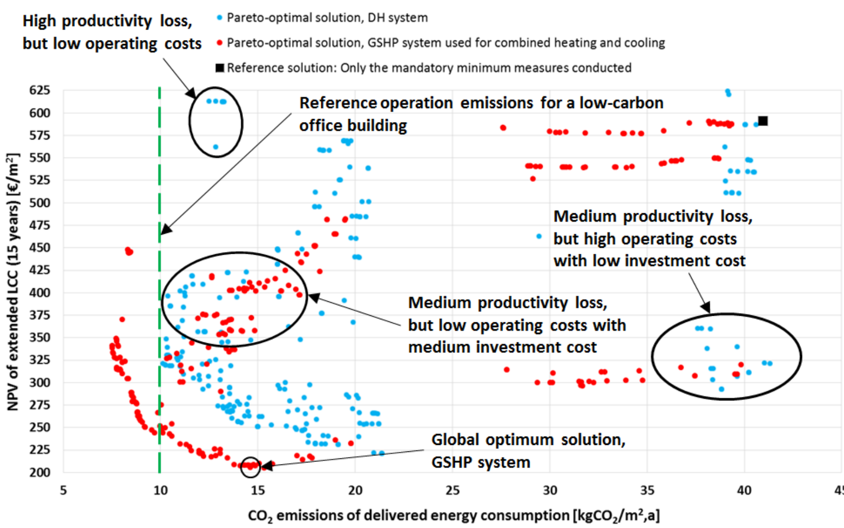

Figure 28. Cost-optimal renovation solutions in owner-occupied office buildings, minimized objectives NPV of LCC and CO_2 emissions presented.

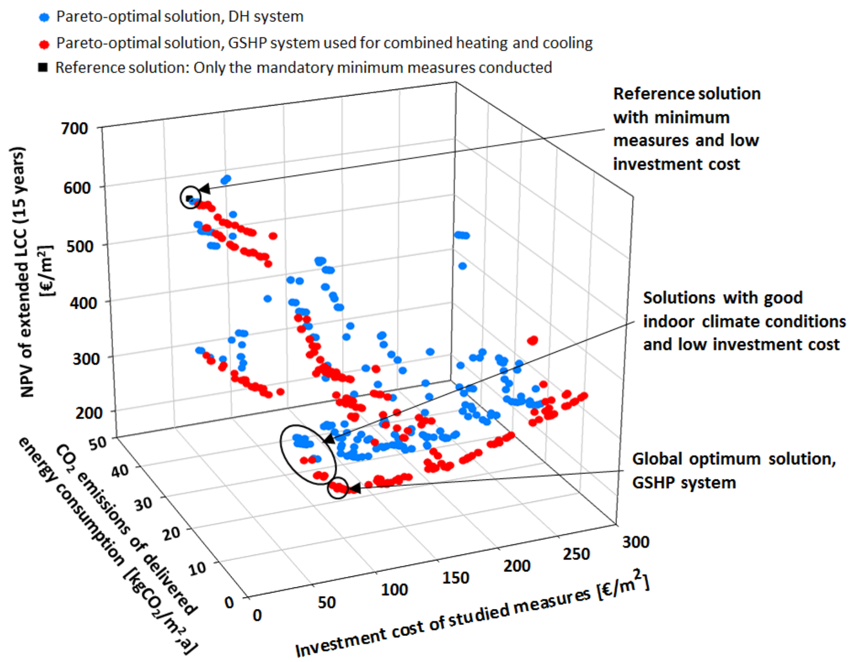

Figure 29. Cost-optimal renovation solutions in owner-occupied office buildings, all minimized objectives (NPV of LCC, CO_2 emissions, and investment cost) presented.

Table 18 presents the cost-optimal renovation concepts for owner-occupied office buildings to reach different environmental performance criteria. The cost-optimal renovation concepts are selected from the Pareto-optimal solutions presented in Figures 28 and 29.

The global optimum solution is achieved by investing in a GSHP system with a relatively small dimensioning power output and by investing in measures improving the thermal comfort conditions of the building. The original district heating system has remained as the main heating system of the building, but the GSHP system with optimum power output is installed to cover the cooling demand of the building and to cover a significant amount of the annual heating demand at the same time. To compare the selected reference and the global optimum overall solutions and to highlight the extended LCC factors (the refurbishment of the building and the productivity of workers) of the solutions, Figure 30 presents the breakdown of the LCC of the reference solution, where only the minimum measures are conducted, and the breakdown of the LCC of the recommended global optimum overall solution.

Table 18. Cost-optimal renovation concepts in owner-occupied office buildings.

CO_2 emissions [kgCO_2/m^2,a]	7.5	9	10	12.5	15, GOS[B]
NPV of extended LCC, 15 years [€/m^2]	341	305	244	218	205
Investment cost [€/m^2]	291	250	175	140	108
IRR of the renovation concept [%/a]	13.8	17.6	29.6	41.7	64.7
Additional thermal insulation of external walls or BR[A] [mm]	+300	+100	0, BR	0, BR	0, BR
Additional thermal insulation of roof or BR[A] [mm]	+400	0, BR	0, BR	0, BR	0, BR
Replacement of windows or BR[A], U- and g-values [W/m^{2}K]	Yes, 0.60, g 0.31	Yes, 0.60, g 0.31	Yes, 1.0, g 0.50	Yes, 1.0, g 0.50	No, BR
Installation of blinds between the inner panes of windows	Yes	Yes	Yes	Yes	Yes
Area of PV panels [m^2]	484	486	401	500	13
Area of STCs [m^2]	0	0	0	0	0
Installation and power output of the GSHP system [kW]	Yes, 430	Yes, 339	Yes, 131	Yes, 181	Yes, 161
Renovation of the AHUs of the building	Yes	Yes	Yes	Yes	Yes
Renovation of the ventilation system to DCV[C]-based system	Yes	Yes	Yes	No	No
Type of renovated lighting system	LED	LED	LED	Fluorescent	Fluorescent
Installation of occupancy + constant light control system	Yes	Yes	Yes	Yes	Yes
Installation of centralized water cooling system	No	No	No	No	No
Installation of centralized room cooling system with ceiling cooling panels	No	No	No	No	No
The total annual amount of lost work due to productivity loss from 1,472,000 working hours of all occupants [h/a]	1	1	173	67	214

[A] Basic refurbishment

[B] Global optimum solution

[C] Demand-controlled ventilation

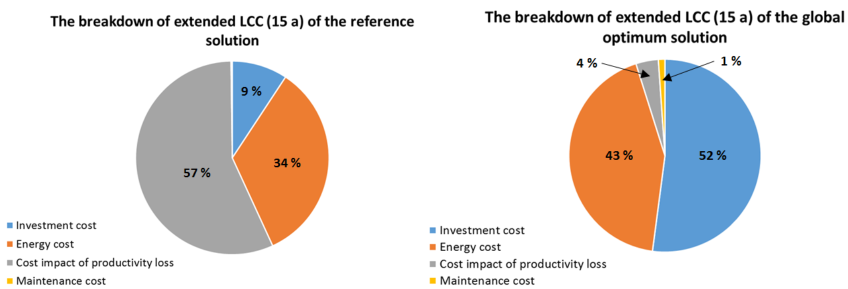

Figure 30. The breakdown of the extended LCC analysis for the selected reference solution (left, €591/m^2) and for the global optimum solution (right, €205/m^2).

As it is demonstrated in Figure 30, the cost impact of productivity loss is the most significant factor in the extended LCC analysis of owner-occupied office buildings, where the productivity loss is combined with the traditional LCC analysis. The traditional LCC analysis is typically limited to investigate the economic viability of different energy efficiency improvement measures. According to the selected productivity loss assessment methodology, the productivity loss of occupants is not occurring when the operative temperatures of office spaces are maintained between 20°C and 25°C. However, it is essential to notice that if the upper temperature limit of the model was reduced from 25°C to, for example, 24°C, the overall content of the global optimum renovation concept would likely be slightly different.

Figure 31 presents the cost-optimal solutions for tenant-occupied office buildings. The minimized objective functions in the analysis were the NPV of the 15-year LCC and the CO_2 emissions of the delivered energy consumption of the case building. The extended LCC analysis method, where the cost impact of productivity loss is included in the overall LCC analysis, was not included in the tenant-occupied building type analyses. The NPV of the 15-year LCC was calculated according to Equation (7) but excluding the value of the work factor used in the equation. The main objective of the analysis was to determine the cost-optimal renovation solutions from the lessor's point of view, where the target is typically to provide sufficient and acceptable indoor thermal comfort conditions but not necessarily to guarantee high performance of occupants.

As in the owner-occupied building analysis, only the Pareto-optimal solutions of the optimization analyses are presented in Figure 31. Over 1,500 individual energy simulations were conducted to determine the Pareto-optimal solutions. The selected reference solution presented in Figure 31 includes the same renovation and retrofitting measures as the reference solution described with the owner-occupied building study.

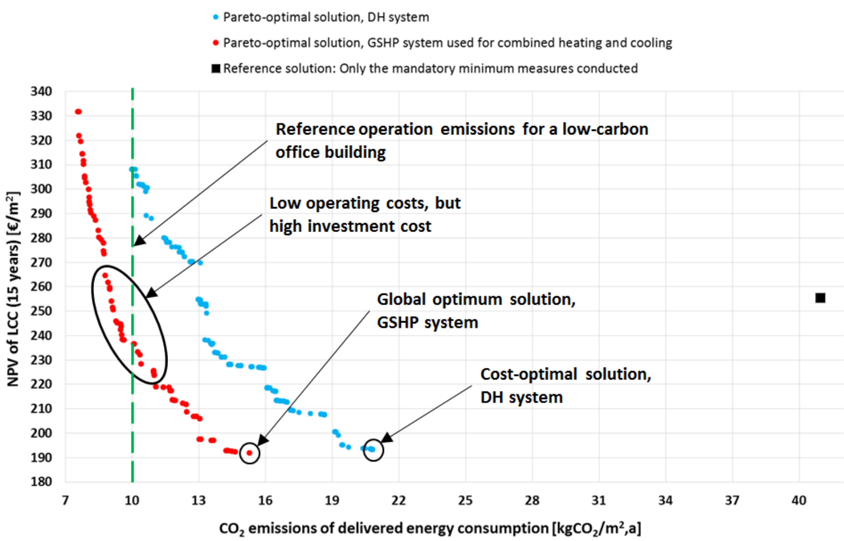

Figure 31. Cost-optimal renovation solutions in tenant-occupied office buildings.

Table 19 presents the cost-optimal renovation concepts for tenant-occupied office buildings to reach different environmental performance criteria. The cost-optimal renovation concepts are selected from the Pareto-optimal solutions presented in Figure 31.

Table 19. Cost-optimal renovation concepts in tenant-occupied office buildings.

CO_2 emissions [$kgCO_2/m^2$,a]	7.5	9	10	12.5	16, GOS[B]
NPV of LCC, 15 years [€/m²]	332	289	232	212	192
Investment cost [€/m²]	281	236	167	135	103
IRR of the renovation concept [%/a]	-2.8	-0.5	4.9	8.9	16.4
Additional thermal insulation of external walls or BR[A] [mm]	+300	+250	0, BR	0, BR	0, BR
Additional thermal insulation of roof or BR[A] [mm]	+300	0, BR	0, BR	0, BR	0, BR
Replacement of windows or BR[A], U- and g-values [W/m²K]	Yes, 0.69, g 0.30	Yes, 0.69, g 0.30	No, BR	No, BR	No, BR
Installation of blinds between the inner panes of windows	Yes	No	Yes	No	No
Area of PV panels [m²]	500	448	483	465	66
Area of STCs [m²]	0	0	0	0	0
Installation and power output of the GSHP system [kW]	Yes, 370	Yes, 151	Yes, 291	Yes, 357	Yes, 146
Renovation of the AHUs of the building	Yes	Yes	Yes	Yes	Yes
Renovation of the ventilation system to DCV[C]-based system	Yes	Yes	Yes	No	No
Type of renovated lighting system	LED	LED	LED	LED	Fluores-cent
Installation of occupancy + constant light control system	Yes	Yes	Yes	Yes	Yes
Installation of centralized water cooling system	No	No	No	No	No
Installation of centralized room cooling system with ceiling cooling panels	No	No	No	No	No

[A] Basic refurbishment

[B] Global optimum solution

[C] Demand-controlled ventilation

To compare the selected reference and global optimum overall solutions and to highlight the different LCC factors of the solutions, Figure 32 presents the breakdown of the LCC of the reference solution, where only the minimum measures are conducted, and the breakdown of the LCC of the recommended global optimum overall solution. By comparing Figure 32 to Figure 30, the breakdown of the traditional LCC analysis is significantly different than the breakdown of the extended LCC analysis, where the cost impact of productivity loss is also included in the analysis. By comparing the cost-optimal renovation concepts (Table 19) of the tenant-occupied office building study to the cost-optimal renovation concepts (Table 18) of the owner-occupied building study, the ROIs of the renovation concepts are significantly lower in the traditional LCC analysis, where the cost impact of productivity loss is excluded from the analysis.

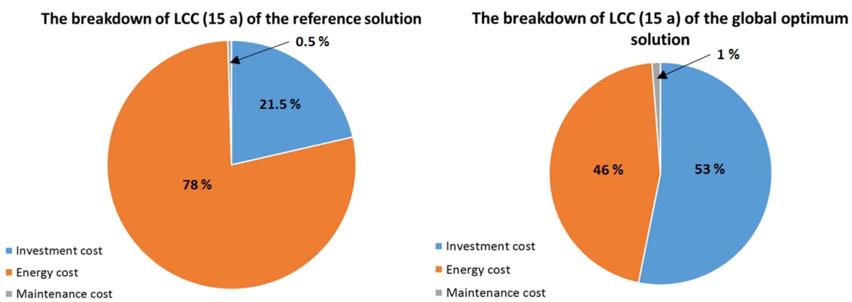

Figure 32. The breakdown of the LCC analysis for the selected reference solution (left, €256/m²) and the global optimum solution (right, €192/m²).

