Towards sustainability with building services systems

– by focusing on material choices, energy use and thermal indoor climates in residential buildings

Dahlblom, Mats

2020

Document Version:
Publisher's PDF, also known as Version of record

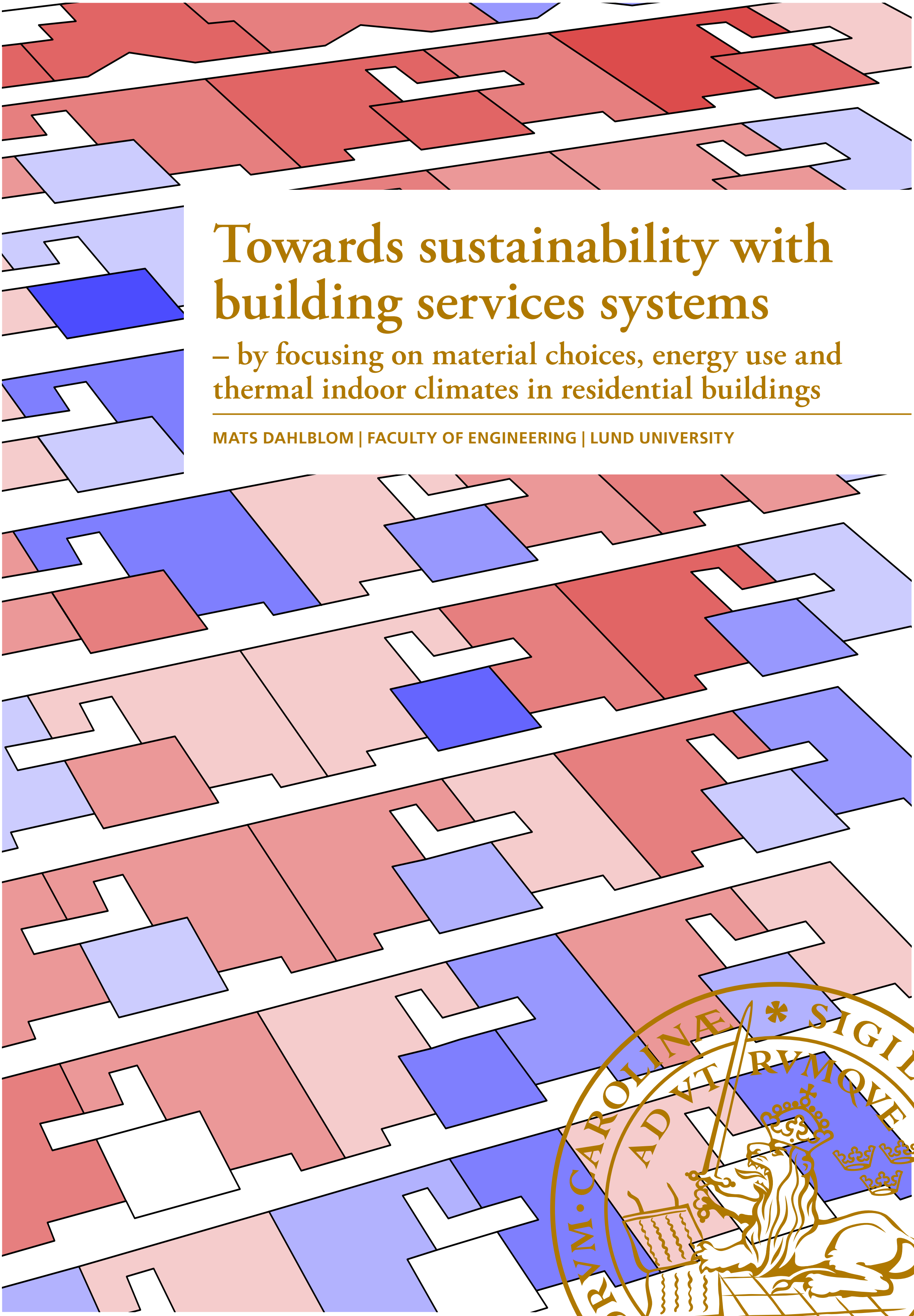
Link to publication

Citation for published version (APA):
Dahlblom, M. (2020). *Towards sustainability with building services systems: – by focusing on material choices, energy use and thermal indoor climates in residential buildings* (1 ed.). Avd Installationsteknik, LTH, Lunds universitet.

Total number of authors:
1

LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00



Towards sustainability with building services systems

– by focusing on material choices, energy use and thermal indoor climates in residential buildings

MATS DAHLBLOM | FACULTY OF ENGINEERING | LUND UNIVERSITY

Printed by Media-Tryck, Lund 2020 NORDIC SWAN ECOLABEL 3041 0903

Lund University
Faculty of Engineering
Department of Building and Environmental Technology

ISBN 978-91-85415-10-6
ISRN LUTVDG/TVIT—20/1001—SE(545)
ISSN 1652-6783

Towards sustainability with building services systems

– by focusing on material choices, energy use and thermal indoor climates in residential buildings.

Mats Dahlblom

DOCTORAL THESIS

by permission of the Faculty of Engineering, Lund University, Sweden.
To be defended at John Ericssons väg 1, the “V-huset” building, lecture hall V:B.
on 17 April 2020 at 1 p.m..

Faculty opponent
Prof. Tor Broström
from
Uppsala University, Department of Art History, Conservation.

Organization
LUND UNIVERSITY

Document name: Doctoral thesis

Date of issue: April 17th 2020

Author: Mats Dahlblom

Title and subtitle: Towards sustainability with building services systems – by focusing on material choices, energy use and thermal indoor climates in residential buildings.

Abstract For a development to be considered sustainable, social, economic and environmental requirements must be met. The Swedish sustainable development goals contain 16 national environmental quality goals. The National Board of Housing, Building and Planning is responsible for achieving the goal "A good built environment". Essential factors chosen for studies are: indoor environmental quality (IEQ) and material and energy use, as these have a major impact on the opportunities for the construction and real estate sector to achieve the goals of sustainable development. The overall aim of the thesis is to provide knowledge about how building services systems (BSS) in residential buildings can contribute to sustainable development in general.

The thesis begins with a literature review (Publ. I) followed by a case study (Publ. II) with life-cycle inventories and energy simulations for two multi-family buildings. Material types, quantities, manufacturing, transport and operating energies and the influence of material choice on the manufacturing energy were analysed. The conclusions were that few materials accounted for 80 % of the weight and for 80 % of the manufacturing energy in BSS, that material choice was an factor that influenced the manufacturing energy. It was found that the service life of materials and components, and reasons for replacements, were poorly known. This led to an interview survey (Publ. III) among property management companies. The reasons for carrying out replacements and the ages for components were analysed and categorized. An attempt was made to assess the service life of some components.

The second part of the thesis begins with a life-cycle cost analysis based on energy simulations and cost calculations. The profitability of a number of energy efficiency measures taken in a multi-family building was compared (Publ. IV). Increased investment costs are paid for by having lower energy costs. Heat recovery with ventilation heat exchangers and exhaust air heat pumps results in about the same life-cycle cost.

A real estate company used a system for individual metering and billing (IMB) of space heating costs, in which the tenants paid for having a specific temperature, which meant that room temperatures were measured in all living rooms and bedrooms. In some estates a feedback control system, based on indoor temperature measurements, was introduced. The purpose was to achieve more even and lower indoor temperatures. The feedback control was evaluated by comparing the independence of the indoor temperatures on the outdoor temperature before and after implementation (Publ. V). The control method clearly indicated a lower dependency.

Based on a large data set with temperature measurements a comprehensive study of the indoor thermal conditions was carried out (Publ. VI). The buildings had hydronic heating systems with feedforward control. Temperatures were almost normally distributed and seemed to vary randomly and independently of location in the building. There was a tendency for cool apartments to be cool all year-round and vice versa. Generally, the temperatures were lower in bedrooms than in living rooms. (Publ. VII). Using a mathematical model of a multi-storey building, it was shown that there was a heat flow up through the building via the floor slabs. (Publ. VIII).

During the heating season, the temperature gradients were measured in ten apartments in a three-storey multi-family building, the gradients being measured for a week in each apartment. The measured gradients were generally smaller than those calculated by the IMB system (Publ. IX).

An additional study was conducted in which the effects of the energy efficiency measures on the energy use in one of the buildings from a previous case study were examined.

The various studies are discussed under the section headings Material resources, Energy use, Indoor environment quality, Laws and regulations and Sustainability concept trends. Issues such as replaceability, flexibility and user interaction are also addressed.

Key words: residential apartment buildings, building services systems, energy use, hvac, hydronic heating system, heating control, feedback control loop, indoor temperature measurements, individual metering and billing, indoor temperature variations, thermal comfort, vertical temperature gradient, case study

ISRN: LUTVDG/TVIT—20/1001—SE(545)

Language: English

ISSN and key title: 1652-6783 Towards sustainability with building services systems

ISBN: 978-91-85415-10-6

Recipient's notes

Number of pages: 545

Security classification

Signature

Date 2020-03-03

Towards sustainability with building services systems

– by focusing on material choices, energy use and thermal indoor climates in residential buildings.

Mats Dahlblom

LUND
UNIVERSITY

Cover picture by Mats Dahlblom

Faculty of Engineering
Department of Building and Environmental Technology
Division of Building Services

ISBN 978-91-85415-10-6
ISRN LUTVDG/TVIT—20/1001—SE(545)
ISSN 1652-6783

Printed in Sweden by Media-Tryck, Lund University
Lund 2020

Printed matter
3041 0903

Media-Tryck is a Nordic Swan Ecolabel
certified provider of printed material.
Read more about our environmental
work at www.mediatryck.lu.se

MADE IN SWEDEN

Finally…

Preface

This thesis was carried out at the Division of Building Services, LTH at Lund University, Sweden. Due to financial matters and work-related commitments, mainly teaching on several courses, work has been in progress for more than twenty years with one long and a number of short breaks.

The first part of this thesis, completed 1998–2001, formed a licentiate dissertation and was part of “Sustainable Building”, a Swedish national research program funded by ByggMISTRA – the Swedish Foundation for Strategic Environmental Research. The program dealt with buildings and their environmental impacts from a life-cycle perspective (Edén & Jönsson, 2002).

The second part, completed 2010–2019, was partly funded by CERBOF, the Centre for Energy and Resource Efficient Construction and Facilities Management, partly by Boverkets Byggkostnadsforum (National Board of Housing, Building and Planning – Forum for Construction Costs) and partly by LKF (the City of Lund´s municipal housing company) who provided a large dataset of indoor temperatures. The final work was financed by the Division of Building Services.

During all these years I have received valuable and indispensable support from my colleagues and I would particularly like to thank my supervisors, both for their formal and informal encouragement, over the years: Professor Lars Jensen – without him this work would not have been possible; Dr. Birgitta Nordquist – my closest colleague who was always ready to discuss ideas and give advice; Dr. Dennis Johansson – for really encouraging me and relieving me from some of my teaching duties to give me the opportunity to complete the work.

I would also like to thank all other, former and present, dear colleagues at Building Services and at our sister division Building Physics, all of whom have been my working-day family for many memorable years.

Limhamn, January 2020

Mats Dahlblom

Abstract

For a development to be considered sustainable, social, economic and environmental requirements must be met. The Swedish sustainable development goals, based on Agenda 2030, contain 16 national environmental quality goals. The National Board of Housing, Building and Planning is responsible for achieving the goal "*A good built environment*". Essential factors chosen for studies are: indoor environmental quality (IEQ) and material and energy use, as these have a major impact on the opportunities for the construction and real estate sector to achieve the goals of sustainable development. The overall aim of the thesis is to provide knowledge about how building services systems in residential buildings can contribute to sustainable development in general.

The work behind the thesis consists of two parts. The first part begins with a literature review (Publication I) followed by a case study (Publication II) with life-cycle inventories and energy simulations for two multi-family buildings. Material types, quantities, manufacturing, transport and operating energies as well as the influence of material choice on the manufacturing energy were analysed. The conclusions were that only a few materials accounted for 80 % of the weight and for 80 % of the manufacturing energy in building services systems, that material choice was an important factor that influenced the manufacturing energy. Furthermore, it was found that the service life of materials and components, as well as reasons for replacements, were poorly known. As this is an uncertainty factor when carrying out life-cycle analyses it led to an interview survey (Publication III) being conducted among property management companies to increase knowledge in these fields. The reasons for carrying out replacements and the ages for components in building services systems in nine estates are analysed and categorized. The study concluded that there were multiple reasons for replacements and the deciding factor was often unclear. An attempt was made to assess the service life of some components. The assessment revealed large uncertainties, either because the data material was limited or because the reality is unpredictable. These three publications formed a licentiate dissertation, approved 2001.

The second part of the thesis begins with a life-cycle cost analysis based on energy simulations and cost calculations. The profitability of a number of energy efficiency measures taken in a multi-family building was compared (Publication IV). Increased investment costs are paid for by having lower energy costs. Heat recovery with ventilation heat exchangers and exhaust air heat pumps results in about the same life-cycle cost, but an exhaust air heat pump means a greater electricity demand.

A residential real estate company used a system for individual metering and billing (IMB) of space heating costs, in which the tenants paid for having a specific temperature, which meant that room temperatures were measured in all living rooms and bedrooms. In some estates a feedback control system, based on indoor

temperature measurements, was introduced. The purpose of the method was to achieve more even and, on average, lower indoor temperatures, which would hopefully result in lower energy needs for heating. The feedback control was evaluated by comparing the independence of the indoor temperatures on the outdoor temperature before and after implementation (Publication V). The control method clearly indicated a lower dependency.

Based on a large data set with temperature measurements during two heating seasons a comprehensive study of the indoor thermal conditions was carried out (Publication VI). The buildings in question had hydronic heating systems with feedforward control. Temperatures were almost normally distributed and seemed to vary randomly and independently of location in the building. There was a tendency for cool apartments to be cool all year-round and vice versa. Systematic variations were observed both during the day and between weekdays and weekends. Temperature variations within apartments were studied according to apartment size (Publication VII). Generally, the temperatures were lower in bedrooms than in living rooms, and the more rooms the larger the differences. Using a mathematical model of a multi-storey building, it was shown that there was a heat flow up through the building via the floor slabs (Publication VIII).

During the heating season, the temperature gradients were measured in ten apartments in a three-storey multi-family building, the gradients being measured for a week in each apartment. The measured gradients were generally smaller than those calculated by the IMB system, which indicated that tenants were invoiced for lower temperatures than those actually achieved (Publication IX).

An additional study was conducted in which the effects of the energy efficiency measures on the energy use in one of the buildings from a previous case study were examined and it was found that increased heat recovery increased the environmental classification grade.

The various studies are discussed under the section headings Material resources, Energy use, Indoor environment quality, Laws and regulations and Sustainability concept trends. Issues such as replaceability, flexibility and user interaction are also addressed.

Sammanfattning

För att en utveckling ska anses hållbar måste mål ur såväl sociala, ekonomiska som miljömässiga aspekter vara uppfyllda. Det svenska miljömålssystemet, baserat på Agenda 2030, innehåller 16 miljökvalitetsmål och ett antal etappmål. För genomförande och uppföljning ansvarar åtta myndigheter, av vilka Boverket har ansvar för målet ”En god bebyggd miljö”. Faktorer som har valts att studera är inomhusmiljö och material- och energianvändning eftersom dessa har stor påverkan på möjligheterna för bygg- och fastighetssektorn att nå målen med hållbar utveckling. Avhandlingens övergripande syfte är att tillföra kunskap om hur VVS-installationer i bostadsbyggnader kan bidra till en hållbar utveckling.

Avhandlingsarbetet, som har pågått i mer än tjugo år, består av två delar. Första delen inleds med en fallstudie (Publikation II) med livscykelinventeringar och energisimuleringar för två flerbostadshus. Materialslag, mängder, tillverknings-, transport- och driftenergier samt inverkan av materialval på tillverkningsenergin har analyserats. Slutsatserna var att ett fåtal material svarade för 80 % av vikten och tillverkningsenergin vid framtagning av VVS-installationer, att materialval hade betydelse för tillverkningsenergin. Vidare konstaterades att materialens och komponenternas livslängder liksom orsaker till byte var dåligt kända, en osäkerhetsfaktor vid livscykelanalyser, vilket ledde till att en intervjuundersökning (Publikation III) genomfördes bland fastighetsförvaltande företag för att öka denna kunskap. De orsaker till byte av installationer och deras ålder som angavs för nio fastigheter med hyreslägenheter analyserades och kategoriserades. Studiens slutsatser var att orsakerna till byten ofta var flera, men vilken som var avgörande var oklart. Ett försök att bedöma livslängd för ett antal komponenter gjordes. Livslängdsbedömningen gav stora osäkerheter, antingen för att datamaterialet var litet eller för att verkligheten var sådan. Dessa tre publikationer utgjorde en licentiatavhandling godkänd 2001.

Avhandlingens andra del inleds med en livscykelkostnadsanalys baserad på energisimuleringar och kostnadsberäkningar. Lönsamheten för ett antal energieffektiviseringsåtgärder för ett flerbostadshus jämfördes (Publikation IV). Ökade investeringskostnader tjänades med marginal in genom lägre energikostnader. Värmeåtervinning med ventilationsvärmeväxlare respektive med frånluftsvärmepump gav ungefär samma livscykelkostnad, men frånluftvärmepump ledde till större elenergibehov.

Ett bostadsfastighetsbolag introducerade i en stor del av sitt bestånd en metod för individuell värmemätning och debitering (IMD), där hyresgästen betalade för temperatur, inte levererad energi, vilket innebar att rumstemperaturen mättes i alla vardagsrum och sovrum. I några fastigheter infördes feedbackreglering baserad på rådande medeltemperatur i byggnaden, som komplettering till den utetemperaturstyrda värmeregleringen. Metodens syfte var att uppnå en jämnare och

i medeltal lägre inomhustemperatur som kunde resultera i lägre energibehov för uppvärmning. Feedbackregleringen utvärderades genom jämförelse av innetemperaturens beroende av utetemperaturen före och efter implementeringen (Publikation V). Reglerprincipen gav tydligt ett lägre beroende.

Baserat på ett stort datamaterial med temperaturmätningar för två uppvärmningssäsonger, från nyss nämnda fastighetsbestånd, genomförs en omfattande undersökning av det termiska klimatet i bostäder (Publikation VI). I byggnaderna, som hade feedforwardreglering var temperaturerna nära normalfördelade och tycktes variera slumpmässigt oberoende av läge i byggnaden. Det fanns en tendens att svala lägenheter var svala året om och vice versa. Systematiska variationer såväl över dygn som mellan vardag och helg iakttogs. Temperaturvariationer inom lägenheter studerades per lägenhetsstorlek (Publikation VII). Generellt var temperaturen lägre i sovrum än i vardagsrum, ju fler rum desto större skillnad fanns. Med en matematisk modell av ett flervåningshus visades att det fanns ett värmeflöde upp genom byggnaden via bjälklag (Publikation VIII).

Under uppvärmningssäsong genomfördes mätningar av temperaturgradienten i några lägenheter i trevåningshus. Temperaturgradienten mättes under ca fem dagar i varje lägenhet. Uppmätta gradienter var generellt mindre än de som beräknades i IMD-systemet, vilket antyder att hyresgästerna debiterades för lägre temperatur än de hade (Publikation IX).

Dessutom genomfördes en kompletterande studie, där energieffektiviseringsåtgärders inverkan på energianvändningen för en av byggnaderna från tidigare fallstudie studerades med resultat att ökad värmeåtervinning kunde höja betyget vid miljöklassning.

De olika delstudierna diskuteras i sektionerna Materialresurser, Energianvändning, Inomhusmiljö, Lagar och regler samt Trender inom området hållbar utveckling. Frågor såsom utbytbarhet, flexibilitet och interaktion med användare behandlas.

Contents

1 Introduction

> *Imagine yourself in the most fabulous building in the world. Now take away the lighting, heating and ventilation, the lifts and escalators, acoustics, plumbing, power supply and energy management systems, the security and safety systems ... ... and you are left in a cold, dark uninhabitable shell. Building Services "bring buildings to life".* (CIBSE[1])

As building services form several important parts of our buildings they have to be designed, manufactured, constructed and managed to give the lowest possible environmental impact during a building's life cycle while still fulfilling all the requirements to achieve a healthy indoor climate with good thermal, visual and acoustic comfort. Building services must also contribute to sustainable development, specifically social, economic and environmentally sustainable development, of which all three equally important.

Figure 1.1 illustrates these three overlapping areas, also known as the "triple bottom line" (Elkington, 1997). Whatever a person, a company, a society, etc. undertakes, all three aspects must be taken into account, otherwise the subject in question cannot be considered sustainable.

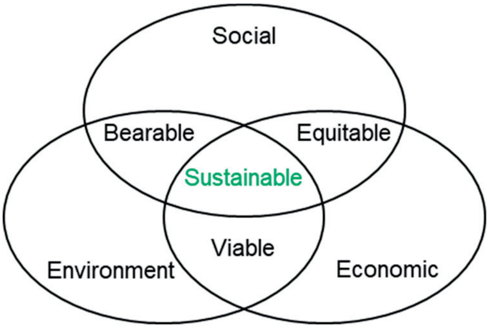


Figure 1.1 Venn diagram illustrating the aspects of sustainability or triple bottom line.

---

[1] Chartered Institution of Building Services Engineers

1.1 Background

To put the subject into a wider context, some aspects of sustainability are presented on global and national levels in this section. Also included are some statistics concerning Swedish conditions with respect to energy use, population and building stock. These are followed by some indoor environment quality aspects, energy performance requirements and tools used for rating buildings from an environmental point of view.

1.1.1 Global sustainability

“Sustainable development” is a broad concept launched in 1987 in the Brundtland Report (United Nations, 1987). It is defined as *"a development that satisfies today's needs without compromising the ability of future generations to satisfy their needs"*. The Brundtland report was developed by the United Nations World Commission on Environment and Development under the chairmanship of Gro Harlem Brundtland, prime minister in Norway (1981, 1986–89 and 1990–96). The report constituted the ideological framework for the UN Environment Conference in Rio de Janeiro in 1992 (commonly referred to as the Rio Conference), with participants from 172 states, of which more than 100 were represented at State or Government level (United Nations, 1992).

The conference was the final step of a two-and-a-half-year long process and led to the adoption of “Agenda 21”, which sets up goals and guidelines to reach sustainable development. It is divided into three main sections: Section I concerns “social and economic dimensions”, Section II concerns “conservation and management of resources for development” and Section III concerns “strengthening the role of major groups”. The agenda also recommends that local agendas should be developed. By 2000, 70 % of the municipalities in Sweden had adopted local agendas. However, the efforts to implement them were weak (Nationalkommittén för Agenda 21 och Habitat, 2003).

The foundation for the work on sustainable development was the “United Nations Conference on Human Environment”, the first international conference was held in Stockholm in June 1972 and therefore also called the “Stockholm Conference”. The conference motto was “Only one earth” and was initiated by the Swedish government. Immediately after the “UN Environment” was formed, in which around 190 countries are members. This is also known as the first “Earth Summit”. One outcome was the Stockholm Declaration in which Principle 21 is held as one of the most important parts.

> *”States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental policies,*

> *and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction.“*

After the Stockholm Conference there have been Earth Summits every ten years: the second was held in Nairobi in 1982, the third in Rio de Janeiro in 1992 (see above), the fourth in Johannesburg in 2002 and the latest took place in Rio de Janeiro in 2012. Besides these, starting in 1995, the UN arranges yearly conferences, the United Nations Climate Change Conferences, which are the formal meetings for the United Nations Framework Convention on Climate Change.

The outcome from Johannesburg was the “Plan of Implementation of the World Summit on Sustainable Development” and the “Johannesburg Declaration on Sustainable Development”. The declaration is an agreement to focus particularly on "the worldwide conditions that pose severe threats to the sustainable development of our people”.

The outcome from Rio de Janeiro in 2012, also called the Earth Summit 2012, was the document “The Future We Want”, which largely reaffirms previous action plans such as Agenda 21.

The United Nations Sustainable Development Summit for the adoption of the post-2015 development agenda was held as a high-level plenary meeting of the General Assembly in New York in September 2015. The meeting adopted the resolution “Transforming our world: the 2030 Agenda for Sustainable development”. The agenda consists of 17 sustainable development goals and 169 targets.

The goals of Agenda 2030 for Sustainable Development

1. End poverty in all its forms everywhere
2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3. Ensure healthy lives and promote well-being for all at all ages
4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5. Achieve gender equality and empower all women and girls
6. Ensure availability and sustainable management of water and sanitation for all
7. Ensure access to affordable, reliable, sustainable and modern energy for all
8. Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
9. Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
10. Reduce inequality within and among countries
11. Make cities and human settlements inclusive, safe, resilient and sustainable
12. Ensure sustainable consumption and production patterns

13. Take urgent action to combat climate change and its impacts
14. Conserve and sustainably use the oceans, seas and marine resources for sustainable development
15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16. Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17. Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

The intention is that every country in the world should work to achieve the goals. Each country´s government is responsible for achieving the goals in their own country. This should be done in cooperation between national and local authorities, organizations and associations, researchers and industry, assisted and encouraged by UN. The goals are to be implemented and achieved in every country from the year 2016 to 2030 (United Nations, 2015).

1.1.2 National sustainability

At a national level, based on the 17 sustainable development goals, the Swedish government adopted 15 national environmental quality objectives (EQOs) in 1999 and in 2005 the 16th objective was adopted, see list below.

1. Reduced Climate Impact
2. Clean Air
3. Natural Acidification Only
4. A Non-Toxic Environment
5. A Protective Ozone Layer
6. A Safe Radiation Environment
7. Zero Eutrophication
8. Flourishing Lakes and Streams
9. Good-Quality Groundwater
10. A Balanced Marine Environment, Flourishing Coastal Areas and Archipelagos
11. Thriving Wetlands
12. Sustainable Forests
13. A Varied Agricultural Landscape
14. A Magnificent Mountain Landscape
15. A Good Built Environment
16. A Rich Diversity of Plant and Animal Life

In 2010, a revised plan, the “Swedish Environmental Objective System”, was adopted which also included a new overall goal of the Swedish environmental policy, called the “*generational goal*”. Over the years, the Swedish Parliament has adopted a number of additional and revised interim targets. These targets are replaced on an ongoing basis with milestone targets, which define the steps on the way to achieving the environmental quality objectives and the generational goal. Decisions on these milestone targets are taken by the Government. Over the years, up to September 2018, about 30 milestone targets have been decided, of which about 20 have not yet been achieved (Naturvårdsverket, 2019b). The targets cover five areas: reduced climate impact, air pollution, biodiversity, dangerous substances, and sustainable urban development and waste. They do not specify a desired state of the environment but do identify where and in what direction measures should be taken and what steps will help to reach the generational goal. A continuously ongoing evaluation of the environmental quality objectives is carried out by government agencies and reported annually.

The Swedish Environmental Protection Agency (Swedish EPA) (Naturvårdsverket, 2019a) has the main responsibility to follow up and evaluate the progress made to achieve the specific environmental goals. Eight national government agencies are responsible for following up and evaluating one or more of the 16 environmental quality objectives (EQO´s). Other agencies work within their respective sectors to promote progress towards the objectives. EQOs 1–7, 9 and 15 are mentioned as relevant for the building and real estate management sector in Sweden, with numbers 1, 4 and 15 as especially relevant (Toller et al, 2011).

The Swedish EPA has surveyed, with the help of the seven other agencies, how the UN’s global goals in Agenda 2030 relate to the Swedish environmental objective system and its 16 environmental quality objectives as well as the generation goal. The National Board of Housing, Building and Planning (NBHBP, Boverket) is responsible for goal number 15: “*A good built environment*” and states that the UN’s goals 3, 9, 11 and 12 all relate to the Swedish environmental quality objective number 15. These goals concern health and well-being, resource economy in terms of energy and material use, sustainable planning and management, recycling and reduced waste generation.

1.1.3 Sustainability in the building sector in Sweden

To follow up objective 15, *A good built environment*, Boverket uses the following indicators (Boverket, 2018a):

- Emission of greenhouse gases
- Emission of nitrogen oxides
- Emission of particles
- Use of fossil fuel

- Use of biofuel
- Use of health and environmentally hazardous chemical products
- Generated waste

The environmental indicators show emissions to air, energy use and waste generation in the building sector, in absolute and relative terms, and their development over time. They show environmental impact from a life-cycle perspective, i.e. from all phases of their existence: production, construction, operation, demolition, recovery and transport. Environmental impacts both upstream and downstream are taken into account, Figure 1.2. (Boverket, 2016).

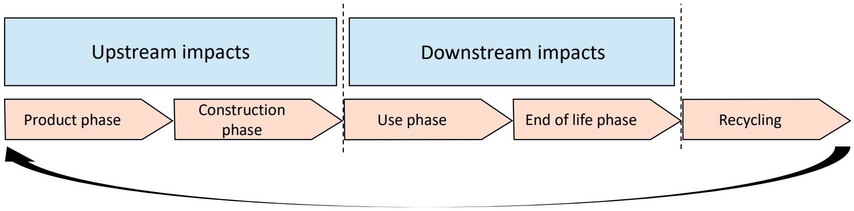


Figure 1.2 The phases in the life cycle of a building (Boverket, 2016).

An example from the follow-up of the indicators for energy use in the construction and real estate management sector in Sweden is shown in Figure 1.3 and Figure 1.4.

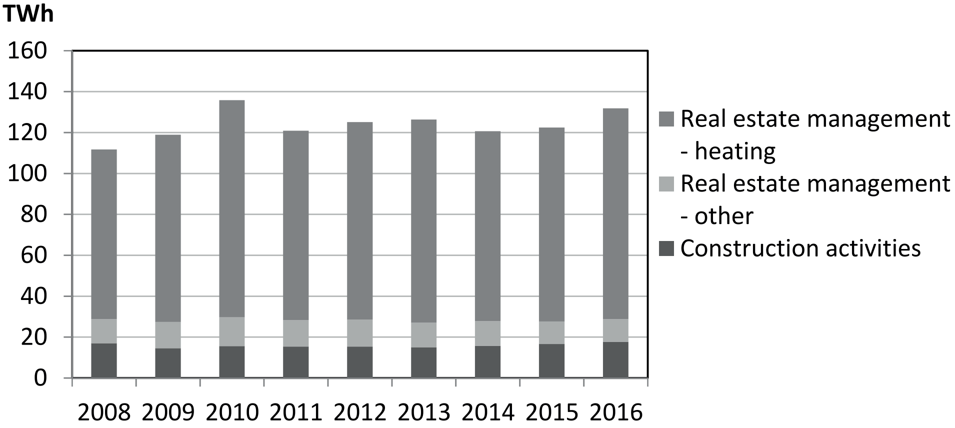


Figure 1.3 Development of total energy use for the construction and real estate management sector in Sweden (national + imported) with respect to use (Boverket, 2019b).

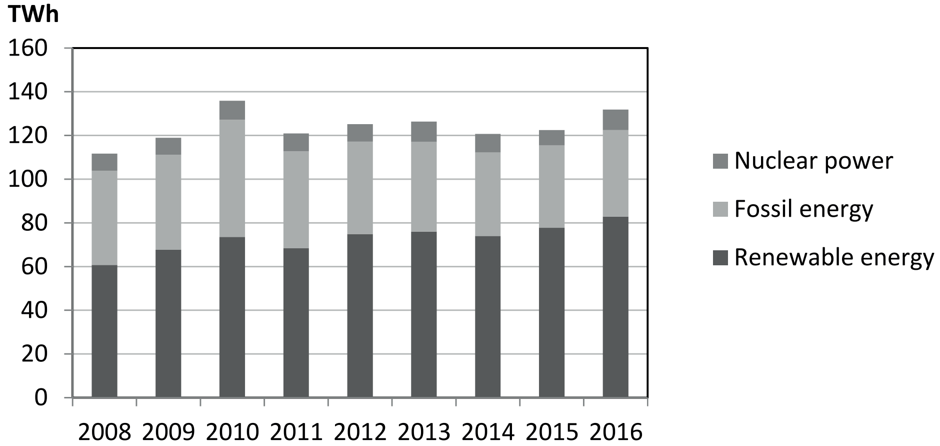


Figure 1.4 Development of total energy use for the construction and real estate management sector in Sweden (national + imported) with respect to energy types (Boverket, 2019b).

In Figure 1.4 it can be seen that energy use has not really changed between 2008 and 2016, though the built area has increased (Table 1.1). The opinion of the Swedish Environmental Protection Agency is that "It is not possible to achieve the environmental quality objective (A Good Built Environment) by 2020 on the basis of policy instruments already decided on or planned".

All the indicators are connected to use of energy and material resources and they all focus on the external environment. To reach a Good Built Environment it is, of course, also necessary to achieve a good indoor environment in all aspects. We must create good and healthy indoor climates with respect to indoor air quality, moisture conditions, thermal conditions, the sound and light environment, with the lowest possible material and energy use. NBHBP carried out an in-depth evaluation of the Good Built Environment objective in 2019 (Boverket, 2019a) in which the thermal indoor climate, indoor air quality and noise are mentioned as areas that must be addressed to reach this objective.

For the construction and real estate sector to reach sustainability, there are a number of factors that have major impacts on both the outdoor environment and the indoor environment and, therefore, are of great importance to study: (i) the indoor environment, because it directly affects human health as we spend about 90 % of our time indoors in our climate (Schweizer et al, 2007), (ii) the use of materials that entails the utilization of natural resources with accompanying energy use and emissions to the environment, because the choice of materials can directly affect the indoor environment and (iii) energy use during a building's use time, which accounts for a significant part of the environmental impact from the real estate sector. This thesis will therefore focus on these three areas.

Data concerning energy, indoor air quality and thermal comfort in the Swedish building stock, with focus on residential buildings, is presented in the following sub-subsections.

1.1.3.1 Basic statistics regarding energy use, population and building stock in Sweden

The total heated area of the Swedish building stock in 2005 was estimated to be 686 000 000 m² (Boverket, 2007). The distribution of types of buildings is shown in Figure 1.5. Data is available for the years 2000, 2004 and 2005 and the differences are small. The residential buildings (single-family and multi-family buildings) constitute the majority of all Swedish buildings, with respect to heated areas.

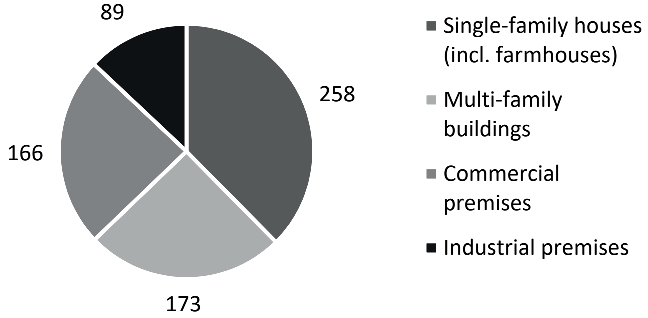


Figure 1.5 Total heated area, million m², of the Swedish building stock in 2005, According to type of building (Boverket, 2007).

Some statistics concerning energy use, population and heated area in Sweden for 1999 and 2015 are presented in Table 1.1, in Figure 1.6 and Figure 1.7. Data was retrieved from Statistics Sweden (2018a, b) and from the Swedish Energy Agency (2018a, b).

Sweden's final energy use is usually divided into three sectors; (i) industry, (ii) transport and (iii) residential and services. The figures for the three sectors for 1999 and 2015 can be seen in Table 1.1. The total energy use for 1999 was 392 TWh, which means that the residential and services sector accounted for 39 % of the used energy. The total energy use for 2015 was 370 TWh, with the residential and services sector again accounting for 39 %. There was a small decrease, though the figures are not climate-corrected, and it may have been within the margin of error. In addition, approximately 155 TWh were recorded for losses and non-energy use (e.g. in the chemical industry and for lubricating oils).

During these 15 years the population in Sweden increased from 8.9 million to 9.9 million (SCB, 2018a), an average growth of 0.7 % per year, and the heated area increased from approximately 600 million m² to approximately 650 million m²

(Swedish Energy Agency, 2018), an average yearly increase of 0.5 %. During the same period, the number of housing units (HU) increased from 4 to 4.7 million (SCB, 2018b), an average yearly increase of approximatively 1 %.

Table 1.1 Basic statistics for energy use, population and building stock in Sweden in 1999 and 2015.

Year	1999	2015
Energy use in the industrial sector /TWh	150	140
Energy use in the transport sector /TWh	91	87
Energy use in the residential and services sector /TWh	151	143
Population	8 900 000	9 900 000
Heated area /m²	600 000 000	650 000 000
Number of housing units (HU)	4 000 000	4 700 000
Total energy use per capita /(kWh/person)	44 000	37 400
Spec. energy use for residential and services /(kWh/m²)	250	220

The total number of housing units in Sweden was almost 4.9 million in January 2018. 43 % were single-family houses, 50 % were in multi-family buildings, 7 % were in housing units for elderly, students and other categories.

The number of housing units in the Swedish building stock at the beginning of 2016 were distributed as shown in Figure 1.6. 56 % of the single-family houses and 77 % of multi-family buildings were built before 1970. More than a third of the housing units were constructed during the period 1960–1980.

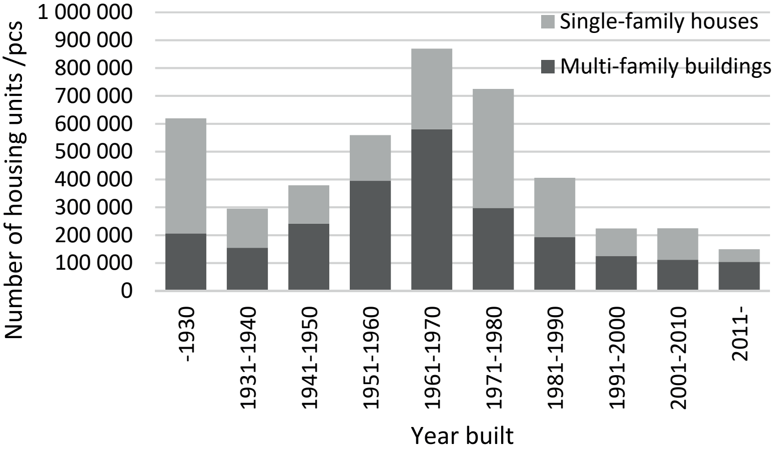


Figure 1.6 Number of housing units in 2016 and Year built (Statistics Sweden, 2018).

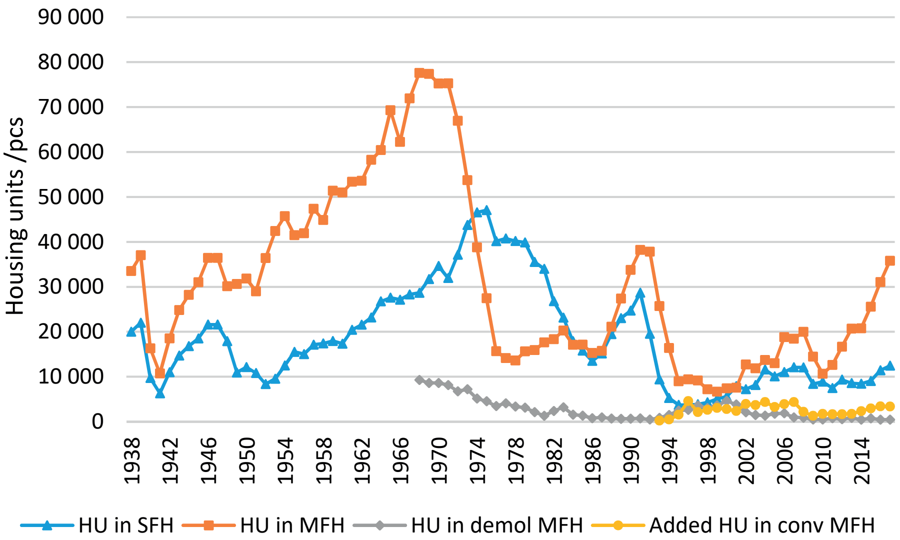


Figure 1.7. Number of completed housing units (HU) shown as single-family houses (SFH), units in multi-family buildings (MFH) (1938-2017), also shown are demolished housing units (1968–2017) and housing units added in converted multi-family buildings in Sweden (1993-2017) (Statistics Sweden, 2018).

The need for new housing units in Sweden according to NBHBP (Boverket) is estimated to be 80 000 units per year until 2025. Influencing factors include overcrowding, urbanization and immigration. Despite this need, a decline in housing construction is forecast, due to recessions in the economy (Sveriges Byggindustrier, 2018).

The replacement rate of housing units is fairly low (Figure 1.6 and Figure 1.7). Newly-built houses are generally more energy efficient than old ones and efficiency requirements are expected to become even stricter. And, although energy efficiency measures are implemented in existing buildings, the buildings will rarely reach the same energy efficiency levels as in new builds. Accordingly, the major part of the building stock will still need large amounts of energy for space heating and it will be necessary to operate the buildings as effectively as possible.

1.1.3.2 Indoor environmental quality (IEQ)

The four most frequently mentioned physical parameters that affect residents' well-being are thermal comfort, indoor air quality, visual comfort and acoustic comfort. The mechanical environment, such as ergonomics and vibrations, is also included in the parameters. An extensive literature review on the impact of indoor environmental quality on the residents' well-being is presented in Al Horr et al (2016). They conclude that it is a complex relationship and necessary to understand to be able to create sustainable buildings. Some background statistics regarding thermal conditions and air change rates from surveys conducted on the Swedish building stock are described briefly in the following.

Thermal comfort

Thermal comfort is a result of a combination of environmental factors and personal factors. The environmental factors include air temperature, temperatures of surrounding surfaces, air velocity, air humidity, vertical temperature gradient and radiant temperature asymmetry. The personal factors include clothing and activity levels. The concept that takes into account these factors describes the comfort experienced by a human being and is called the operative temperature.

Operative temperature is defined as “the uniform temperature of an enclosure in which a resident would exchange the same amount of heat by radiation and convection as in an existing non-uniform environment” (SIS, 2001).

The operative temperature can be negatively affected by the building envelope. The poorer the building envelope, due to poor insulation and poor airtightness, the more the operative will be affected. During the heating season the inner surfaces of the external walls and windows will have low temperatures, which directly lower the operative temperature and, in turn, often lead to higher indoor air temperatures to compensate. Furthermore, poor airtightness, which leads to draught problems, may also lead to a desire for a higher air temperature in a room, to compensate both for the draught and the increased heat losses. From an energy efficiency perspective this is not the correct way to address the problem. During warm summer periods the opposite situation might occur, possibly leading to a desire for comfort cooling.

During the heating season from October 2007 until April 2008, the NBHBP (Boverket), commissioned by the Swedish Government, carried out a nationwide survey of the Swedish building stock. The survey, called BETSI (acronym for Buildings Energy, Technical Status and Indoor environment), included energy use in buildings, their technical status and their indoor environments. It was a statistical survey in which each selected building corresponded to a specific number of other similar buildings and the results were extrapolated to cover the entire Swedish building stock. Data was collected through surveys, measurements and questionnaires, drawings were studied, and interviews were conducted with property owners and property managers (Boverket, 2009).

The results of temperature measurements carried out every 15 minutes showed that the mean temperature in single-family house was 21.2 ± 0.2 °C and in residential apartments it was 22.3 ± 0.2 °C. The temperatures in both categories were often lower in older buildings than in newer buildings. Figure 1.8 shows the frequencies of different indoor temperatures in the study.

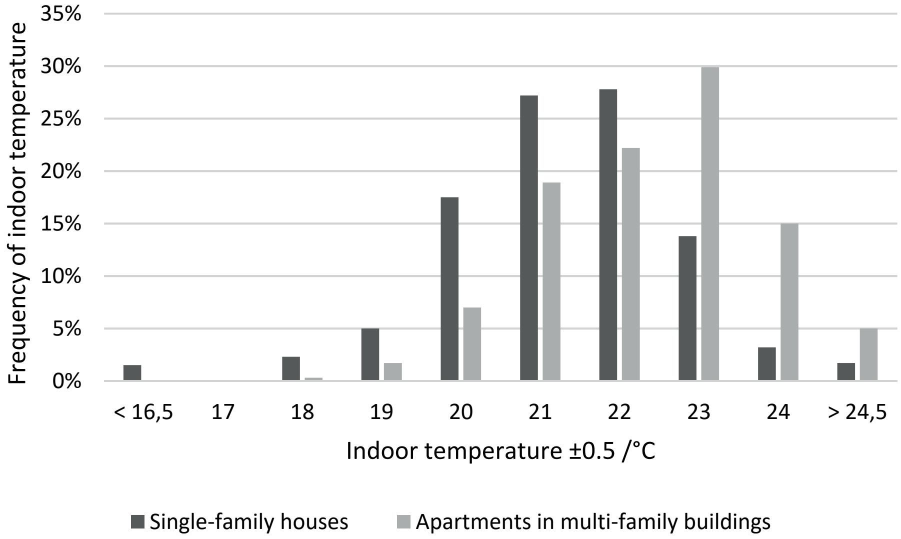


Figure 1.8 Frequencies of measured indoor temperatures during the heating season from October 2007 until April 2008 in single-family houses and apartments in multi-family buildings. (Boverket, 2009a).

Indoor air quality

The indoor air quality can be affected by several pollutants, particulate and gaseous, emanating from pollutants outdoors or produced indoors by the residents and their activities, and from interior materials.

As a national average, the air change rate was 0.40 air changes per hour (ACH) in single-family houses and 0.52 ACH in residential apartments. Figure 1.9 shows the frequencies of different ACHs measured in the BETSI study. The result can be compared to the requirements in the Swedish building codes (BBR) at that time, which was 0.35 L/s per m² floor area, corresponding to 0.5 ACH for a room with a height of 2.5 m. Nearly 78 % of the single-family houses and 52 % of the apartments did not meet the requirements in the building codes.

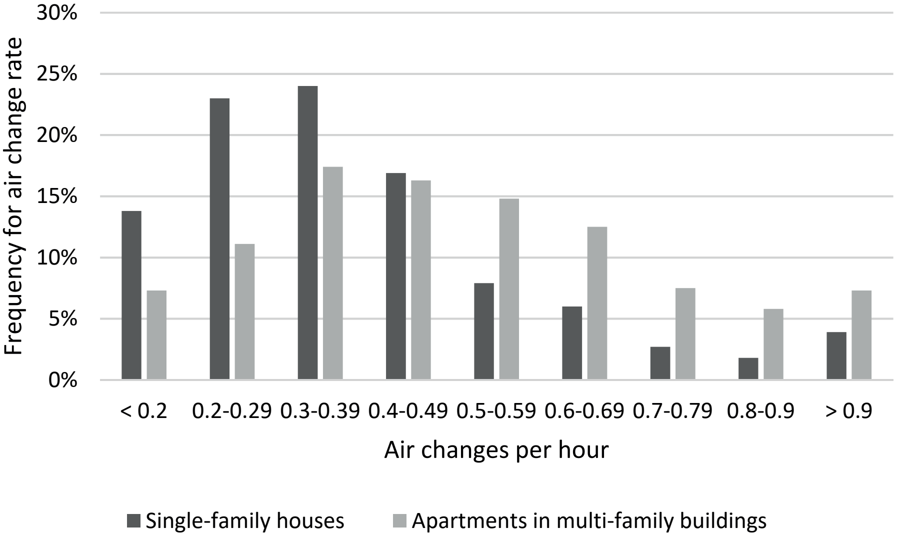


Figure 1.9 Frequencies of measured air change rates during the heating season from October 2007 until April 2008 in single-family houses and apartments in multi-family buildings. (Boverket, 2009a).

1.1.3.3 Energy performance requirements stipulated in the Swedish building code

Before the energy crisis in 1973, the Swedish energy policy focused on ensuring energy supplies to the nation. The building codes were not really concerned about energy management at all. Their main concern was the design of buildings and their installations in order to achieve a healthy and good indoor climate, both from thermal comfort and indoor air quality aspects. From 1978, in a supplementary code to the 1975 code (Statens planverk, 1976), the requirements regarding U-values were made considerably stricter and requirements regarding maximum air leakages were introduced. The next version of the building code, SBN 80 (Statens planverk, 1980), introduced requirements regarding better energy efficiency in whole buildings. Instead of only limiting heat transfer coefficients for different building elements, the overall average heat transfer for a whole building was not to exceed that for a “reference building”, with maximum U-values stipulated for all building elements, which provided flexibility when designing a building. The building code maximized heat loss, expressed as $W/(m^2K)$, together with a maximized air leakage factor expressed as $L/(s \cdot m^2)$ at a 50 Pa pressure difference across the building envelope. Small revisions were then made over a quite long period. This principle meant that the system boundaries for energy use were located within the building and all types of energy were valued equally, for example, it did not matter whether a heat-pump had a low or high COP. All energy directly delivered from the building services systems was included.

The principle of limiting the energy use for heating was changed in the BBR 12 building code (Boverket, 2006). The building code then stated that a residential building was allowed to use a maximum amount of energy per square meter heated area (HA), excluding household electricity. This meant that the specific energy use expressed as kWh/m^2_{HA} was given a limit. This limit was dependent on building use and geographical location. After two years of operation, it had to be shown that the real energy use met the requirements. During the following years the requirements gradually became stricter. The system boundary then included energy generated in a building's own systems, such as via thermal solar panels and photovoltaic panels, but limited to the amount that the building could utilize. When calculating the specific energy use, all energy, with the exception of energy generated in the building's own systems, delivered by the building services systems should be included, and household and occupants' operational electricity use excluded.

From 2017 the energy use in a building was required to be expressed as primary energy. This meant that the system boundary was moved from delivered energy to also include losses in production and delivery systems. In practice this meant that different energy sources were given different weighting coefficients and production and delivery losses were to be taken into account. When calculating the energy use, all energy used to generate and distribute the delivered energy had to be taken into account, with "primary energy factors" being differentiated depending on energy source. This meant that a building's energy use measured as primary energy would be dependent on the type of energy source (Boverket, 2018c).

The next step will probably be to take other environmental effects, besides energy use, of a building into account, e.g. emissions to the air, waste, and the use of environmentally and health hazardous chemical products. Initially this could be done by requiring a life-cycle analysis, at a reasonable level, to be carried out for new buildings. (Boverket, 2018b).

1.1.3.4 Material use

A building uses material and energy resources in all phases of its life cycle, from "cradle to grave". A building's life cycle can be divided into three main phases: The first phase, the pre-use phase, comprises resources for the production of materials including the extraction of raw materials, transport and the manufacturing of products, as well as the construction of the building, including transport. The next phase, the use phase, is the longest, usually at least fifty years, and includes all activities and measures taken during occupancy, i.e. operation, maintenance as well as small and large renovations. The last phase, the end-of-life phase, includes demolition of the building, sorting, transport, re-use, recycling and/or deposal.

1.1.3.5 Rating tools

Except for the above-mentioned requirements in the Swedish building code, there is, worldwide, a large number of different, often voluntary, systems for rating or certifying buildings, processes, organizations, companies, etc.

The overall aim of these systems is to push the boundaries for sustainability. The systems assess and certify whether the buildings, processes, etc. meet specific requirements or standards, e.g. with regard to energy use and IEQ, and can thereby attain a certain rating level. (World GBC, 2018).

The leading organization for sustainable urban development in Sweden is the Sweden Green Building Council (SGBC), which is a member of the World Green Building Council, the global network of Green Building Councils. The most commonly used system in Sweden for certification is “Miljöbyggnad” (eco-building). It was developed in Sweden for Swedish conditions. The rating levels are Bronze, Silver and Gold. SGBC is also responsible for BREEAM-SE, an adaptation of BREEAM, the oldest international certifying system, as well as for a Swedish adaptation of the LEED™ Green Building Rating System, reckoned as the internationally most well-known rating system, developed and administrated by the U.S. Green Building Council. Among other things, these systems take into account energy use, green-house gases, chemicals used in materials, indoor air quality and indoor thermal climate. (SGBC, 2018).

To expedite the implementation of energy efficiency measures in the real estate sector, a system called Green Building was developed within the European Union (EU). If you managed to decrease a building’s energy use to a level at least 25 % below the requirements in the national building code the building can be labelled as a “Green Building”. (SGBC, 2018).

Besides the above-mentioned certification systems, there are several other systems for environmental classification, both in Sweden and in other countries.

Several European countries have regulations and definitions (official, semi-official or unofficial) regarding the requirements a building must meet to be classified as a “low-energy house”, a “passive house” or a “zero-energy house”. The terms used may differ from one country to another. Standards and criteria for low-energy buildings in nine European countries were studied by Thullner (2010). In Sweden the criteria were developed by the Swedish Forum for Energy Efficient Construction (Forum för Energieffektivt Byggande, FEBY), founded in 2010 as a non-profit member-based organization. The latest criteria, FEBY18 – Specification of requirements for energy-efficient buildings, were published in 2018. Instead of the terms low-energy house, passive-house and zero-energy house, the ratings bronze, silver and gold were introduced, with even stricter requirements. (Forum för Energieffektivt Byggande, 2018).

In the United States there is a certification system called “Energy Star”, in which anything from small electrical appliances to large buildings can be certified. However, the requirements for homes and buildings differ between the states from east to west and north to south. (Energystar, 2019).

Many efforts to integrate different rating systems such as BREEAM, LEEDS, Swedish Miljöbyggnad, etc. into BIM-systems have been made. Biswas et al (2009) have suggested a framework to address the requirements when integrating different rating systems into BIMs to support sustainable design processes. One problem that was identified concerned importing updates of the rating systems into BIM systems.

1.2 Research scope

In the light of what is described in the different sub-sections of Section 1.1, it would be reasonable to conclude that everyone must contribute to the changes ahead, to "saving the earth" and to striving towards a sustainable society from all aspects: environmental, economic and social. This requires major changes at all levels throughout the world.

To reach the climate goals everyone must do what they can. It is necessary to have both a bottom-up and a top-down approach, in all sectors. To achieve the overall goals of sustainability, as presented in the background, more knowledge is required regarding how building services installations should be designed, manufactured, constructed and managed to give the lowest possible environmental impact during a building’s life cycle while fulfilling all the requirements to achieve a healthy indoor climate with good thermal comfort.

1.3 Aims and objectives

The overall aim of this thesis is to examine important aspects regarding how building services can contribute to push residential buildings towards sustainability.

The thesis focuses on building services for heating, ventilation, water and sanitation in buildings, or more specifically:

- Material use during a building’s life cycle.
- Energy use during a building’s life cycle.
- Indoor thermal comfort and how to control it.

1.4 Process

This thesis is a compilation thesis, which consists of scientific reports, journal articles and conference papers. The first part presents results from research carried out between 1998 and 2001. The outcome of this research is presented in three scientific reports written in Swedish (Publications I – III). Together they formed a licentiate dissertation, defended and approved in February 2001. Summaries in English are presented in Chapter 3.1 – 3.3. The complete publications are appended. The second part of the thesis presents results from research carried out between 2012 and 2018. The outcome of this research is presented as articles in peer-reviewed scientific journals (Publications V – VI) and as papers at peer-reviewed international conferences (Publications IV, VII, VIII and IX). Short summaries of these are presented in Sections 3.4 – 3.9. The complete publications are appended.

The work on this thesis started with a literature study to obtain a picture of the state of the art in the research field. Gaps were found concerning which materials and what amounts were being used in building services for heating, ventilation, tap water and sanitation and the energy use for producing and transporting them.

A life-cycle inventory was therefore carried out, to obtain more knowledge about material and energy flows in systems and components in building services. From this study it was concluded that the use phase of maybe 50 years was crucial for the total energy use. It was also found that the knowledge about the service life of systems and components and the reasons for their replacement were poor.

As a gap was found in the data about the service life of different materials and components, the next study tried to find out which factors decided the service life of materials and components used in building services. This study was carried out with structured personal interviews with respondents in different positions in the property management sector.

These early studies led to the conclusion that most of the environmental impact was created during the use phase, i.e. the energy use during at least the first 50 years would be decisive. Therefore, it is of paramount importance to run a building in the most energy-efficient way possible. To do this, the systems must quite simply deliver just as much energy as is needed at every moment to achieve the desired indoor climate.

A major part of the energy demand for a building in the Nordic climate during the use phase is for heating. The predominant heating system in Sweden is a hydronic heating system with hot water radiators. The water can be heated by a boiler or heat-pump but is mostly done by district heating systems via a heat exchanger. Independently of how this is done, a control system is necessary, i.e. a system that controls the temperature of the supply water. The predominant control principle used is based on feedforward signals, which are based on the properties of the building and the heating system and on the prevailing outdoor temperature. This guarantees a hot water supply temperature that at its lowest provides the set point temperature in the building. Using this control principle there is a risk, that should not be ignored, of excess temperatures. These can be caused by, among other things, internal heat gains and solar gains.

This led to the study that investigated the effects that a feedback control system could have in terms of having less influence from outdoor temperature on indoor temperature. The study was made in buildings with existing hydronic heating systems with a feedforward control system, on which a feedback control method was applied based on indoor temperature measurements. At the same time an attempt to find out the potential for space heating energy saving was made.

However, it is also important to investigate the sustainability aspects of achieving a good built environment. A number of investigations regarding prevailing indoor temperatures were available, but only a few showed more than average temperatures for whole buildings. A more nuanced picture was desirable both in order to know what actually occurred in buildings and to be able to make more accurate energy simulations. Together, these ideas initiated further studies of thermal indoor comfort from different aspects.

The publications in which the focused areas were treated are shown in Table 1.2, and Table 1.3 lists who was responsible for the research printed in the different publications.

Table 1.2 Primary references to the studied areas in the appended publications, I – IX. Improve heading layout in table

Studied area **Publication**	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**
Material amounts	x	x							
Product manufacturing energy	x	x							
Transport energy		x							
Space heating energy		x		x	x				
Domestic hot water energy		x		x	x				
Communal electricity				x	x				
Thermal indoor climate					x	x	x	x	x
Reasons for replacement			x						
Service life	x		x						
Life-cycle cost				x					
Control	(x)				x				

Table 1.3 Participation in the publications.

Publication	Distribution of work
I	Dahlblom was sole author and carried out all the research.
II	Dahlblom was sole author and carried out all the research.
III	Dahlblom was sole author and carried out all the background research. Chapter 4, An attempt to assess service life, was carried out in cooperation with Jensen.
IV	Dahlblom carried out the energy simulations. Johansson carried out the LCC-calculations. Both contributed to the writing.
V	Dahlblom was the main author and carried out the analyses. Nordquist contributed to the writing and supervised the work. Jensen and Dahlblom wrote the Matlab scripts. LKF provided temperature data.
VI	Dahlblom was the main author and carried out the analyses. Nordquist contributed to the writing and supervised the work. Jensen and Dahlblom wrote the Matlab scripts. LKF provided temperature data.
VII	Dahlblom was the main author and carried out the analyses. Nordquist supervised and reviewed the work. Jensen and Dahlblom wrote the Matlab scripts.
VIII	Dahlblom and Jensen contributed to the writing. Jensen created the model and wrote the Matlab scripts. The analyses and the writing were carried out by both authors.
IX	Dahlblom was the main author and carried out the analyses. Nordquist contributed to the writing and supervised the work. Jensen and Dahlblom wrote the Matlab scripts. Nordquist, Wallentén and Harderup carried outcarried out the measurements.

1.5 System boundaries and limitations

It must be mentioned that installations for building services exist in a larger context, they form actual parts of a building. A building and its building services are intimately connected, they function together and affect each other, and practically all buildings have building services systems. Furthermore, a building exists for a reason, a purpose, and the indoor environment should fulfil the requirements for that purpose. The occupants and their activities will affect the indoor environment and vice versa. How a building and its services are designed and controlled and the requirements the users have will have a direct effect on the energy needs. A holistic approach must be applied.

The scope, however, has to be limited. In this thesis focus has been placed on the building services systems in residential buildings in Sweden, which constitute the largest proportion of the heated areas in the Swedish building stock.

To place the studied areas in a context, Figure 1.10 provides a schematic overview of the three main phases during a building's life cycle with activities and resources.

The pre-use phase causes upstream environmental impacts, the use phase and end-of-life phase causes downstream impacts (Figure 1.2). The areas focused on in this thesis are shown in bold type.