The main results of the additional SBO analysis conducted to maximize the productivity of the building users are presented in Figure 33. Table 20 presents the optimal renovation concepts and HVAC system set points to maximize the indoor thermal conditions. Figure 33 also highlights the concept of Pareto-optimality in a multi-dimensional optimization problem. The optimal room temperature set points for heating and cooling to maximize the indoor thermal conditions of occupants are presented in Table 20. The optimized objectives of the additional SBO analysis were:

- The total occupant hours of dissatisfaction (minimized objective 1)
- The overall investment cost of the renovation measures (minimized objective 2)
- The CO_2 emissions of the delivered energy consumption (minimized objective 3).

According to the definition of Pareto-optimality, all the solutions presented in Figure 33 are non-dominated solutions and mathematically equally valuable. They all meet the optimized three objectives equally well, depending on the objectives and perspectives (weighting of the optimized objectives) of the analysis. To clarify the analysis, certain main conclusions and logic of the solutions to meet the three optimized objectives are highlighted in Figure 33 to make the interpretation of the results easier. The reference solution presented in Figure 33 includes the same renovation and retrofitting measures as the reference solution described with the owner-occupied building study in the beginning of this section.

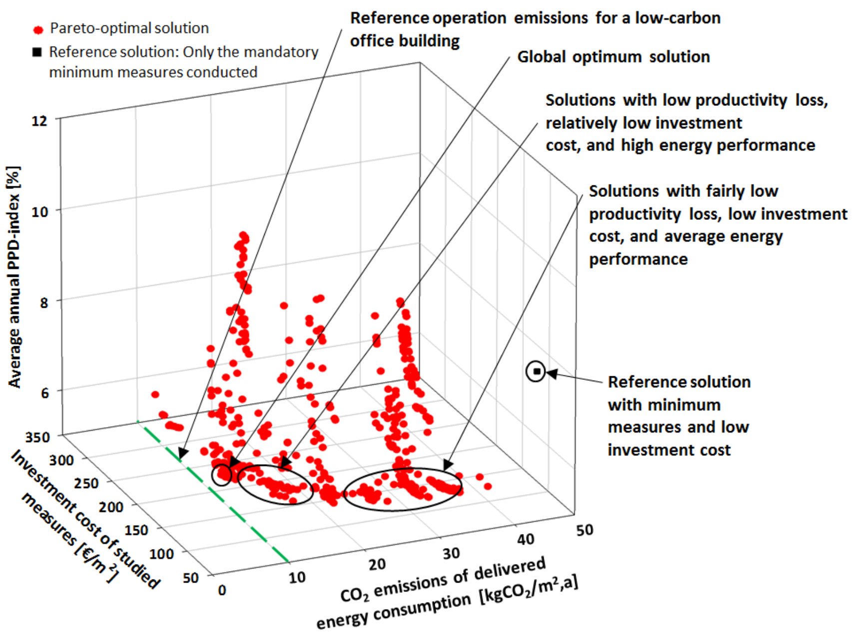

Figure 33. Optimal renovation solutions and HVAC system set points to maximize the indoor thermal conditions and minimize both the investment cost and the CO_2 emissions of energy consumption in office buildings located in cold climate conditions.

Table 20. Optimal renovation measures and HVAC system set points to maximize the indoor thermal conditions and minimize both the investment cost and the CO_2 emissions of energy consumption in office buildings with typical [2–3 dm^3/(s,m^2)] airflow rates.

Average annual PPD index of all occupants [%]	**7.5**	**6**	**5.7**	**5.4**	**5.1, GOS[A]**
Total PDH [h/occupant,a]	36.2	28.6	28.2	26.6	25.4
The total annual amount of lost work due to productivity loss of all occupants [h/a]	9,600	2,400	1,800	560	0
Investment cost [€/m^2]	57	61	69	94	234
Renovation of the ventilation system to DCV[B]-based system	No	No	No	Yes	Yes
Outdoor airflow rate of the ventilation system [dm^3/s,m^2]	2.0	2.0	2.0	3.0	3.0
Indoor air temperature set point for heating [°C]	22.5	22.5	22.5	22.5	22.5
Indoor air temperature set point for cooling [°C]	23.3	23.4	23.4	23.4	23.5
Installation of centralized water cooling system	No	No	No	No	Yes
Installation of centralized room cooling system with ceiling cooling panels	No	No	No	No	No
Additional thermal insulation of external walls or BR[C] [mm]	0, BR	0, BR	0, BR	0, BR	+250
Additional thermal insulation of roof or BR[C] [mm]	0, BR	0, BR	0, BR	0, BR	0, BR
Replacement of windows or BR[C], U- and g-values of windows [W/m^{2}K]	No, BR	No, BR	No, BR	No, BR	Yes, 0.69, g 0.30
Installation of blinds between the inner panes of windows	No	Yes	Yes	Yes	Yes
Renovation of the AHUs of the building	No	No	No	No	Yes
Type of renovated lighting system	Fluores-cent	Fluores-cent	LED	Fluores-cent	LED
Installation of occupancy + constant light control system	No	No	No	No	No

[A] Global optimum solution

[B] Demand-controlled ventilation

[C] Basic refurbishment

Several additional sensitivity analyses were carried out in the study with different LCC calculation parameters and energy price escalation rate scenarios. According to the results of the additional sensitivity analyses, the cost impact of productivity loss dominates in the extended LCC calculation analysis over the energy cost, and it is economically viable to invest in cost-effective renovation measures that also improve the indoor thermal conditions of the building, but unnecessary over-investments should be avoided.

Additional SBO analyses were conducted in the study, where the PE performance of the studied office building was maximized for both the owner- (extended LCC analysis) and tenant- (traditional LCC analysis) occupied office buildings. The cost-optimal renovation concepts to maximize the PE performance were similar with the results presented in this section. In addition to the global optimum renovation concept presented in Table 18, the global optimum PE performance renovation concept included new windows with high energy performance (U-value 0.69 W/m^{2}K, g-value 0.30), an LED-based lighting system, a GSHP system with higher dimensioning power output (200 kW), and an approximately 210 m^2 area of PV panels.

The IRR of the global optimum PE performance renovation concept was as high as 61% with a total initial investment cost of €151/m^2. For comparison, the total initial investment cost of the global optimum renovation concept presented in Table 18 was €108/m^2. In addition, the proposed preliminary nearly zero-energy office building requirements could be achieved cost-effectively in deep renovations of office buildings. The cost-optimal nZEB renovation concept delivered up to 38% ROI in owner-occupied office buildings and up to 10% ROI with a total initial investment cost of €136/m² in tenant-occupied office buildings.

4.2 Performance analysis of a novel GSHP application

4.2.1 Experimental analysis

The performance measurements of the experimental analysis included a total of three 16-hour measurement cycles for both studied heat pump applications. The average temperatures of both the DHW and the DHW heat storage tanks for the conventional and new developed GSHP systems are presented in Figure 34. The temperatures presented in Figure 34 represent the measured average temperatures of one 16-hour measurement cycle. The average inlet temperature of DCW was approximately 7.5°C in all the measurement cycles. The average inlet temperature of brine was approximately 1.6°C for the novel GSHP system and approximately 2.5°C for the conventional heat pump system. The difference in the average brine inlet temperatures was occurring because of the measurement arrangements.

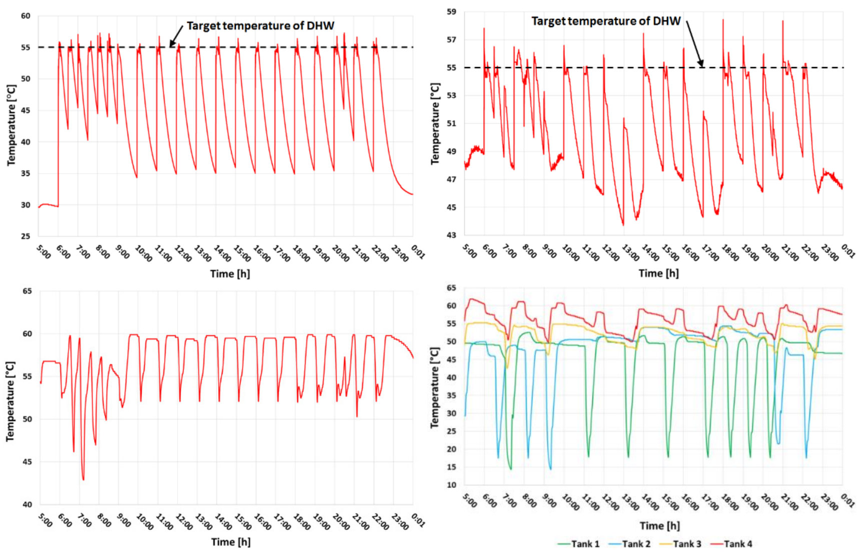

Figure 34. Average outlet temperatures of DHW with the conventional (above left) and new developed (above right) GSHP systems. Average temperatures of the DHW heat storage tanks with the conventional (below left) and new developed (below right) GSHP systems.

While the targeted daily DHW consumption was 4,200 dm³ for both studied applications, the measured average DHW consumptions of the measurement cycles were:

- Conventional GSHP system application: 4,394 dm³/day
- New developed GSHP system application: 4,288 dm³/day.

The average cumulative heating energy produced and the average cumulative electrical energy consumed by the studied heat pump systems during a 16-hour measurement cycle are presented in Figure 35. As presented in Figure 35, the conventional heat pump system produced more energy than the new system because approximately 2.5% more DHW was heated by the system. The main reason for the higher DHW consumption was the lower pressure loss of the DHW system in the conventional heat pump system configuration. When DHW was consumed according to the time periods presented in Table 12 (e.g., 525 or 960 seconds), higher water volume was flowing through the conventional heat pump configuration due to the lower pressure loss of the DHW connection principle (see Figure 17). In addition, more energy was produced because of higher accumulator heat losses. Furthermore, the temperature of DHW was 1–4.5°C lower than the 55°C temperature requirement with the developed heat pump system during several consumption cycles of the average 16-hour measurement cycle (see Figure 34). An energy efficient control strategy (charging and discharging cycles of tanks 1 and 2) of the developed GSHP system was used in the measurements of the experimental analysis, which resulted in the situation that the target temperature of DHW was not achieved in all 21 consumption cycles. The main results related to the energy efficiency of the studied heat pump systems are presented in Table 21.

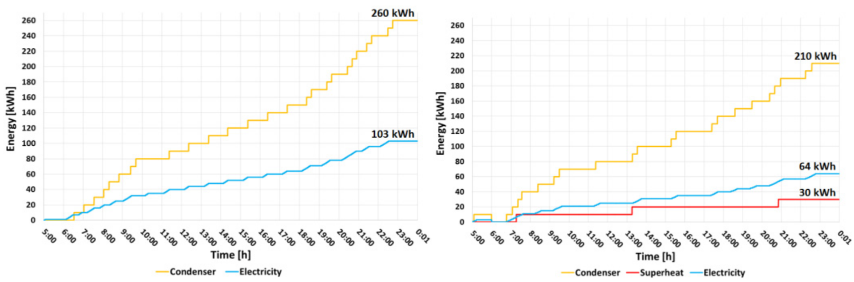

Figure 35. The average heating energies produced and electrical energies consumed by the conventional (left) and new developed (right) heat pump systems in laboratory measurements.

Table 21. Measured energy flows and calculated SPFs of the studied heat pump systems.

Heat pump system	$Q_{condenser}$ [kWh]	$Q_{superheat}$ [kWh]	$Q_{heat,total}$ [kWh]	$Q_{elec.,HP+aux.}$ [kWh]	SPF
Conventional	260	-	260	103	2.52
Novel step-based	210	30	240	64	3.75

The new developed system provides significant improvements in the dynamic operation of the heat pump unit. The average number of start-ups of the compressor decreased by approximately 40% with the new system compared to the conventional system. In addition, the measured average condensing pressures were approximately 28% lower with the new system. These factors reduce the stress and improve the longevity of the compressor. The average operating times of the compressors and the average evaporating and condensing pressures for both studied heat pump applications are presented in Figure 36.

According to the measurement results of the test cycles, the repeatability of the results was good with both studied heat pump systems. The average difference in the measured parameters was 1–3% between the three measurement cycles. Furthermore, the temperature trends, operating times, and performance data of the measurement cycles followed the trends, data, and features presented in Figures 34–36 and Table 21 accurately with both studied systems. The control strategies of the systems remained unchanged between the measurement cycles to determine if similar results were achievable from several cycles and to exclude any potential cycle-specific measurement errors or operation problems.

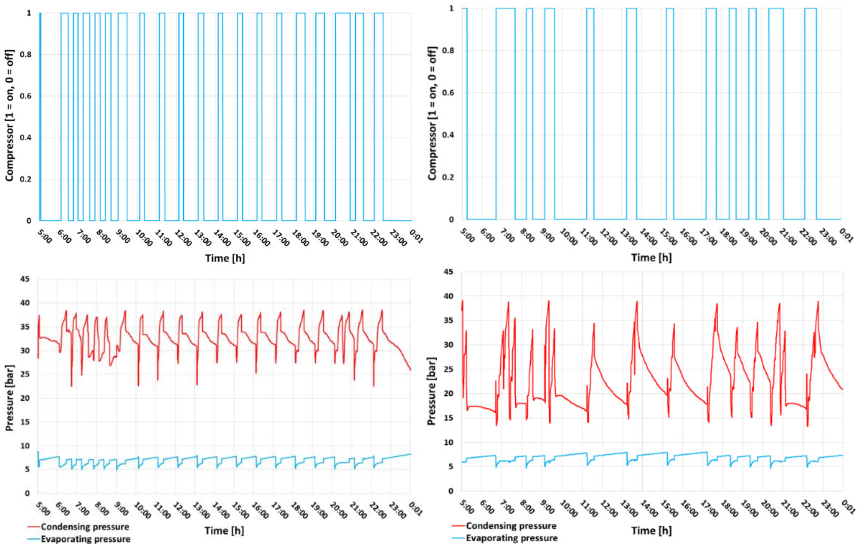

Figure 36. Average operating times of the compressors for the conventional (above left) and new developed (above right) GSHP systems. Average evaporating and condensing pressures for the conventional (below left) and new developed (below right) GSHP systems.

4.2.2 Computational analysis

The total DHW consumption was selected to be 4,288 dm³/day according to the laboratory measurements in all the studied simulation cases. The inlet temperatures of both brine and DCW used in the simulation models were adjusted to correspond to the temperature data of the experimental analysis. The simulated temperatures of DHW in different simulation cases are presented in Figure 37. The simulated temperatures of the DHW storage tanks for the step-based heat pump concept are presented in Figure 38. Figure 38 presents the temperatures of the DHW storage tanks from the regular control strategy simulation case. As in the experimental analysis, the temperature set point of the DHW heat storage tank was 60°C in the conventional heat pump system simulation cases.