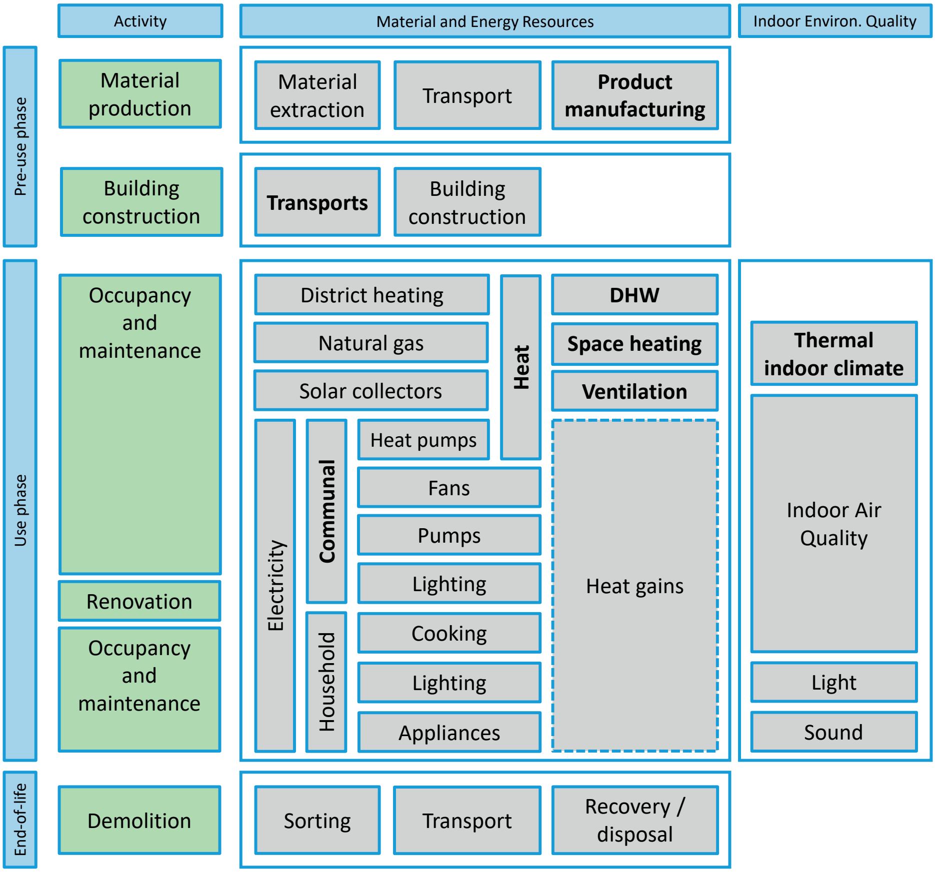


Figure 1.10 Overview of the three main phases during a building's life cycle with activities and resources. Focus areas in this thesis are highlighted in bold type. (The size of each box is insignificant.)

This thesis addresses the building sector and examines the building stock in all phases of a building's life cycle, though it is concentrated on the building services for heating, ventilation, tap water and sanitation under Swedish conditions. Only residential buildings, in which these systems are very important, have been investigated, mostly multi-family buildings, but also groups of terraced houses.

Only material- and energy use in the different phases is handled, i.e. neither carbon dioxide equivalents nor other indicators that can be included in a LCA, are analysed.

1.6 Research questions

This thesis investigates the following research questions:

- What materials, material amounts and energy flows can be associated with building services installations in residential buildings?
- What are the reasons for replacing building services installations and at what age are they replaced?
- What opportunities are there to motivate energy efficiency measures based on LCC analyses?
- What are the possibilities of achieving indoor temperatures that are less dependent on the outdoor temperature when using feedforward enhanced by feedback to control the indoor temperature?
- What distribution and variation of indoor temperatures could be found in residential apartment blocks from the 1960s with individual metering and billing of space heating costs?
- What annual, monthly and daily differences and variations in indoor temperature could be found within and between the residential apartments of different type and size?
- What influence does improved insulation have on vertical heat transport and indoor temperatures in multi-storey buildings?
- What vertical temperature gradients occur inside radiator heated rooms and how do they affect temperature measurements in an IMB system?

The answers to these questions will, hopefully, contribute to knowledge regarding how a building and its building services installations can contribute to developing social, economic and environmental sustainability.

1.7 List of publications

The thesis consists of the following publications:

I. Dahlblom, M. (1999a). Installationer ur ett livscykelperspektiv – En litteraturstudie. [Building Services Installations from a Life-Cycle Perspective – A Literature Review.] (Rapport TABK–99/3058). Building Science, Lund University, Lund, 1999. 97 p.

II. Dahlblom, M. (1999b). Material- och energiflöden i VVS-installationer – Fallstudie. [Material- and Energy Flows in Building Services Installations – Case Study.] (Rapport TABK–99/3059). Building Science, Lund University, Lund, 1999. 102 p.

III. Dahlblom, M. (2001). Orsaker till byte av VVS-installationer – En intervjuundersökning. [Reasons for Replacement of Building Services Installations – An interview survey.] (Rapport TABK–01/1020). Building Science, Lund University, Lund, 2001. 131 p.

IV. Dahlblom, M. & Johansson, D. (2009). Decreasing energy use of industrially produced multi-family dwellings in Sweden, Proceedings of Cold Climate HVAC, Sisimiut. Greenland, 8 p.

V. Dahlblom, M., Nordquist, B. & Jensen, L. (2018). Evaluation of a feedback control method for hydronic heating systems based on indoor temperature measurements. Energy and Buildings 166 (2018) 23-34.

VI. Dahlblom, M., Nordquist, B. & Jensen, L. (2015). Distribution and variation of indoor temperatures in apartment blocks with individual metering and billing of space heating costs – on building, apartment, and room level. Energy Efficiency (2015) 8: 859-880.

VII. Dahlblom, M., Nordquist, B. & Jensen, L. (2014). Variations in indoor temperature in residential apartments of different size and building category, NSB 2014: 10th Nordic Symposium on Building Physics, 15-19 June 2014 Lund, Sweden. 830-837.

VIII. Dahlblom, M. & Jensen, L. (2014). Vertical temperature increase in multi-storey buildings, NSB 2014: 10th Nordic Symposium on Building Physics, 15-19 June 2014 Lund, Sweden. 814-821.

IX. Dahlblom, M., Nordquist, B., Wallentén, P., Harderup, L-E. & Jensen, L. (2019). Vertical temperature gradients in apartments with hydronic radiator heating, Cold Climate HVAC 2018: Sustainable Buildings in Cold Climates. Springer, 575-585.

2 Methods

Philosophers have traditionally divided epistemology into two arts, rationalism and empiricism. In rationalism the main source of knowledge is logical thinking by a person using a deductive method for conclusions, i.e. a logical consequence. In empiricism the main source of knowledge is personal experience using an inductive method for conclusions, i.e. by generalization. However, the most used method in empiricism is the hypothetic-deductive method (Persson and Sahlin, 2013). Furthermore, according to the scientific approach, it is often divided into positivism and hermeneutics (or interpretivism). Traditionally, quantitative methods are applied in positivism and qualitative methods in hermeneutics. A third approach, pragmatism, in which mixed methods are used, is a third approach proposed by Mitchell (2018), among others.

When planning and carrying out research studies it is necessary to consider what methods that could be used and what conclusions that could possibly be drawn depending on the method chosen. In this thesis, a number of different methods have been used, from literature studies, case studies and interviews to simulations and the development of physical models. The methods used were mainly quantitative, but with qualitative elements and they could possibly be characterised as pragmatic. An overview of the methods used are shown in Table 2.1 and they are described in more detail and motivated in the sections below.

Table 2.1 Overview of the methods used in the appended publications, I – IX.

Publication	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**
Method									
Literature study	x	x	x	x	x	x	x	x	x
Case study		x	x	x	x	x	x	x	x
Life-cycle inventory (LCI)		x							
Energy simulation - Enorm		x							
Energy simulation - VIP+/VIP Energy				x					
Life-cycle cost analysis (LCC-analysis)				x					
Interviews			x						
Measurements					x	x	x	x	x

2.1 Literature review

An initial literature review is presented in Publication I. Literature searches were carried out in the LIBRIS database hosted by the National Library of Sweden, in databases such as IBSEDEX, BRIX/Flair, NTIS, Compendex, Pascal and Byggdok and via several internet sites. The references used were technical reports, books, papers in scientific journals and from scientific conferences, and articles in popular science magazines. The reference selection was carried out with the restriction that it would reflect and be applicable to Swedish conditions. Literature studies were also carried out throughout the whole work.

2.2 Case study

In all studies, except the literature review, data from real buildings was used to carry out the studies. The concept "case study" meant "a study that takes the context into account, i.e. the studied phenomenon is not isolated from its surroundings". A study of one or a few single cases can give a wider and deeper understanding (Gerring, 2004). In this thesis, both qualitative and quantitative data collections have been used. The studies were based on existing documents and should be characterised as retro-perspective case studies (Säfsten and Gustavsson, 2019).

2.3 Simplified life-cycle inventory

A life-cycle assessment (LCA) is divided into four main phases: goal and scope definition, life-cycle inventory (LCI), impact assessment and interpretation. A complete LCA should comprise all phases from cradle to grave and take into account resource use, human health and ecologic consequences. The method chosen in Publication II is a simplified LCI. The goal for the study was to obtain knowledge of the materials, material amounts and energy amounts that were used in systems for building services for tap water, sanitation, space heating and ventilation in two buildings with residential apartments. The scope of the study was limited to the pre-use and use phases of two buildings, more specifically to the material and energy use for manufacturing, transport and operation. The functional unit used for comparison was kWh/m^2_{HA} over fifty years.

This limited method was considered sufficient to fulfil the aim of the study. Two residential buildings were selected for the case study, one with 6 apartments and the other with 47 apartments for elderly people. Based on drawings and technical specifications, an inventory of the materials used and their amounts was drawn up. Means of transport and distances from factories to the building sites were estimated.

Energy use and types of energy for production and transport were retrieved from databases for LCA.

2.4 Life-cycle cost analyses

One housing company used a construction principle in which volumetric modules were produced in a factory and thereafter transported to the actual building site where they were mounted in a steel skeleton. To be able to legally transport the modules on the road the size of a module was restricted. After assembly on site the roof was constructed and the façades were insulated, and a panel or brick façade was added. Stricter energy codes forced the company to improve the energy performance. To evaluate which of a number of possible measures and combinations of these was the better alternative, life-cycle cost analyses were carried out. The life-cycle cost included increased initial costs, energy use during the first fifty years of service life, and increased maintenance costs during this time. This made it possible to compare and select the most favourable combination of measures.

2.5 Energy simulations

As a method to estimate annual energy use energy simulations were carried out in 2 studies. In Publication II and Publication IV two different programs were used to simulate energy use during a building's operational phase, i.e. for space heating, domestic hot water (DHW) and operational electricity. In Publication II the Enorm 1000 software was used (Munther, 1996). For the energy calculations presented in Publication IV the VIP+ software was used (Strusoft, 2007) and for the complementary study, presented in Chapter 4, the VIP Energy software was used (Strusoft, 2012).

2.6 Interviews

In Publication III - Reasons for replacement of building services installations, structured personal interviews with a few selected representatives from the property management companies were carried out. In collaboration with each company the persons were selected from the most relevant positions. The reason for this approach was that different companies had different organizational structures. In addition, the age of the building stock, the strategies for replacement, etc, in different companies were most likely to differ, both between the companies and over time. To facilitate explanation of the questions, by asking supplementary questions, and to reach a higher response rate the interviews were carried out with the help of a questionnaire with structured questions (Newcomer, 2015; Säfsten and Gustavsson, 2019). The questionnaire was drawn up based on a range of possible answers and tested in a pre-interview. The interviews aimed to verify the hypothesis among a small number of respondents. This method can be characterised as both qualitative and quantitative as the respondents' answers were interpreted and some were quantified and numerically analysed.

2.7 Temperature measurements

A large part of this work (Publications V, VI, and VII) was based on temperature measurements retrieved from a municipal housing company in southern Sweden. The temperature measurements were conducted in all bedrooms and living rooms in 10 estates, comprising 1177 rental apartments with 3248 rooms in total and during almost 2 years. The main purpose of these measurements was to create a basis for individual metering and billing (IMB) of space heating in the apartments. The IMB system was managed by the property manager and from their point of view it was necessary to find a robust system with reasonably cheap temperature sensors and acceptable accuracy, in this case ± 0.15 °C. The system was programmed by the system provider to retrieve indoor temperatures every 15 minutes, as that was considered to provide sufficient resolution for the main purpose.

The study presented in Publication IX was based on temperature measurements carried out in ten residential apartments in estates built in the 1960s. With two data loggers and two external sensors mounted inside a black painted spherical globe, mounted on a stand at four heights above floor level, temperatures were recorded every 5 minutes. This sampling interval was chosen to monitor behaviour related temperature changes caused by, for example, window airing. More details are presented in Publication IX.

3 Appended publications

The appended scientific publications are of different character. Publications I, II and III were, according to praxis when they were published, written as technical reports in Swedish. Together they formed a licentiate dissertation, defended and approved in February 2001. Publications V and VI were peer-reviewed journal articles. Publications IV, VII, VII and IX were peer-reviewed conference papers. All publications had been published. In Sections 3.1 – 3.9 there are summaries of all the publications showing their aims, main results and conclusions. The methods used are presented in Chapter 2.

3.1 Publication I – Building services from a life-cycle perspective

The start of the work with this thesis was a literature overview of the state of the art in the field of building services from a perspective of sustainability. The study covers energy during the pre-use phase and use phase as illustrated in Figure 1.10.

3.1.1 Introduction

This publication (a report in Swedish) consists of a literature review regarding the current level of knowledge around 1999. The aim of the study was to learn about sustainability in general and to investigate the state of the art within the area of building services installations. The study looked at the subject in general, service life, life-cycle analyses of materials and components in building services, operation and maintenance of installations for building services, and aspects of environmentally sound construction.

3.1.2 Method

The method used is described in Section 2.1.

3.1.3 Results

The main part of the findings dealt with investigations into life spans or the service life of different building services, most of them concerned sewage pipes made of cast iron and plastic. The importance of commissioning, management and maintenance to achieve well-functioning services and, consequently, a lower environmental impact, was also described. The reviewed publications about environmental assessments report one study on material amounts in ventilation system and three publications written about systems for environmental classification of building services and components. Publications about refurbishments reported that it was not always failures in design or components that were the reasons for replacement. The reasons could be economical, social, functional, legal, and obsolescence or the implementation of alternative technical solutions.

3.1.4 Conclusions

From this literature study the following conclusions were drawn:

The service life of materials and components is a central and complicated concept and the data used with regard to service life was mostly assumed, i.e. not calculated or experienced.

Material and energy flows for building services are poorly known.

Little is known about the reasons for the replacement of parts and components in building services systems.

Great efforts have been made to find ways of reducing water damage caused by building services.

With regard to the need for flexibility, this will probably not lead to drastic increases in capacity demands on building services, with the possible exception of ventilation systems.

3.2 Publication II – Material and energy flows in building services

As one of the conclusions from the literature study was that there was a lack of knowledge about both material and energy flows in building services, this study was subsequently initiated and carried out. This publication covers the subjects denoted in bold type in the pre-use and use phases, under the heading Material and Energy Resources, as shown in Figure 1.10.

3.2.1 Introduction

The aim of the study presented in Publication II (a report in Swedish) was to determine material quantities, manufacturing energy, transport energy for deliveries from manufacturers to the building site, all with respect to the building services.

3.2.2 Method

The study was carried out as a case study of two residential buildings, A and B. An inventory of materials used for tap water, sanitation, space heating and ventilation services was carried out based on drawings, specifications and other relevant documents. Information about the materials and amounts in each product and component, as well as regarding manufacturing energy, was obtained from the manufacturers' environmental product declarations, from other documentation and from internet databases (see Appendix in Publication II).

The documentation was used to perform a life-cycle inventory (LCI), see Section 2.2. To be able to compare energy use for the different phases of the life cycles for the buildings, energy use for operation during a life cycle of fifty years was simulated, see Section 2.4.

3.2.2.1 Description of the buildings

Building A was a four-storey residential apartment building with 47 small apartments designed for elderly persons. The building was constructed in 1999 and had a heated area (HA) of 3369 m^2. It was designed with a ground slab (no basement), cast-in-situ concrete loadbearing walls, filigree flat plate system with cast-in-situ concrete topping, and external curtain walls with wooden studs and mineral wool insulation. The building had a hydronic heating system connected to a district heating system. Space heating was provided by radiators connected to the hydronic two-pipe system. The main pipes were placed below the ceilings on the ground floor and the vertical supply water pipes were placed visibly along the external walls. All these pipes were made of galvanized steel. Short sections were insulated and embedded in the floor structure above the basement. This meant that most parts of the heating system were easily replaceable. The ventilation system was a mechanical supply and exhaust air system with heat recovery. The air handling unit was located in the attic and served the whole building. As the building was designed for elderly persons it had communal kitchens with separate extractor hoods. Additionally, every apartment had a pantry with an extractor hood connected to the central air handling unit. The ductwork was made from circular zinc coated sheet steel. Horizontal ducts in the attic were fireproofed and vertical ducts were placed in fireproofed shafts. Supply air ducts in apartments were placed above a false ceiling and some exhaust ducts were embedded in the concrete slabs. The water piping, both for potable water and domestic hot water, was made of chrome plated copper pipes inside bathrooms. The main pipes, including those for hot water circulation, both below the ceiling on the ground floor and in the vertical shafts, were made of polypropylene (PP). Finally, the horizontal wastewater pipes were made of polyethylene (PEH) and the vertical pipes of cast iron (MA-system).

Building B was a two-storey residential building with 6 apartments and storage rooms in the attic. The building was constructed in 1996 and had a heated area (HA) of 700 m^2. The building was designed with a ground slab, external loadbearing walls of lightweight concrete insulated with mineral wool, and with a brick façade. The non-loadbearing external walls were insulated wooden stud walls with gypsum boarding internally and a brick façade, internal slabs were filigree flat plates with cast-in-situ concrete topping. The building had a hydronic underfloor heating system connected to a district heating system via a heat exchanger. The main pipes were of copper and the underfloor heating pipes of diffusion-sealed polyethylene (eval-PEX). The ventilation system was a mechanical supply and exhaust air system with heat recovery. Each apartment had its own air handling unit (AHU). Air intakes were placed in the façades from which ducts insulated against condensation lead to the AHU. The ductwork was made of circular zinc-coated sheet metal, uninsulated and cast into the internal slabs. The horizontal parts of the exhaust air ducts inside each apartment were placed below the ceiling and led to shafts from where they were connected to extractor hoods on the roof. The water piping for the potable water, domestic hot water and circulating hot water was made of polyethylene (PEX). In the substation for the district heating, the piping was made of stainless steel. Sanitary fittings were made of chrome plated brass. The horizontal wastewater pipes under the ground slab were made of PVC. Horizontal wastewater pipes in internal slabs were made of polyethylene (PEH) and the vertical pipes of cast iron (MA-system).

3.2.3 Results

3.2.3.1 Material flows

A comparison of the total material amounts in the two studied buildings, divided into the four categories and related to the heated floor area (HA) is shown in Figure 3.1, and per apartment in Figure 3.2. The total material amount is 86 % greater in building A than in building B when related to the heated floor area, but only 15 % greater per apartments. The differences between the buildings can be explained by differences in material choice but also by the choice of ventilation system: A supply and exhaust air system with heat recovery was used in both cases, but with a central air handling unit in building A and small air handling units in each apartment in building B, which meant shorter ductwork.

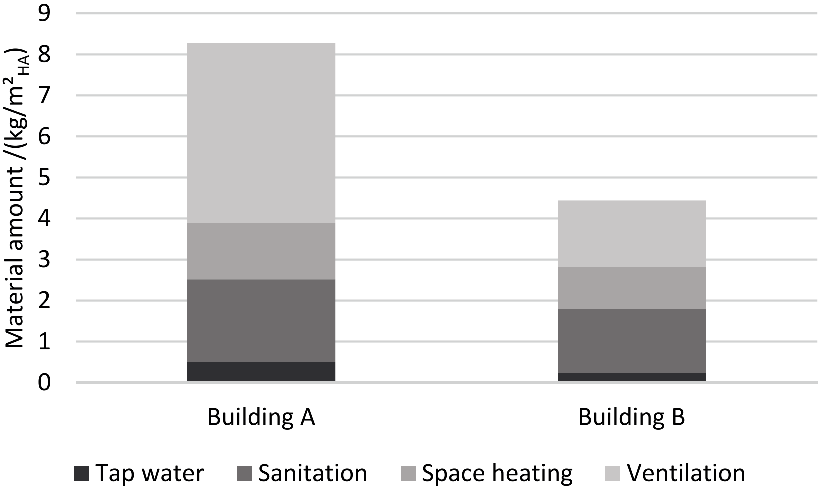


Figure 3.1 Material amounts in kg/m²HA.

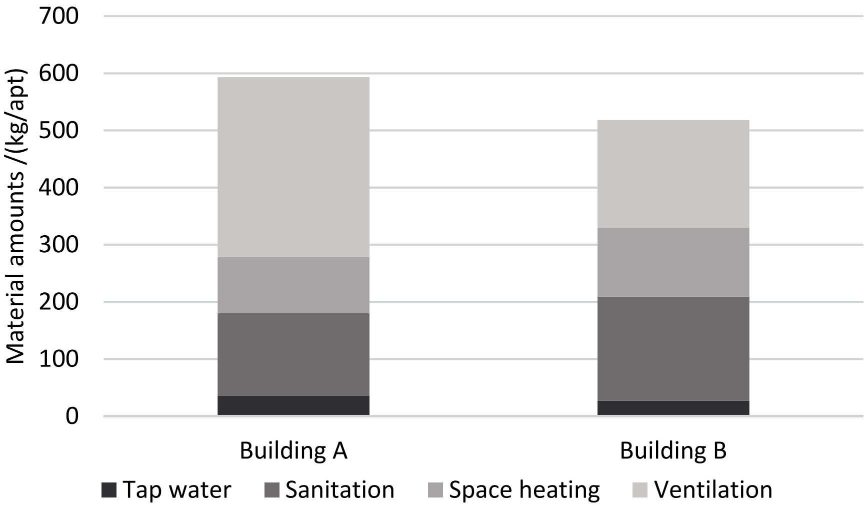


Figure 3.2 Material amounts in kg per apartment (apt).

Depending on the building services category, most used material amounts differ. However, in both buildings, two or three materials constitute 70–80 % of the material amounts. Table 3.1 (for details, see Publication II).

Table 3.1 The most used materials in the four categories of building services. All figures show the percentage of the total mass in each category.

	Ventilation		**Space heating**		**Tap water**		**Sanitation**	
Building	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**
Steel, galvanized	57	66	24					
Mineral wool	32	14						
Steel, enamelled			48	15				
Steel			8	40			11	22
Copper				17	25			
Polypropene					31			
Brass, chrome-plated					23	32		
Steel, stainless						22		
PEX						20		
Cast iron							35	34
Sanitary ware							32	24
Sum / %	89	80	80	72	79	74	78	80

3.2.3.2 Energy flows

The total energy needed for the buildings was comprised the energy needs for manufacturing materials and components, for transport from factories to building sites, and for operation during a life cycle of fifty years.

Manufacturing energy

Based on the material flows in the previous section and data from a number of LCA sources (databases and manufacturers' information, see appendix in Publication II), building product declarations and environmental product declarations, the energy needs for manufacturing the materials and components were calculated. The manufacturing energy included feedstock energy for raw material when applicable. Figure 3.3 shows this energy in terms of kWh/m$^2_{HA}$ for building A and building B respectively, proportioned according to the four building services categories. The manufacturing energy was 56 % higher for building A, when calculated per square meter heated area. Figure 3.4 shows the same manufacturing energy proportioned per apartment instead and this was 4 % lower in building A. Building services for tap water and sanitation are dependent on the number of apartments while building services for space heating and ventilation depend more on the heated area, which is reasonable as there is one bathroom and one kitchen both in a single-room and a triple-room apartment.

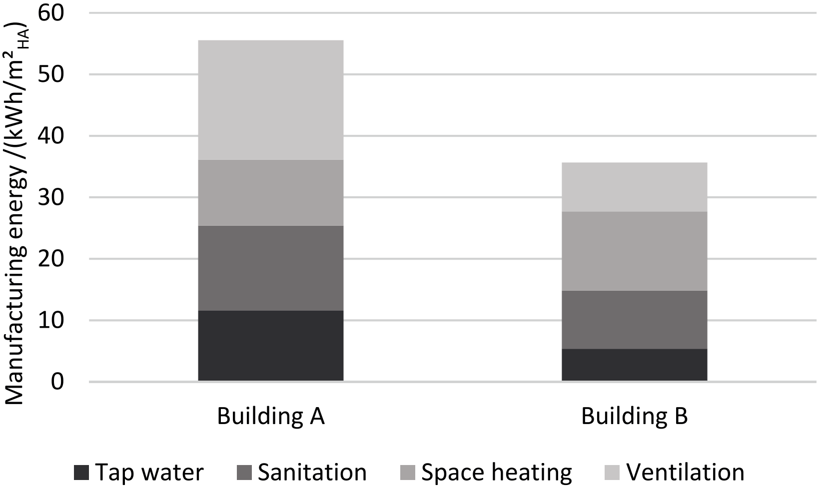


Figure 3.3 Manufacturing energy in kWh/m$^2_{HA}$.

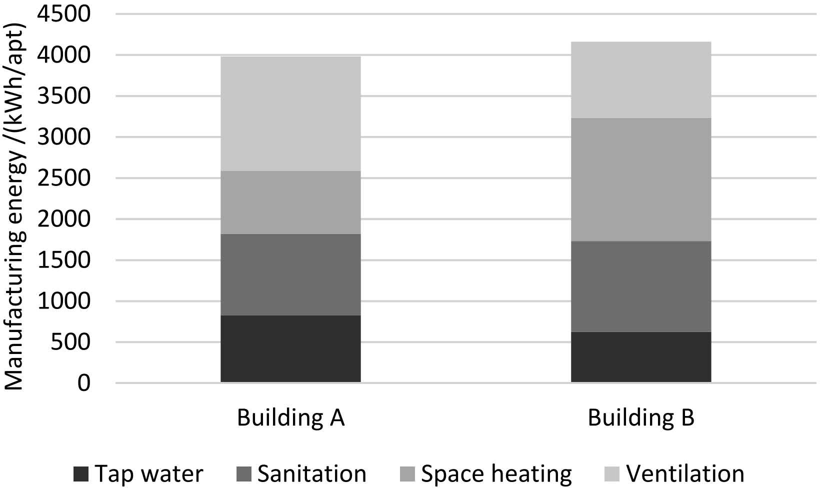


Figure 3.4 *Manufacturing energy in kWh per apartment (apt).*

Transport energy

Transport energy was regarded as the energy used for transport between factories and building sites according to means of transport, e.g. shipping, train or lorry, and also taking into account any storage in warehouses and transhipments before delivery to the final destination, Figure 3.5 and Figure 3.6.

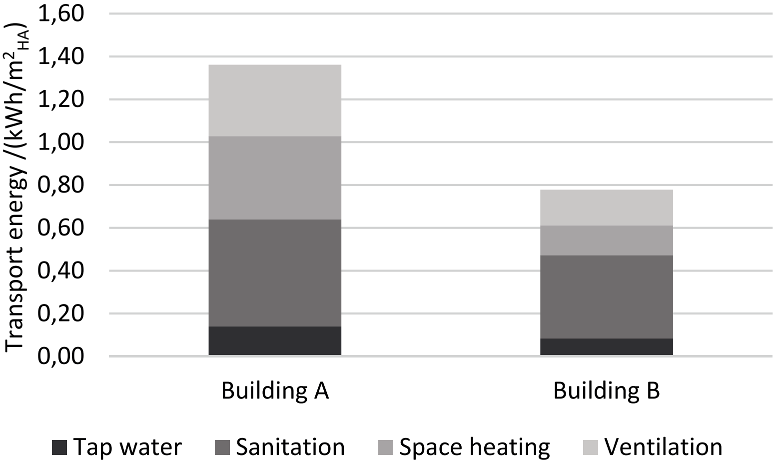


Figure 3.5 *Transport energy from factories to building sites in kWh/m²$_{HA}$.*

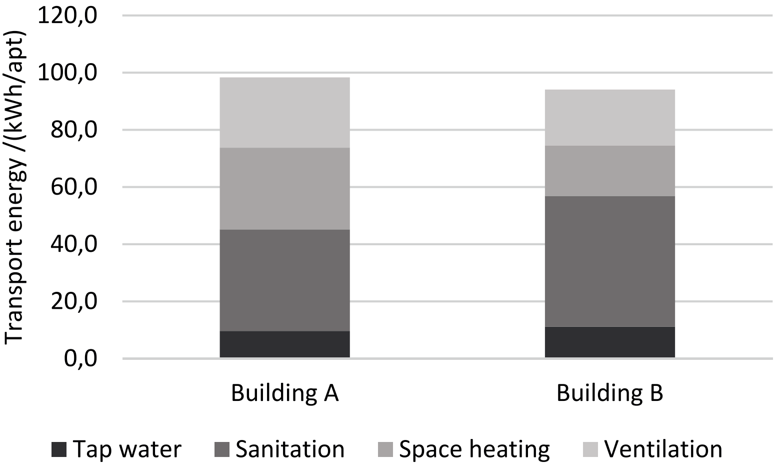


Figure 3.6 Transport energy from factories to building sites in kWh per apartment (apt).

Operational energy

Operational energy was calculated using the Enorm software (Munther K., 1996). A weather file for a standard year in Malmö was used for both buildings, A and B. The annual energy need was then expanded to fifty years. The figures include energy for space heating, domestic hot water, electricity for pumps and fans and household electricity, Figure 3.7. (For details, see Publication II).

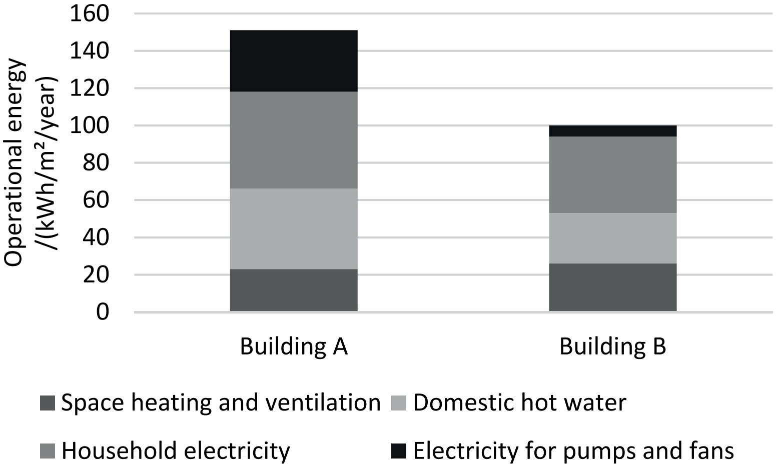


Figure 3.7 Annual operational energy for buildings A and B.

Compilation of energy flows

These energy amounts were compared to the buildings' energy needs during their service lives, assumed to be fifty years, Table 3.2. Energy needed for construction was neglected and as was the energy needed for the deconstruction phase.

Table 3.2 Energy needs for the three phases in the buildings' life cycles.

	Building A /(kWh/m$^2_{HA}$)	**Building B /(kWh/m$^2_{HA}$)**
Manufacturing energy	56	36
Transport energy	1.4	0.8
Operational energy over 50 years	7533	5028
Total	7590	5064

3.2.3.3 Influence of alternative material choices

To increase knowledge about how material choices influence manufacturing energy needs, calculations for alternative material choices were carried out for building A.

Generally, for materials and components in the distribution systems, there were alternative choices. In tap water installations, pipes of polypropylene were replaced with copper piping. In sanitation installations, all pipes, i.e. of cast iron, PVC and PEH, were replaced with pipes of stainless steel, and floor drains of ABS were replaced with drains of stainless steel. The space heating systems, with radiators and galvanized steel pipes, were replaced with floor heating systems with PEX-tubes, vertical pipes of galvanized steel were kept. The floor heating systems required distribution cabinets on each storey. For the ventilation systems there was no realistic alternative and these were kept intact.

These replacements used greater amounts of energy with regard to the manufacture of tap water and space heating services, but lower amounts for sanitation services. According to this study, a poor choice could increase the manufacturing energy needs by 25 % compared to a good choice, e.g. when copper was chosen for tap water pipes instead of PEX, and when underfloor heating pipes of PEX were chosen instead of steel radiators. Very often, however, there was no realistic alternative, e.g. for water closets porcelain ware was the only alternative and air handling units were only available in galvanized steel sheet. Through a combination of best choices and worst choices this investigation showed 29 % higher manufacturing energy needs for the worst combination compared to the best combination (Figures 4.1–4.4 in Publication II).

3.2.4 Conclusions

The results for the two buildings are similar. The building services systems consists of more than 30 materials of which 9 constitute 80 % of the weight and 11 constitute 80 % of the manufacturing energy.

The manufacturing energy need can be affected by the material choice.

The third conclusion was that service life is not a sufficiently described factor and further investigations are necessary.

3.3 Publication III – Reasons for replacement of building services installations

One result from the study in Publication II was that there are some uncertainties that cannot be ignored when predicting service lives for the building services. The study presented in Publication III (a report in Swedish) was therefore aimed at providing more knowledge about the service lives of materials and products in building services systems and, hopefully, clarify the reasons for replacing them. This would mean better input data for LCA analyses. The study dealt with the subjects denoted in bold type in the boxes in the use phase, as illustrated in Figure 1.10.

3.3.1 Introduction

Interviews were carried out with representatives of the property management companies. The results from the interviews were systemized and analysed, and an attempt was made to create a model that described causal connections and another model that described how replacements were carried out.

Before the interviews were carried out, an attempt was made to put the different reasons for replacement of installations for building services for heating, ventilation, water and sanitation into one or more of seven categories. Table 3.3 gives examples of each category.

Table 3.3 Categories of reasons for replacement, with examples.

Category	**Reasons**
Technical	· Component does not work · New technology that lowers resource use
Economical	· Replacement preferred to reparation if economy allows · Not loose possibility to rent out · New components will lower maintenance costs · Increased standard makes property easier to rent out
Activity change	· A replacement will be carried out when change in use of a building is required
Change in ownership	· A new owner wants to modernize · The owner's business idea is "buy-renovate-sell"
Modernization	· Improving appearance
Authority requirements	· Adaptation for disabled users · Air rate change level cannot be met without replacement
Subsidization	· Early replacement if beneficial financing is available

These categories had various prevalences in different parts of the installations for building services. For example, in the category Modernization, a mixer for tap water might be replaced for aesthetical reasons whereas this would hardly be the case for a water pipe. There are obviously large differences between buildings depending on their uses, for example, between residential buildings and office buildings. This study, however, dealt only with residential buildings.

3.3.2 Method

The decision to carry out interviews was based on the belief that it was possible to obtain higher quality answers, as there was an opportunity to clarify, deepen and extend the questions during the interview. The respondents were picked from the most relevant positions, as judged by the real estate companies. Both private and municipal estate managers were included, all in southern Sweden.

A questionnaire was prepared to assure the best possible uniformity of the interviews. It consisted of one section concerning basic data about the building and the policy of the estate owner or manager. Thereafter there was one section for each of the four studied types of building services covering alternative measures, reasons, extent of replacements and age on replacement. The intention was to conduct interviews to include about twenty estates, all of which had rented residential apartments and had been built between 1940 and 1973. The interviews were terminated after nine estates, as they showed the same patterns of response. This extent was too small for statistical analyses, but despite this some statistical analyses were still carried out. The answers from the interviews are given in Publication III, with conclusions for each estate.

3.3.3 Results

3.3.3.1 Reasons for replacements

An analysis of the respondent’s answers about the reasons for replacements showed that it was seldom easy to determine the reason for a particular measure. The reasons given were expressed at different levels. A total of 16 measures were selected to illustrate the “chains of causalities”. For example, Figure 3.8 shows causalities and reasons for replacement of a bathtub, either with a new bathtub or a shower. Starting with the measure, in this case “replacement of bathtub”, there were four possible reasons based on three different functional deficiencies, in turn based on three reasons for the deficiencies. The measure taken would also cause a number of accompanying measures, in this case new surface layers, a new mixer, new pipes, and so forth. Regardless of what the reason might have been, the measure was often the same.

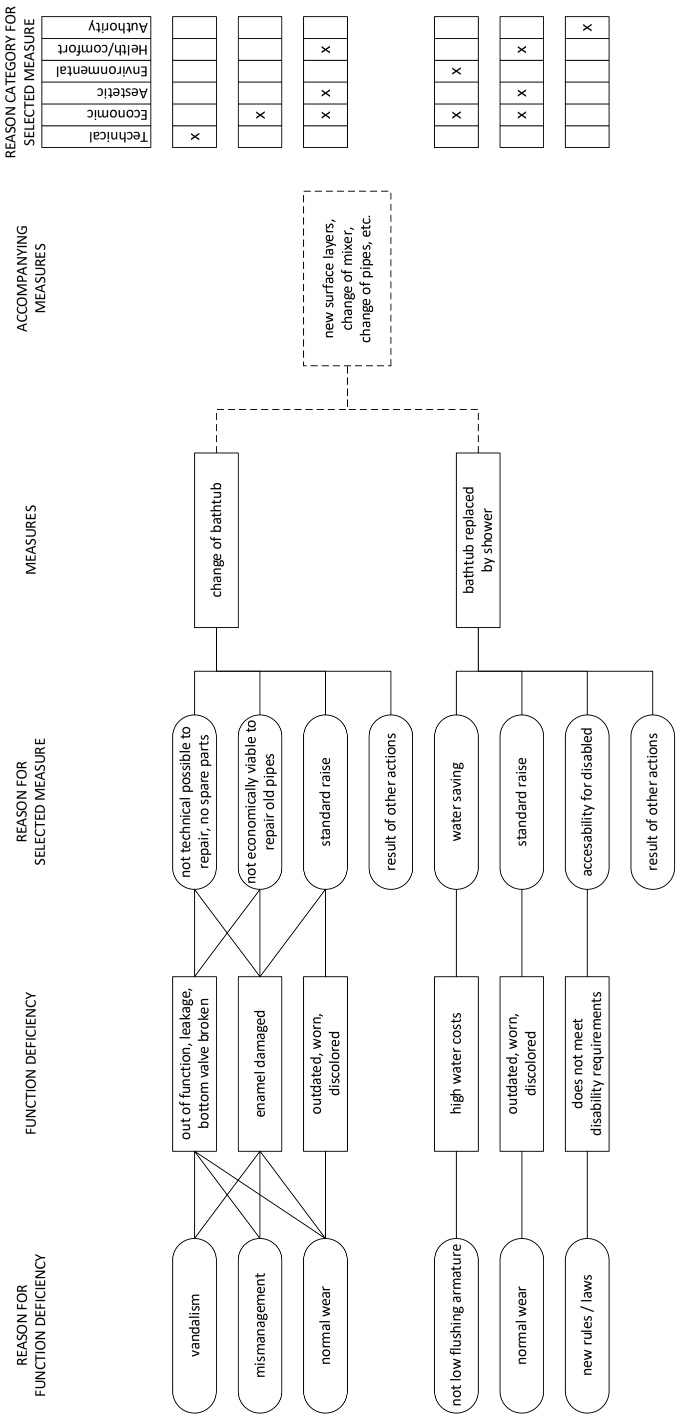


Figure 3.8 Causal chains when replacing a bathtub.

The next step in this model was to sort the reasons into one or more of the six categories in Table 3.3. The result of this classification for the 16 studied situations is presented in Figure 3.9. From this rough compilation it can be seen that almost half of the replacements had neither a technical nor an economic reason.

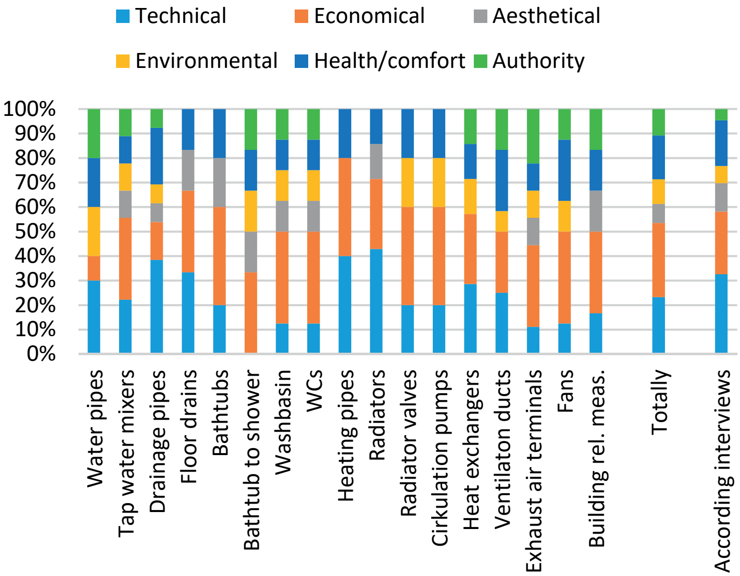


Figure 3.9 Distribution of categories for replacements of system parts or components.

3.3.3.2 Attempt to assess service life

In the interview survey respondents were also asked about when replacements of components and system parts were done, how old the parts were and the extent of the replacements. Figure 3.10 and columns 3–4 in Table 3.4 show the results for 21 components or system parts. (Wastewater pipes, tap water pipes and mixers are shown separately for kitchens and bathrooms.)

The 21 components and system parts were investigated in the nine estates. For example, all estates have wastewater pipes, which meant that there were at least nine observations of this system part. When a major replacement of wastewater pipes was completed the new pipes constituted a new observation. As replacement of wastewater pipes had been carried out in just one of the estates, the total number of observations was 10, as in 8 of the estates the original pipes were still in use (8 observations), in one estate the pipes had reached the end of their service lives (1 observation) and were replaced with new pipes still in use (1 observation), a total of 10 observations. Although there were only nine estates, the number of observations were, in fact, greater than nine, as a new observation was recorded after making a replacement. In the oldest estates the maximum was 25 observations.

From the observations it can be seen that system parts such as pipes and ducts have longer service lives than components such as pumps, fans, bathtubs, water closets and mixers.

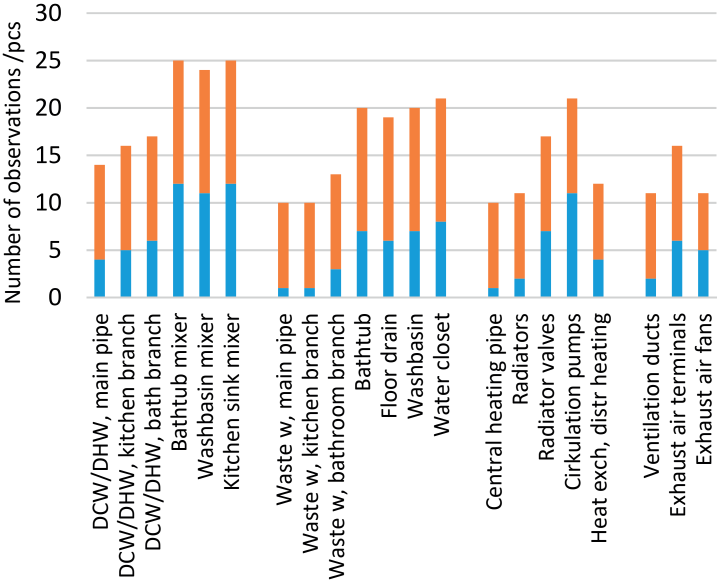


Figure 3.10 Number of observations of replacements (bottom of the bar) compared to total number of observations (total bar).

An age quota can be defined as the average age when a part or component is replaced divided by the average age of all parts or components, Figure 3.11. If the replacements are random this quota will be equal to 1 and if they are deterministic the quota will be close to 0.5. In all cases, except for wastewater pipes and heating pipes, the quota was below 1. When the quota exceeds 1, the average age in the current stock is older than the average age of the replaced component. This phenomenon occurred due to the fact that the parts and component populations were small and single items exhibiting large deviations from normal had a disproportionate influence on the quota. In the case of wastewater pipes, these had been replaced in the most recently built building. An average age for random replacement (column 9 in Table 3.4 and Figure 3.11) can be estimated from values in Table 3.4 using the following equation:

$$average\ age = \frac{number\ of\ observations \cdot average\ age\ for\ whole\ population}{number\ of\ replacements}$$

Table 3.4 Number of replacements and observations, average age on replacement of the current stock and of the whole population, age quota and estimated average age on random replacement.

Building services system	**Measurement number**	**Replacement measure**	**Number of replacements**	**Number of observations**	**Average age on replacement /years**	**Average age of current stock /years**	**Average age of whole population /years**	**Age quota**	**Estimated average age of random repl acement /years**
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
Tap water	1	dcw/dhw, main pipe	4	14	24.2	21.0	22.5	0.87	79
	2	dcw/dhw, kitch. branch	5	16	24.3	19.5	22.3	0.80	71
	3	dcw/dhw, bath branch	6	17	23.6	18.8	21.6	0.80	61
	4	bathtub mixer	12	25	15.9	14.6	15.3	0.91	32
	5	washbasin mixer	11	24	15.8	14.6	15.2	0.92	33
	6	kitchen sink mixer	12	25	16.0	14.4	15.3	0.90	32
Wastewater	7	wastew, main pipe	1	10	29.0	31.5	31.3	1.09	313
	8	wastew, kitchen branch	1	10	29.0	31.5	31.3	1.09	313
	9	wastew, bathroom branch	3	13	25.8	21.0	22.6	0.81	98
	10	bathtub	7	20	26.6	17.5	19.3	0.66	55
	11	floor drain	6	19	25.6	19.0	21.4	0.74	68
	12	washbasin	7	20	26.6	17.5	21.0	0.66	60
	13	water closet	8	21	27.1	16.5	20.6	0.61	54
Heating	14	central heating pipe	1	10	29.0	31.4	31.2	1.08	312
	15	radiators	2	11	28.8	30.8	30.6	1.07	168
	16	radiator valves	7	17	21.3	19.5	20.2	0.92	49
	17	circulation pumps	11	21	24.0	15.7	19.3	0.65	37
	18	heat exchanger	4	12	22.4	14.3	17.3	0.64	52
Ventilat.	19	ventilation ducts	2	11	29.4	27.0	27.4	0.92	150
	20	exhaust air terminal	6	16	26.4	15.7	20.0	0.59	53
	21	exhaust air fans	5	11	27.8	3.5	15.1	0.13	33

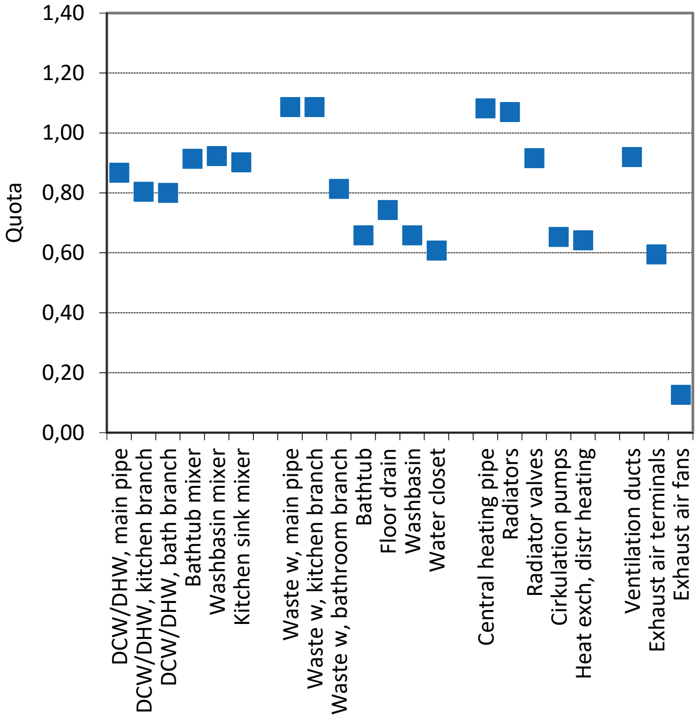


Figure 3.11 Quotas between average ages for present stock and average ages on replacement.

By analysing the observations of the age for a certain type of component, a deviation function was introduced (Equation 3.1). For assumed service lives, *t*, between 0 and 60 years, a value was calculated of the deviation of the observed ages compared to the assumed service life. The deviation function consists of two terms. The first handles the deviation in age for all replaced components and is described as the absolute value of the difference between observed age and assumed service life. The second term handles the deviation in age for all components that are in operation and is described as the difference between observed age and assumed service life, if observed age is higher than assumed service life, otherwise zero. The age at which the deviation function has its minimum indicates the age that, with the least error, can be assumed to be the service life of the component in question.

$$U(t) = \sum_{j=1}^{n_x} |x_j - t| + \sum_{i=1}^{n_r} max(0, r_i - t) \tag{3.1}$$

where:

n_x = number of observations of replaced units
n_r = number of observations of units in operation

x_j = observed age of replaced units
r_i = observed age of units in operation
t = assumed service life (from 0 to 60 years)

Dividing $U(t)$ by the total number of observations gives an average error and a normalized deviation function:

$$u(t) = \frac{U(t)}{(n_r + n_x)} \tag{3.2}$$

Calculations using these equations, for all 21 replacement measure, using the values from the observations presented in Table 3.4 and with an assumed service life of 60 years have been carried out. The results are presented in Table 3.5, and indicate the minimum mean errors for the corresponding assumed service lives.

Table 3.5 Lowest average deviation *u*(*t*) at the end of a service life *t* for the different replacement measures.

Measure	Replacement measure	Assumed service life /years	Average deviation /years
1	dcw/dhw, main pipe	40	5.6
2	dcw/dhw, kitch. branch	32	5.8
3	dcw/dhw, bath branch	40	6.1
4	bathtub mixer	25	5.4
5	washbasin mixer	26	6.0
6	kitchen sink mixer	25	5.6
7	wastew, main pipe	53	3.1
8	wastew, kitchen branch	53	2.4
9	wastew, bathroom branch	50	4.6
10	bathtub	34	4.7
11	floor drain	35	5.3
12	washbasin	34	4.7
13	water closet	34	4.0
14	central heating pipe	53	3.1
15	radiators	45	5.1
16	radiator valves	25	7.1
17	circulation pumps	25	2.8
18	heat exchanger	25	2.4
19	ventilation ducts	31	2.0
20	exhaust air terminal	30	6.1
21	exhaust air fans	30	2.7

To give an example: based on the observations regarding replacement of radiator valves, the smallest deviation of approximately 7 years for an assumed service life of 25 years is given by the equation, shown in Figure 3.12. The deviation function $u(t)$ has a slope of -1 for small values of assumed service life and a slope $n_x / (n_r + n_x)$ for large values of assumed service life. Generally, the uncertainty is quite large for the investigated measures.

Figure 3.12 Average deviation, u(t) for replacement of radiator valves (case 16).

3.3.4 Conclusions

A service life of roughly 25 years can be assumed for all the studied components and system parts, except mixers for which a service life of 16 years was assumed.

Traditional methods to assess a service life, which rely on two factors, a technical and an economical service life, would probably give misleading results, as other aspects, e.g. esthetical, were identified.

The reasons for replacement were quite complex and there was often more than one reason, and which reason was the decisive one is unclear.

Some replacements were random and some were deterministic.

The estimated average ages on random replacement were high, but the relationships between the different components and system parts seemed to be reasonable.

The uncertainty was large, but this might, in fact, have reflected the prevailing conditions.

The principle shown here can be proposed as a method to assess service life of components and system parts, but a larger number of observations, i.e. from more estates, is needed.

3.4 Publication IV – Decreasing energy use of industrially produced multi-family dwellings in Sweden

An important piece of knowledge from Publication II was that the energy required during a use phase of fifty years far exceeds the energy needs for the transport and manufacturing of components and system parts for building services. Even when the energy needs for transport and manufacturing of materials and components for the entire building are taken into account, the operational energy during the first fifty years dominates completely. It is therefore of great importance to strive to attain low operational energy needs, and this is explored in Publication IV. This publication covers the subjects denoted in bold type in the boxes for energy during pre-use and the use phase as shown in Figure 1.10.

3.4.1 Introduction

This publication, a conference paper, explores 21 combinations of technical measures used to decrease energy use in a four-storey residential building in order to fulfil stricter requirements in the building code. The measures were carried out on both the building envelope and on the building services. The building was constructed using volumetric modules produced in a factory, which were transported to the building site and installed in a steel skeleton. Additional external insulation, façades and a roof were then added. The module size was restricted due to a maximum size limit for road transport, which meant that any enlargements had to be carried out on the building site. All installations within the modules were completed in the factory, while the assembly to form complete systems was carried out on the building site. The aim of the publication was to analyse measures to reduce energy use in order to fulfil the requirements in the new building code, BBR 12 (Boverket, 2006) and to lower life-cycle costs.

3.4.2 Method

Changes, mainly in thermal insulation, air tightness and in ventilation systems, alone and in different combinations, made up the 21 analysed cases. Energy simulations were carried out using the VIP+ software (Strusoft, 2007) and life-cycle costs for a service life of 50 years were calculated using Sektionsfakta (Wikells, 2007). Energy costs, initial costs for the measures taken and maintenance costs were added. The base case building (case 04) had a heat transfer coefficient of 0.316 $W/(m^2 \cdot K)$, was ventilated using a mechanical exhaust system with a specific ventilation flow of 0.40 $L/(s \cdot m^2)$ heated floor area (HA). The building was heated by a hydronic radiator system. The air leakage was assumed to be 0.8 $L/(s \cdot m^2)$

enclosed area. Energy for space heating was calculated for an indoor temperature of 22 °C. Heat costs were assumed to be 0.7 SEK/kWh and electricity costs 1.0 SEK/kWh.

3.4.3 Results

Figure 3.13 (Figure 4 from the publication) shows the results. As can be seen, the energy costs for space heating and domestic hot water during the use phase dominate completely. The simulated building was to be built in Malmö in the far south of Sweden and the life-cycle costs for the two best cases, one with supply and exhaust ventilation with heat recovery (SEH) and the other with an exhaust air heat pump (EHP), were similar. However, with a heat pump the electricity cost was higher than the heating cost, Figure 3.13.

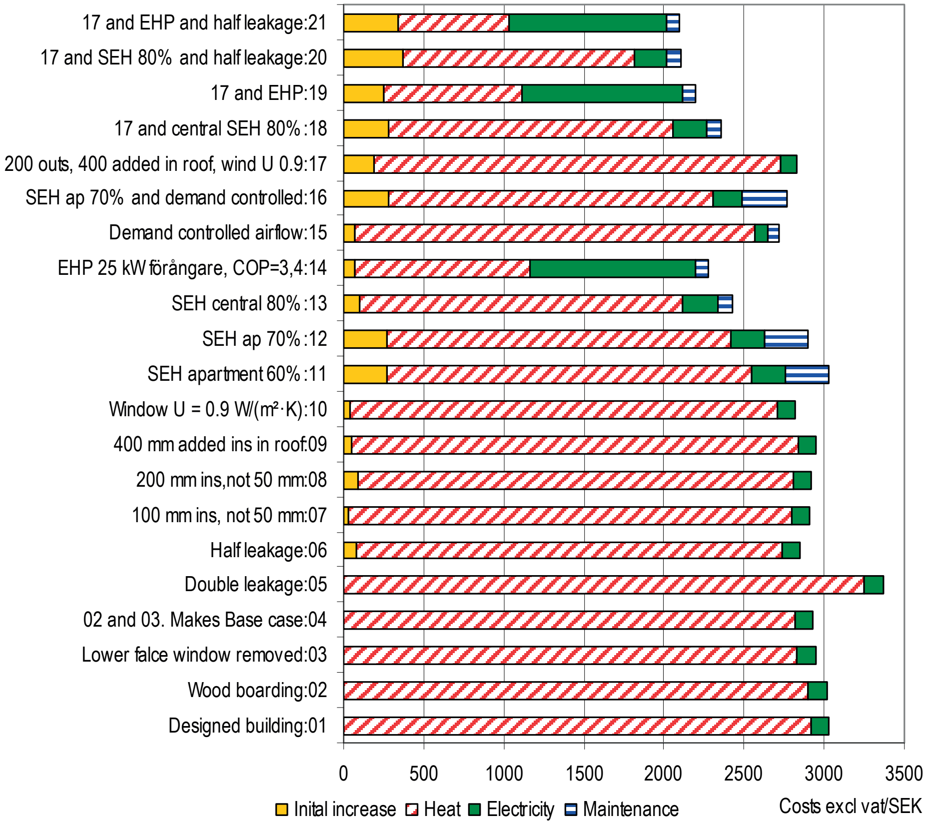


Figure 3.13 Life-cycle costs per m^2 heated floor area divided into cost types. Household electricity is not included. Regarding "Heat" and "Electricity" the entire life span cost is included while "Initial increase" and "Maintenance" refer to increases compared to the building as designed. "Initial increase" occurs on construction while the other costs occur over the life span.

To investigate whether the result was dependent on the outdoor climate, the location was changed to Kiruna in the far north of Sweden. In this cold climate, supply and exhaust ventilation with heat recovery (SHE) was the better choice, both the total annual energy use and the life-cycle costs would be lower, Table 2 in the publication.

3.4.4 Conclusions

From a life-cycle cost perspective it is beneficial to take measures to decrease energy use.

The basic case showed that it was possible to fulfil the requirements regarding purchased energy stipulated in the building codes then in force, though the margin was small.

Case 20 and 21 indicated that it might even have been possible to fulfil the then current passive house standard of a maximum of 45 kWh/m^2_{HA} (Swedish Energy Agency, 2007).

3.5 Publication V – Evaluation of a feedback control method for hydronic heating systems based on indoor temperature measurements

To reach good energy efficiency of a building's space heating, it is crucial to control the indoor temperature, i.e. to achieve a desired thermal indoor climate and prevent overheating and through this enable utilisation of heat gains from occupants, lighting, electrical appliances, solar radiation, etc. It is therefore of great importance to strive for the best possible control of the indoor temperature, and this is explored in Publication V. The publication covers thermal indoor climate and energy use during a building's use phase.

3.5.1 Introduction

Today, indoor temperatures in most apartment buildings with hydronic heating systems are indirectly controlled, the supply water temperature in the radiator system is a function of the outdoor temperature, i.e. without regarding the indoor temperature. The principle is called feedforward or open loop control.

This control method means that the outdoor temperature is the only parameter that can influence the supply water temperature to the radiators. A disadvantage is that it does not take into account the factors and conditions inside the rooms that can affect the resulting indoor temperature. These factors, sometimes called "disturbances", such as additional heat gains from the sun, tenants, electrical appliances and other internal heat sources, are not taken into account, neither are various cooling factors such as ventilation caused by wind, airing or natural ventilation.

Appropriate settings that consistently provide indoor temperatures above the complaint threshold must be found. However, generous margins may result in negative impacts on energy use. Excessively high indoor temperatures imply that there is an unnecessary use of energy. Overheating may also lead to airing by the tenants to control the indoor temperature, which will also increase energy use. If airing is not carried out, excessive indoor temperatures result in poorer thermal comfort. It is, therefore, important to find more accurate control methods with respect to both indoor thermal comfort and energy use. To utilize the above-mentioned heat gains, the prevailing indoor temperature can provide a feedback signal to the control system, which then lowers the supply water temperature when the indoor temperature is too high.

The aim of the study was to investigate to what extent the feedback control system made the indoor temperatures less dependent on the outdoor temperature, which, basically, is the purpose of the control system, i.e. to keep the indoor temperature as close as possible to the set point temperature. The effect the feedback control system had on energy use for space heating was also investigated.

3.5.2 Method

The evaluation of the feedback control system was carried out by comparing the dependency of the indoor temperatures on the outdoor temperature before and after the enhanced control system was implemented. This was carried out in a test group consisting of 10 housing estates comprising 116 separate residential buildings with a total of 1177 apartments, all in southern Sweden. The buildings on 6 estates (named as objects in the publication) were apartment blocks constructed from 1963 to 1973 and on the other 4 were terraced houses (named as row-houses in the publication) constructed from 1986 to 1995. 8 estates had mechanical exhaust ventilation systems and 2 had balanced ventilation with heat recovery. The buildings had individual metering and billing (IMB) of space heating costs, based on measured room temperatures in all living rooms and bedrooms. The rental terms included a daily average indoor temperature of 21 °C with the possibility to achieve between 18 °C and 24 °C. If the average indoor temperature was below 21 °C the tenant was refunded and for temperatures above 21 °C the tenant was extra invoiced. Control of the supply water temperature for each estate during the first period was carried out by a conventional feedforward control system based on the outdoor temperature and augmented by local feedback control using thermostatic valves (TRVs). During the second period, the control system, i.e. feedforward plus TRVs, was enhanced by a central feedback control based on the indoor temperature of a building in order to increase or decrease the supply temperature. The indoor temperature was the mean of all measured temperatures, i.e. in all living rooms and bedrooms, in a specific estate, where temperatures in living rooms were doubly weighted because of their size. Due to the temperature gradients in the rooms, the indoor temperatures were recalculated to a position 1.2 m above floor level, reckoned to better represent the experienced indoor temperature. The local feedback control with TRVs remained in use as before and gave the tenants the opportunity to adjust the indoor temperature.