In general, the simulation results showed good agreement with the measured performance and temperature data of the experimental analysis. As demonstrated in Figures 37 and 38, the control strategy of the step-based heating process of DHW has impact on both the outlet temperature of DHW and the energy performance of the heat pump system. As the priority of the DHW system is to deliver 55°C water to occupants, the control strategy should be adjusted and optimized so that the temperature requirement is achieved in all circumstances with energy efficiency as high as possible.

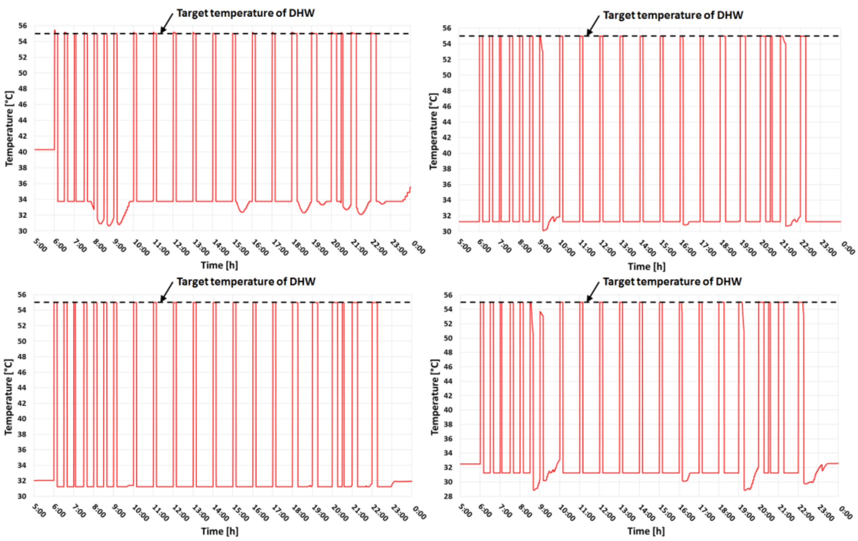

Figure 37. Simulated outlet temperatures of DHW with the conventional heat pump system (above left) and new developed GSHP system utilizing regular (above right), tight (below left), and loose (below right) control strategies.

Three different control strategies (regular, loose, and tight) were studied with the developed step-based GSHP system concept in the computational analysis of the study. The temperature profiles of tanks 1–4 with the loose and tight control strategies were similar with the temperature profile of the regular control strategy presented in Figure 38. The main difference was that the temperatures of the tanks were slightly higher with the tight control strategy and slightly lower with the loose control strategy. The heat pump system responded either faster (tight strategy) or slower (loose strategy) to the reduction in temperatures of the tanks to maintain sufficiently high temperatures to supply 55°C DHW throughout the simulation period. Tanks 1 (or tank 2 when the heating process is switched), 3, and 4 are connected in series so that the outlet water of tank 1 (or 2) is the inlet water of tank 3, and the outlet water of tank 3 is the inlet water of tank 4. The outlet water of tank 4 is DHW supplied to the DHW system. There is also a three-way control valve after tank 4 (see Figure 17) to mix preheated DHW to the outlet water of tank 4, if needed, so that the supply temperature of the DHW is 55°C.

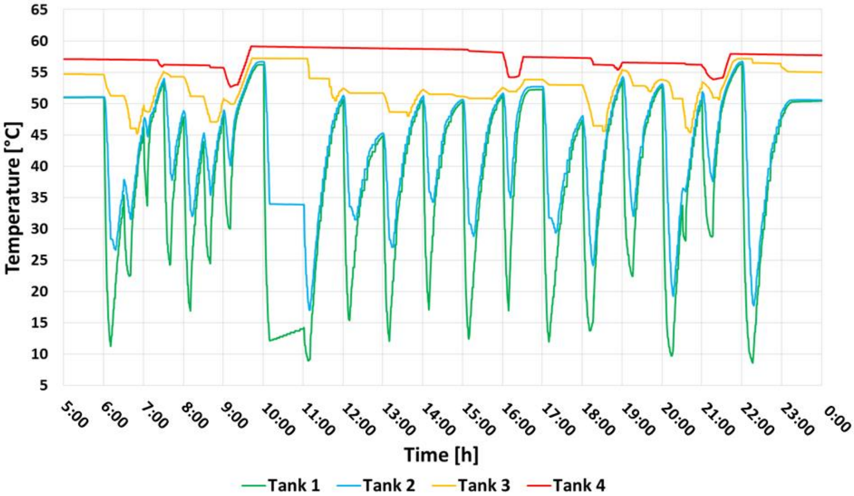

Figure 38. Simulated temperatures of the DHW storage tanks with the new developed GSHP system utilizing the regular control strategy.

The last simulation case of the computational analysis studied a scenario where a more efficient heat exchanger was used for heating DHW (see Figure 17). The minimum temperature difference (pinch point) of the counter-flow heat exchanger was reduced to 2.0 K from the original 3.5 K, which resulted in an average of 1.5°C lower inlet and outlet temperatures (heating/condenser side) of the heat pump unit. According to preliminary estimations based on previous studies and literature, the authors estimated that the overall efficiency of the heat pump unit should increase by approximately 4% due to the lower inlet and outlet temperature levels. The additional simulation case using the calibrated heat pump simulation model was conducted to confirm the estimation and to provide further information on the potential improvements in energy efficiency and operation of the developed step-based heat pump system concept. The simulation results utilizing the more efficient heat exchanger showed improvements in the energy performance of the heat pump system with all the studied control strategies. According to the simulation results, the average improvement in the energy performance of the developed system was approximately +2.1%, when the 1.5°C lower inlet and outlet temperature levels were applied and other parameters remained unchanged in the simulations.

A summary of the simulation results related to the energy efficiency of the studied heat pump systems and control strategies is presented in Table 22. The heat losses of the DHW storage tanks were also simulated and used in the calculation of the overall energy performance of the systems. The average thermal transmittance of the tank coatings, including the top and bottom parts of the tanks, was 0.2 W/(m^2 K) and the room air temperature, where the storage tanks are located, was set to 21.0°C in all of the simulation models.

Table 22. Simulated energy flows and calculated SPFs of the studied heat pump systems.

Simulated heat pump system	Q_{DHW} [kWh]	$Q_{losses,storage}$ [kWh]	$Q_{heat,total}$ [kWh]	$Q_{elec.,HP+aux.}$ [kWh]	SPF
Conventional system	236.9	1.4	238.3	92.8	2.57
New step-based system					
- Loose control strategy	235.6	1.0	236.6	62.5	3.79
- Regular control strategy	236.5	1.0	237.5	63.4	3.75
- Tight control strategy	236.9	1.1	238.0	64.7	3.68
New step-based system equipped with more efficient heat exchanger					
- Loose control strategy	235.6	0.9	236.5	61.3	3.86
- Regular control strategy	236.5	1.0	237.5	62.0	3.83
- Tight control strategy	236.9	1.0	237.9	63.3	3.76

4.2.3 Performance analysis in existing buildings

The heat pump system has been operating since December 2016, and the system has both annual and cumulative energy metering for produced heating energy and consumed electrical energy. The energy metering consists of calibrated Kamstrup measurement equipment. A more detailed description of the measurement equipment used in the study is presented in the appended Publication 5. All 140 apartments included in the studied case buildings have been fully occupied since the beginning of April 2017. The measured cumulative performance data of the GSHP system operating in the case buildings is presented in Tables 23 and 24. Table 23 presents the cumulative performance data and SPFs on April 20, 2017, and Table 24 presents the corresponding data on June 16, 2017. The SPF of the heat pump units and the overall performance of the system were calculated using Equation (9) and the definition and system boundaries described in Section 3.5.11.

Table 23. Measured cumulative energy flows and calculated SPFs of the GSHP system operating in the studied case buildings on April 20, 2017.

Heat pump unit	$Q_{condenser}$ [MWh]	$Q_{superheat}$ [MWh]	$Q_{heat,total}$ [MWh]	$Q_{elec.,HP+aux.}$ [MWh]	SPF
GSHP 1	267.2	7.2	274.4	50.3	5.46
GSHP 2	95.4	7.8	103.2	33.9	3.04
Overall system performance	***362.6***	***15.0***	***377.6***	***84.2***	***4.48***

Table 24. Measured cumulative energy flows and calculated SPFs of the GSHP system operating in the studied case buildings on June 16, 2017.

Heat pump unit	$Q_{condenser}$ [MWh]	$Q_{superheat}$ [MWh]	$Q_{heat,total}$ [MWh]	$Q_{elec.,HP+aux.}$ [MWh]	SPF
GSHP 1	313.4	11.1	324.5	62.7	5.18
GSHP 2	125.6	13.2	138.8	44.8	3.10
Overall system performance	***439.0***	***24.3***	***463.3***	***107.5***	***4.31***

The energy performance of the system is carefully monitored, and continuous updates are conducted to optimize both the efficiency and overall operation of the system, as the real dynamic operation of a large-scale GSHP system with over 100 apartments differs from carefully monitored laboratory testing arrangements. Tables 23 and 24 indicate that heat pump unit 2 has been primarily utilized for heating DHW, and heat pump unit 1 has been primarily utilized for heating room spaces via the hydronic floor heating system. The control strategy for heating room spaces has been implemented so that heat pump unit 2 will start to heat the room spaces if the full capacity of heat pump unit 1 is not sufficient to maintain the required supply water temperature of the floor heating system. However, as the heat pump units have been connected in parallel, both are required to heat DHW when higher consumption peaks occur. Furthermore, the heating priority of the heat pump units can be switched for autumn so that heat pump unit 1 will be prioritized for heating DHW and heat pump unit 2 for heating room spaces to balance the annual operating times of the units.

As presented in Tables 23 and 24, the full potential of the developed system has not been reached yet when the measured cumulative performance data are compared to the measured performance data of the experimental analysis. The main reason for this is that the installed GSHP system has been prioritized to heat DHW so that there is always DHW available for the occupants and the 55°C temperature requirement of the current Finnish building regulations is achieved in all circumstances. However, the performance of the studied system will likely improve over time when the charging and discharging cycles of the step-based heating tanks have been optimized because it takes time to determine a stable and continuous DHW consumption profile in new multi-family apartment buildings with a large number of apartments where previous DHW consumption data are not available. As the results of the experimental analysis demonstrated, as high as 3.7–3.85 SPFs are achievable in the heating process of DHW with an optimally controlled GSHP system utilizing the step-based heating of DHW, depending on the specific case conditions, such as temperatures of DCW and brine inlet.

An essential factor affecting the performance of the GSHP systems in real case conditions is the DHW circulation system. In the studied case buildings, the continuous heat demand of the DHW circulation system is approximately 3 kW with a high temperature level requirement of 55/50°C. This means that the heat pump units must also heat tanks 3 and 4 of the system separately at regular intervals even though there is no actual DHW consumption because the total volume of tanks 3 and 4 is 1,080 dm^3 for the two GSHP units, meaning that the temperature of the tanks decreases relatively fast even when there is no actual DHW consumption occurring (e.g., during night times).

Based on the operation of the studied GSHP system so far, the authors estimate that there is approximately a 10% improvement potential in the overall energy performance of the system and approximately 12–15% energy efficiency improvement potential in the heating process of DHW after the optimum dynamic control strategy has been determined and fine-tuned. An important factor of the case study is also to monitor the adequacy of DHW, as one step-based DHW heating concept with four tanks has a total volume of 1,080 dm^3, which is sufficient for approximately 50 apartments in typical operating conditions. While there are two step-based systems installed in the case buildings, the total number of apartments is 140, which means that the overall capacity of the installed systems is at the upper limit. This is also the main reason why the overall energy performance of the system has not reached its full potential yet, as the adequacy of DHW has been ensured by maintaining slightly higher temperatures in the DHW storage tanks than what would be necessary after a stable

DHW consumption profile has been determined and the control strategy of the step-based DHW heating process has been optimized.

The studied case apartment buildings are equipped with building-specific sewage water heat recovery systems, where the heat included in the sewage water is collected from each apartment building. The nominal heat recovery capacity of each sewage water recovery unit is approximately 4 kW, resulting in a total capacity of 16 kW. The recovered heat is utilized in the brine collector system of the GSHP system by installing the heat recovery system in parallel with the boreholes. The GSHP system includes 16 boreholes with each borehole being 285 meters deep. The installation of the GSHP system setup was presented in Figure 19.

The sewage water heat recovery system installed in the studied buildings also improves the overall energy performance of the GSHP system. The total nominal heat recovery capacity of the system is approximately 16 kW, but it is only achieved when domestic water consumption occurs in the buildings and a significant share of the water consumption is DHW. This means that the energy flow from the sewage water heat recovery system is not continuous and it is not occurring during night times. However, as the collected heat is utilized in the brine collector system of the GSHP system, where the average temperature level of the brine is typically below 5°C, some energy can also be collected from the DCW (e.g., flush water of toilets) flowing through the heat recovery units. This means that the overall efficiency of the sewage water heat recovery system is high when maximum collected heat energy is discussed.

According to the temperature measurements carried out in the GSHP system, the average brine inlet temperature of the system has been approximately 4.5°C since the commissioning of the system. While the sewage water heat recovery system definitely has some impact on the brine inlet temperature and on the overall performance of the GSHP system, it is difficult to determine the precise effect of the actual heat recovery system on the overall performance of the GSHP system because the heat collected from the heat recovery units is transferred to the boreholes when the GSHP units are off. Furthermore, the groundwater flow inside the boreholes also affects the temperature of the brine, meaning that the collected heat of the sewage water heat recovery system might not be fully utilized because part of the collected heat is transferred to the bedrock due to strong groundwater flow. In addition, the maximum nominal capacity of the boreholes (16 x 285 meters) is approximately 150 kW compared to the 16-kW nominal capacity of the sewage water heat recovery system, meaning that the sewage water heat recovery system has a relatively low effect on the brine inlet temperature if the GSHP system is operating at full capacity. However, in actual operating conditions, the effect of the heat recovery system on the brine inlet temperature is higher because the GSHP system seldom operates at full capacity.