The intention was also to investigate how feedback control affected energy use. To do this, two control groups were formed to be compared to the main group.

3.5.3 Results

What can be observed is that the slope for 9 of 10 estates declined from 2010 to 2011, i.e. the indoor temperature varied less with outdoor temperature. However, the average temperatures for the estates increased from 21.46 °C in 2010 to 21.73 °C in 2011. As an example, Figure 3.14 (Figures 2 and 3 in the publication) shows the results for estate 2.

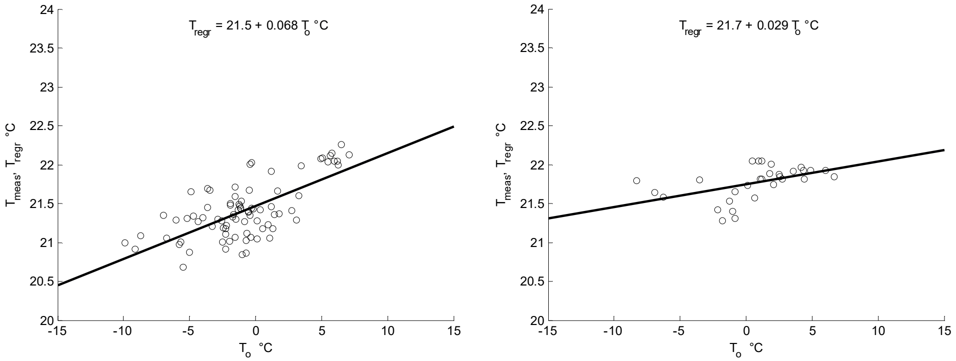


Figure 3.14 Measured indoor temperature, T_{meas} and calculated T_{regr} as a function of T_o, daily mean values. Estate 2, 2010 to the left and 2011 to the right.

Figures in Table 7 in Publication V show a decline in heat energy use, both for the main group and the control groups. One explanation for the common decline is that the mean outdoor temperature had increased. For the main group, the reduction could have possibly been larger if the indoor temperature had not been increased.

3.5.4 Conclusions

The proposed feedback control resulted in more even indoor temperatures, i.e. the indoor temperatures became less dependent on the outdoor temperature when compared to the control method with feedforward and thermostatic radiator valves. The conclusion was drawn that the feedback control resulted in less outdoor temperature dependency and, based on that fact, that the enhanced control had, on the whole, been effective. The aim of the proposed control method, in terms of temperatures, was fulfilled. This implied that the method was worth considering when choosing control methods. The results supported the conclusion that the feedback method was a promising control method to apply in multi-family buildings.

The study also provided knowledge relating to implementation and commissioning. An overall conclusion was that the system for retrieving the indoor temperature measurements should be made more robust to avoid data losses.

3.6 Publication VI – Distribution and variation of indoor temperatures in apartment blocks with individual metering and billing of space heating costs - on building, apartment, and room level

One way to reduce energy needs for space heating is to simply lower the indoor temperature in our buildings. However, the indoor environmental quality, especially thermal comfort, must be ensured independently of energy saving measures. After a measure has been implemented it is necessary to examine the thermal comfort. Furthermore, when carrying out energy simulations, the indoor temperature was often set, in previous studies, to a constant level for the entire building and over the heating season. It was found that too low indoor temperatures had been assumed for the simulations, which gave too optimistic results. True values of indoor temperatures were scarce or even missing. The work in Publication VI, which covers indoor environmental quality during a building's use phase, more specifically the thermal indoor climate (Figure 1.10), investigates temperature conditions in single- and multi-family buildings.

3.6.1 Introduction

The indoor temperature is important because it affects a building's energy demand for space heating. With a well-balanced heating system it is theoretically possible to lower the building's mean temperature and achieve lower energy use. Although different occupants have different needs or preferences regarding the indoor temperature, the thermal indoor climate must be within the human comfort zone. A system in which the tenants have adequate opportunity to individually control their indoor temperature increases their chances of experiencing thermal comfort. Individual metering and billing of space heating is often proposed as a solution to both achieving individual thermal comfort and to reducing heating needs for the building. The study explores whether this was a correct assumption.

The overall aim of this study was to investigate and present how indoor temperature varies in multi-family buildings with IMB of space heating costs to give a more differentiated picture of the thermal climate in this type of buildings.

3.6.2 Method

A case study of five estates (named as objects in the publication) built 1965–1973 as apartment blocks, with a total of 419 apartments in sizes from 1 room and a kitchen to 4 rooms and a kitchen, was carried out. The buildings had hydronic heating systems and mechanical exhaust ventilation. Temperature readings from a system for individual metering and billing (IMB) of space heating costs were used. The indoor temperatures in all living rooms and all bedrooms (in total 1055 rooms) were registered every 15 minutes.

In these five estates temperatures at apartment and room level were studied from different aspects, such as their ranges, variations between apartments, variations over time and variations with outdoor temperature. General statistical data was recorded for heating periods and non-heating periods including mean, minimum, maximum and median temperatures as well as standard deviations, skewness and kurtosis.

For one estate, with 9 floors, 3 staircases, 75 apartments and 198 rooms, more thorough analyses were carried out. All months were studied and variations in mean temperatures between apartments were analysed. This estate was orientated with the long sides and entrances to the south, closest in Figure 3.15.

3.6.3 Results

A graphical overview of the temperature variations within one nine-storey building with the median temperature for two individual heating months is shown in Figure 3.15 (Figure 4 in the publication) using a colour scale in which blue is cold and red is warm; the darker the shade the more intensive the cold/heat. It can be seen that the distribution seems to be random.

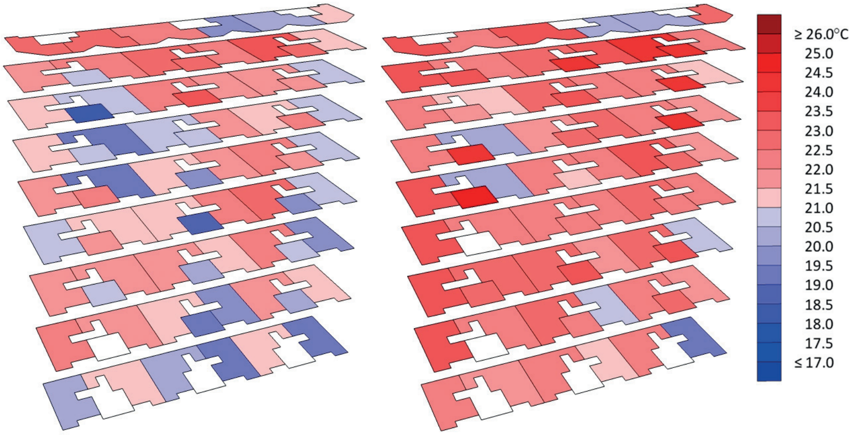


Figure 3.15 Median apartment temperatures in January (left), $T_{out,mean}$ *= −3.4 °C and April (right),* $T_{out,mean}$ *= 7.1 °C. White indicates staircases (without temperature sensors) and apartments where temperature registration failed.*

There was a tendency for warm apartments to be warm throughout the year, which probably implied that different tenants had different desires regarding comfort temperature, Figure 3.16 (Figures 12 and 13 in the publication). It was also shown that despite this there was a slight tendency towards increasing temperatures upwards in the building (Figure 11 in the Publication).

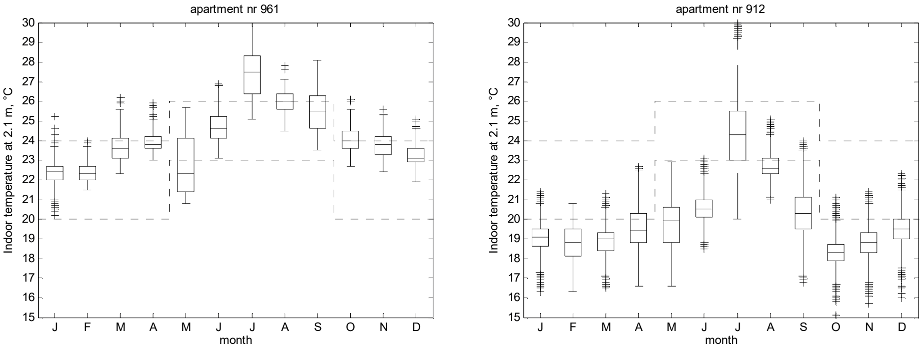


Figure 3.16 Temperature variations January–December for one warm and one cold apartment. The dotted lines show the comfort limits according SS-EN ISO 7730:2006.

Every single indoor temperature registration was plotted as a function of the outdoor temperature in contour diagrams, shown in Figure 3.17 (Figure 15 in the publication) for estate number 2.

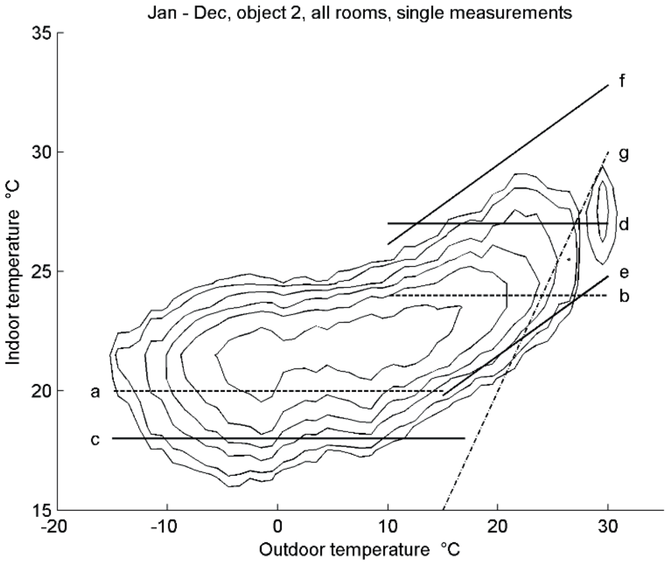


Figure 3.17 Contour lines for fifteen-minute measurements of indoor temperature as a function of outdoor temperature for all 198 rooms in estate number 2 for a whole year covering all seasons. Iso-lines from the outermost to the innermost denote 1 %, 2 %, 5 %, 10 %, 20 % and 50 % of the temperatures. The straight lines refer to Swedish legislation (a, b), to international standards for thermal indoor climate (c – f) and to outdoor temperature (g).

50 % of all registrations lie within the innermost contour line and this is also within the limits, line **a** and line **b**, for indoor temperatures according to Swedish legislation. Worth mentioning is that the indoor temperature sometimes are lower than the outdoor temperature. This could, at least partly, be explained by the thermal inertia for the building.

3.6.4 Conclusions

It can be concluded that there are variations in temperature between different apartments; both variations in temperature levels and in temperature ranges.

The overall conclusions are that differences in indoor temperatures are achievable for different apartments in an apartment block with a certain set point temperature and that the temperatures are not dependent on an apartment's location in the building.

Both the building owner's goal to keep a certain average temperature for energy saving reasons, and the tenants' goals, and the possibility to vary the indoor temperature at individual apartment level, seem to be possible to reach.

The measured temperatures are close to being normally distributed, though they have a slight negative skewness and a slight kurtosis during heating periods. The results support the assumption that indoor temperatures can be modelled as normally distributed in energy simulations of buildings.

Furthermore, it can be seen that temperature variations follow the seasons. The temperatures at individual apartment level show that there is a tendency for warm apartments to be warm all the year round and vice versa.

There are also daily variations, with magnitudes of 0.3–0.4 °C, and with 0.1–0.3 °C differences between weekdays and weekends.

Every single indoor temperature measurement for a whole year covering all seasons as a function of outdoor temperature is presented in iso-plots. Temperature levels are mainly within the limits of the standards for thermal comfort, thus showing that a satisfying thermal indoor climate is met in these apartment blocks using IMB.

3.7 Publication VII – Variations in indoor temperature in residential apartments of different size and building category

Previous studies presented in this thesis have shown that, seen over a building's total life cycle, the energy use during the use phase will cause the greatest environmental impact, i.e. this is where the opportunities are greatest to make a difference. The indoor temperatures are essential with regard to the need of space energy. This publication covers the subject of thermal indoor climate, as shown in Figure 1.10.

3.7.1 Introduction

What must always be kept in focus is the indoor environmental quality, i.e. a desirable thermal climate and an indoor air quality that fulfils the formal requirements. There were indications of excess temperatures and uneven temperatures, both within and between rooms, as well as in entire buildings. The aim of the study was to investigate the indoor temperatures the control method (feedforward control) used resulted in. It also aimed to clarify the magnitude of the differences and retrieve more accurate temperature data that could be useful for energy simulations in residential buildings.

3.7.2 Method

Based on a large dataset from a system for individual metering and billing of space heating costs (IMB-system), indoor temperatures during the heating periods, i.e. January–April and October–December, were investigated. The dataset comprised temperature data, recorded every 15 minutes, from two categories of residential buildings: apartment blocks (6 estates built 1963–1973 with 695 apartments with 1–4 rooms, in total 1835 rooms) and semi-detached or row houses (4 estates built 1986–1995 with 482 apartments with 2–5 rooms, in total 1413 rooms). The buildings were the same as in Publication V. The data was analysed from different aspects.

3.7.3 Results

Generally, indoor temperatures were higher during spring and autumn than during winter. Estates (named as objects in the publication) in the category row houses had higher mean temperatures and larger standard deviations than the apartment blocks, though they had the same set point temperatures. It can generally be noted that the temperatures were lower in bedrooms, different bedrooms being approximately similar though with some exceptions, especially in larger apartments. The differences were larger the larger the apartments were, Figure 3.18 (Figure 3 in the publication).

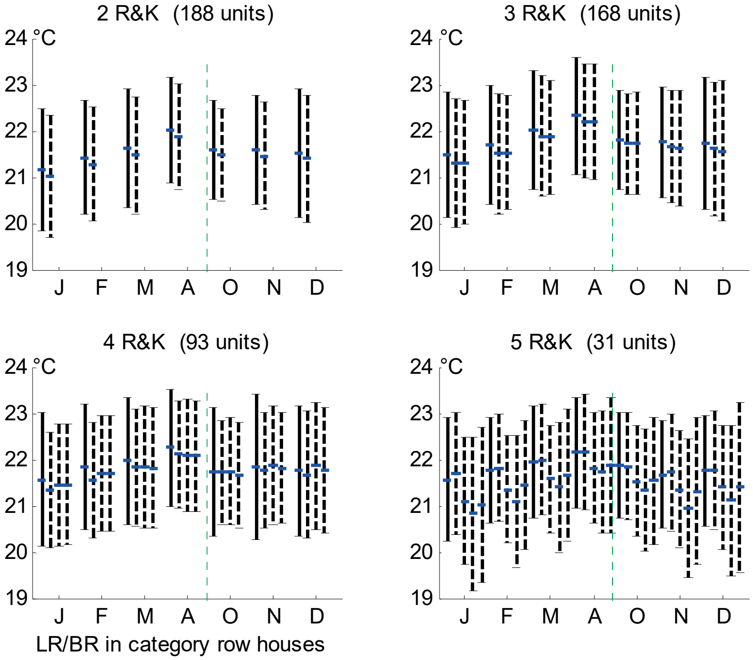


Figure 3.18 Monthly mean values and standard deviations for heating months at room level, according to apartment size, for the category row houses. The solid lines represent living-rooms, the dashed lines bedrooms. (R&K = Rooms & Kitchen).

The study also investigated the duration of temperature differences between rooms. In Figure 3.19 below (Figure 5 in the publication) the relative durations of temperature differences between bedrooms and living rooms are shown.

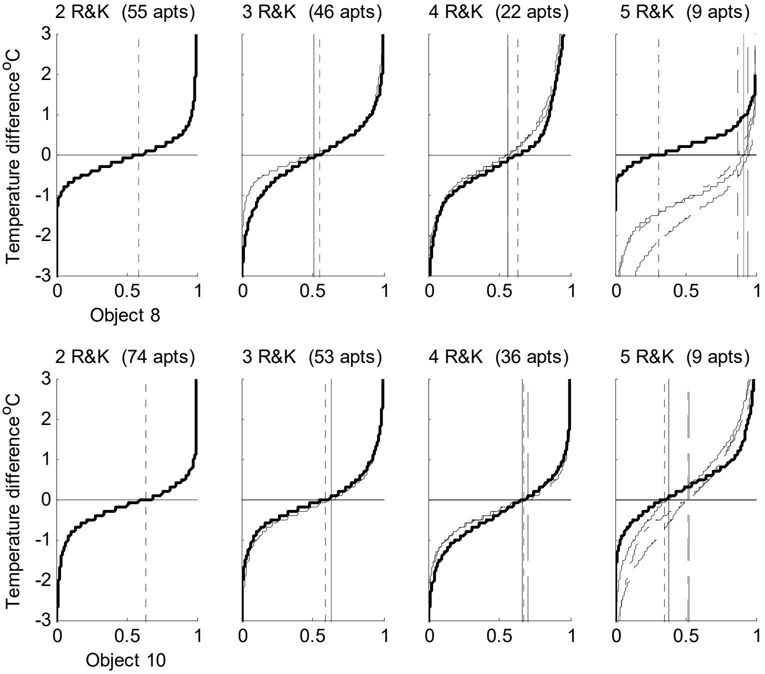


Figure 3.19 Duration of temperature differences between living rooms and bedrooms; Bold line = bedroom 1, thin = bedroom 2, broken = bedroom 3 and chain = bedroom 4. Objects 8 and 10, category row houses. (R&K = Rooms & Kitchen).

3.7.4 Conclusions

Indoor temperatures in row houses were slightly higher than in apartment blocks, though they had the same set point temperature, 21°C. This is contrary to previous experience and may be due to the different ages of the categories.

Differences in mean temperatures between living rooms and bedrooms, within all units in both categories were in the range 0.1°C – 0.5°C, being larger in the larger units.

The temperatures in bedrooms were generally below the temperatures in living rooms, but with large individual variations.

Only measuring temperatures in living rooms, as is done in some IMB systems, may give unrepresentative temperature values.

3.8 Publication VIII – Vertical temperature increase in multi-storey buildings

In connection with the study in Publication VI, with temperature measurements within a system for individual metering and billing of heating costs (IMB-system) it was recognised that it was often warmer in the upper parts of multi-storey buildings. This might cause problems for tenants trying to achieve their desired indoor temperatures and was therefore studied further in this publication. This publication covers the thermal indoor climate, as shown in Figure 1.10.

3.8.1 Introduction

The thermal indoor climate is also in focus in this study and especially with regard to the opportunities for tenants to achieve a desired temperature. This will help avoid paying for an unwanted excess temperature which, in the long run, would also increase the environmental impact. The overall aim of this study was to show, using a theoretical model, why and how vertically adjacent apartments thermally affect each other.

3.8.2 Method

Based on a case study of an apartment block, the temperature measurements were analysed. A linear mathematical model, normalized to 1 m² floor area, was programmed to simulate the heat transport upwards in the building. Thermal connections to the surroundings on each storey were related to this floor area. Using parameters that were approximately the same as those used for residential apartment blocks in previous studies, and well representative of the apartment blocks built in Sweden in the 1960s, a basic case was simulated ($U_{façade} = 0.6$ W/(K·m²), $U_{window} =$ 2.5 W/(K·m²), $U_{internal\ slab} = 2.7$ W/(K·m²)). Using Matlab a parametric study was carried out, in which the U-values for external walls and windows, U-values for internal slabs and for bottom and top slabs varied.

3.8.3 Results

The results show that there was a vertical heat transfer, on average 0.8 W/m², upwards from storey to storey throughout the building. The number of storeys was varied from 4 to 28 (basic case plus cases 1–3). The mean temperature deviations of a building in thermal balance are shown in Figure 3.20 (Figure 4 in the publication). The temperatures were calculated as the mean temperatures of four nodes, in this model the surface temperatures of the floors and ceilings, and air temperatures adjacent to the floors and ceilings. The deviations were concentrated to the bottom and the top storeys. The temperature differences between the bottom and top storeys in a 4-storey building was about 0.5 °C and for 7, 14 and 28 storeys the differences were about 0.7 °C. The study also showed that the better insulated the building envelope was the larger the heat transfer would be (cases 4–7 in Publication VIII).

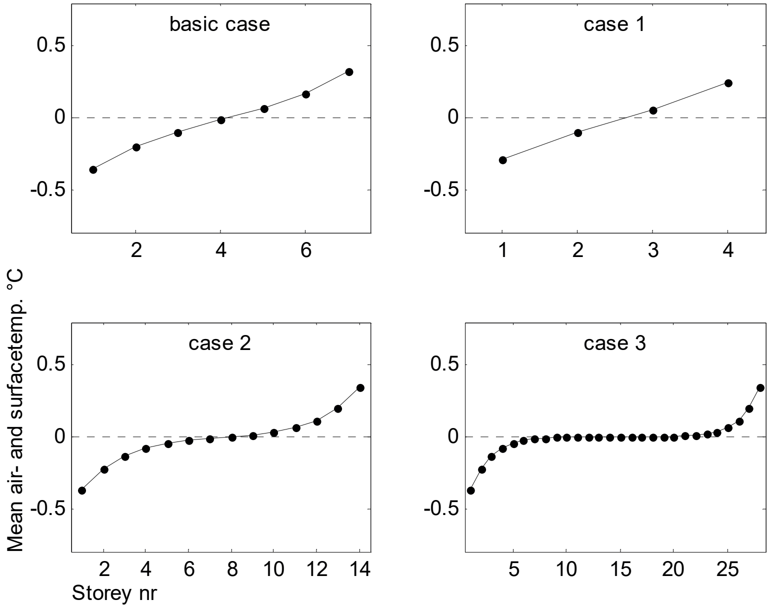


Figure 3.20 Mean temperatures of the 4 nodes on each storey, i.e. the deviations relative to a building in thermal balance, basic case (7 storeys) and cases 1–3 (4, 14 and 28 storeys).

3.8.4 Conclusions

The results in the model were close to the measured temperature differences for the building in the case study, which indicated that the model gave reasonable values.

It can be concluded that there is an upwards internal vertical heat transport in multi-storey buildings.

Better insulation can increase or decrease the vertical heat transport, depending on where the insulation is improved: improving the envelope will increase the temperature deviations while improving the floor slabs between storeys will decrease them.

3.9 Publication IX – Vertical temperature gradients in apartments with hydronic radiator heating

In the previous studies, Publications V – VIII, a large dataset with registrations of indoor temperatures in multi-family buildings and single-family houses was analysed. All sensors were placed 2.1 m above floor level and an equation to recalculate the registered temperature to a height 1.2 m above floor level was used to get more representative values of temperatures in the occupied zone, primarily for use in the IMB system. This study was carried out in an attempt to validate this equation. This last publication also deals with thermal indoor climate during a building's use phase (Figure 1.10).

3.9.1 Introduction

In a heated room it is expected to find a vertical temperature gradient. How steep this gradient is depends on how the room is heated, e.g. by radiators or underfloor heating. It is also dependent on the type of ventilation and the occupants and their activities in the room, and of the heat load, which in turn depends on the difference between the outdoor temperature and the indoor temperature, and the heat losses through external surfaces. The slope of the gradient is of interest as it affects the thermal indoor comfort. The purpose of the paper was to examine whether a proposed equation for vertical temperature stratification coincided with measured temperature gradients in apartments. Its purpose was also to obtain reference values for temperature gradients in apartments heated by a hydronic system, with radiators in each room and ventilated by a mechanical exhaust system with air intake terminals through the façade.

3.9.2 Method

The proposed equation that recalculated a measured internal temperature (T_{meas}), due to an external (outdoor) temperature (T_e), from 2.1 m above floor level to 1.2 m above floor level was:

$$T_i = T_{meas} - 1 + 0.025 \cdot T_e \tag{3.3}$$

At an outdoor temperature of 0 °C, the recalculated temperature at 1.2 m was 1 °C lower than at 2.1 m, i.e. the equation gave a gradient of 1.11 K/m. Temperatures were measured at four levels in the inner parts of the living rooms and in one bedroom in each of ten residential apartments, the apartments being in normal use by the tenants. The same equipment was used in all the apartments. The measurement period was one week during the heating season, both days and nights, in each apartment, for a total of ten weeks with readings taken every 5 minutes.

Three gradients were measured in each apartment: one in the master bedroom and two in the living room of which one close to the exterior wall and windows, and one in the inner part of the room. Three temperature gradients were calculated based on the temperature differences between two levels, 0.1–1.7 m, 1.1–1.7 m and 0.0–1.7 m above floor level. Vertical temperature gradients as a function of the outdoor temperature were plotted in diagrams and linear regression was used.

The outdoor temperature was measured at a location 2.5 kilometres from the buildings.

3.9.3 Results

The gradients that were recalculated using the proposed equation (solid line with circles in the figures) were in general steeper than the measured gradients in the apartments. The best agreements were seen for the gradients measured as the differences between 1.1 and 1.7 m above floor level. In four apartments the measured gradients were less than half of the calculated values, in one apartment they agreed very well and in one they were negative. Figure 3.21 and Figure 3.22 show the measured gradients compared to the calculated gradients in two of the apartments. The solid line without circles corresponds to the 1.1–1.7 m gradients, the dotted line corresponds to the 0.1–1.7 m gradients and the dashed line to the 0.0–1.7 m gradients.

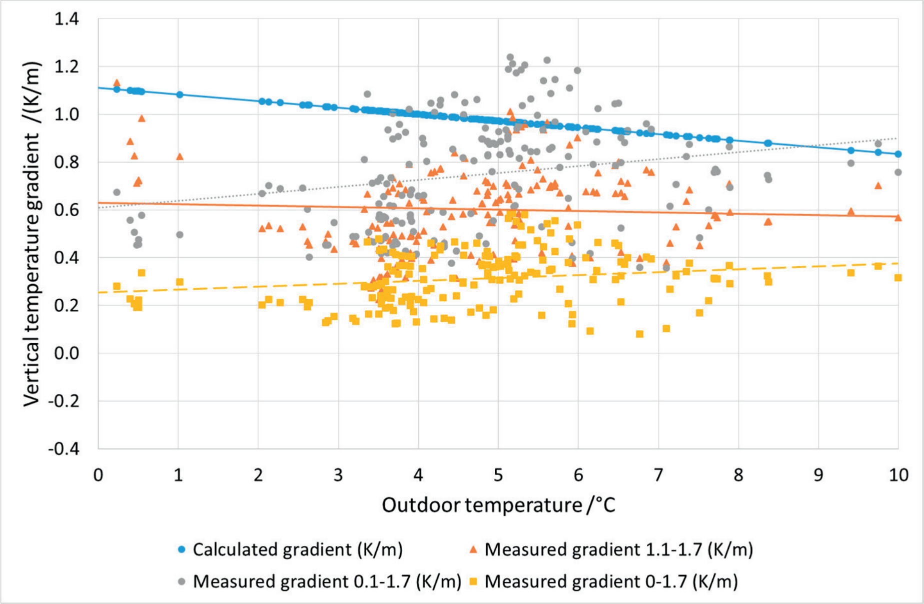


Figure 3.21 Vertical temperature gradients as a function of outdoor temperature. Apartment no. 5. 2017-02-16–2017-02-24.

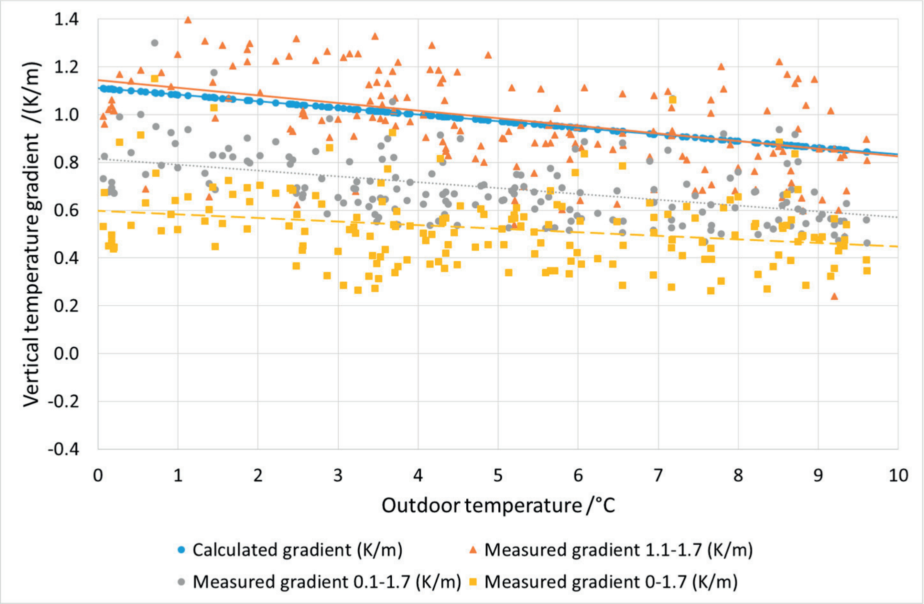


Figure 3.22 Vertical temperature gradients as a function of outdoor temperature. Apartment no. 8. 2017-03-12–2017-03-20.

3.9.4 Conclusions

The recalculated gradients using the proposed equation were in general steeper than the measured gradients in the apartments, implying that the equation overestimated the gradients under the studied conditions.

The measured vertical temperature gradients were not steep during the heating season in the inner parts of the living rooms in apartments heated by a hydronic system and ventilated by mechanical exhaust ventilation.

Thermal comfort with respect to the vertical temperature gradients was satisfactory in the studied apartments under the studied conditions.

The risk of a tenant being invoiced for a higher indoor temperature than delivered was minimal, at least in the system for IMB referred to here.

4 Additional studies

Twenty years have passed since the first studies in this thesis were carried out. During this time the authorities' requirements have gradually been tightened in parallel with ongoing technical developments in the building sector, resulting in more energy-efficient buildings, buildings that need greater material amounts and, consequently, have greater manufacturing energy demands in the pre-use phase. Energy simulation software has also become increasingly more advanced during these years.

One question that arises is whether all these changes have had any considerable consequences with regard to the proportions of energy demands between the different phases in a building's life cycle, for instance, has the pre-use phase become significantly more demanding. Another question is how improvements of building services systems can contribute to a more sustainable building.

In Publication II, two buildings situated in southern Sweden were studied from material and energy aspects. The first was a four-storey residential apartment building, built in 1999, with a heated area of 3369 m² comprising 47 small apartments designed for elderly persons (building A). The second building, built in 1996, was a two-storey residential building with a heated area of 700 m² comprising 6 apartments and storage rooms in the attic (building B). In this additional study, only building B was investigated to see what the effects of a few measures would be when trying to make the building more energy efficient. It was also of interest to see whether the measures could meet the then current building code requirements and possibly also allow the building to be classified as a low-energy building according to voluntary requirements. The building's design is described in section 3.2.2.1.

Both buildings A and B were, in the first study, simulated using Enorm 1000 (Munther, 1996). Enorm was a Swedish commercial energy simulation program first introduced in 1988 to verify whether a building could meet the energy demand requirements in the Swedish building code. It was a steady-state program, which carried out calculations using constant time steps of 24 hours and did not take into account the building's thermal inertia. Values for solar radiation came from "The BKL METHOD computer programme", a hand calculation method computerized by Källblad (1994), which handled solar radiation in a simplified manner, and that could overestimate solar heat gain (Engqvist and Fredriksson, 2004). However, at the end of 1990s it was the most used energy simulation program in Sweden, intended to be used to verify that the energy requirements in the building code were fulfilled.

4.1 Aims

The aims of this additional study carried out on a residential building were to investigate whether dynamic energy simulation software could give a result closer to the measured energy use, how much improved building services installations could decrease heating energy needs, what measures taken on a building envelope could lead to fulfilling passive house standards and how these measures would affect the relative proportions of upstream and downstream energy flows.

4.2 Method

Building B was simulated again, this time using the dynamic energy simulation program VIP Energy, version 1.5.1 (Strusoft, 2012). VIP Energy contained several calculation models and these could be used to investigate heat storage in building structures, air flows through the ventilation systems and air infiltration through building parts, solar radiation through windows, and effects of heat pumps and solar collectors.

4.2.1 Course of action

The first step in this study was to carry out an energy simulation of the original building (B) using the more advanced programme VIP Energy. The original input dataset, i.e. the same designs, areas, U-values, ventilation air flows, operating hours, etc. were used (Table 4.3). To investigate whether the then current building code requirements, and possibly also the voluntary Swedish criteria for low-energy buildings and passive houses, were met, the energy efficiency of the building was improved in three steps and compared to the requirements in the two versions. The first, FEBY 12 (Sveriges Centrum för Nollenergihus, 2012), was introduced in 2012 and an updated standard, FEBY 18 (Forum för Energieffektivt Byggande, 2018), was introduced in 2018.

The first step concerned the building services systems only while the following two steps also included parts of the building envelope, as follows:

Step 1: Improvement of the performance of the building services, i.e. replacement of the small AHU’s in each apartment by using a central

AHU with higher performance both for the fans and the heat recovery, and by installing wastewater heat recovery.

Step 2: Measures in *Step 1* plus better windows.

Step 3: Measures in *Step 2* plus an overall improved climate envelope including lower air leakage.

All were simulated using VIP Energy, with input data according to Table 4.3.

When simulating the energy demands, according to FEBY 12 the household electricity demand was assumed to be 30 kWh/m²/year, the domestic hot water (DHW) demand assumed to be 25 kWh/m²/year and the air leakage flow at 50 Pa, q_{50} , was assumed to be a maximum of 0.30 L/(s·m²) instead of 0.80 L/(s·m²).

To be able to compare with the requirements for energy-efficient buildings according to the Swedish specifications in FEBY 12 and FEBY 18, it was necessary to calculate the heat loss factor for the winter external design temperatures (HLF_{WEDT}).

To meet the Swedish criteria in FEBY 12 for a *minimum energy house* and *passive house* in southern Sweden (climate zone III) the parameters according to Table 4.1 must be fulfilled and to meet the Swedish criteria in FEBY 18 for *gold*, *silver* and *bronze* in southern Sweden where the winter external design temperature (WEDT) is above -17 °C, the parameter values according to Table 4.2 must be fulfilled. The general requirements regarding energy performance expressed as primary energy use (EP_{peu}), i.e. with respect to primary energy factors for different energy sources, must also be met. According to BBR (Boverket, 2018c) EP_{peu} must not exceed 85 kWh/m²$_{HA}$ in order to meet the requirements for multi-family buildings.

The measured energy use for heating and communal electricity figures were provided by the estate manager.

Table 4.1 Rating criteria in FEBY 12.

	Minimum energy house	**Passive house**
HLF_{WEDT} /(W/m²$_{HA}$)	< 20	< 15
Delivered energy if not heated by electricity /(W/m²$_{HA}$)	< 70	< 50
Delivered energy if heated by electricity /(W/m²$_{HA}$)	< 33	< 25

Table 4.2 Rating criteria in FEBY 18.

	Gold	**Silver**	**Bronze**
HLF_{WEDT} /(W/m²$_{HA}$)	< 14	< 19	< 22
Delivered energy if heated by electricity /(W/m²$_{HA}$)	< 26	< 32	< 38

4.2.2 Input data

Table 4.3 Input data for simulations using Enorm, VIP Energy and for calculating HLF_{WEDT}.

	Enorm	$\mathbf{VIP_{orig}}$	$\mathbf{VIP_{step\ 1}}$	$\mathbf{VIP_{step\ 2}}$	$\mathbf{VIP_{step\ 3}}$
Indoor temperature /°C	20	21	21	21	21
Heated Area (HA) /m²	700	700	700[1]	700[2]	700[3]
$U_{external\ wall\ shortside}$ /(W/(m²·K))	0.255	0.255	0.255	0.255	**0.190**
$U_{external\ wall\ longside}$ /(W/(m²·K))	0.214	0.214	0.214	0.214	**0.136**
U_{roof} /(W/(m²·K))	0.169	0.169	0.169	0.169	**0.127**
U_{slab} /(W/(m²·K))	0.19	0.19	0.19	0.19	**0.09**
U_{window} /(W/(m²·K))	1.85	1.85	1.85	**0.73**	**0.73**
U_m /(W/(m²·K))	0.323	0.323	0.323[1]	**0.259**[2]	**0.180**[3]
Enclosed area, A_{env} /m²	1000	1000	1000[1]	1000[2]	1000[3]
Supply air flow q_{sup} /(m³/s)	0.24	0.18	0.18[1]	0.18[2]	0.18[3]
Exhaust air flow q_{ex} /(m³/s)	0.24	0.20	0.20[1]	0.20[2]	0.20[3]
Heat recovery for AHU	0.50	0.50	**0.85**[1]	**0.85**[2]	**0.85**[3]
Fan efficiency	-	0.3	**0.7**	**0.7**	**0.7**
Air leakage at 50 Pa, q_{50} /(L/(s·m²))	0.8	0.8	0.8[1]	0.8[2]	**0.3**[3]
Wastewater heat recovery	0	0	**0.3**	**0.3**	**0.3**

[1] to calculate HLF_{WEDT} in *Step 1*.
[2] to calculate HLF_{WEDT} in *Step 2*.
[3] to calculate HLF_{WEDT} in *Step 3*.

4.3 Results

The results of the new energy simulations compared to the original simulation and to measured energy use are shown in Table 4.4 and Figure 4.1 as Cases 1–6:

1. Energy demand formerly simulated using Enorm 1000 ($T_{indoor} = 20$ °C).
2. Measured and purchased energy use.
3. Energy demand simulated using VIP Energy (1.5.1) with same input data as in 1.
4. Energy demand with energy efficiency measures in *Step 1*.
5. Energy demand with energy efficiency measures in *Step 2*.
6. Energy demand with energy efficiency measures in *Step 3*.

Table 4.4 Comparisons of energy demands for the six cases in the list above and energy performance expressed as primary energy use (EP_{peu}) /(kWh/m²$_{HA}$).

Case	**1**	**2**	**3**	**4**	**5**	**6**
	Enorm orig	**Meas**	**VIP En. orig**	**VIP En. step 1**	**VIP En. step 2**	**VIP En. step 3**
Space heating (heating system and ventilation)	26[1)]	70[2)]	53	42	30	20
Domestic hot water (DHW)	27	26[2)]	26	18[3)]	18[3)]	18[3)]
Household electricity and lightning	41	30[4)]	30[4)]	30[4)]	30[4)]	30[4)]
Communal electricity	6	4	5	3	3	2
Total	100	130	114	93	81	70
Total excl. household electricity	*59*	*100*	*84*	*63*	*51*	*40*
Energy performance (EP_{peu})	-	-	87	65	53	41

[1)] simulated at an indoor temperature of 20 °C.

[2)] total heating energy use was measured, energy for DHW was estimated using the default value.

[3)] energy for DHW according to FEBY12 should be 25 kWh/m²/year. When taking into account wastewater heat recovery it should be 18 kWh/m²/year.

[4)] according to FEBY12 household electricity should be 30 kWh/m²/year.

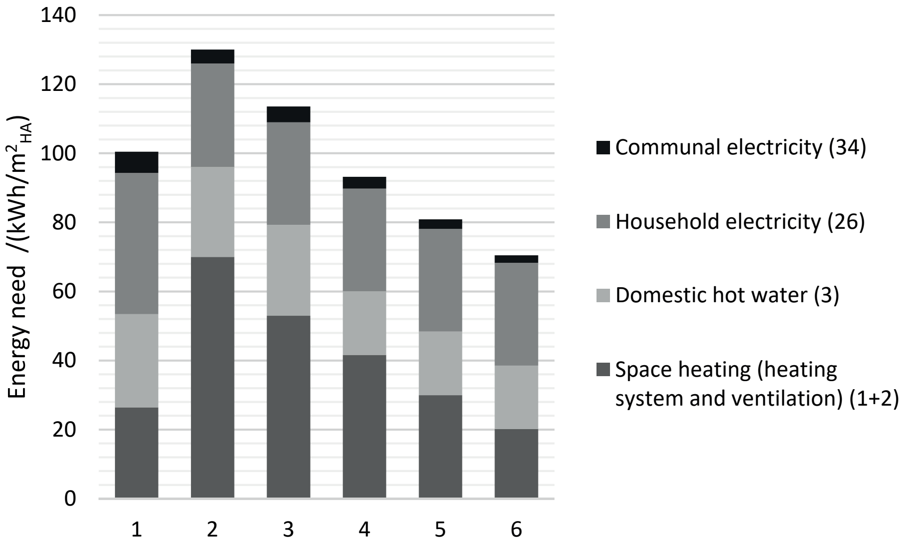


Figure 4.1 Annual energy demand for the six cases in the list above.

The criteria in FEBY12 (Sveriges Centrum för Nollenergihus, 2012) are clear when a building should be considered as being "electrically heated" or "not purely non-electrically heated", but when a building should be considered as "purely non-electrically heated" is not clear. Here it has been interpreted as buildings in which electricity is used only for pumps, fans, etc, i.e. in the distribution systems, and neither intended for space heating nor domestic hot water. The studied building was connected to a district heating system for both these purposes; thus it could be considered as being "non-electrically heated".

The heat loss factor at the winter external design temperature (HLF_{WEDT}), according to FEBY 12 and FEBY 18, for the three steps was calculated to be 17.3 W/m²HA, 14.6 W/m^2_{HA} and 9.5 W/m^2_{HA} respectively, as shown in Table 4.5, in which it can also be seen which building classes are fulfilled according to FEBY 12 (Sveriges Centrum för Nollenergihus, 2012) and FEBY 18 (Forum för Energieffektivt Byggande, 2018). According to the energy performance figures (EP_{peu}), the "bronze" level in FEBY 18 corresponds to the requirements in the Swedish building code, BBR (Boverket, 2018c).

Table 4.5 Calculated values of HLF_{WEDT} compared to the requirements in FEBY 12 for climate zone III and in FEBY 18.

	Calculated HLF_{WEDT} /(W/m^2_{HA})	**Fulfilled class in FEBY 12 /(W/m^2_{HA})**	**Fulfilled class in FEBY 18 /(W/m^2_{HA})**
Step1:	17.3	Minimum energy house (<20)	Silver (<19)
Step2:	14.6	Passive house (<15)	Silver (<19)
Step3:	9.5	Passive house (<15)	Gold (<14)

Step 1 comprises measures to be taken regarding the building services, i.e. better performance of fans, higher rates of heat recovery and heat recovery from wastewater.

Increased heat recovery from the ventilation system decreased the annual energy need for space heating by 11 kWh/(m^2_{HA}) and heat recovery from wastewater decreased the annual energy need for DHW by 8 kWh/(m^2_{HA}), i.e. together 19 kWh/(m^2_{HA}) less heating energy. In addition to this, the higher fan efficiency decreased the annual need for electrical energy by 2 kWh/(m^2_{HA}).

4.4 Discussion

The previous simulation of energy use, carried out using Enorm 1000, gave results that were too low for space heating energy, both when compared to measured energy use and calculated energy use using VIP Energy. The differences were too large to be explained by the lower indoor temperatures (20 °C). However, as the measured heating energy was the sum of the space heating energy and DHW energy, the energy for the DHW was assumed to have the same value as in the simulation using VIP Energy. It is known that a 1 °C higher indoor temperature results in at least a 5 % higher space heating demand, but not even this correction can help explain the difference. Deeper analyses of the Enorm simulation were not carried out, but the program has been seen to overestimate the energy input of the solar gain. Household electricity calculated using Enorm 1000 was higher than that calculated using VIP Energy and so was the communal electricity.

In the case study (Publication II) two newly built buildings, one a small residential building with six apartments and one a residential building with 47 small apartments for elderly, were studied. The calculation took into account the manufacturing energy for all materials and products used in the building services for heating, ventilation tap water and wastewater, the transport energy for these materials and products from factory to building site and finally the operational energy over 50 years for space heating, DHW, communal electricity and household electricity (Figure 3.14 and Table 3.17 in Publication II).

The energy quota for manufacturing and transport of building services products were almost negligible, together less than 0.6 % of the total energy demand over 50 years. If the buildings had been built according to the Swedish criteria for energy-efficient buildings, FEBY 18 (Forum för Energieffektivt Byggande, 2018), this quota would have been larger, but still almost negligible, assumed to be about 1 % of the total demand over 50 years.

Here it has been assumed that the manufacturing and transport energy was the same as when the original study was carried out; even if it were doubled it would still only represent less than 2 % of the total use.

As a building itself should be regarded as a system, i.e. including the building services systems and the building users, this way of comparing energy use might appear to be unfair, as it compares the building's total operational energy need for 50 years to the manufacturing and transport energy only for the building services system components, i.e. manufacturing and transport energy for all other parts in the building are not taken account for. A more relevant boundary would have been to include the manufacturing and transport energy for all materials in the building.

Step 1 was meant to investigate whether improvements made only on building services systems could contribute to a more sustainable building. A comparison was made between manufacturing energy needs and operational energy needs for 50 years To implement measures in *Step 1*, i.e. to replace the AHUs in six small apartments with one central AHU with a high heat recovery coefficient would have increased the material amounts, mainly of galvanized steel sheet and aluminium. Here it was assumed that the amounts were doubled, resulting in a total manufacturing energy for the ventilation system of 33940 MJ, i.e. 13.5 kWh/m². Compared to the energy savings, this measure had an "energy pay-back period" of 1.2 years. The material amounts for a wastewater heat exchanger for up to 4 apartments were approximatively 30 kg copper and, as they were only available in standard sizes, two were needed, i.e. 60 kg copper. Using the LCA data used in the original study this would increase the manufacturing energy by 4440 MJ, i.e. 6.34 kWh/m². Compared to the energy savings, this measure had an "energy pay-back period" of 0.8 years. Looked at in this way it appeared to be unwise not to take *Step 1*, but if the costs for the measures were calculated, the picture might be another.

4.5 Conclusions

It is important to use energy simulation software that can take into account the internal heat gains and the thermal mass of a building.

The original building was close to fulfilling the building codes requirement on energy performance.

The results implied that it was fairly easy to fulfil criteria for Silver classification in FEBY 18, only using measures taken on the building services installations.

According to this study with measures taken on the building services installations and the installation of better windows, the results were close to fulfilling the criteria for Gold classification in FEBY 18.

5 Discussion

As stated in Section 1.1.1, “to achieve a sustainable development all three perspectives of development, i.e. *social*, *environmental* and *economic* development, must be included”, Figure 1.1.

The studies in this thesis treat the three perspectives of sustainable development to varying degrees.

Several of the UN´s goals for sustainable development concern the social dimensions of development, e.g. ending poverty and hunger, enjoying healthy lives, ensuring equitable education and achieving gender equality. What can primarily be associated with the perspective *social sustainability* in this thesis is that everyone should be able to experience the conditions for good health. The four parameters that are usually considered to have an effect on human health, performance and well-being are *thermal comfort*, *air quality*, *light quality* and *acoustics*. These four parameters form what is called “*the indoor environmental quality*” (IEQ). Among these parameters focus has been on indoor thermal conditions.

To a large extent, the studies deal with the thermal indoor climate in existing housing. In a climate like ours, in northern Europe, many of us spend almost 90 % of our time indoors. In a study with more than 1400 respondents in seven European cities, it was found that people were at home on average 14 hours per day (Schweizer et al, 2007). With this in mind, it is not difficult to realize that the IEQ is important to us all. Among the Swedish national environmental quality objectives, it is especially Objective 15: *A good built environment* (Section 1.1.2) that refers to the thermal indoor climate. Concerning indoor air quality, which has not been studied in this thesis, it is Objective 4: *A non-toxic environment* that is connected to health aspects (section 1.1.2).

The perspective *environmental sustainability* is the most investigated in the studies. The building sector has a major impact on ecosystems, i.e. impacts from the use of natural resources and emissions to the air, water and soil. This perspective also coincides well with the national environmental quality objective number 15: *A good built environment* (section 1.1.2). Above all, it is a building’s material and energy uses throughout its lifetime that has an environmental impact. Choice of materials and choice of energy systems are also addressed in the national environmental quality objective 1: *Reduced climate impact* and objective 4: *A non-toxic environment*.

A major method of attaining a low environmental impact from a building is to ensure low levels of energy and material use during its life cycle, though a good IEQ must always be prioritized before low energy use. To ensure this, IEQ matters must be addressed throughout all the phases of a building's life cycle, i.e. when planning, designing, constructing, operating, maintaining and renovating. At the same time the building and its building services systems must be made energy efficient. The goal must be to achieve a desired indoor environmental quality with the lowest possible environmental impact.

Finally, there is the perspective *economic sustainability,* which is interpreted somewhat differently in different contexts. Here it has been chosen to correspond to the following definition: *an economic development that does not have negative consequences for ecological or social sustainability*. Thus, an increase in economic capital must not be created at the expense of a reduction in natural capital or social capital. The perspective of economic sustainability has explicitly only been addressed in the study presented in Publication IV, in the LCC calculations when choosing energy efficiency measures. In other studies it has only been indirectly addressed, as energy efficiency measures must be economically motivated, otherwise they will probably not be implemented, unless a number of measures are combined in a package in which measures having good profitability will finance less profitable measures. In this perspective the IEQ is also essential; good IEQ is a prerequisite for making apartments, offices and other premises desirable to rent.

In the following sections, 5.1–5.5, resources and thermal indoor comfort, and the interaction between these, are discussed from the perspective of sustainability, laws, regulations and sustainable trends. Resources can be renewable or finite, either in the case of material resources or energy resources.

5.1 Material resources

There is a global scarcity of non-renewable resources, e.g. metals and minerals. However, this scarcity does not seem to influence price trends (Henckens et al, 2016). It is therefore necessary to use as little of the resources as possible, and cause low environmental impacts both when extracting raw materials and manufacturing goods. It is also of highest importance to produce as little waste as possible, which also means reusing products and recycling materials. This, in turn, will lead to lower demands for both materials and manufacturing energy. Materials must not be contaminated or mixed with other materials, if they are, it will be difficult or impossible to sort, reuse and recycle. It is unavoidable that some will be dispersed in the environment. Henckens et al (2014) identifies 17 metals that will not be available for future generations due to ongoing extraction, among them copper and zinc, both commonly used in building services installations.

5.1.1 Use

Issues concerning material use have been addressed in Publications II and IV and to a certain extent in the additional studies in Chapter 4. Publication II also studies manufacturing energy for the material used in components and systems for building services. This study was carried out in 1999. During the two decades since then, it is most probable that some things have changed concerning materials and amounts that are used for building services and energy needs for manufacturing. However, as the study only presents the situation for two buildings, and as no dramatic changes have occurred in this discipline concerning energy use, the demands in the operational phase still dominate. In 1999, the question of greenhouse gases (carbon dioxide equivalents) had not yet been given the importance it has today.

5.1.2 Choice

In some of the installations it was possible to choose alternative products, produced using other materials, which meant different demands on manufacturing energy, both of these factors resulting in different carbon dioxide equivalents. A calculation taking into account alternative choices for one estate showed that the manufacturing energy for installations for heating, water and sanitation in the worst-case combination could have been approximatively 30 % higher than the best case combination (Publication II). For ventilation installations there were hardly any alternatives, the dominating material in these was galvanized steel sheet. Even with the worst combination of material choices, the manufacturing energy constituted less than 1 % of the energy use over 50 years of operation, i.e. it was almost negligible. One way to address these issues connected to material choice is to use an LCA and prioritize materials with low environmental impact and use LCC in planning to achieve energy-efficient buildings.

5.1.3 Service life

An important factor that influences the total material use is the service life of products and components. The “practical life span”, i.e. for how long a product or component, independent of replacement reason, is actually in use is important when assessing the total material use and environmental impact connected to it during a building’s life cycle.

The results in the study in Publication III show that reasons for replacement can be technical, economical, aesthetical, environmental, health/comfort or due to legal requirements or a combination of these. A limited interview survey (Publication III) carried out among personnel from different categories of professions in real estate companies gave a wide variety of reasons, as shown in Figure 5.1. Traditionally, when assessing the expected service life of a product or component, it is done with respect to its technical and/or economical life span. However, according to the survey, these reasons were only valid in just over half of the cases. Methods to assess service life based on the other categories have not been found. The study was only small and could only indicate the problems when assessing service life, though it reinforced the preconceptions of being poorly known. The results show that it is necessary to also take account of other reasons for replacements than technical and economical.

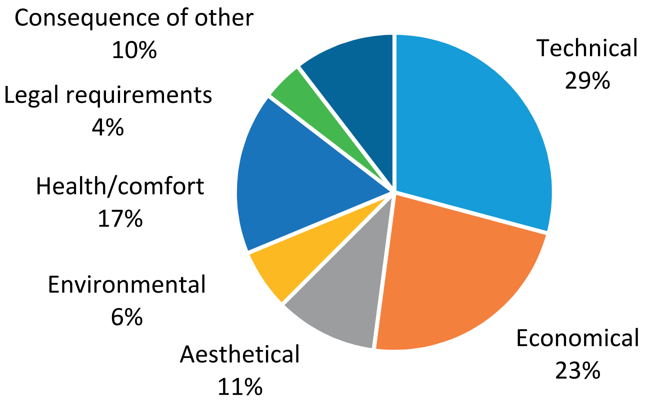


Figure 5.1 Distribution of reasons for replacement of installations for building services.

Systems for building services installations can be divided into three categories, (a) central parts or main systems, (b) distribution systems and (c) local parts or sub-systems. The service life of a component is roughly dependent on which of these categories it belongs to. The shortest service lives are found for local parts and systems, which are also often visible and directly exposed to wear from the users (tenants, residents). This is also supported by older studies. An observation from the estates in Publication III was that the piping for tap water had a surprisingly high age.

If the component makes up a part in a basic system for the building and is more or less independent of occupational activity, probably in category (a) or (b), then its service life will probably be decided by its practical life span. If the component is connected to an occupational activity, i.e. if the component or its capacity is a prerequisite for a certain professional activity, probably in category (b) or (c), then its service life will be determined by how long this activity is carried out. If the component is visible, probably in category (c), it is very likely that its service life will be decided by aesthetic reasons; a kitchen mixer will be replaced if it is shabby, scratched or just considered to be ugly.

The expected service life of systems and their components is dependent on the use of the building. It is likely that a building constructed as a residential building will continue to be used as a residential building during its entire life cycle, though there are examples on residential buildings being converted into office buildings, especially in city centres.

Outside the context of this thesis it should be noted that other conditions may be valid for other buildings, e.g. for commercial premises. Although office buildings are more generic, they are often adapted to specific company profiles, with specific demands on design, but also with demands on what building services they offer. E.g. office premises once built with standard cell offices can be rebuilt to offer an open plan office or activity-based office, which in turn often means a higher occupancy density. This then results in the need for higher ventilation flow rates per square meter and, possibly, the redesign of the whole ventilation system, i.e. the service life for the building services installations comes to an end. A third case could be facilities for industry, were both building and installations are completely dependent on the activities, i.e. the service life (life cycle) for both the building and its building services installations will be ended.

When carrying out LCA and LCC-analyses, it is important to assume a realistic estimated service life for all constituent materials and components. Poorly functioning components must be replaced, preferably according to an operation and maintenance plan, though not only routinely. If systems and components are replaced prematurely, the environmental impact will increase due to unnecessary material use. On the other hand, if they do not work as intended, the energy need and environmental impact risk being increased.

5.1.4 Replaceability

It is important to use materials as efficiently and wisely as possible, i.e. materials must be suitable for their specific purposes and situations, which means having suitable properties, capacities and qualities to provide the desired service lives. When designing the installations for a building it is necessary to decide to what extent they should be easily replaceable. If a product or component is easily replaceable it will only require a “quick action” to change it and, consequently, it will cause less damage to surrounding materials. If, for some reason, it is not easily replaceable the demand for more durable material will increase, which demands more accurate knowledge about an expected service life. In this context the total material masses during the life cycle of a building must be taken into account, not only for the materials in building services installations.

The conclusions from a pilot study carried out by Dahlblom and Ziegert (2002) were that the design would be somewhat more complicated if designed to be easily replaceable, the implementation would be affected and material usage would increase but sorting on demolition would be easier, the technical function and operation would be the same, maintenance would be easier and furnishability and cleanability would be worse. The aesthetics could be negatively affected, which could ultimately be decisive. The tendency today is not to make the installations easily replaceable and therefore to select materials with higher endurability.

In residential buildings the main building services systems are for heating, ventilation, water and sanitation. In more complex buildings there will also be services for cooling, sprinklers, gas, etc., which make the subject even more complicated.

When routing pipes and ducts the principle is "biggest first, but first of all the gravity sewers". This will cause problems in connection with replacements or repairs, especially when the space is as scarce as it tends to be.

5.1.5 Flexibility

Flexibility, when related to replaceability, could mean the flexibility to be able to adapt the building services installations to changed conditions in one or another respect. There could be, or become, a shortage of capacity in the installation systems in residential buildings due, for example, to overcrowding. In Sweden this is probably concentrated to areas where the urbanisation process takes place quickly and young people cannot afford apartments in newly built residential buildings. Immigrants, too, who have not yet established themselves in working life often have no other choice than to move in with relatives. Overcrowding can cause severe health problems due to dimensioned ventilation flows. Building services systems are not normally designed to be flexible and are only dimensioned for a certain maximum density of occupants. Maybe this is an issue that should be addressed in connection with renovation measures in residential buildings. Until then, assumptions must be made with regard to what extent a building needs to be flexible, i.e. for changed use, changed occupational density, changed climate, etc., while keeping in mind that over-dimensioned installations lead to unnecessary material use.

A problem related to overcrowding, due to personal economic situations, is fuel poverty, further discussed in section 5.3.1.

5.2 Energy use

Issues concerning energy use have been investigated in Publications II, IV and VIII, Table 1.2 and Figure 1.10. Energy use throughout a building's entire life cycle includes energy use during the *pre-use phase*, mainly for extraction of raw materials, for production and for transport, energy use during *the use phase*, mainly for operation of the building, but also for renovation and maintenance, and, finally, during the *end-of-life phase*.

5.2.1 During the pre-use phase

In this thesis have energy demands for manufacturing components and products used in building services systems for heating, ventilation, water and sanitation and for transport to building site been studied specifically. These energies were then compared to energy demands for the occupational phase, expected to last 50 years (Publication II). Some results indicated that manufacturing energy together with energy for transport constituted less than 1 % of the energy demand for 50 years of operation. In turn, energy for transport constituted less than 2.5 % of the manufacturing energy. This way to compare energy needs is a consequence of the system boundaries, which, in this thesis, are the building services systems. Energy needs, however, are also affected by the properties of other parts of a building, i.e. the system boundary could have been the entire building.

The use of materials is both a question of what materials should be chosen and the material amounts. In many applications it is possible to choose between two or more materials, e.g. pipes in a hydronic space heating system can be made of a number of different materials and qualities. Material choice is based on a compromise of a number of factors; pipe routing, the need for easy replaceability, whether visible installations can be accepted, necessary service life, necessary capacity, maximum pressure drops, acoustic aspects, for what medium, the price of piping, the price of installation, preferences expressed by the installer and builder, etc.

More recent LCA studies of two new low-energy buildings, one with a concrete framework (Liljenström et al, 2015) and one with a solid wood frame (Larsson et al, 2016), both designed to reach a maximum of 55 kWh/m^{2}HA, indicated that, as CO_2 equivalents, the pre-use phase and the use phase over 50 years would contribute equally to the environmental impact, which implies that for new-build low-energy buildings it is important to focus on the environmental impact also during the pre-use phase.

5.2.2 During the use phase

Energy needs for space heating and space cooling during a building’s use phase depend largely on:

- The building’s insulation standard
- The building’s ventilation – type of ventilation and air change rate
- The building’s airtightness
- The building’s indoor temperature
- The outdoor climate – temperature, wind and solar radiation
- The heat gains – solar radiation, internal heat loads

The first three are directly associated with the building itself, to the building’s properties. The last three last are associated with the building’s the geographical location, the local microclimate and user behaviour. User behaviour can include preferences regarding indoor temperature, airing patterns, occupational density, cooking habits and the use of miscellaneous appliances.

Energy needs for domestic hot water (DHW) depend largely on:

- The used amount of DHW
- The temperature of the cold water
- The temperature of the hot water
- The length of the piping system
- The standard of any hot water circulation system
- The heat losses from heat exchangers or boilers for DHW

The first parameter is, to a great extent, connected to user behaviour, while the others depend on the hot water system itself.