4.3 Dynamic simulation methods of heat pump systems

4.3.1 Validation of a GSHP simulation model

The study reported in Publication 6 focused on validating a dynamic simulation method used to simulate the performance of different heat pump systems as a part of dynamic energy simulations of buildings. The studied simulation tool was IDA ICE (version 4.6) and the recently implemented ESBO plant model of IDA ICE. The main results of the GSHP validation process are presented in this section. The studied GSHP unit was a Carrier 61WG-090 brine-to-water heat pump unit equipped with a scroll-type compressor. The nominal power output of the selected system is 87.4 kW at 0/35°C (brine inlet temperature 0°C/outlet water temperature 35°C) and 100.9 kW at 5/35°C operating conditions. The heat pump system was simulated in multiple operating conditions to determine the overall performance of the simulated heat pump model. A more detailed description of the validation procedure and the theory regarding the calibration of the GSHP system are presented in the appended Publication 6.

Figures 39 and 40 present the main results of the GSHP simulation model validation. The performance of the default GSHP simulation model included in the ESBO plant model of IDA ICE is also presented in Figures 39 and 40.

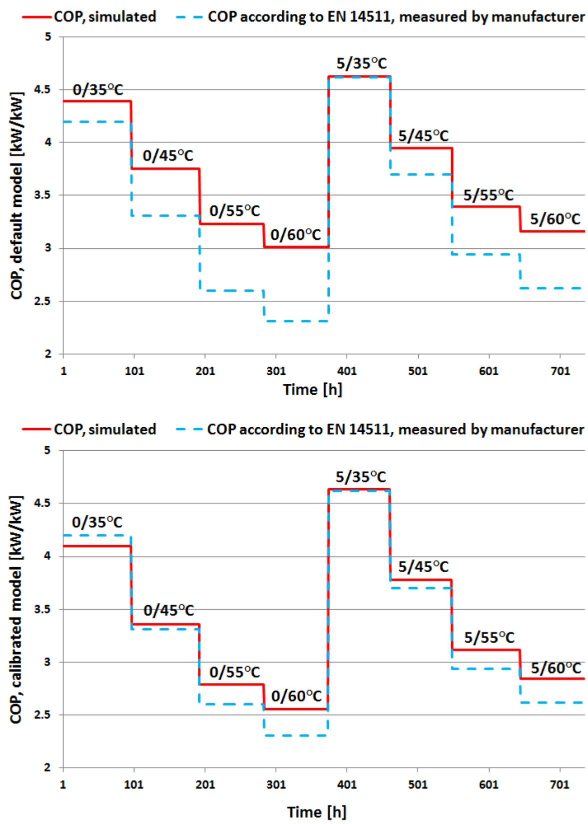

Figure 39. The energy performance of the simulated GSHP system model, the default heat pump model (above), and the calibrated heat pump model (below) according to the 5/35°C rating conditions presented.

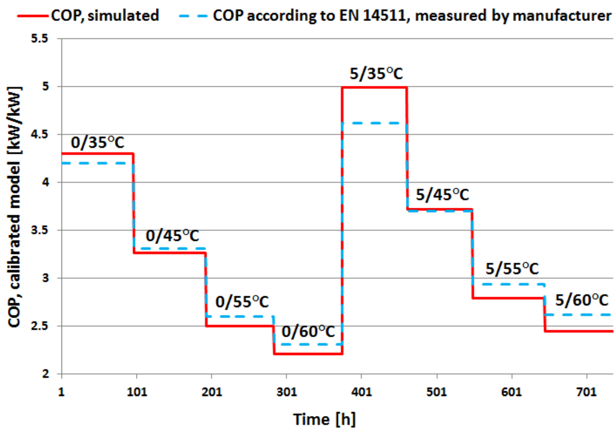

Figure 40. The energy performance of the simulated GSHP system model, calibrated heat pump model according to the 5/45°C rating conditions presented.

According to the results of the simulations, the performance of the default heat pump simulation model corresponds accurately to the performance of the actual heat pump system only at the operating point (rating conditions), which was used to enter the input data of the simulated system (5/35°C). As a conclusion, the default heat pump model generally gives slightly high energy performance compared to an actual system. However, it is important to notice that no default parameters should be accepted in a simulation of an actual heat pump system without a critical review because the default heat pump parameters are determined for just one of many plausible heat pumps.

The calibrated heat pump model corresponds to the measured performance data of the actual heat pump unit fairly accurately. The optimal values of the calibration parameters depend heavily on the simulated case. In addition, the same performance can be achieved by a slightly different combination of calibration values.

The simulations indicated that the rating conditions used to enter the input data in IDA ICE have little effect on the overall performance of the simulated heat pump model. This is presented in Figure 40, where the calibration process was carried out according to the 5/45°C rating conditions, which were used to enter the input data in IDA ICE.

According to the simulations, slightly better overall simulation model accuracy can be achieved by carrying out the calibration process using rating conditions that represent the average operating conditions of several operating points to enter the input data (e.g., 5/45°C instead of 5/35°C or 5/55°C).

4.3.2 Validation of an A2WHP simulation model

The main results of the air-to-water heat pump validation process are presented in this section. The studied A2WHP unit was a Mitsubishi Electric CAHV-P500YA-HPB air-to-water heat pump system with scroll-type compressor and inverter-type control. The nominal power output of the selected system is 63.2

kW at 7/45°C (intake air temperature 7°C/outlet water temperature 45°C) operating conditions. However, due to the inverter-type control, the power output of the system can be controlled between 10 kW and 63 kW. The heat pump system was simulated in multiple operating conditions to determine the overall performance of the simulated heat pump model. A more detailed description of the validation procedure and the theory regarding the calibration of the A2WHP system are presented in the appended Publication 6.

Figure 41 presents the main results of the A2WHP simulation model validation. The performance of the default A2WHP simulation model included in the ESBO plant model of IDA ICE is also presented in Figure 41.

For the default air-to-water heat pump model, all the heat pump calibration parameters are again default values of the ESBO plant model that are meant to be used with a typical air-to-water heat pump system. The performance of the heat pump system is determined according to the 7/45°C rating conditions in IDA ICE in both studied cases (default and calibrated).

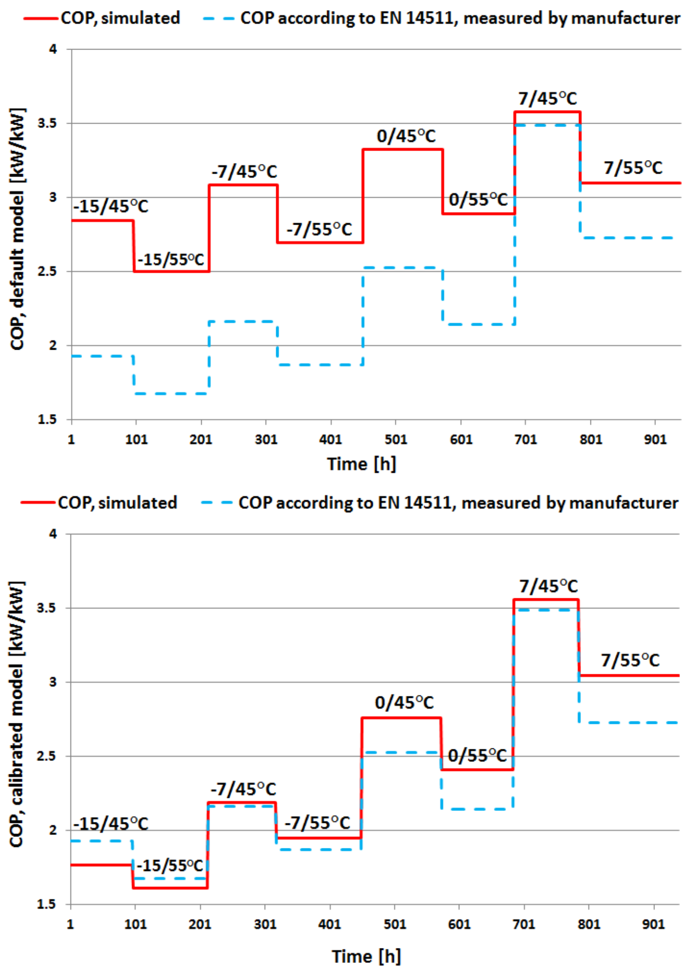

Figure 41. The energy performance of the simulated A2WHP system model, the default heat pump model (above), and the calibrated heat pump model (below) according to the 7/45°C rating conditions presented.

As with the GSHP system model, the performance of the default heat pump simulation model corresponds accurately to the performance of the actual heat pump system only at the rating conditions, which were used to enter the input data of the simulated system (7/45°C). As a conclusion, the default heat pump model gives too high energy performance, especially in cold climate weather conditions. However, the calibrated heat pump model corresponds to the measured performance data of the actual heat pump unit fairly accurately in all the studied operating conditions (see Figure 41). The optimal values of the calibration parameters depend heavily on the simulated case. In addition, the same performance can be achieved by a slightly different combination of calibration values.

4.3.3 Validation according to specific case conditions

The calibration process of simulated heat pump systems can also be weighted according to specific and more detailed case conditions, where the operation of the simulated heat pump system is not equally balanced between different operating conditions. In this approach, the calibration is carried out by weighting the operation times of different operating conditions according to the specifications of the studied case building. This way, the calibration parameters determined from the analysis are weighted more accurately according to the actual climate conditions and temperature levels of the heating systems occurring in a specific case study building.

This is demonstrated in Figure 42, where the outlet water and outdoor air temperatures are logged from a specific case study simulation. The operation times in each operating condition are used to determine the weighted calibration parameters for the case study. The red lines in Figure 42 present the average operating conditions during the specific operating time periods. The weighted operating conditions used in the calibration process of the air-to-water heat pump simulation model in the case study were (Figure 42):

- 1*: the heat pump system is operating at the -15/60°C operating point for 210 h → *3%* of the total time of the heating season
- 2*: the heat pump system is operating at the -7/55°C operating point for 820 h → *12%* of the total time of the heating season
- 3*: the heat pump system is operating at the 0/45°C operating point for 2,800 h → *41%* of the total time of the heating season
- 4*: the heat pump system is operating at the 7/35°C operating point for 2,620 h → *38%* of the total time of the heating season
- 5*: the heat pump system is operating at the 15/30°C operating point for 450 h → *6%* of the total time of the heating season.

The outdoor air temperature data presented in Figure 42 are the outdoor temperature data of the Helsinki-Vantaa TRY2012 presented in Figure 13 (Kalamees et al., 2012). The studied heat pump model can now be calibrated by weighting the operating times of the calibration model at each operating point according to the simulated case conditions presented in Figure 42. The DHW heating system must also be accounted for in the calibration process in addition to the radiator heating system. The weighted calibration process of a GSHP simulation model can be carried out in the same way. Typically, the average annual brine inlet temperature is more constant than the outdoor air temperature, so the more detailed calibration of the GSHP simulation model is faster and simpler to perform.

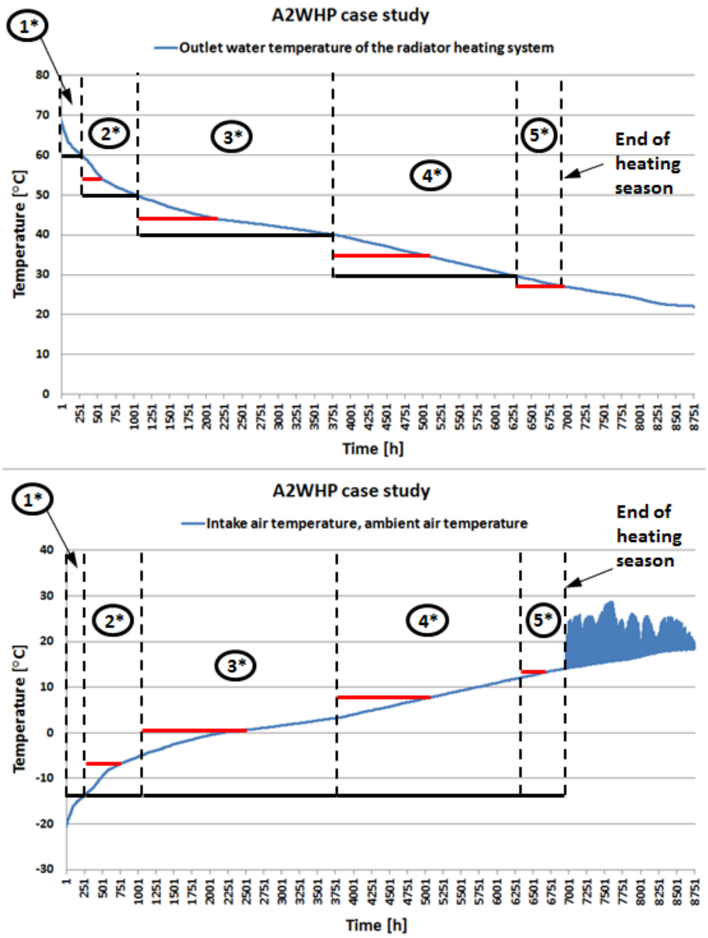

Figure 42. The annual outlet water temperature data of the radiator heating system (above) of the studied building and the annual outdoor conditions (below) for the detailed calibration process of the air-to-water heat pump system.

According to simulations in multiple case study buildings, where the performance of actual dynamic heat pump systems is monitored and measured, the calibrated heat pump models perform accurately in dynamic simulations of buildings. The performance of the simulated heat pump models (SPF, heating energy produced, and electrical energy consumed) was within a 3–5% error margin in actual case studies, where the detailed calibration of the heat pump models was used. The case studies were conducted for the A2WHP, GSHP, and EAHP systems, where the performance of the actual installed heat pump systems was compared to the performance of the calibrated heat pump simulation models. The case studies also indicated that the installation method of the actual heat pump system has a relatively significant impact on the energy performance of the system. According to the results of the studies reported in Publications 5 and 6, the operation of the ESBO plant model corresponds accurately to the variable condensing operation of actual heat pump systems, which makes it an effective method for the simulation of the modern energy efficient heat pump systems.

5. Discussion

5.1 Simulation and optimization methods

An essential part of the research was the development, validation, and utilization of novel energy simulation and multi-objective optimization methods. As the SBO analysis was the main research method utilized in this thesis, the performance, accuracy, and reliability of the SBO methodology was carefully investigated and analyzed in each of the individual studies. A general conclusion is that the utilized SBO methodology is a highly efficient and reliable research method to be used in complex building performance studies, where multiple conflicting objectives are studied simultaneously. The simulation and optimization methods applied in the study were functional and reasonably simple to use. In addition, the MOBO tool has been specifically developed for multi-objective building optimization analyses, and it also has a functional graphical user interface, which improves the usability of the software significantly.

An essential question of the research is: What is the reliability and accuracy of the results achieved by the SBO analyses? To answer this question, the following arguments can be presented:

- The energy simulation method, IDA ICE, used in the study has been successfully validated over the last 15 years in several individual studies, including studies where the performance of IDA ICE has been tested against measurements. The common conclusion of the validation studies is that IDA ICE is a reliable and accurate dynamic simulation tool to be used in energy and indoor climate simulations of buildings.
- The optimization method used in the study, MOBO, is still a relatively new optimization tool. However, the genetic optimization algorithms, such as the NSGA-II algorithm, included in MOBO and utilized in the SBO analyses of the study have been tested and validated years ago as functional, accurate, and reliable optimization algorithms. Even though the multi-objective optimization method is a relatively new method in the building sector, it has been successfully used in the automotive, space, transportation, and industry sectors for decades. Thus, the main optimization engine, the optimization algorithms, included in MOBO has been validated previously. In addition, Hamdy (2012) compared the performance of MOBO to other more established optimization tools, such as MATLAB, in his dissertation.

Based on the arguments presented above, the accuracy and reliability of the results achieved by the SBO analysis are highly dependent on the accuracy of the initial input data used in the analysis, such as the input data used to construct the energy simulation model and especially the cost data used in the analysis. According to the results and the sensitivity analyses conducted in the study, the accuracy of the cost data is the most important factor of a successful SBO analysis. For this reason, obtaining cost data of different measures as detailed and accurate as possible should be the main priority of the analysis.

The energy simulation of different heat pump systems using the IDA ICE software was also tested and validated in this thesis. The rapid development of energy systems requires that reliable and validated simulation methods are needed to simulate the performance and operation of different on-site RESs and complex hybrid energy systems. The results of the studies reported in Publications 5 and 6 demonstrated that the studied IDA ICE software can accurately simulate different heat pump systems by calibrating the default heat pump models included in the ESBO plant model of IDA ICE. The energy performance of the calibrated models corresponded accurately to the measured performance of actual systems in simulations where multiple operating conditions were used.

According to the results, the default simulation models of air-to-water and GSHP systems delivered too high of a performance, especially in cold climate conditions during the heating season. The results of the study reported in Publication 6 demonstrate that the difference between the default heat pump simulation models and the corresponding actual heat pump units is significant enough to affect the results of actual case studies. As the energy performance of the default heat pump models is higher than the actual performance of the corresponding heat pump systems, the economic viability of heat pump system applications is easily overestimated in feasibility studies conducted using dynamic energy simulations. However, it is important to notice that no default parameters should be accepted in a simulation of an actual heat pump system without a critical review.

The main conclusion related to the dynamic simulation methods of heat pump systems is that the studied dynamic simulation tool is an accurate and reliable method for simulating the energy performance of the modern variable condensing heat pump systems operating in cold climate conditions. However, calibration of the default heat pump models included in IDA ICE is required and recommended for more accurate and reliable energy simulations. The studied simulation tool is also a recommended platform to be used to simulate the performance and operation of other on-site renewable energy production systems, such as STC and PV-panel systems.

The effect of different optimization algorithm parameter values on the accuracy, reliability, and computational time of the SBO analyses was carefully studied in this thesis. All the global optimum solutions obtained from the SBO analyses were manually verified to a sufficient extent by conducting manual comparisons to the close-to-optimal solutions. It was determined that typical error margins of the analyses, caused by the optimization algorithm parameter values, were as follows:

- The optimum area of PV panels could be 122 m^2 or 129 m^2 instead of 125 m^2, which was obtained from the SBO analysis
- The optimum area of solar thermal collectors could be 53 m^2 or 58 m^2 instead of 56 m^2, which was obtained from the SBO analysis
- The optimum dimensioning power output of a heat pump system could be 64 kW or 69 kW instead of 66 kW, which was obtained from the SBO analysis.

The convergence of the Pareto-Archive NSGA-II optimization algorithm was studied and tested in Publications 1, 2, and 4 by performing additional sensitivity analyses with a higher number of simulations and also by optimizing the objective functions separately using single-objective optimization analyses. Based on the performed sensitivity analyses, it was determined that the convergence of the selected optimization algorithm was sufficient with the parameter values presented in Table 8 in the SBO analyses carried out in Publications 1, 2, and 4.

In Publication 1, single-objective optimization analyses with the Omni-Optimizer optimization algorithm were performed in order to determine if the same global optimum solutions could be achieved. The optimization algorithm parameter values used with the Omni-Optimizer algorithm were:

- Population size: 16
- Number of generations: 32
- Mutation probability: 0.05
- Crossover probability: 0.8.

When the NPV of the 25-year LCC was minimized in the single-objective optimization analysis, the same optimum solution was achieved with the analysis as the global optimum solution of the multi-objective optimization analysis was. When the PE consumption was minimized using the single-objective optimization analysis, the same optimum solution was achieved as with the primary multi-objective optimization analysis. When the convergence of the Pareto-Archive NSGA-II algorithm, which was used in the multi-objective optimization analyses, was studied, it was determined that by using the optimization algorithm parameter values presented in Table 8, the convergence of the algorithm was sufficient after approximately 400 simulations. No significant improvement (less than 1% on average, when the number of simulations was increased from 400 to 800) was seen in the Pareto front after 400 simulations. Therefore, it was concluded that the optimization algorithm parameter values used in the SBO analyses carried out in Publication 1 were sufficient and that the typical error margin of the Pareto optimal solutions was approximately what was presented above in this section.

Similar sensitivity analyses were carried out in Publication 2, and a similar trend was noticed in the development of the results of the SBO analyses. Increasing the number of simulations from approximately 400 did not deliver a significant improvement (less than 1% on average, when the number of simulations was increased from 400 to 800) in the Pareto front, so the optimization algorithm parameter values presented in Table 8 were determined to be a sufficient compromise between computational time and accuracy. In addition, the typical error margin of the Pareto optimal solutions was determined to be approximately what was presented above in this section.

In Publication 4, more sensitivity analyses were carried out because the SBO analyses of the study included three-dimensional optimization problems, where three equally valuable objectives were optimized simultaneously. A similar approach was applied in the sensitivity analyses to determine sufficient optimization algorithm convergence, as in Publication 1. The same global optimum solutions were determined for all three optimized objectives from single-objective (900 simulations per analysis) and multi-objective (1,500–2,400 simulations per analysis) optimization analyses. In addition, the convergence of the optimization algorithm was determined to be sufficient after approximately 750 simulations in the multi-objective optimization analyses, including two optimized objectives, and after approximately 1,300 simulations in the multi-objective optimization analyses, including three optimized objectives. It was determined that increasing the number of simulations from the aforementioned did not deliver a significant improvement (less than 1% on average, when the number of simulations was doubled in the analysis) in the Pareto front, so the optimization algorithm parameter values presented in Table 8 were determined to be a sufficient compromise between computational time and accuracy. In addition, the typical error margin of the Pareto optimal solutions was determined to be approximately what was presented above in this section.

The optimization algorithm parameter values of the SBO analyses carried out in Publication 3 were selected based on the experiences and results of the SBO analyses carried out in Publications 1, 2, and 4. In Publication 3, it was determined that when the population size was approximately 30 and the number of generations was more than 20 (a total of 600 simulations), a sufficient optimization algorithm convergence was achieved in the multi-objective optimization problem investigated, in regards to computational time and accuracy of the analyses. The typical error margin of the Pareto optimal solutions was determined to be approximately what was presented above in this section.

In the study reported in Publication 6, the SBO analyses utilized in the study delivered optimal solutions that met the objectives of the analyses satisfactorily, regardless that a multi-objective optimization algorithm was used to solve a single-objective optimization problem. The results of the study reported in Publication 6 demonstrate that the calibration parameters obtained from the SBO analyses utilized in the study provide accurate results, when the performance of the heat pump simulation models is compared to the measured performance of the corresponding actual heat pump units. In addition to the good agreement in the performance, the numerical errors occurring in the dynamic IDA ICE heat pump simulations decreased significantly compared to situations where close-to-optimal heat pump calibration parameters were used in the simulations. Therefore, it can be concluded that the heat pump model calibration parameters obtained from the SBO analyses utilized in the study reported in Publication 6 were definitely optimal to a sufficient extent, even though a multi-objective optimization algorithm was used to solve a single-objective optimization task. When the results of the optimization analyses related to the calibration of the heat pump models were examined, the error margins of the analyses were as follows:

- GSHP model:
  - Target SPF according to the measured performance: 3.2875
  - Simulated SPF with the calibrated heat pump model: 3.2873
- A2WHP model:
  - Target SPF according to the measured performance: 2.3155
  - Simulated SPF with the calibrated heat pump model: 2.3154.

The comparison of the results shows that the error of the optimized objective function can be identified in the fourth decimal, indicating that the optimization algorithm parameter values were correctly selected and that the convergence of the multi-objective optimization algorithm solving the single-objective optimization problem was very good.

5.2 Cost-optimal renovation concepts

A common aspect of the cost-optimal renovation concepts of all the studied building types was that the investments should be focused on renewable energy production technologies and on technical systems of the buildings instead of investing in major renovations of the building envelope. Especially the modern heat pump systems delivered significant improvements in both the energy performance of the buildings and in the cost-effectiveness of the deep renovation in all the studied building types.

The cost-optimal renovation concepts of the studied residential apartment buildings showed good agreement with each other. The initial setting of the deep renovation was slightly different in the apartment building studies because the typical refurbishment methods applied to the renovation of prefabricated concrete large panel-structured external walls are different than the typical methods applied to the renovation of brick-structured external walls. In brick-structured external walls, the cost-optimal renovation measure is typically a basic refurbishment using a three-layer plastering or equivalent refurbishment measure. In some cases, the outer brick layer must be demolished because of its poor condition, and in these cases, the original thermal insulation layer is typically also replaced. This latter scenario makes it possible to improve the energy efficiency of the building envelope more cost-effectively by installing a thicker layer of thermal insulation to the wall structure under the new outer brick structure layer.

According to the surveys conducted in this thesis, the demolishing alternative is a more common renovation method of external walls in the concrete large panel apartment buildings, where the outer concrete layer structure is often carbonized and requires demolition because of its poor condition. Even in this renovation scenario, where additional thermal insulation can be cost-effectively installed, it is not cost-efficient to improve the energy efficiency of the building envelope beyond the current national building regulations regarding the energy performance of new buildings. While it is important to reduce the energy demand of apartment buildings by improving the energy performance of the building envelope, the economic viability of deep renovations, including major renovations of the building envelope, is simply not feasible to apartment building owners. According to the results of the residential apartment building studies, the cost-optimum level of the deep renovation was close to the current minimum energy performance requirement level of new Finnish apartment buildings ($E_{primary} \leq 130$ kWh/m^2,a) in both apartment building cases.

An essential difference in the economic calculations of the residential apartment building studies was that the residual value of different renovation measures was included in the LCC calculations of the brick apartment building renovation study. When the residual value is included in the economic calculations, the actual technical operating times of different renovation and retrofitting measures are calculated. For example, if the estimated technical operating time of a major renovation of the building envelope is 40 years and the life-cycle period used in the economic calculations is 25 years, there is still 37.5% of the technical operating time remaining after the 25-year calculation period. The same principle can be applied to other measures as well (e.g., to the installation of a GSHP system). In a GSHP system investment, the materials and infrastructure related to the borehole collector system account for the most significant share of the investment. The typical technical operating time of the plastic collector pipes, valves, and other equipment included in the borehole system is approximately 50–60 years, which means that the borehole brine collector system has just reached 50% of the estimated technical operating time of the system after the 25-year calculation period.

The residual value is normally calculated by using the typical technical operating times of different measures and the initial investment costs of the measures. If a low real interest rate level is used in the economic calculations, the effect of the residual value will have a relatively significant impact on the outcome of the LCC calculation. However, while the residual value is often implemented in the economic calculations of individual research projects, it is typically excluded from the economic calculations of actual renovation projects because the building owners experience the concept of the residual value difficult to understand or they feel that the residual value makes the calculation more complex and difficult to interpret. For this reason, both scenarios related to the residual value were studied in this thesis (included in Publication 1 and excluded in Publication 3) because the most important objective of the apartment building studies was to determine economically viable and technically feasible renovation concepts for apartment building owners that are also well implementable in the majority of the actual deep renovations.

The cost-optimal renovation concepts of the studied educational building (Publication 2) included similar findings to the studies regarding the residential apartment buildings. However, the significance of the renovation and retrofitting measures related to the HVAC systems of the studied building played a more significant role in the deep renovation. In educational buildings, providing high-quality indoor environment conditions, including thermal, acoustic, and lighting conditions, and IAQ should be the priority of the renovation because the indoor environment conditions have such a significant impact on the learning performance of students and on the productivity of building users.

As in the residential apartment building studies, renovation measures related to the energy production and technical systems of the building delivered higher improvements in the energy performance of the building when cost-effectiveness of the renovation was discussed. As in the apartment building studies, the initial setting and the refurbishment requirements of the deep renovation determine the cost-optimal case-specific renovation concept. The studied educational building included brick-structured external walls that were in decent condition and did not require any demolition-related renovation measures. In this specific case, the cost-optimum renovation measure of external walls was the basic refurbishment, including three-layer plastering. If the external structures required more extensive renovation measures because of their poor condition in the beginning, the cost-optimal renovation concept would be slightly different. However, based on the results of the other case studies conducted in this thesis, improving the energy performance of the building envelope beyond the reference energy performance requirements of the current national building regulations (NBCF part D3, 2012) is not recommended in any renovation scenario when cost-effectiveness, building physical functionality of the structure solutions, and overall improvements in the energy performance of the building are discussed. According to the results of the educational building study, the cost-optimum level of the deep renovation was close to the energy performance requirement level of the preliminarily proposed nearly zero-energy educational buildings ($E_{primary} \leq 104$ kWh/m^2,a).