Energy needs for communal electricity energy depend largely on:

- Ventilation fans – number, flow rates, pressure losses, efficiencies
- Pumps in the piping systems – number, flow rates, pressure losses, efficiencies
- Cooling equipment (if there is a comfort cooling system)
- Lighting for communal use on the estate
- Lifts and other common electrical appliances

Of the above listed parameters, those included in the thesis are discussed below.

5.2.2.1 The influence of materials on energy needs

The material amounts can be a factor that is connected to the energy use during a building's life cycle, e.g. the number of panes in windows, the thickness of insulation in external walls, the thickness of insulation around pipes and ducts, the type of ventilation, the sizes of air handling units, the type of heat recovery, etc. Initially larger amounts of material would naturally mean a higher initial level of material use, a higher use of manufacturing energy and higher costs, but, if materials are chosen wisely, the result would be lower resource needs during the use phase and, subsequently lower operating costs, so that the final result would be a lower life-cycle cost (LCC). If a choice has to be made between a number of alternatives, an LCC analysis would provide a suitable method (Publication IV). However, there will always be uncertainties in LCC analyses. What rates of interest for heat, electricity and maintenance costs should be assumed? What service life should be assumed for the LCC analysis and what are the service lives of all the components and systems?

5.2.2.2 Space heating

The energy need for space heating is dependent on the properties of the building envelope, i.e. insulation and air tightness, and on the ventilation: system type, heat recovery efficiency and air change rate. The geographical location and microclimate, as well as the indoor temperature, have a large impact on the need for space heating. This has been explored in Publications II and IV and in Chapter 4. The studies in Publication II as well as in Chapter 4 showed that it was possible to fulfil low-energy standards by making quite limited improvements to the building envelope and that heat recovery with a high temperature efficiency provided good profitability.

A poor building envelope will mean low surface temperatures on external walls which will influence the experienced temperature (the operative temperature) and hence the need for an increased indoor air temperature to compensate this. Draught problems from air intakes and leakages also influence the experienced temperature.

Personal preferences differ and are adaptable within certain limits, see Sub-subsection 5.2.2.5 Behaviour related energy use, Preferences regarding indoor temperature.

5.2.2.3 Ventilation

In older building stock, the ventilation flow rates, according to BETSI (Boverket, 2006), were lower than the requirements in the building code. In buildings with natural ventilation, it was not possible to do much about this except to ensure that the air intakes and valves were not clogged. In buildings with mechanical exhaust ventilation there are regular checks of the ventilation systems and, if they do not meet the requirements, the property owner is obliged to remedy the deficiencies (Boverket, 2017). An increased ventilation flow will, of course, lead to an increased energy demand, unless the ventilation system is rebuilt to become a mechanical supply and exhaust ventilation system with heat recovery. The effect of two principles for heat recovery was studied in Publication IV, i.e. using an exhaust air heat pump and, supply and exhaust ventilation with heat recovery. Both gave approximately the same results in southern Sweden, though the heat pump increased the demand for electrical power. In northern Sweden, the supply and exhaust ventilation system with heat recovery showed to be the better choice. It also allowes for better thermal comfort.

5.2.2.4 Communal electricity

Publication V shows that communal electricity use can vary quite considerably. The reasons for this were, however, not studied, but generally it can be said that the use of more energy-efficient fans and pumps will, to some extent, decrease the need for communal electricity. Though there is a risk of an increased need for cooling energy if we are not careful when designing new buildings and renovating existing ones. A need for cooling may cause an increased demand for electricity to operate pumps and fans, depending on the technical solutions.

Communal lighting might be a rather limited part of the communal energy needs, but with LED lighting systems it will be significantly reduced.

5.2.2.5 Behaviour related energy use

As the variations and uncertainties when predicting the occupants' behaviour-related energy demands will cause uncertainties in the results of energy simulations, as well as when measuring the energy use, these questions are discussed shortly here.

Preferences regarding indoor temperature

In Publications V – IX, and especially in Publication VI, it was shown that the differences in indoor temperatures between different apartments in multi-family buildings could be quite large, indicating a variation of preferences. The studied buildings were provided with individual metering and billing (IMB) of space heating costs. Experience showed that the possibilities to save money were not very large. The average temperatures in these buildings were close to the set point temperatures for the buildings. More information about indoor temperatures and indoor thermal climates is given in Section 5.3. Studies carried out by Andersen et al (2016) in Denmark gave the opposite result, i.e. the IMB had an impact on the IEQ, both with regard to thermal conditions and air quality measured as CO_2 concentration.

Household electricity

The use of household energy was not studied, but in general it is known that the greater the use of electricity, the greater the generation of internal heat, which, during the heating season, contributes to the space heating, but during the rest of the year may cause overheating and possibly result in a cooling demand. As household electricity is outside the system boundary for a building's energy needs (according to the Swedish building code the system boundary is defined as delivered energy to a building, with the exception of household electricity in residential buildings and occupants' operational electricity in commercial premises), this use of electricity will help to fulfil the requirements as long as the building does not have a cooling system.

Window airing

Another important aspect that was not studied in this thesis was the impact of window airing in residential apartments. In BETSI (Boverket, 2009a) air change rates were presented as measured values. In multi-family buildings there was an average of 0.52 ACH and in single-family houses an average of 0.40 ACH, window airing included, Figure 1.9. The air change rate should be at least 0.5 ACH, window airing excluded. Studies carried out showed that more than 50 % of residents in new built apartment buildings with distributed ventilation, i.e. with individual ventilation units for each apartment, were airing daily with open windows (Nordquist, 2017). This behaviour will, of course, negatively influence the energy use. Questionnaires showed that, both in older buildings (Boverket, 2009) and in newly built buildings (Nordquist, 2017), the majority of tenants aired by opening windows during the heating season. The air flows could be quite large and lead to large energy losses. The air flow through an open window could be of the same order of magnitude as the required air flow according to the building regulations, i.e. the total air flow caused by ventilation and airing would be doubled. This aspect is not addressed in this thesis but is an important factor that influences the energy need for space heating. Window airing is, of course, a question of energy losses, but even more of IEQ, especially with regard to indoor air quality and indoor air temperature. These aspects are investigated in Section 5.3, Indoor environmental quality.

User interaction with technical systems

Nowadays, there is an awareness that factors other than technical, such as the users' interaction with the building services systems, can influence energy needs. These factors must be regarded as contributing to a dynamic and complex system with multiple interactions. This must be transdisciplinary and holistically studied in the future, i.e. also with regard to all other parameters that have proved to be increasingly important (Wierzbicka et al, 2018). Systems must be designed so that users can understand how to handle them; the more advanced the systems the more advanced the personnel required to operate them. It must, within reasonable limits, be possible and simple for tenants to achieve a desired indoor temperature. In a reasonably large building the temperatures will be close to those in a normal distribution. If it is easy for tenants to adjust the indoor temperature, the use of window airing as a method for temperature control will probably decrease. Studies performed by Andersen (2012) show that the users' interactions with building controls will result in better building performance in terms of occupant satisfaction, which in turn will influence both the IAQ and energy need.

Domestic hot water

The use of domestic hot water (DHW) is also behaviour related and difficult to predict, which of course will contribute to the uncertainty in energy simulations. The pattern for use of DHW has been studied by Bagge & Johansson (2011) and Bagge et al (2012, 2015). Over a period of five years the use of DHW increased yearly by 3 %. Even if the absolute use, due to technical solutions and environmental awareness among the users, were to decrease, it would still account for an increasingly larger part of the total energy needs, as the need for space heating, due to better building envelopes and efficient heat recovery in ventilation systems, etc., would decrease. Technical solutions to reduce energy needs for DHW include, for example, energy-efficient mixers that provide an equivalent cleaning effect at lower water flow rates and heat recovery from wastewater. The influence of heat recovery from wastewater was discussed briefly in Chapter 4, Additional studies.

5.3 Indoor environmental quality

Issues concerning indoor environmental quality (IEQ), with focus on thermal aspects, have been dealt with in Publications V, VI, VII, VIII and IX.

The IEQ influences all three perspectives of sustainability: social, environmental and economical. A good IEQ is essential for the residents' well-being and health. It is also an important factor in many rating systems (Section 1.1.3.5, Rating tools).

During the work on this thesis, it was found that the use phase is the most important during a building's life cycle, with respect to environmental impacts. The crucial challenge is to attain a desired indoor environmental quality with the lowest possible environmental impact.

5.3.1 Thermal indoor comfort

In the estates, from which the studied temperature data was retrieved, the property manager had implemented a system for IMB of heating costs in an attempt to lower energy use. The hypothesis was that some tenants would prefer a lower and some a higher indoor temperature and that the average temperature would be close to, and hopefully even below, the set-point temperature (and pay-limit temperature) of 21 °C with a reasonable distribution of variants.

The last five of the nine appended publications in this thesis investigate the thermal indoor climate in existing buildings with residential apartments. To get a more nuanced picture of the thermal conditions in these apartments different parameters were studied from different aspects. The indoor temperature distribution within a building over time is presented in Publication VI, the temperature distribution within residential apartments in Publication VII, the vertical temperature gradients within rooms in Publication IX and the vertical temperature gradients in multi-storey buildings in Publications VI and VIII. The effects of a control system with feedback on indoor temperatures is presented in Publication V. As discussed in section 5.2.2.5, personal preferences are different, also with regard to thermal conditions. It is well known that a person's thermal sensation is mainly related to the thermal balance of the person's body as a whole, a balance that is influenced by physical activity and clothing, as well as air temperature, mean radiant temperature, air velocity and air humidity. In addition, a person's general health, age and gender are parameters that are, traditionally, considered important. This has however been questioned. In a review of 112 papers Wang et al (2018) concluded that there were no significant differences between males and females regarding comfort temperature under the same conditions, although females tended to have less clothing than males and were therefore more critical about the thermal environment than the males and there were no significant differences between younger and older persons with regard to comfort temperature, although the comfort ranges were narrower for the elderly.

The studies carried out on thermal comfort in residential apartments (Publications VI, VII and IX) showed that the indoor temperature seemed to vary independently of where in the apartment block the apartment was situated. This could have been a result of different occupant preferences with some desiring a lower and some a higher temperature than the pay limit of 21 °C. The registered temperatures gave a close to normally distributed dataset, though with a slight skewness and a kurtosis that diverges from a normal distribution. Different temperatures in different rooms within an apartment were also registered, but generally there were small differences between the rooms, except in larger apartments where the temperature was lower in one of the bedrooms, probably the parent's bedroom (Publication VII). Generally, many people like to have a lower temperature when they sleep. However, as no questionnaire was carried out, it is not known whether that was the reason here. These observations support the importance of allowing for and making it possible to have different temperatures in different rooms and apartments.

In Publication VI, an indoor reference temperature for each month was calculated using an expression that took into account the vertical temperature gradient as a function of the outdoor temperature (Equation 1 in Publication VI). The set point temperature of 21 °C at a height of 1.2 m gave a reference temperature of 22 °C at a height of 2.1 m when the outdoor temperature was 0 °C. The study in Publication IX, in which the vertical temperature gradient was registered in ten apartments, indicated that this equation overestimated the slope of the gradient. This meant that the calculated reference temperatures in Publication VI were too high. The comparisons with the boxplots indicated that the mean temperature in several apartments in January was lower than the pay limit (the set point had been recalculated to a reference temperature), which meant that the indoor temperature used for billing in the IMB system had been underestimated and the tenants were not paying for the actual temperatures attained. Positive for the tenants, but of course a drawback for the property manager.

The property manager's experiences were that many of the tenants preferred to have a somewhat higher indoor temperature and were not reluctant to pay for it as the extra costs in this case were regarded as modest. A situation like this would, of course, be dependent on cost levels and energy prices. In this case, what was intended to lead to energy savings led to the opposite.

Another phenomenon, that could possibly be a problem, both in terms of comfort temperature and fair distribution of space heating costs, is that there is normally an upward vertical heat transport in multi-storey buildings (Publication VIII). This means that it could be difficult to achieve a desired lower temperature within an apartment even if the radiators were turned off, and the tenants would then have to pay for a higher temperature than they really wanted, unless they lowered the temperature by window airing, an unwanted behaviour from an energy efficiency point of view. How significant this vertical heat flow is for the thermal conditions in a building could be further investigated.

SS-EN ISO 7730 states with regard to acceptable thermal environments for comfort:

> *"Thermal comfort is that condition of mind which expresses satisfaction with the thermal environment. Dissatisfaction can be caused by warm or cool discomfort of the body as a whole, as expressed by the PMV and PPD, or by unwanted cooling (or heating) of one particular part of the body.*
>
> *Due to individual differences, it is impossible to specify a thermal environment that will satisfy everybody. There will always be a percentage of dissatisfied occupants. But it is possible to specify environments predicted to be acceptable by a certain percentage of the occupants. ..."*

Furthermore SS-EN ISO 7730 states with regard to adaptation:

> *In determining the acceptable range of operative temperature according to this international standard, a clothing insulation value that corresponds to the local habits and climate shall be used.*
>
> *In warm or cold environments, there can often be an influence due to adaption. Apart from clothing, other forms of adaptation, such as body posture and decreased activity, which are difficult to quantify, can result in the acceptance of higher indoor temperatures. People used to working and living in warm climates can more easily accept and maintain a higher work performance in hot environments than those living in colder climates (see ISO 7933 and ISO 7243).*

This approach, i.e. to strive for a steady-state indoor climate, might be too narrow. A change of the thermal conditions, within wider limits than ISO 7730 recommend, can be perceived as pleasant. E.g., if a person for any reason feels too warm indoors it would be pleasurable to go outside to cool down (if it is colder outside). The opposite will give the same reaction. A given external stimulus can be perceived pleasant or unpleasant depending on signals from inside the body. For this phenomenon Cabanac (1971) proposed the expression "alliesthesia" (from greek αλλαγή [*allagí*] = change and αίσθηση [*ésthisi*] = sensation). In de Dear (2011), in Parkinson & de Dear (2015) and in Parkinson et al (2016) the concept of alliesthesia is further elaborated. This supports the claim that it is important that tenants can open their windows.

Using data from the BETSI-survey (Boverket, 2008), Teli et al (2018) investigated indoor temperature distributions in Swedish households during a 2-week winter period and during a winter day. Figure 1 in Teli (2018) shows the average indoor temperatures and corresponding average outdoor temperatures for 1400 residential apartments in Sweden, but not for temperatures below 18 °C. This figure can be compared to Figure 15 in Publication VI, in which all 15-minute registrations at 2.1 m above floor for a multi-family building in southern Sweden for a whole year was shown. Although the data on which the figures were based differs, similarities in temperature distribution patterns can be seen, e.g. the temperatures are mainly within the range recommended by the Public Health Agency of Sweden and in EN15251.

Fuel poverty is a phenomenon that has probably existed for many years but has lately been given more attention. The project "European Fuel Poverty and Energy Efficiency (EPEE)", 50 % financed by the EU and with participants from France, Belgium, Spain, Italy and the United Kingdom, concluded that fuel poverty could cause health problems. A strict definition of the phenomenon is, however, not possible to state, as, among other things, climate conditions differ greatly around the world. An unprecise definition of fuel poverty proposed by EPEE was "*when a household finds it difficult or impossible to ensure adequate heating in the dwelling at an affordable price*". Each country may then adapt this definition to reflect national characteristics and criteria, while retaining a common view of the problem. Another outcome of this project was that one household out of seven in Europe experienced fuel poverty or was close to fuel poverty during 2007 (EPEE, 2009). The temperature conditions in the buildings studied in this thesis have not indicated that fuel poverty was a problem in Sweden.

5.3.2 Window airing

Publication VI presents a number of boxplots showing all registered 15-minute values of indoor temperature for each of 75 residential apartments on an estate built in 1965, for January and April. The distribution of temperatures differs considerably between different apartments. The lower outliers can be interpreted as long or short airing episodes. Some apartments had a median temperature close to the adjusted reference temperature but still had many outliers 3–5 °C below the reference temperature. The upper outliers could be the results of sunlight entering an apartment when no one was at home. Whether the window airing was due to bad indoor air quality or excess temperatures was not known, as no interviews or questionnaires were carried out. In cases where there were raised temperatures, the occupants probably felt comfortable with the change in temperature, an alliesthesia, a concept discussed in previous sub-section. Experiencing a raised temperature, i.e. the feeling of being too warm, could, of course, be the result of actually having a high indoor temperature, but it could also be due to an occupant's activities and their clothing or their mood and health. These airing episodes are important to the occupants in order to give them an overall positive experience of the thermal indoor climate. In other apartments there were hardly any low outliers, which may indicate a habit of not opening windows. However, nothing was known about who lived in the apartments nor how many they were. The pattern of low outliers does not seem to be connected to the median temperature for the apartment in question, which could indicate that independent of whether a person preferred lower or higher indoor temperatures they had a need for window airing, possibly for air quality reasons. In Publication VI the monthly temperature pattern for a warm and a cold apartment for a whole year are shown. The tenant(s) in the warm apartment did not seem to air, while the opposite was assumed in the colder apartment.

The habit of window airing is a combination of "getting better indoor air quality", "getting rid of excess heat" and "enjoying the change". No matter how perfect the air quality is and how precisely the preferred indoor temperature is kept, there will always be a wish for window airing.

5.3.3 Temperature control

To achieve the desired indoor temperature, irrespective of what this is and how it is decided, it is necessary to have a system to control the temperature. In Publication V a feedback control method for hydronic heating systems based on indoor temperature measurements was evaluated.

As mentioned in Publication V, the most common principle for controlling a hydronic heating system is by using a feedforward signal, i.e. based on the actual outdoor temperature, the building's properties and the properties of the heating system a suitable supply temperature will be decided. A complement would be the thermostatic radiator valves (TRVs) mounted on every radiator. However, a drawback of many TRVs is that they have a long time constant, 20 minutes or more, which leads to excess temperatures before they close the water supply to the radiator.

A feedback control system, in which the supply temperature in the hydronic heating system takes account both of outdoor temperature and prevailing indoor temperature will provide indoor temperatures that are less dependent on the outdoor temperature, i.e. more constant indoor temperatures. This makes it possible to avoid excess indoor temperatures and utilise heat gains from the sun and from persons and their activities. The most representative value of the indoor temperature is an average temperature based on all individual room temperatures, maybe weighted according to room size. However, as this probably entails a high cost for the installation of the sensors, only a few sensors are usually installed in representative apartments in a building. Some questions then arise: which apartments are representative and how large can the errors become with a declining number of sensors, i.e. how many sensors are needed? One conclusion in Publication VII was that living rooms had higher temperatures than bedrooms, i.e. if these were used to determine an average temperature there would be a small error. Of greater importance would be the risk of only placing sensors in cold apartments, which will trick the control system into providing a higher supply temperature than necessary, with the following risk of having warm apartments becoming even warmer. Future studies could be carried out to investigate how many sensors are needed and how to place them in different situations.

The property manager who provided the temperature data owned several estates built from the middle of the 1960s until the middle of 1970s, i.e. they were a part of what was known in Sweden as “the million programme”. Many of these have already been renovated while in others ongoing renovations are taking place. In these latter estates a temperature sensor is being installed in each apartment to monitor and keep track of the indoor temperatures. An opportunity that arises here is to also use these sensors for feedback control of the heat supply.

The benefits of having a more accurate temperature control system are not only a question of achieving the desired thermal indoor climate and lower energy use for space heating but also the reduction of the heat load, which is especially advantageous for the district heating provider at extremely low outdoor temperatures. The benefit for the provider is both environmental and economic. The heating plants used in these extreme situations, at peak loads, often use fossil fuels and these are very expensive on spot markets.

5.4 Laws and regulations

Laws and regulations, both national and at EU-level, are constantly changing. The goal is to achieve a sustainable society, in all aspects. How legislation is expressed will control the direction, rate and level of development towards sustainability. A short review of the regulations concerning energy use that have been stipulated in the Swedish building codes from 1993 until the present is given below.

5.4.1 Building codes and system boundaries

When comparing energy use it is of the utmost importance that the same system boundaries are used. In the Swedish building codes the system boundaries have been extended from (a) “net energy use”, i.e. a building’s need for energy for space heating, cooling, domestic hot water (DHW) and for appliances, to (b) “delivered (purchased) energy”, i.e. energy delivered to the building’s building services systems for space heating, cooling, DHW, lighting and appliances, and finally to (c) “primary energy use”, i.e. the total energy demand required to generate the energy delivered to the building services systems in a building. See section 1.1.3.3, Energy performance requirements stipulated in the Swedish building code.

When the buildings in Publication II were built, the Swedish building code BBR94 (Boverket, 1993) was in force. In BBR94, the energy performance requirements were not expressed as limits for energy use, but in requirements regarding the building envelope, the heat transmission coefficient and the air tightness. If the present building code (Boverket, 2018c) had been used, building A would not have been approved, but building B would. Building A had a calculated energy demand of 99 kWh/m^{2}HA, excluding household energy. Corrected for its geographical position, the so-called primary energy factor would have been 124 kWh/m^{2}HA. Building B had a calculated energy demand of 60 kWh/m^{2}HA, excluding household electricity, which corrected for its geographic position would have been 67 kWh/m^{2}HA. For multi-family buildings the primary energy factor must be below 85 kWh/m$^2_{HA}$ to be approved. In publication IV some alternative measures to decrease energy use were investigated. It was shown that energy recovery, either by an exhaust air heat pump or by a heat exchanger in an exhaust/supply ventilation system, was the single measure that could decrease energy use significantly. Otherwise, a combination of several measures was needed to reach significantly lower levels of energy use.

Even if all new buildings were built as "nearly zero-energy buildings" (NZEB), these will still make up a minor part of the building stock for many years to come. The part of the total energy use that will be most affected is space heating. The energy needs for domestic hot water will, thanks to different technical developments of mixer taps, for example, the use of less water while providing the same results, thus saving both water and energy. Kitchen mixers, basin mixers, shower mixers and bath mixers can be certified according to two Swedish standards (SS 820000 and SS 820001). Another energy-saving measure in DHW systems is heat recovery from wastewater, used to pre-heat the incoming tap water by 8 to 10 °C.

At the time of writing, the National Board of Housing, Building and Planning (Boverket, 2019d) has sent out a referral regarding coming changes in the present BBR. In general, the changes are expected to mean stricter energy requirements and introduce the concept of nearly zero energy buildings. Modified weighting factors for energy types have also been proposed, for example the weighting factor for district heating would be lowered and for electrical energy raised. Furthermore, changes in geographical factors have been proposed and for some localities the permitted primary energy figure would be increased. A quick check indicates that the energy requirements in some cases have been reduced.

5.4.2 Requirements regarding life-cycle assessment in the building code

Throughout this thesis the measures for decreasing environmental impact from the building and real estate management sectors have been limited to energy efficiency, i.e. the reduction of energy needs during the manufacturing of materials and during the use of buildings. However, there are studies that show that if the goal is to reduce climate change, other measures must also be taken into account, e.g. the reduction of emissions from material production and from transport. (Toller et al, 2011).

In the annual follow-up of the environmental goals in 2016, it was stated that life-cycle assessments (LCA) for buildings are more often mentioned as methods for analyzing where in the construction, operation and demolition phases measures should be taken to reduce environmental impacts. It was also stated that LCAs are complex and require special knowledge and data (Miljömålsberedningen, 2016). This can be interpreted as an expectation to implement these ideas along with other requirements. Several of the most recognized environmental assessment methods require some form of LCA, which means that their use is increasing.

What has happened so far is that the National Board of Housing, Building and Planning (NBHBP) is responsible for coordinating the Swedish efforts within various EU and international working groups on life-cycle analyses. To date, NBHBP has built a website with tips and instructions for the building sector when carrying out life-cycle assessments, Boverket (2019c).

According LCA analyses several software tools have been developed during the last two decades, a number of them are available free of charge on the Internet. Some are generic and some specific for the building sector. Some work with a specific LCA database while others allow the user to select and add data.

5.5 Sustainability concept trends

When the LCI studies in Publication II were carried out, they only focused on energy aspects. At present, more and more focus is being place on how the climate is being influenced in terms of carbon dioxide equivalents or global warming potential (GWP).

Liljenström et al (2015) carried out a life-cycle assessment of a newly built multi-family building constructed with a concrete frame and stated that the proportions between upstream and downstream energy use had been altered since Adalberth (2000), from about 15 %/85 % upstream/downstream relationship to about 35 %/ 65 %. In terms of GWP the proportions would be about 50 %/50 %. A similar study of a comparable building with a solid wood frame resulted in nearly the same proportions as the concrete building in terms of GWP (Larsson et al, 2016).

As mentioned in Section 5.4.1, the system boundaries for a building's energy use have gradually been extended. This means that it is not only the building's energy needs, but also the losses in distribution and production that must be accounted for. Differences in the energy sources that are used throughout a building's total life cycle will influence the resulting environmental impact. Hence, agreements on how this should be handled are necessary in order to enable comparisons between different building techniques.

6 Conclusions

Based on the results from the studies that have been carried out and the discussions in the previous section, I will return to the research questions one by one and make following conclusions:

What materials, material amounts and energy flows can be associated with building services installations in residential buildings?

The case study concluded that the building services systems consisted of more than 30 materials of which 9 constituted 80 % of the weight of the materials and 11 constituted 80 % of the manufacturing energy, and that the manufacturing energy was dependent on the material choice. To be able to perform reliable life-cycle assessments, it is necessary to have access to reliable and comprehensive LCA data for all materials, system parts and components, including their service lives.

What are the reasons for replacing building services installations and at what age are they replaced?

Traditional methods to assess service life, which rely on two factors, technical and economical service life, will probably give misleading results, as other aspects, e.g. aesthetical, were identified. The deciding reason for replacement of building services installations was unclear and, based on the observations in the studied estates, it seems that some replacements were random and some deterministic. The uncertainty is large, but this might, in fact, reflect the prevailing situation.

What opportunities are there to motivate energy efficiency measures based on LCC analyses?

An LCC study showed that, from a life-cycle cost perspective, it was beneficial to carry out measures to decrease energy use. Making only small improvements on prefabricated modules for multi-family buildings it was shown that it was possible to fulfil the stricter requirements in the new building codes with regard to purchased energy, though the margin was small.

What are the possibilities of achieving indoor temperatures that are less dependent on outdoor temperatures when using feedforward enhanced by feedback to control the indoor temperature?

A proposed feedback control method resulted in more even indoor temperatures, i.e. the indoor temperatures became less dependent on the outdoor temperature when compared to the control method with feedforward and thermostatic radiator valves. The conclusion was drawn that feedback control resulted in a lower level of outdoor temperature dependency. Experiences related to the study suggest that more attention must be given to the implementation and commissioning of control systems. An overall conclusion was that to make the method useful and reliable, it must be more robust, not possible for tenants to manipulate and guarantee that data losses are avoided.

What distribution and variation of indoor temperatures could be found in residential apartment blocks from the 1960s with individual metering and billing of space heating costs?

From extensive analyses of a large dataset it can be concluded that there were variations in temperature between different apartments, both in temperature levels and in temperature ranges. The overall conclusions were that differences in indoor temperatures are achievable for different apartments in an apartment block with a certain set point temperature and that the temperatures are not dependent on the apartment's location in the building. Both the building owner's goal, to keep a certain average temperature for energy saving reasons, and the tenants' goals, the possibility of varying the indoor temperature at individual apartment level, seem to be possible to reach. The measured temperatures were close to being normally distributed, though they had a slight negative skewness and a slight kurtosis during the heating periods. Furthermore, it could be seen that temperature variations follow the seasons. The temperatures at individual apartment level showed that there was a tendency for warm apartments to be warm all the year round and vice versa. There were also daily variations, with a magnitude of 0.3–0.4 °C, and with 0.1–0.3 °C differences between weekdays and weekends. Iso-plots of every single indoor temperature measurement for a whole year covering all seasons plotted as a function of the outdoor temperature showed that temperature levels were mainly within the limits of the standards for thermal comfort, thus showing that a acceptable thermal indoor climate was met in these apartment blocks using IMB.

What annual, monthly and daily differences and variations in indoor temperature could be found within and between the residential apartments of different type and size?

Indoor temperature in row houses were slightly higher than in apartment blocks, though they had the same set point temperature, 21°C. This is contrary to experience and was maybe due to the different ages of the buildings in each category. Differences in mean temperatures between living rooms and bedrooms, within apartments and for all apartments within each category, were in the range 0.1°C–0.5°C, with the greater temperature differences being recorded in the larger apartments. The temperatures in bedrooms were generally, but not always, below the temperatures in the living rooms, but with large individual variations. A further conclusion that could be drawn was that to only measure temperatures in living rooms, as is done in some IMB systems, risked recording unrepresentative temperatures, which could cause a bias in feedback control systems.

What influence does improved insulation have on vertical heat transport and indoor temperatures in multi-storey buildings?

From a theoretical study it was concluded that there was an upwards internal vertical heat transport in multi-storey buildings. This had a negative effect on the possibilities for tenants in different apartments to achieve their desired indoor temperatures. Better insulation can increase or decrease the vertical heat transport, depending on where the insulation is improved. An improved envelope will increase the temperature deviations while improved slabs between storeys will decrease them.

What vertical temperature gradients occur in radiator heated rooms and how do they affect temperature measurements in an IMB system?

Field measurements in apartments heated by a hydronic system and ventilated by mechanical exhaust ventilation indicated that vertical temperature gradients during the heating season in the inner parts of living rooms had only slight slopes. The thermal comfort in terms of the vertical temperature gradients was acceptable in the studied apartments under the studied conditions. In the apartments using IMB for space heating costs the temperature sensors were placed 2.1 m above floor level. As the upper parts in a room are normally warmer, the IMB system used a proposed equation to recalculate the registered temperature to a temperature 1.2 m above floor level, which were assumed to be more representative for the experienced indoor temperatures. The gradients that were recalculated with the proposed equation were, in general, steeper than the measured gradients in the apartments, implying that the IMB system overestimated the gradients under the studied conditions.

Finally…

The overall aim of this thesis was to examine important aspects regarding how building services systems can contribute to push residential buildings towards sustainability by focusing on material and energy use during a building's life cycle as well as on indoor thermal comfort and how to control it.

The overall conclusions are that it is necessary to consider a building as a system, a system that consists not only of the building itself and the building services systems but also the operating staff and the users of the building. Well-thought-out designs combined with conscious choices of materials and technical solutions for whole buildings, including the building services systems, can contribute to achieving a sustainable building stock. Figure 6.1 is an attempt to show to what extents the different studies address the different aspects of sustainability. Only studies V and VI address all aspects, though to a quite limited extent.