In Finland, the majority of the existing educational buildings and kindergartens built in the 1960s, 1970s, and 1980s are in average, below average, or poor overall condition. These buildings require major renovation measures, especially for the building services systems, to improve the indoor environmental conditions of the buildings to an acceptable level. There is also a current ongoing discussion at the national level about whether these educational buildings and kindergartens should undergo a deep renovation or be completely demolished and rebuilt because of their extensive renovation debt. An important aspect affecting the renovation of existing educational buildings is the occupant density of the building after the renovation. Increased occupant density requires increased airflow rates, which may not be easy to implement in existing educational buildings with increased technical space requirements.

The cost-optimal renovation concepts of the studied office building (Publication 4) included a balanced combination of renovation measures that simultaneously improve both the indoor environment conditions and the energy performance of the building. By using the extended LCC calculation method, where the cost impact of productivity loss is merged into the traditional LCC calculation, in the owner-occupied office building type analysis, the results clearly indicate that the reduction in performance of workers due to unfavorable indoor thermal conditions has the highest individual economic impact on the total LCC. The cost impact of productivity loss accounts for up to 60–70% of the extended LCC over the 15-year life-cycle period in the presented reference solution where only the mandatory minimum renovation and refurbishment measures are conducted. This means that the benefits of the improved indoor climate conditions are substantial in the owner-occupied office buildings because the benefits of the improved conditions come directly to the building owner. By using a longer life-cycle period than 15 years, the share of the productivity loss is even higher. Therefore, it is profitable and highly recommended for building owners to improve the thermal comfort conditions in deep renovations of existing office buildings. According to the results of the study, investments in the cost-optimal renovation concepts deliver close to 65% ROI in owner-occupied office buildings, where the cost impact of productivity loss is included in the economic calculations. The high ROI achieved by the cost-optimal renovation concepts demonstrates that it is difficult to find a more profitable investment opportunity than the investment in the cost-optimal concepts. The overall investment cost of the renovation concept was approximately €110/m² at the cost-optimum level. According to the results of the office building study, the cost-optimum level of the deep renovation was approximately 35% better than the current national minimum energy performance requirements of new office buildings ($E_{primary} \leq 170$ kWh/m²,a) in the owner-occupied building study and approximately 30% better in the tenant-occupied building study.

According to the results of the tenant-occupied office building analysis, the maximum ROI achieved by the investments in the cost-optimal renovation concepts was approximately 15–17%; this is compared to the over 60% ROI of the owner-occupied building scenario. The differences in the results of the two analyses demonstrate that it is extremely profitable and highly recommended to invest in renovation measures that improve the indoor thermal comfort conditions of the building in addition to improving the energy performance. The best ROI in the tenant-occupied building scenario was achieved by investing approximately €100/m².

In tenant-occupied buildings, the improved thermal comfort conditions and increased productivity must be taken into account by increasing the rent according to the potential financial benefits achieved by the building users because of improved performance of workers to make the higher investment economically viable to the building owner. In many cases, it can be difficult to justify the larger investment to tenants and building owners because the concept of productivity loss due to thermal comfort or indoor environment conditions is somewhat difficult to understand by people other than the technical personnel working in the building sector. In general, the building owner invests in the renovation measures, but the potential benefits of the improved indoor climate conditions come to the tenant in tenant-occupied office buildings.

The IAQ affects the performance of occupants in addition to the indoor thermal conditions. Therefore, it is important to ensure high-level IAQ conditions in both owner- and tenant-occupied office buildings by applying sufficient ventilation efficiency and airflow rates in office spaces, meeting rooms, and working areas.

According to the results, the reference low-carbon office building criteria can be achieved by 5% ROI in tenant-occupied office buildings and by up to 30%

ROI in owner-occupied buildings. However, the composition of delivered energy carriers plays a significant role in the environmental impact analysis. If renewable electrical energy is purchased from the electricity grid, the operation emissions (CO_2e) can be significantly reduced. Furthermore, if the district heating energy is produced by using RESs, this also affects the CO_2e emissions significantly. Due to the aforementioned aspects, the energy infrastructure and the techno-economic environment of the building have a significant impact on the overall environmental impact reduction potential of office buildings.

When the productivity loss is included in the extended LCC analysis, the global optimum overall concept is not achieved by investing substantially in the more expensive measures that improve the thermal comfort conditions further (e.g., investment in the room space-specific cooling system). The main reason for this is that the basic investment in the centralized air-conditioning system (cooling of the supply air of the ventilation system) already guarantees good thermal conditions when the specific cooling load of office spaces is low. In general, the cooling loads of office appliances have decreased substantially over the last decade because the energy efficiency of office appliances, such as monitors, laptops, and printers, has improved significantly. The average occupancy rates of office buildings have also decreased as more and more people are working remotely.

An important aspect related to the centralized air-conditioning systems is that the centralized system cannot be individually controlled so that all occupants would be satisfied. The personal preferences of the occupants are different when optimal indoor thermal conditions are discussed, which inevitably leads to the situation where some of the occupants are dissatisfied with the thermal conditions. Personal occupant-specific temperature control is required to reach optimal thermal conditions that satisfy all occupants. In general, this kind of control is impossible to implement in offices with an open layout design, as it would require a specific personal ventilation-based solution that would have poor adaptability, cost-effectiveness, and control. In the traditional office room layout design, the personal occupant-specific temperature control would be easier to implement. However, while the thermal conditions would be individually adjustable in this case compared to the centralized air-conditioning system, the overall cost-effectiveness and the increased maintenance need of the more complex system are not feasible for office building owners, especially in deep renovations.

In deep renovations of office buildings, measures such as improved windows with low g-value and integrated window shading, which significantly reduce the solar-based cooling loads and have fair ROI, are relatively low investments compared to the centralized room space-specific cooling system. However, as the climate conditions, energy prices, techno-economic environments, energy and emissions policies, local construction methods, and CO_2 emissions factors of different energy carriers can be vary significantly in different countries and regions, the cost-optimal renovation concepts and recommended measures will also be different. Typically, the more extensive measures that improve the indoor thermal conditions further and increase the cooling capacity (e.g., the room space-specific cooling system with chilled beams, ceiling cooling panels, or fan coils) become more profitable in office buildings located in warmer climates because the lost performance of occupants caused by the productivity loss has such a significant impact on the economic calculations. However, it is also important to acknowledge that while the perceived indoor thermal environment has a significant impact on the performance of workers, it is highly dependent on the personal preferences of occupants.

According to the results of the individual case studies conducted in this thesis, the energy performance requirements of the preliminary national nZEB regulations can be achieved cost-effectively in deep renovations. In the educational building study, the cost-optimum level of the deep renovation was already better than the proposed preliminary nZEB requirement level of new educational buildings. In the residential apartment building studies, the preliminary nZEB proposal was also cost-effectively achievable in the deep renovation. The preliminary nZEB requirement was achieved by approximately 10–15% ROI in both residential apartment building studies with a GSHP system, which was the global optimum main heating system concept in both apartment building types. According to the results of the office building study, the preliminary nZEB requirements of new office buildings were cost-effectively achievable in the deep renovation. The preliminary nZEB energy performance requirements were achieved by approximately 38% ROI in the owner-occupied building study and by approximately 10% ROI in the tenant-occupied building study.

After a careful evaluation of the revised building type-specific nZEB requirements, it can be determined that the revised nZEB requirements are easier to achieve. Even though the PE weighting factors are lower and the actual PE consumption is also lower, the revised requirements are in fact looser than the preliminarily proposed requirements. A summary of the comparison between the preliminary and revised PE consumption requirements of the studied building types is as follows:

- Residential apartment buildings:
    - Preliminary requirement (higher PE factors): *116 kWh/(m²,a)*
    - Revised requirement (lower PE factors): *90 kWh/(m²,a)*
    - Revised requirement when the PE consumption is normalized to correspond to the preliminary requirement: *128 kWh/(m²,a)*
- Educational buildings:
    - Preliminary requirement (higher PE factors): *104 kWh/(m²,a)*
    - Revised requirement (lower PE factors): *100 kWh/(m²,a)*
    - Revised requirement when the PE consumption is normalized to correspond to the preliminary requirement: *147 kWh/(m²,a)*
- Office buildings:
    - Preliminary requirement (higher PE factors): *90 kWh/(m²,a)*
    - Revised requirement (lower PE factors): *100 kWh/(m²,a)*
    - Revised requirement when the PE consumption is normalized to correspond to the preliminary requirement: *145 kWh/(m²,a)*.

As demonstrated above, the revised national nZEB requirements of educational buildings are approximately 29% looser than the preliminary nZEB requirements, and the revised nZEB requirements of office buildings are approximately 38% looser than the preliminary requirements. The revised nZEB requirements of residential apartment buildings are approximately 9% looser than the preliminary requirements. In fact, the increase in the energy performance requirements of new buildings is 15% for office buildings, 14% for educational buildings, and only 2% for residential apartment buildings compared to the current minimum energy performance requirement level of the corresponding building types. While the revised nZEB energy performance requirements are easier to achieve in deep renovations, the fact is that the revised requirements are far from the cost-optimal levels of new educational, office, and residential apartment buildings. The energy performance requirements of nZEBs should definitely be higher and more ambitious.

As conclusions from the renovation case studies reported in Publications 1–4, the environmental impact reduction potential of existing office, educational, and residential apartment buildings is significant. The environmental impact of the studied building stocks can be significantly and cost-effectively reduced by decreasing the delivered energy consumption of the buildings (e.g., by installing modern heat pump systems). In Finland and in many other developed countries, the effect of construction materials on the total greenhouse gas emissions is low compared to the environmental impact of the delivered energy consumption of buildings. Therefore, reducing the delivered energy consumption of buildings by investing in cost-effective renovation concepts and utilizing RESs in the energy production of buildings has the most significant impact on the overall environmental impact reduction potential of existing buildings.

The deep renovations are typically financed by loans, which inevitably lead to the situation among building owners where reasonable economic viability and ROI are required for the investments to partially finance the loan. Investments in the more expensive renovation measures, such as additional thermal insulation of external walls in a majority of the cases, are difficult to be justified for the building owners, regardless of the potential savings in the energy consumption of the building.

5.3 On-site renewable energy production technologies

According to the results of all the individual case studies, the GSHP system was the global optimum main heating system concept and delivered the best energy performance improvements when cost-effectiveness is discussed. However, in many cases, the GSHP system cannot be selected as the main heating system of the building in dense urban areas because the plot size of the building is often too small for drilling a sufficient number of boreholes or for installation of a sufficient amount of horizontal plane heat collector pipes.

According to the results of the residential apartment building studies, the air-to-water heat pump system also delivered excellent energy performance and cost-effectiveness in the climate of southern Finland. The modern air-to-water heat pump systems are functioning well in cold climates and delivering good energy performance at the same time. In addition, the investment cost of the air-to-water heat pump system is typically considerably lower than the investment cost of the GSHP system, making the A2WHP system a cost-effective solution to improve the energy performance of residential apartment buildings. Furthermore, the results of the recent heat-pump-related study conducted by Häkämies et al. (2015) provide similar conclusions.

All the studied heat pump systems delivered better energy performance and cost-effectiveness than the district heating system. The results indicate that major improvements in energy performance can be achieved by investing in the heat pump systems. The main reasons for this is that the studied modern heat pump systems are operating at a high energy efficiency level when they are optimally dimensioned according to the individual case conditions of buildings. The results of the study reported in Publication 5 also confirmed this, as the measured overall energy efficiency (seasonal performance) of the studied GSHP system was approximately 4.5 in residential apartment buildings that included 140 apartments. The performance of the heat pump systems decreases in existing buildings with high-temperature heat distribution systems or with a high DHW consumption, but the overall cost-effectiveness achieved by the heat pump systems is still typically better than the cost-effectiveness achievable by the district heating system with the current energy prices. However, it is important to note that the price of electrical energy is relatively low in Finland currently, as the average total price of electricity is approximately €100–110/MWh for the consumer, whereas the average price of district heating is approximately €70–80/MWh in Finland, depending on the location of the building.

An important aspect related to the utilization of heat pump systems is also the fact that extensive use of heat pump systems would likely change the energy policy. This would significantly change the ratio between district heating and electricity consumption at the national level and would also affect the national energy infrastructure. Efficient demand response strategies and smart control technologies would be required in order to manage the electricity grid if the heat pump systems increased their popularity as the main heating systems of buildings. Another important aspect related to the economic viability of the heat pump systems is the pricing of district heating. In Finland, the energy companies providing and selling district heating are often monopoly companies that can solely decide the pricing of the district heating energy in their own service area. If the pricing of the district heating energy is not reasonable, building owners will seek for alternative solutions, such as heat pump systems, to reduce their energy costs. This setting also works the other way around, and reasonable pricing of the district heating energy will ensure that the district heating concept remains a feasible and economically viable main heating system concept among the building owners.

The educational building study demonstrated that even though the GSHP system is the cost-optimum main heating system concept in the studied educational building, unnecessary over-investments in the GSHP system should be avoided when cost-optimality is discussed. The results of the educational building study highlight the importance of taking the individual case conditions into account in the analysis. In the studied educational building, a high dimensioning power output of the borehole-based GSHP system was not a cost-optimum measure when LCC and total PE consumption of the studied building are discussed. The main reason for this was the high investment cost of the GSHP system due to the relatively deep (≥40 meters) clay-based ground soil material that increases the drilling costs of the boreholes significantly. Another important factor affecting the economic viability of a heat pump system in actual case conditions is the price of the heating energy (e.g., district heating) that the heat pump system replaces. In addition, the cost-optimal dimensioning of heat pump systems should always be based on the actual case conditions of the studied building—not solely on the results and conclusions of previous studies.

According to the results of the individual case studies, installation of a solar-based electricity production system with PV panels is a highly recommended and cost-effective measure with all the studied main heating systems when PE performance with the Finnish PE weighting factors is discussed. In addition, a solar-based thermal production system is recommended to be installed with the district heating system, where it is delivering good cost-effectiveness, but it is not recommended to be used with any of the heat pump systems in any of the studied building types located in cold climate conditions because the high energy performance of the modern heat pump systems reduces the cost-effectiveness of the solar thermal system significantly. In Finland, an essential aspect in the designing process of the PV-panel system is to dimension the system so that all the produced electricity can be used on-site. This requires careful matching analysis of the building's electricity production and consumption profiles and loads in the designing process so that the dimensioning of the PV-panel system matches the electricity consumption profile and loads of the building. While the produced electrical energy can also be exported back to the grid and sold to the energy company, it is not cost-effective or recommendable for building owners with current Finnish electrical energy tariffs.

Another important aspect affecting the PE performance of the solar-based electricity production system is the national PE weighting factors used in the calculation of the PE consumption. The PE weighting factor for electricity is currently 1.7 in Finland, which means that any savings in the delivered electricity energy use provide high gains in the total PE consumption of the building. In addition, even with the new lower PE weighting factors (1.2 for electricity), investments in the PV-panel systems are economically viable and recommended. In addition, as the PE weighting factor of district heating is significantly lower than the PE weighting factor of electricity (currently 0.7 for district heating), the PE performance of hybrid energy systems, where, for example, a heat pump system with a relatively low dimensioning power output is combined with the district heating system, is typically improved.

According to the results of the concrete large panel apartment building study reported in Publication 3, over 90% of the total CO_2 emissions are generated from the delivered energy consumption of the building in deep renovations.

Therefore, renovation measures related to the renewable energy production systems of the building are recommended because they effectively decrease the delivered energy consumption of the building. When the total CO_2 emissions are discussed, the share of embodied material emissions is low when typical modern construction materials with high material efficiency are used. It is also important to note that the emissions factors of different energy carriers play a significant role in the calculation of CO_2 emissions of the delivered energy consumption. The heat pump systems are no longer environmentally friendly heating alternatives if the district heating energy is produced by RESs and the electricity purchased from the grid is produced by fossil fuels. In this case, investments in heat pump systems would increase the overall environmental impact of the building. However, typically, it is also possible to purchase electrical energy produced by RESs from the electricity grid, depending on the location of the building, which would reduce the CO_2 emissions of delivered energy consumption of the heat pump system to zero. Of course, the price of renewable electrical energy is typically higher, so the cost-optimal dimensioning of the heat pump system is important in this case.

5.4 Novel GSHP system application

As the energy efficiency of both the building envelope and building services systems improves in deep renovations, heating DHW can easily account for more than 50–60% of the total heating energy demand in new low-energy multi-family apartment buildings. Furthermore, the recast EPBD requires that the reduced energy demand of nZEBs and high-performance buildings should be covered by RESs to a significant extent. Typically, heat pump systems, such as GSHP systems, are one of the best applications to utilize on-site RESs when energy performance and cost-effectiveness are discussed. To improve the efficiency of the GSHP systems, especially in heating DHW, the majority of the previous studies have focused on research related to SAHPs to improve the efficiency of the heat pump unit in producing the higher temperature levels required for heating DHW. However, in many cases, the investment in solar thermal energy is not the most economically viable measure, especially in cold climate conditions when cost-optimality is discussed.

The results of the study reported in Publication 5 indicate that the novel method developed for energy efficient heating of DHW is functional and has a significant energy savings potential compared to the conventionally used GSHP system applications. The measurement results of the experimental analysis demonstrated that up to 49% improvement in energy efficiency of the heat pump system was achieved with the developed heat pump application, when compared to the conventionally used application. While the measurement results between the conventional and new developed systems were not fully comparable because the temperatures of DHW were below the target temperature (55°C) in a few measurement cycles with the developed system, the difference in efficiency is so substantial that it can be concluded that the developed system operates significantly more efficiently in heating DHW than the conventional system. However, the average temperature of the brine inlet was approximately 1.0°C higher in the measurements with the conventional system, resulting in better performance. Furthermore, the target temperature of DHW can be easily achieved with the step-based heating concept by increasing the temperatures of the DHW storage tanks or by further fine-tuning the control parameters of the system.

According to the results of the experimental analysis conducted in Publication 5, other essential benefits of the developed GSHP system concept were the significantly longer operating times and lower condensing pressure levels of the studied heat pump unit, resulting in improved longevity and reliability of the system. The start-ups of the heat pump unit decreased by approximately 40% with the developed step-based heating process application. As a result of the lower condensing pressure levels, the average temperature level of the superheated gas of the refrigerant was approximately 27% lower during the measurement cycles with the new developed system. While there are more DHW storage tanks and control automation included in the developed system, which inevitably increases the maintenance need of the system in actual case buildings, the finalized operation principle of the system has been simplified as much as possible by using only the necessary control equipment. In addition, the developed system can be combined with all the major commercial heat pump makes and models that include separate superheat recovery of the refrigerant. The developed system can also be implemented in existing GSHP systems by installing the additional DHW storage tanks, heat exchanger, and control equipment.

According to Tom Allen Senera Oy, the investment cost of the developed GSHP system (Publication 5) is approximately 5–10% higher than the investment cost of a corresponding GSHP system equipped with the conventional DHW heating operation. In an apartment building with 100 apartments, the initial investment cost of the developed system is approximately 5% higher than the investment cost of the conventional system, and in an apartment building with 30 apartments, the investment cost of the developed system is approximately 10% higher. For comparison, the technical space requirement for one four-tank configuration is approximately 1.5 floor-m^2, whereas the technical space requirement for the corresponding conventional DHW heat storage configuration with one 1.3 m^3 tank is approximately 0.9 floor-m^2. Other components of both the conventional and the developed GSHP systems require approximately the same amount of technical space, so the increased technical space requirement of the developed concept is approximately 0.6 m^2 for each four-tank configuration installed in the building.

Due to the relatively complex installation principle of the developed system, the on-site installations of the system have been minimized to ensure correct and fast installations. Each four-tank assembly comes pre-installed from the Gebwell factory so that all the main components, such as the heat exchanger, exchange and one-way valves, temperature sensors, insulations, and connections have been installed at the Gebwell factory. In addition, the operation of the main components has also been tested at the factory so that the on-site installation and commissioning of the systems in actual buildings is as simple and efficient as possible. In addition to the more complex and detailed installation of the developed system, it is essential to notice that the increased maintenance need of the system requires relatively comprehensive metering and careful monitoring of the system.

The five-step heating process of DHW presented in Figure 1 of the appended Publication 5 is an example to demonstrate the basic thermodynamic principle and the effectiveness of the step-based heating method in a specific case, where DHW is heated from 5°C to 55°C. In general, the optimum number of heating cycles should be selected according to the heat pump and thermal storage applications used in the implementation. The majority of commercially manufactured heat pump units have been optimized to operate using specific temperature differences for the heat exchangers of both the evaporator and the condenser. A typical temperature difference between the inlet and outlet brine of the evaporator is 3–5 K, whereas a typical temperature difference between the inlet and outlet water of the condenser is 6–8 K. This means that a typical commercially manufactured heat pump unit can increase the temperature of the heating water (condenser side) by approximately 7°C during one heating cycle. Therefore, by using typical commercial heat pump units, the actual number of heating cycles is approximately 7-8 if DHW is heated from 5°C to 55°C and the stratification phenomena of water in the heat storage tank are also considered.

According to the preliminary results of the case study, the performance of the installed GSHP system operating in real case conditions has not reached its full energy-saving potential yet. A significant factor affecting the performance of the system in actual case buildings is the dimensioning and heat demand of the DHW circulation system, which was excluded from the experimental analysis. A high temperature requirement (e.g., 55/50°C or even 58/55°C) and continuous heat demand of the DHW circulation system decrease the performance of the heat pump unit, increase the number of start-ups of the unit, and force the system to operate shorter time periods especially during night times when there is little or no actual DHW consumption occurring in the building. If the heat demand of the DHW circulation system is, for example, 3–5 kW and the smallest power output of the heat pump unit is 30–40 kW, the operating conditions are challenging even with a properly dimensioned heat storage system. The performance and operation of the GSHP system installed in the studied case buildings will be constantly monitored, and improvements in the control strategy, heating set points, and other operating parameters are continuously performed in order to maximize the energy performance of the system without sacrificing the adequacy of DHW.

The developed system has already been installed in over 40 multi-family apartment buildings, the majority of the buildings are apartment buildings that have been renovated since March 2016, and all the installed systems have performed efficiently after the control strategy of the system has been fine-tuned and synchronized with the individual DHW consumption profile of the building. In general, this means that the DHW consumption profile of the building must first be determined and then co-optimized with the system performance of the GSHP system.

Future development of the novel GSHP system application should include research related to implementation of machine learning features in the building automation control unit, which controls and operates the entire GSHP system concept. Based on the recent development of machine learning applications used in the building sector, the implementation of the modern machine learning features has a high potential to significantly improve the operation and efficiency of processes such as the phased step-based heating of DHW developed in the study reported in Publication 5. Functional machine learning applications would make the co-optimization of individual DHW consumption profiles of different buildings and the performance and operation of the GSHP systems automatic and highly efficient. An interesting aspect for future development is to determine the improvements of the sewage water heat recovery system in the energy performance of the developed GSHP system concept by conducting individual laboratory or field measurements. Different heat storage alternatives, such as applicable tank-in-tank solutions, could also be considered for improved energy performance and reduced heat losses of the system in the future development of the concept.

5.5 Summary of the research

The research consists of six original publications that were carried out to fulfill the initial research objectives of the thesis. The research questions of the thesis address several different, yet still related, issues. Studies reported in Publications 1–4 are dealing with cost-optimal renovation strategies that can be applied in deep renovations of Finnish residential, educational, and office buildings built during different decades. As presented in the results of the studies reported in Publications 1–4, the modern renewable energy production technologies, and especially the modern heat pump systems, proved to be the cost-optimal main heating systems in all the studied building types. Therefore, the studies reported in Publications 5 and 6 focused on studying and developing the simulation methods related to estimating the performance of different heat pump applications operating in different case conditions.

Moreover, the research reported in Publication 5 focused on the development of the novel heat pump application that can be used for energy efficient heating of DHW. It is a well-known issue that the performance of heat pump systems decreases when the temperature level of the heating system increases, and therefore, it is important to develop methods that can be used to improve the operation and performance of heat pump applications. When the energy efficiency of both the building envelope and the ventilation system of the building are improved in deep renovations, the temperature level of the heating system can typically be decreased to a sufficient and energy efficient level (e.g., an original 80/60°C radiator heating system can be balanced to a 65/50°C or even to a 60/45°C temperature level) in regards to the energy performance and operational characteristics of the modern heat pump applications. However, heating DHW still remains an issue, as the temperature requirement of DHW is typically 55–60°C to prevent legionella growth. The research reported in Publication 5 aimed at developing a novel and energy efficient heat pump concept that would address this issue. In addition, the simulation environment (IDA ICE) of complex heat pump applications was further developed in the research reported in Publication 5 by utilizing the calibration methodology developed in the study reported in Publication 6 and by extensively testing both the simulation and control capabilities of the IDA ICE ESBO Plant simulation environment.

While the individual Publications 1–6 may appear somewhat disparate, their findings, connection, and relevance in the joint context defined by the title of the thesis is clear in regards to the above-mentioned aspects. As a summary, the outcome of all six publications can be connected to the joint topic of the thesis as follows:

- Publications 1–4 address the main objectives of the thesis: To determine the cost-optimal renovation concepts of typical residential, educational, and office buildings in the Finnish climate conditions toward nZEBs
    - Main findings: Modern heat pump technologies were determined to be cost-optimal main heating system concepts in all the studied building types.
- Publication 6 addresses an important objective supporting the main findings obtained from Publications 1–4: How accurate and reliable are the dynamic energy simulations of different heat pump systems operating at both standardized test conditions and actual case conditions?
    - Main findings: The studied and utilized IDA ICE simulation environment is an accurate and recommended platform to simulate the performance and operation of the modern variable condensing A2WHP, EAHP, GSHP, and hybrid heat pump systems. However, calibration of the default heat pump simulation models is required for accurate and reliable simulations. The developed calibration methodology proved to be efficient, fast, and simple to use in actual case studies, where the heat pump simulation model is required to be calibrated to correspond to the performance data of an actual manufacturer heat pump unit. The calibration methodology developed in Publication 6 was also utilized in the calibration and validation of the simulated heat pump models in the studies reported in Publications 1–5.
- Publication 5 complements Publications 1–4 and provides an advanced method to further improve the cost-effectiveness and energy performance of the heat pump systems: How can DHW be heated more efficiently with a heat pump system without decreasing the temperature level of DHW below the required 55°C temperature level?
    - Main findings: The developed method improved the energy efficiency of the DHW heating process by up to 45–50%. The performance was verified by comprehensive laboratory measurements. In addition, a functional simulation model of the novel

system was developed, tested, and validated in the study. The calibration methodology developed in Publication 6 was also successfully utilized in the validation of the simulation model. The novel DHW heating method developed in the study is interesting and feasible in all the building types studied in Publications 1–4, but it is particularly relevant and feasible in the residential apartment building types studied in Publications 1 and 3.

The literature review demonstrates that there is an increasing trend in research related to both development and utilization of SBO analyses as research methods. The literature review also demonstrates that the SBO approach has been successfully applied in numerous renovation studies. These aspects provide further justification for the use of SBO methods in the designing process of deep renovations. The majority of the previous studies have also concluded that the parametric-based analyses or individual simulation-based analysis techniques, including a limited number of predefined renovation cases (e.g., 5–30), cannot guarantee the cost-optimal renovation combinations that also meet different energy performance criteria due to the large number of potential renovation options. However, the literature review indicates that thorough understanding of the basic theory and main limitations related to the utilization of the SBO as a research method are required.

According to the literature review, the majority of the previous studies have focused on the development of different SBO methods that can be applied to determine the optimal renovation measures in different conditions and situations. The operation and performance of the developed SBO methods have been tested in different case studies undergoing energy retrofits, mandatory refurbishments of building envelopes and technical systems, and installations of renewable energy production technologies. The literature review demonstrates that the SBO methods are superior and recommended in detailed renovation studies where a large number of possible renovation alternatives is studied simultaneously, but the literature review also indicates that the usability and versatility of the SBO methods developed in the previous studies are the major limiting factors preventing the methods from gaining greater popularity among non-academic users.

This thesis demonstrates that a highly efficient SBO method can be successfully applied in deep renovations of several different building types, including multiple different optimized objectives, and that the usability and versatility of the applied method are sufficient to be used in the designing processes of deep renovations by consultants, designers, architects, and other non-academic users. Therefore, the thesis complements the existing literature related to the utilization of the SBO methods in renovations of buildings well.