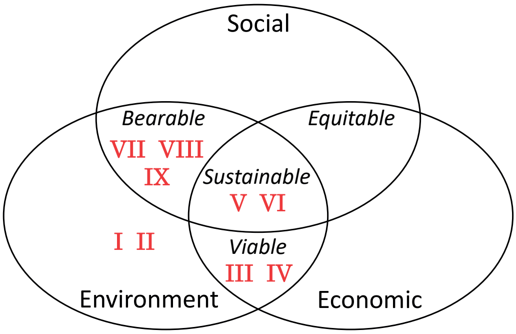


Figure 6.1 Illustration showing where the nine studies behind the publications fit in the sustainability diagram.

Taking into consideration the low rate of replacement of the building stock, it is, in the short term, more a question of running all buildings as energy efficiently as possible while fulfilling the requirements to provide a healthy and comfortable indoor environment for the users.

Epilogue

As this work has been in progress for two decades, some reflections are due

The term sustainable…

I cannot say that I was familiar with the term *sustainable* (Figure 1.1) nor with the concept of *sustainability* when I started this work. At that time the Swedish translation of the term had not yet settled to become “*hållbar*”, which certainly didn’t make it easier. *Hållbar* was interpreted as durable, lasting or perhaps tenable, but most of all as “something that could resist different loads or forces”, whether it was houses, bridges, clothes or whatever. Today, it is more or less used by everybody in all parts of society. The additional terms *bearable*, *viable* and *equitable* are still not well-defined in Swedish and not used in everyday conversation.

How to find references….

Some twenty years ago the method was usually to figure out some relevant search terms and concepts, make an appointment with a specialist and wait a few days for the results, which could turn out to be either a never-ending list, if the terms were to wide, or almost nothing, if the search criteria were too narrow. The next step was to try to find out which references that could be of use and then order copies of them, sometimes a very time-consuming procedure. Thanks to the Internet, lot of scientific papers are available immediately, although some databases do require membership in one organisation or another. “References through references” is, of course, still a method to find relevant papers.

How slow some things change…

LCA, as a tool to assess the environmental impact, was introduced into the building sector for research purposes a few years before 2000. Now it is starting to be implemented in the building sector and will soon become an integrated part in the design phase. LCAs were carried out in the building material industry, but not for whole buildings. A huge problem then was to access LCA data for building products and for some of the building materials. LCA software had not yet been developed. Software for energy simulations have undergone extensive development and this is still ongoing. The status of the software has gradually changed, from only being used by a few experts to becoming an important tool in a consultant's daily work.

References

Adalberth, K. (2000). Energy Use and Environmental Impact of New Residential Buildings. Dissertation. (Report TVBH–00/1012). Lund: Building physics, Lund University, 2000.

Al Horr, Y., Arif, M., Katafygiotou, M., Mazroei, A., Kaushik, A. and Elsarrag, E. (2016). Impact of indoor environmental quality on occupant well-being and comfort: A review of the literature. International Journal of Sustainable Built Environment. 2016, vol 5, pp 1–11. https://doi.org/10.1016/j.ijsbe.2016.03.006.

Andersen, R. K. (2012). The influence of occupants' behaviour on energy consumption investigated in 290 identical dwellings and in 35 apartments. Abstract from 10th International Conference on Healthy Buildings, Brisbane, Australia.

Andersen, S., Andersen, R. K., & Olesen, B. W. (2016). Influence of heat cost allocation on occupants' control of indoor environment in 56 apartments: Studied with measurements, interviews and questionnaires. Building and Environment, 101, 1-8. https://doi.org/10.1016/j.buildenv.2016.02.024.

Bagge, H. and Johansson, D. (2011). Measurements of household electricity and domestic hot water use in dwellings and the effect of different monitoring time resolution. Energy 36 (2011) pp 2943–2951. https://doi.org/10.1016/j.energy.2011.02.037.

Bagge, H., Johansson, D. and Lindstrii, L. (2012). Brukarrelaterad energianvändning. Resultat från mätningar i 1300 lägenheter. [User-related energy use. Results from measurements in 1300 apartments.]. LÅGAN Rapport 2012.

Bagge, H., Johansson, D. and Lindstrii, L. (2015). Brukarrelaterad energianvändning. Mätning och analys av hushållsel och tappvarmvatten. [User-related energy use. Measurement and analysis of household and domestic hot water.]. LÅGAN Rapport 2015.

Biswas, Tajin; Wang, Tsung-Hsien; and Krishnamurti, Ramesh (2009). Framework for Sustainable Building Design. School of Architecture. Paper 47. Available: https://www.researchgate.net/publication/30868018_Framework_for_Sustainable_Building_Design. Accessed: 2017-12-15.

Boverket (NBHBP) (1993). BFS 1993:57. Boverkets byggregler, BBR94. [Boverkets building regulations, BBR94.] Karlskrona: Boverket. Available: https://rinfo.boverket.se/BBR/PDF/1993-57BBR-1.pdf. Accessed: 2019-08-27.

Boverket (NBHBP) (2006). BFS 2006:12 Boverkets föreskrifter om ändring i verkets byggregler (1993:57) – föreskrifter och allmänna råd, BBR 12. [BFS 2006:12 Boverkets regulations regarding changes in the building code, BBR 12.] Karlskrona: Boverket. Available: https://rinfo.boverket.se/BBR/PDF/BFS2006-12BBR12.pdf. Accessed: 2008-05-15.

Boverket (NBHBP) (2009a). Så mår våra hus - redovisning av regeringsuppdrag beträffande byggnaders tekniska utformning m.m. (BETSI - Byggnaders energi, tekniska status och inomhusmiljö). [The state of our buildings. Report from government assignment according technical design, etc.]. Karlskrona: Boverket.

Boverket (NBHBP) (2009b). Bygg- och fastighetssektorns miljöpåverkan. [Environmental impact from construction and real estate sector.] Available: https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/publikationer/2009/bygg-och-fastighetssektorns-miljopaverkan/. Accessed: 2018-06-18.

Boverket (NBHBP) (2009c). Energieffektivisering av industriellt nyproducerade flerbostadshus. [Energy efficiency improvement of industrially newbuilt multi-family buildings.] Available: https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/publikationer/2009/energieffektivisering-av-industriellt-nyproducerade-flerbostadshus/. Accessed 2009-03-31.

Boverket (NBHBP) (2010). Socialt hållbar stadsutveckling: en kunskapsöversikt. [Socially sustainable urban development: an overview.] (Dnr: 2011-4094/2009). Available: https://www.boverket.se/globalassets/publikationer/dokument/2010/socialt-hallbar-stadsutveckling.pdf. Accessed 2018-11-19.

Boverket (NBHBP) (2014). Miljöpåverkan från bygg- och fastighetssektorn. [Environmental impact from construction and real estate sector.] Rapport: 2014:23. (ISBN pdf: 978-91-7563-155-4).

Boverket (NBHBP) (2016). Miljö- och klimatanpassade byggregler. Förstudie. Rapport: 2016:14. [Environmental and climate adapted building code. Pilot study.] Available: https://www.boverket.se/globalassets/publikationer/dokument/2016/miljo-och-klimatanpassade-byggregler.pdf. Accessed:

Boverket (NBHBP) (2017). BFS 2011:16 med ändringar till och med BFS 2017:10. Boverkets föreskrifter och allmänna råd om funktionskontroll av ventilationssystem och certifiering av sakkunniga funktionskontrollanter. [BFS 2011:16 with amendments up to BFS 2017:10. Boverket's regulations and general advice on functional control of ventilation systems and certification of expert function controllers.] Karlskrona: Boverket. Available: https://www.boverket.se/sv/lag--ratt/forfattningssamling/gallande/ovk---bfs-201116/. Accessed: 2019-08-27.

Boverket (NBHBP) (2018a). Miljöindikatorer 2018. [Environmental indicators 2018.] Available: https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/miljoindikatorer---aktuell-status/om-miljoindikatorerna/. Accessed: 2018-06-18.

Boverket (2018b). Hållbart byggande med minskad klimatpåverkan. [Sustainable building with reduced climate impact]. Available: https://www.boverket.se/sv/byggande/uppdrag/klimatpaverkan-i-byggprocessen/. Accessed: 2018-08-14.

Boverket (NBHBP) (2018c). BFS 2011:6 med ändringar till och med BFS 2018:4 (2018). Boverkets byggregler – föreskrifter och allmänna råd, BBR. [BFS 2011:6 with amendments up to BFS 2018:4. Boverket's building regulations – mandatory provisions and general recommendations, BBR.] Karlskrona: Boverket.

Boverket (NBHBP) (2019a). Fördjupad utvärdering av God Bebyggd Miljö 2019. [In-depth evaluation of Good Built Environment 2019]. Karlskrona: Boverket.

Boverket (NBHBP) (2019b). Miljöindikatorer 1993-2016. [Environmental indicators 1993-2016]. Karlskrona: Boverket. Available: https://www.boverket.se/sv/om-boverket/publicerat-av-boverket/oppna-data/miljoindikatorer/. Accessed: 2019-08-13.

Boverket (2019c). LCA i byggprocessen. [LCA in the building process]. Karlskrona: Boverket. Available: https://www.boverket.se/sv/byggande/hallbart-byggande-och-forvaltning/livscykelanalys/lca-i-byggprocessen/. Accessed: 2019-08-15.

Boverket (2019d). Remiss: Förslag till ändring av Boverkets byggregler (2011:6) – föreskrifter och allmänna råd, BFS 2020:xx. [Referral: Proposal for amendment of Boverket's building rules (2011: 6) – regulations and general advice.].

Cabanac, M. (1971). Physiological role of pleasure. Science, 173(4002), 1103–1107. doi:10.1126/science.173.4002.1103.

Chartered Institution of Building Services Engineers (CIBSE) (2019). Available: https://www.cibse.org/Building-Services/What-s-so-special-about-Building-Services-Engineer/Building-Services-Engineers-Bring-Buildings-to-Lif. Accessed 2019-08-12.

Dahlblom, M. (1994). Utbytbara installationer. Program. [Replaceable building services for heating, ventilation and sanitation. Program.] (Rapport TVBP–94/3044). Construction Management, Lund University, Lund, 1994.

Dahlblom, M. (1999a). Installationer ur ett livscykelperspektiv – En litteraturstudie. [Building Services Installations from a Life-Cycle Perspective – A Literature Review.] (Rapport TABK–99/3058). Building Science, Lund University, Lund, 1999.

Dahlblom, M. (1999b). Material- och energiflöden i VVS-installationer – Fallstudie. [Material and Energy Flows in Building Services Installations – Case Study.] (Rapport TABK—99/3059). Building Science, Lund University, Lund, 1999.

Dahlblom, M. (2001). Orsaker till byte av VVS-installationer – En intervjuundersökning. [Reasons for Replacement of Building Services Installations – An interview survey.] (Rapport TABK—01/1020). Building Science, Lund University, Lund, 2001.

Dahlblom, M. and Ziegert, A. (2002). Utbytbara installationer – en fallstudie. [Replaceable installations for heating, ventilation and sanitation – a case study.] (Rapport TVBP—02 /3075). Construction management, Lund University, Lund, 2002.

Dahlblom, M. and Johansson, D. (2009), Energieffektivisering av industriellt nyproducerade flerbostadshus. [Energy efficiency measures for industrially produced apartment buildings.] (Dnr 504-3479/2006). Boverket (NBHBP), Byggkostnadsforum, Karlskrona, 2009.

Dahlblom, M. & Johansson, D. (2009). Decreasing energy use of industrially produced multi-family dwellings in Sweden, Proceedings of Cold Climate HVAC, Sisimiut. Greenland, 8 s.

Dahlblom, M. and Jensen, L. (2011). Reglering av värmesystem i flerbostadshus med individuell värmemätning. Slutrapport för forskning med stöd från CERBOF [Control of Heating Systems in Apartment Buildings with Individual Metering of Space Heating Costs. Final report of research supported by CERBOF]. (Rapport TVIT–11/3006). Lund: Building Services, Lund University.

Dahlblom, M., Nordquist, B. & Jensen, L. (2014). Variations in indoor temperature in residential apartments of different size and building category, NSB 2014: 10th Nordic Symposium on Building Physics,15-19 June 2014 Lund, Sweden. 830-837.

Dahlblom, M. & Jensen, L. (2014). Vertical temperature increase in multi-storey buildings, NSB 2014: 10th Nordic Symposium on Building Physics,15-19 June 2014 Lund, Sweden. 814-821.

Dahlblom, M., Nordquist, B. & Jensen, L. (2015). Distribution and variation of indoor temperatures in apartment blocks with individual metering and billing of space heating costs – at building, apartment, and room level. Energy Efficiency (2015) 8: 859. https://doi.org/10.1007/s12053-015-9328-4.

Dahlblom, M., Nordquist, B. & Jensen, L. (2018). Evaluation of a feedback control method for hydronic heating systems based on indoor temperature measurements. Energy and Buildings 166 (2018) 23-34. https://doi.org/10.1016/j.enbuild.2018.01.013.

Dahlblom, M., Nordquist, B., Wallentén, P., Harderup, L-E. & Jensen, L. (2019). Vertical temperature gradients in apartments with hydronic radiator heating, Cold Climate HVAC 2018: Sustainable Buildings in Cold Climates. Springer, 575-585.

de Dear, R. (2011). Revisiting an old hypothesis of human thermal perception: Alliesthesia. Building Research & Information, 39(2), 108–117. https://doi.org/10.1080/09613218.2011.552269.

DOE Zero Energy Ready Home National Program Requirements. Rev. 06 (2017). Available: https://www.energy.gov/sites/prod/files/2017/04/f34/DOE%20Zero%20Energy%20Ready%20Home%20National%20Program%20Requirements%20Rev06%20-%20Final_0.pdf. Accessed: 2018-11-05.

Edén, Michael & Jönsson, Åsa (editors) (2002). MISTRA sustainable building: experiences from a cross-disciplinary research programme. Göteborg: Chalmers University of Technology, Göteborg, 2002.

Elkington, John (1997). Cannibals with forks: the triple bottom line of 21st century business. Oxford: Capstone.

Energy Star (2019). Energy Efficient New Homes & Apartments. Available: https://www.energystar.gov/newhomes/homes_prog_reqs/national_page. Accessed: 2019-01-20.

Engqvist, L. and Fredriksson, V. (2004). Uppföljning av Energiprestanda i Flerbostadshus [Evaluation of Energy Performance in Multi-dwelling Blocks.] Examensarbete No 337, Byggnader och installationer, KTH.

European Commission (2018). Energy, Data and analysis, Building stock observatory. Available: https://ec.europa.eu/energy/en/data-analysis/building-stock-observatory. Accessed: 2018-09-17.

European Fuel Poverty and Energy Efficiency (2009). EPEE project Publishable Result-oriented report. https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/epee_european_fuel_poverty_and_energy_efficiency_en.pdf. Accessed: 2019-11-18.

Forum för Energieffektivt Byggande (2018). Kravspecifikation för energieffektiva byggnader. Bostäder och lokaler, FEBY 18. [Specification of requirements for energy-efficient buildings. Dwellings and facilities.]

Fransson, V., Nordquist, B. & Lindberg, O. (2014b). Window-opening and indoor climate in new multi-family dwellings: A questionnaire survey. NSB 2014: 10th Nordic Symposium on Building Physics, 15–19 June 2014. Lund, Sweden: Full Papers, pp 908–915. Lund: Lund University.

Gerring, J. (2004). What is a case study and what is it good for? The American Political Science Review, Vol. 98, No. 2 (2004), pp. 341–354.

Henckens, M.L.C.M., Driessen, P.P.J. and Worrell, E. (2014). Metal scarcity and sustainability, analyzing the necessity to reduce the extraction of scarce metals. Resources Conservation and Recycling. 93, 1–8. https://doi.org/10.1016/j.resconrec.2014.09.012.

Henckens, M.L.C.M., van Ierland, E.C., Driessen, P.P.J. and E. Worrell. (2016). Mineral resources: Geological scarcity, market price trends, and future generations. Resources Policy 49 (2016) 102–111. http://dx.doi.org/10.1016/j.resourpol.2016.04.012.

Kontes, G.D.; Giannakis, G.I.; Horn, P.; Steiger, S.; Rovas, D.V. (2017). Using Thermostats for Indoor Climate Control in Office Buildings: The Effect on Thermal Comfort. Energies 2017, 10, 1368; https://doi:10.3390/en10091368.

Källblad, K. (1994). The BKL-METHOD Computer Programme. User Manual. (Report TABK—94/3019). Building Science, Lund University, Lund, 1994.

Larsson, M., Erlandsson, M., Malmqvist, T. and Kellner, J. (2016). Byggandets klimatpåverkan. Livscykelberäkning av klimatpåverkan för ett nyproducerat flerbostadshus med massiv stomme av trä. [The climate impact of the building process. LCA calculation of the climate impact for a newly produced multi-family building with solid wood frame.] (Report B 2260). IVL Svenska Miljöinstitutet.

Liljenström, C., Malmqvist, T., Erlandsson, M., Fredén, J., Adolfsson, I., Larsson, G. and Brogren, M. (2015). Byggandets klimatpåverkan. Livscykelberäkning av klimatpåverkan och energianvändning för ett nyproducerat energieffektivt flerbostadshus i betong. [The climate impact of the building process. LCA calculation of climate impact and energy use for a newly produced energy-efficient multi-family building in concrete.] (Report B 2217). IVL Svenska Miljöinstitutet.

Mensah J. (2019). Sustainable development: Meaning, history, principles, pillars, and implications for human action: Literature review. Cogent Social Sciences (2019), 5. https://doi.org/10.1080/23311886.2019.1653531.

Miljömålsberedningen (2016). En klimat- och luftvårdsstrategi för Sverige, Del 1 (SOU 2016:47). Stockholm: Naturvårdsverket.

Miljö- och jordbruksutskottets betänkande (2010). Svenska miljömål (2009/10:MJU25). [Swedish environmental targets (2009/10: MJU25).] Stockholm: Sveriges riksdag. Available: https://www.riksdagen.se/sv/dokument-lagar/arende/betankande/svenska-miljomal_GX01MJU25. Accessed: 2018-09-17.

Miljö- och jordbruksutskottets betänkande (2017). Ett klimatpolitiskt ramverk för Sverige (2016/17:MJU24). [A climate policy framework for Sweden.] Stockholm: Sveriges riksdag. Available: http://www.riksdagen.se/sv/dokument-lagar/arende/betankande/ett-klimatpolitiskt-ramverk-for-sverige_H401MJU24. Accessed: 2018-09-17.

Munther, K. (1996). Enorm 1000. Stockholm, Sweden: AB Svensk Byggtjänst.

Nationalkommittén för Agenda 21 och Habitat (2003). En hållbar framtid i sikte. Slutbetänkande (SOU 2003:31). [A sustainable future in sight. Final report (SOU 2003: 31).] Stockholm: Regeringskansliet. Available: https://www.regeringen.se/contentassets/59fe59061e4e4861a6dd7579b720ca51/en-hallbar-framtid-i-sikte. Accessed: 2019-01-11.

Naturvårdsverket (Swedish Environmental Protection Agency) (2019a). Fördjupad utvärdering av miljömålen 2019 – Med förslag till regeringen från myndigheter i samverkan. [In-depth evaluation of the environmental goals 2019 – With proposals to the government from authorities in collaboration.] Available: https://www.naturvardsverket.se/Documents/publikationer6400/978-91-620-6865-3.pdf?pid=24098. Accessed: 2019-02-20.

Naturvårdsverket (Swedish Environmental Protection Agency) (2019b). Miljömålen. Årlig uppföljning av Sveriges nationella miljömål 2019 – Med fokus på statliga insatser. Reviderad version. [The environmental objectives. Annual follow-up of Sweden's national environmental goals 2019 - With focus on government initiatives.] Available: https://www.naturvardsverket.se/Om-Naturvardsverket/Publikationer/ISBN/6800/978-91-620-6890-5/. Accessed: 2019-10-14.

Newcomer, Kathryn E., Hatry, Harry P. & Wholey, Joseph S. (red.) (2015). Handbook of practical program evaluation. Fourth edition [San Francisco]: Jossey-Bass, A Wiley Imprint.

Nordquist, B., Fransson, V. & Lindberg, O. (2014a). Perceived and measured indoor climate in new family buildings including identifying technical deficiencies. NSB 2014: 10th Nordic Symposium on Building Physics, 15–19 June 2014 Lund, Sweden: Full Papers, pp 846-853. Lund: Lund University.

Nordquist, B & Fransson, V. (2015). Insufficient air supply rates in new build apartments with energy efficient ventilation: Including aspects of human perception and behavior. Healthy Buildings Europe Conference, 18–20 May 2015, Eindhoven, Netherlands.

Nordquist, B. (2017). Fördjupad uppföljning av Flagghusen: Studie av inneklimat, ventilationssystem och vädringsbeteende. [In-depth follow-up of Flagg-husen: Study of indoor climate, ventilation system and airing behavior]. LUTVDG/TVIT, nr. 3009, vol. 17, Building Services, Lund University, Lund.

Olanrewajua, AbdulLateef and Anahveb, Paul Junior. (2015). Duties and responsibilities of quantity surveyors in the procurement of building services engineering. Creative Construction Conference 2015 (CCC2015) Procedia Engineering 123. Krakow, Poland 21–24 June 2015, pp 352–360.

Parkinson, T., & de Dear, R. J. (2015). Thermal pleasure in built environments: Physiology of alliesthesia. Building Research & Information, 43(3), 288–301. https://doi:10.1080/09613218.2015.989662.

Persson, J., & Sahlin, N-E. (2013). Vetenskapsteori för sanningssökare. [Philosophy of science for truth seekers]. Fri tanke förlag.

Petitjean, R. (1997). Total hydronic balancing: a handbook for design and trouble-shooting of hydronic systems- 2. ed. Ljung: Tour & Andersson Hydronics.

Schweizer, C., Edwards, R. D., Bayer-Oglesby, L., Gauderman, W. J., Ilacqua, V., Jantunen, M. J., Lai, H. K., Nieuwenhuijsen, M. & Künzli, N. (2007). Indoor time–microenvironment–activity patterns in seven regions of Europe. Journal of Exposure Science and Environmental Epidemiology (2007) 17, 170–181.

Sellin, N. and Magnusson, R. (2018). Renoveringsåtgärders och brukarbeteendes effekt på energianvändning och inomhusmiljö i frånluftsventilerade flerbostadshus En fallstudie av miljonprogramhus i Lund. [The effect of renovation measures and user behavior on energy use and indoor environment in exhaust air ventilated apartment buildings. A case study of a "million home programme" multi-family building in Lund]. (Rapport TVIT--18/5062). Lund University.

SFS 2017:720. Klimatlag. [Climate law.] Stockholm: Miljö- och energidepartementet. (2017). Available: https://www.riksdagen.se/sv/dokument-lagar/dokument/svensk-forfattningssamling/klimatlag-2017720_sfs-2017-720. Accessed: 2018-11-05.

SGBG (2019). Certifiering. [Certifying]. Available: https://www.sgbc.se/certifiering/ Accessed: 2019-01-20.

Statens planverk, (1975). Föreskrifter, råd och anvisningar för byggnadsväsendet utfärdade med stöd av 76 § byggnadsstadgan. [Regulations, advice and instructions for building.] Stockholm.

Statens planverk, (1976). SBN 1975 Supplement 1, Energihushållning mm. [Swedish building code 1975, Supplement 1, Rational use of energy, etc.] Stockholm.

Statens planverk, (1980). PFS 1980:1 Svensk byggnorm, SBN 1980. [Swedish building code 1980, SBN 1980.] Stockholm.

Statistics Sweden, SCB (2018a). Folkmängden den 1 november efter region, ålder och kön, år 2002-2018. [Population on 1 November by region, age and gender, in 2002–2018]. Available: http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__BE__BE0101__BE0101A/FolkmangdNov/. Accessed: 2019-02-01.

Statistics Sweden, SCB (2018b). Kalkylerat bostadsbestånd efter region och hustyp, år 1990-2012. [Calculated building stock by region and type of house, year 1990-2012]. Available: http://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__BO__BO0104/BostadsbestandK/. Accessed: 2019-02-01.

Strusoft (2007). VIP+, Software for building energy balance. Malmö, Sweden.

Strusoft (2012). VIP Energy, Software for building energy balance. Malmö, Sweden.

Sveriges Byggindustrier (2018). Byggkonjunkturen – konjunkturrapport från Sveriges Byggindustrier, nr 1–2018. [Business cycle report from Sweden's Construction Industries, 1–2018]. Available: https://www.sverigesbyggindustrier.se/Userfiles/Sveriges_Byggindustriers_byggkonjunkturprognos_mars_2018.pdf. Accessed: 2018-09-12.

Sveriges Centrum för Nollenergihus (2012). Kravspecifikation för nollenergihus, passivhus och minienergihus – Bostäder, FEBY 12. [Specification of requirements for zero energy buildings, passive houses and low energy buildings – Dwellings.]

Swedish Energy Agency (2007). Kravspecifikation för passivhus i Sverige – Energieffektiva bostäder, Energimyndighetens program för passivhus och lågenergihus, version 2007:1. [Specification of requirements for passive houses in Sweden - energy efficient dwellings, Swedish Energy Agency´s program for passive houses and low energy buildings, version 2007:1.]

Swedish Energy Agency (2018a). Energy in Sweden 2017. Available: https://energimyndigheten.a-w2m.se/Home.mvc?ResourceId=5733. Accessed: 2018-09-17.

Swedish Energy Agency (2018b). Energy in Sweden 2018 – Facts and figures. Available: http://www.energimyndigheten.se/globalassets/statistik/energilaget/energy-in-sweden-2018_20180419.xlsx. Accessed: 2018-11-05.

Swedish Energy Agency (2019). Energilyftet – en webbutbildning. [Energy lift – a web based course]. Available: http://energilyftet.learnways.com. Accessed: 2019-09-12.

Swedish Standards Institute (SIS) (2001). SS-EN-ISO 7726:1998 Ergonomics of the thermal environment – Instruments for measuring physical quantities. Stockholm: SIS.

Swedish Standards Institute (SIS) (2006). SS-EN ISO 7730:2006. Ergonomi för den termiska miljön - Analytisk bestämning och bedömning av termisk komfort med hjälp av indexen PMV och PPD samt kriterier för lokal termisk komfort. [Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria] (ISO 7730:2005).

Swedish Standards Institute (SIS) (2011a). SS 820000:2010 Sanitary tapware – Method for determination of energy efficiency of mechanical basin and sink mixing valves.

Swedish Standards Institute (SIS) (2011b). SS 820001:2010 Sanitary tapware – Method for determination of energy efficiency of thermostatic mixing valves with shower.

Säfsten, K. and Gustavsson, M. (2019). Forskningsmetodik för ingenjörer och andra problemlösare. [Research methodology for engineers and other problem solvers.] Studentlitteratur AB, Lund, Sweden.

Teli D., Langer S., Ekberg L. & Dalenbäck JO. (2019). Indoor Temperature Variations in Swedish Households: Implications for Thermal Comfort. In: Johansson D., Bagge H., Wahlström Å. (eds) Cold Climate HVAC 2018. CCC 2018. Springer Proceedings in Energy. Springer, Cham.

Thullner, Katharina (2010). Low-energy buildings in Europe – Standards, criteria and consequences. A study of nine European countries. (Report TVIT–10/5019). Lund: Building Services, Lund University.

Toller, S., Wadeskog, A., Finnveden, G. and Miliutenko, S. (2011a). Miljöindikatorer för bygg- och fastighetssektorn 1993-2007. [Environmental indicators for the construction and real estate sector 1993-2007.] Boverket: Rapport 2011:2. Karlskrona, 2011.

Toller, S., Wadeskog, A., Finnveden, G., Malmqvist, T. and Carlsson, A. (2011b). Energy Use and Environmental Impacts of the Swedish Building and Real Estate Management Sector. Journal of Industrial Ecology. Volume 15, Number 3. pp 394–404. https://doi.org/10.1111/j.1530-9290.2011.00340.x.

United Nations (1948). Universal Declaration of Human Rights. Available: http://www.un.org/en/universal-declaration-human-rights/. Accessed: 2017-12-08.

United Nations (1973). Report of the United Nations Conference on the Human Environment (Stockholm declaration): Stockholm, 5–16 June 1972. New York: United Nations. Available: http://www.un-documents.net/unchedec.htm. Accessed: 2017-12-08.

United Nations (1987). World Commission on Environment and Development. Our Common Future. (Brundtland Report). Oslo, March 1987. Available: http://www.un-documents.net/wced-ocf.htm. Accessed: 2017-12-08.

United Nations (1992). Conference on Environment & Development. AGENDA 21. Rio de Janerio, Brazil, 3–14 June 1992. Available: https://sustainabledevelopment.un.org/content/documents/Agenda21.pdf. Accessed: 2017-12-08

United Nations (2002). World Summit on Sustainable Development, WSSD. Johannesburg Declaration on Sustainable Development. Johannesburg Summit, Johannesburg, South Africa, 26 August–4 September 2002. A/CONF.199/20. Available: http://www.un-documents.net/jburgdec.htm. Accessed: 2018-09-17.

United Nations (2012). The future we want. Resolution adopted by the General Assembly of the United Nations, Rio de Janeiro, Brazil, 27 July 2012. A/RES/66/288. Available: http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/66/288&Lang=E. Accessed: 2018-09-17.

United Nations (2015a). Resolution adopted by the General Assembly on 25 September 2015. A/RES/70/1. Transforming our world: the 2030 Agenda for Sustainable Development. Available: http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E. Accessed: 2017-12-12.

United Nations (2015b). Adoption of the Paris agreement. FCCC/CP/2015/L.9/Rev.1. Available: https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf. Accessed: 2018-12-12.

Wierzbicka, A., Pedersen, E., Persson, R., Nordquist, B., Stålne, K., Gao, C., Harderup, L.-E., Borell, J., Caltenco, H., Ness, B., Stroh, E., Li, Y., Dahlblom, M., Lundgren-Kownacki, K., Isaxon, C., Gudmundsson, A., Wargocki, P. (2018). Healthy Indoor Environments: The Need for a Holistic Approach. Int. J. Environ. Res. Public Health 2018, 15, 1874. https://doi:10.3390/ijerph15091874.

World GBC (2019). About green building. Available: https://www.worldgbc.org/. Accesed: 2019-01-29.