In addition, the calibration methodology of heat pump simulation models developed in the thesis complements the existing literature related to the calibration of dynamic heat pump simulation models. Simple and efficient simulation model calibration methods are required because the rapid development of modern energy systems requires that reliable and validated simulation methods are needed to simulate the performance and operation of different heat pumps, renewable energy production, and complex hybrid energy systems. Furthermore, the literature review revealed that there was a limited number of calibration studies where functional and reliable calibration methods of heat pump simulation models were presented for the IDA ICE simulation environment, which is nevertheless a popular energy simulation tool internationally.

5.6 Evaluation of the research

Typically, the research quality is evaluated by the reliability and validity of the research. Reliability is normally related to demonstrating that the procedures and operations can be repeated and end with the same results. Basically, this means that if another person repeats the research by carrying out the same case study with the same research methods, the same conclusions and findings could be obtained. In order to achieve a high-level repeatability, the research process must be well documented.

In this research, all the essential data related to the original publications have been stored. The data include cost data of different renovation and retrofitting measures, energy simulation models of the studied case buildings used in the analyses, economic calculations conducted in the studies, energy consumption data of the buildings, and all the results of both the principal analyses and additional sensitivity analyses. In addition, all the multi-objective optimization settings and data and the research process have been carefully organized and stored. The tolerance of all the measurement equipment used in the laboratory measurement and on-site field studies is no more than ±2%, and all the measurement equipment was calibrated before the tests. The latest test reference year 2012 weather data, which is the official and the most recent weather data to be used in energy performance and power demand calculations of buildings, were used in all the simulations, calculations, and analyses.

The validity of quantitative research is typically divided into two aspects, the internal and external validities. Normally, the internal validity aims to answer the question: Was the research conducted correctly? The internal validity also aims to determine if more than one possible independent variable are acting simultaneously and affecting the outcome of the research (e.g., reliability of the cost data or accuracy of the building's energy simulation model). The external validity aims to answer the question: Can the results and findings of the research be generalized, or how well can the data and theory from one setting apply to another setting?

In this study, the assessment of the external validity mainly focuses on how well the results and conclusions of the study can be generalized to a larger building stock. Even though only one case building was investigated from each building type studied in the research, all the studied case buildings were carefully selected after a detailed survey, where typical features of the studied building types were determined. Studied features included sizes of buildings, technical and building services systems and their conditions, energy efficiencies and conditions of the building envelopes, and energy consumption data. Based on the results of the surveys, suitable and representative case buildings were selected for the research to represent the studied building types. The laboratory measurements conducted in Publication 5 were also carried out using realistic user profiles and operation environments. The optimization algorithm parameter values used in all the individual SBO analyses of the research were carefully selected after extensive consideration. The effect of the optimization algorithm parameter values on the convergence of the algorithm, accuracy of the results, and reliability of the SBO analyses carried out in the research was studied, tested, and critically approached.

In addition, all the results of the individual sensitivity analyses conducted in the research and several individual consultancy projects conducted for actual buildings outside this research provide similar findings and conclusions as the results presented in this summary and in the original publications. Furthermore, the characteristics of different building types built during the same eras (e.g., in the 1960s, 1970s, or 1980s) are very similar in Finland, so the same renovation concepts can be applied to a large building stock with relatively good accuracy, although the case-specific features should also be taken into account in every individual renovation project. Therefore, the research results provide renovation concepts for typical Finnish residential apartment buildings, educational buildings, and office buildings that can be generalized to a large building stock. In addition, all the conclusions derived from the research complement the conclusions and main findings of previous studies related to renovations of buildings well. Furthermore, the results and conclusions of the research can be generalized to deep renovations of buildings located in similar climate conditions and techno-economic environments.

Due to the complexity and versatility of the SBO analyses, the assessment of the internal validity of the research includes several factors. The main aspect of the internal validity process is to determine whether there are confounding variables included in the research that affect the conclusions derived from the results of the research. In high-quality research, the objective is to control as many confounding variables as possible, although all of them cannot typically be controlled. Examples of confounding variables included in this research are the cost data of different measures and energy carriers and the CO_2 emissions data used in the analyses.

While a significant share of the Finnish building stock is located in Helsinki, case buildings located in the city of Helsinki were not included in the analysis. The main reason for this was the pricing of district heating in Helsinki. The price of district heating is approximately 20–25% lower in Helsinki than the average Finnish district heating price. Using energy prices with this much deviation from the average energy price data would definitely affect the results. In fact, the conclusions regarding the economic viability of different heat pump and solar-based thermal production systems would likely be different as well. The results of the analysis would benefit building owners operating in the city of Helsinki, but they could not be generalized or utilized in other Finnish cities as well as they can be when more universal and applicable cost data are used in the analysis.

Another variable with a significant confounding effect is the CO_2 emissions data used in the analysis. Again, if more detailed city-specific CO_2 emissions data of different energy carriers were applied in the analysis, the results of the analysis would not be generalizable to a larger building stock. In some Finnish cities, the district heating energy is produced to a significant extent by RESs, while in other cities, fossil fuels are still used in the energy production of district heating. Utilizing city-specific data, where the district heating energy is produced solely by RESs, in the analysis would change the conclusions derived from the results regarding the cost-optimal renovation concepts to maximize the environmental impact reduction potential of residential apartment and office buildings. The same principle applies to electrical energy. If electrical energy produced by RESs was used in the analysis, the conclusions derived from the results of the study would likely be different again. The same principle can also be applied to the recommended renovation concepts. Unrealistic, infeasible, and non-functional renovation solutions must be identified and excluded from the recommended measures, even though they might be feasible and functional in a specific individual building.

In general, the internal validity of the research was carefully assessed and included in the research. However, as the research presented in this thesis includes several of these aforementioned confounding variables, and all of them cannot be controlled at the same, there are limitations related to the research, such as taking potential external financial supports of different renovation measures into account in the economic calculations or considering feasible financial solutions for building owners in order to conduct deep renovations of buildings beyond the cost-optimum level. The importance of the internal validity of the research was acknowledged and included in this thesis. In addition, the essential and relevant confounding variables and limitations related to the research were also identified and included as well as possible.

The research carried out in this thesis provides justified answers for all the original research objectives and questions defined in the beginning of the research.

5.7 Future research

Based on the results, findings, and limitations of the research carried out in this thesis, future research is also required. There are several aspects that are recommended to be addressed in future research. The first aspect is to determine competitive external financial solutions especially for apartment building owners to conduct deep renovations that exceed the cost-optimum level because the main motivation of apartment owners to conduct energy performance improvement measures is typically cost savings instead of environmental impact reduction. Competitive and usable financial solutions are required to be determined for other building types as well, in addition to apartment buildings. External financial support mechanisms and competitive financial solutions are perhaps the most important aspects in encouraging the building owners to take the next step in deep renovations of their buildings by lowering the economic risks related to the renovation.

The second aspect is to determine cost-effective renovation concepts for the studied building types built in the late 1970s, 1980s, and 1990s, as the development of national building regulations, performance of the building services systems, and energy efficiency of buildings built in different decades after the mid-1970s are typically different. In addition, while the studied case buildings represent the typical features related to the building envelope and the building services systems of the studied building types, further analyses are still recommended to be conducted for similar residential apartments and educational and office buildings located in cold climate conditions in the future to compare the results with the key findings and conclusions presented in this research.

The third recommended aspect is to conduct similar analyses for deep renovations of the studied building types located in different techno-economic environments and in different climate conditions, where the economic level of construction materials, technical systems, labor, and energy prices are different. Comparison of the results and findings would be interesting.

An interesting aspect that is also recommended to be addressed in future research is to study and compare the results of CO_2 emissions analyses, including applicable heat pump and renewable energy production systems, of apartment and office buildings located in different climate conditions with different CO_2 emissions factors of energy carriers.

An important aspect related to the results and recommended renovation concepts presented in this research is that extensive use of heat pump systems will likely change the energy policy because the consumption of district heating energy will decrease and the consumption of electrical energy will increase. According to the current knowledge of the national energy policy, the economic viability of both the exhaust air and the air-to-water heat pump systems used in existing residential apartment buildings will be high in the future as well, as they are typically used as an auxiliary heating system, which is combined with the original—typically district heating—main heating system. However, the economic viability of the GSHP system, which typically uses significantly more electrical energy, could change if the energy policy is drastically changed. This potential scenario, where heat pump systems are more extensively used in larger buildings (larger than detached and row houses), requires further research. The global optimum renovation concepts related to the heat pump systems will likely be different in this case as well.

More future research is required to better understand the concept of productivity loss in different climate conditions and to further develop the multi-objective optimization method that can be used to study and optimize both the indoor environment conditions and the environmental impact reduction potential in deep renovations of office buildings in more detail.

Finally, the economic viability, technical feasibility, functionality, and performance of the modern on-site renewable energy production systems located in different climates and operating conditions still require further research and validation. Future research related to the cost-optimum dimensioning and utilization of the renewable energy production technologies is also required. The development of simulation and modeling methods plays an important role in this matter because the rapid development of the modern energy systems requires that reliable and validated simulation methods are needed to simulate the performance and operation of different RESs and complex hybrid energy systems. Future research is also recommended to be conducted by installing and monitoring the developed novel GSHP systems in buildings, where both the techno-economic environment and climate conditions are different.

6. Conclusions

The existing building sector plays a significant role in restraining the global climate change by reducing the final energy consumption and greenhouse gas emissions of buildings. Cost-effective renovation of the existing building stock is a challenging and important task to significantly reduce the environmental impact of the built environment. Determining cost-effective renovation concepts for buildings inevitably leads to a multi-dimensional optimization problem because cost-effectiveness and energy efficiency are conflicting objectives with each other. The building owners are interested in solid renovation concepts that reduce the operating costs of the building together with a healthy and comfortable indoor climate but also deliver a reasonable ROI and a reasonable payback period.

The main objective of this thesis was to study and determine the cost-optimal renovation concepts for the common Finnish building types that also have a significant energy efficiency improvement and environmental impact reduction potential. The studied building types were typical brick apartment buildings, concrete large panel apartment buildings, educational buildings, and office buildings. The objective was to take all applicable energy efficiency improvement measures, including the modern heat pump and on-site renewable energy production technologies, into account in the assessment of each building type. In addition to studying the economic viability of different renovation concepts, technical, functional, feasibility, and quality aspects, such as the productivity of occupants in office buildings, were examined closely.

In addition to the individual renovation studies, a key objective of this thesis was to study, develop, and validate the current dynamic simulation methods used for analysis and optimization of complex energy systems. As the heat pump and other renewable energy production systems are increasing their popularity, validated accuracy and reliability of the simulation methods used in the analysis play an essential role in optimum dimensioning of the systems and in ensuring optimum operation of the systems. An essential objective of the research was to study and develop the modern optimization methods used for building performance analyses because the SBO analyses are increasing their popularity as a research method by making detailed analyses, where thousands or even millions of individual solution combinations are studied simultaneously, possible.

A common solution of the cost-optimal renovation concepts of all the studied building types was that the investments should be focused on renewable energy production technologies and on technical systems of the buildings instead of investing in major renovations of the building envelopes. Especially the modern heat pump systems delivered significant improvements in both the energy performance of the buildings and in the cost-effectiveness of the deep renovation in all the studied building types. The studied heat pump systems delivered better cost-effectiveness than the district heating system in all the studied building types. However, cost-optimal dimensioning of heat pump systems is case-specific and requires careful designing. If the building envelope requires major renovation measures due to its poor condition, it is not cost-efficient or recommended to improve the energy efficiency of the building envelope beyond the current national building regulations regarding the energy performance of new buildings. The energy efficiency improvement measures are always recommended to be integrated to the mandatory maintenance and repair measures of buildings to maximize the cost-effectiveness of the renovation.

According to the results, the cost-optimum level of the deep renovation was close to the minimum energy performance requirement level of new Finnish apartment buildings in both apartment building types. In educational buildings, the cost-optimum level of the deep renovation was close to the energy performance requirement level of the preliminarily proposed nearly zero-energy educational buildings. In office buildings, the cost-optimum level of the deep renovation was close to the current B class of the EPC. The results demonstrate that the current national minimum requirements for improving energy performance in renovations are not at the cost-optimum level and could be tightened. In deep renovations of residential apartment buildings, a 10% tightening in the minimum PE performance requirements is recommended. In deep renovations of educational buildings, a 30% tightening in the minimum PE performance requirements is recommended. Finally, a 20% tightening in the minimum PE performance requirements related to deep renovations of office buildings is recommended. External financial support mechanisms and competitive financial solutions are essential factors and motivators to encourage building owners to take the next step in deep renovations of buildings by lowering the economic risks related to the renovation. The proposed national nZEB requirements can be cost-effectively achieved in deep renovations.

The results demonstrated that it is highly profitable for office building owners to improve the indoor environment conditions in deep renovations of office buildings because the financial impact of productivity loss caused by unfavorable indoor environment conditions accounts for the most significant share in the economic calculations. Up to 65% ROI was achieved by the cost-optimal renovation concepts in deep renovations of owner-occupied office buildings, where the same organization is responsible for the salaries of employees and the operating costs of the building. The cost-optimal renovation concepts of office buildings included a balanced combination of renovation measures improving both the indoor environment conditions and the energy performance of the building.

According to the results, investments in the modern and optimally dimensioned renewable energy production technologies are highly recommended to significantly reduce the environmental impact of existing buildings when cost-effectiveness is discussed. New and highly efficient heat pump applications, such as the novel DHW heating application presented in this thesis, are also constantly developed, improving both the energy efficiency and cost-effectiveness of heat pump systems. However, extensive use of heat pump systems might change the energy policy and thus affect the economic viability of the heat pump systems replacing district heating.

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Cost-effective renovation of existing buildings is a challenging and important task to significantly reduce the environmental impact of the built environment. Determining cost-effective renovation concepts for buildings inevitably leads to a multi-dimensional optimization problem because cost-effectiveness and energy efficiency are conflicting objectives with each other. The building owners are interested in solid renovation concepts that reduce the operating costs of the building but also deliver a reasonable return on investment. The objective of this thesis was to determine the cost-optimal renovation concepts for the common Finnish building types that also have a significant energy efficiency improvement and environmental impact reduction potential. The study demonstrates that the proposed national nZEB requirements can be cost-effectively achieved in deep renovations. Investments in the modern and optimally dimensioned heat pump technologies are highly recommended to significantly reduce the environmental impact of the existing building stock.

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