Department of Built Environment

Evaluation of Energy Efficiency in Educational Buildings

Tiina Sekki

Aalto University

DOCTORAL DISSERTATIONS

Aalto University publication series
DOCTORAL DISSERTATIONS 57/2017

Evaluation of Energy Efficiency in Educational Buildings

Tiina Sekki

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall M1 of the school on 12th May 2017 at 12.

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Aalto University publication series
DOCTORAL DISSERTATIONS 57/2017

ISBN 978-952-60-7359-0 (printed)
ISBN 978-952-60-7358-3 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-60-7358-3

Unigrafia Oy
Helsinki 2017

Finland

NORDIC ECOLABEL
441 697
Printed matter

Aalto University

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Abstract

Author
Tiina Sekki

Name of the doctoral dissertation
Evaluation of Energy Efficiency in Educational Buildings

Publisher School of Engineering

Unit Department of Built Environment

Series Aalto University publication series DOCTORAL DISSERTATIONS 57/2017

Field of research Real Estate Economics

Manuscript submitted 2 December 2016 **Date of the defence** 12 May 2017

Permission to publish granted (date) 20 March 2017 **Language** English

☐ **Monograph** ☒ **Article dissertation** ☐ **Essay dissertation**

Abstract

The facility strategy of the City of Espoo emphasises improvements in the energy efficiency and efficient use of buildings. This means i.e. improving space efficiency and increasing operating times. Increasing the use of facilities often increases energy consumption. For this reason, the targets i.e. energy savings and increased use of facilities may partly be contrary to each other if individual buildings are considered. In order to encourage relevant efficiency efforts, it is essential to know how to measure energy efficiency, especially in the building operational phase.

The aim of this dissertation is to increase knowledge about the evaluation of energy efficiency in educational buildings. The dissertation studies three research questions. The first question provides an overall picture of energy consumption and assesses the factors that are used in evaluating measured energy. The second question explores ways in which building usage and occupancy influence the measured energy consumption and energy cost. The third question examines the ability of alternative indicators to function as comparative indicators in improving energy efficiency.

The research was conducted by exploring the issues in existing educational building. The energy efficiency was examined in a statistical and multiple case study approach. The study started with a broad survey in order to generalize the results to a building stock and then, in the second phase, focused on qualitative case studies to collect detailed views from the building stock to help explain the initial quantitative survey.

Results showed that the energy consumption of the studied buildings varied considerably regarding all studied factors when examining both building types and individual buildings. The variation cannot be explained only by the factors themselves. Results showed that energy efficiency can be measured by using alternative indicators and confirmed that different indicators make a different impact on results showing efficiency. The choice of indicators to use depends on the needs of the indicator user, as well as the situation and the objectives of the analysis. This dissertation suggests using a set of indicators.

In the future, the assessment of the energy efficiency of the operational phase should include, beside physical characteristics, parameters describing building use such as occupant levels, operating times and space efficiency. In addition to technical measures, the City of Espoo can also optimise the need of spaces of daycare centres and schools. The dissertation suggests developing energy audits to take into account the energy efficiency perspective, not only the perspective of energy savings.

Keywords energy efficiency, energy consumption, energy costs, energy efficiency indicators, building usage, daycare centres, schools

ISBN (printed) 978-952-60-7359-0 **ISBN (pdf)** 978-952-60-7358-3

ISSN-L 1799-4934 **ISSN (printed)** 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2017

Pages 123 **urn** http://urn.fi/URN:ISBN:978-952-60-7358-3

Aalto-yliopisto

Aalto-yliopisto, PL 11000, 00076 Aalto www.aalto.fi

Tiivistelmä

Tekijä
Tiina Sekki

Väitöskirjan nimi
Opetusrakennusten energiatehokkuuden arviointi

Julkaisija Insinööritieteiden korkeakoulu

Yksikkö Rakennetun ympäristön laitos

Sarja Aalto University publication series DOCTORAL DISSERTATIONS 57/2017

Tutkimusala Kiinteistötalous

Käsikirjoituksen pvm 02.12.2016 **Väitöspäivä** 12.05.2017

Julkaisuluvan myöntämispäivä 20.03.2017 **Kieli** Englanti

☐ **Monografia** ☒ **Artikkeliväitöskirja** ☐ **Esseeväitöskirja**

Tiivistelmä

Espoon kaupungin toimitilastrategian keskeinen tavoite on tilojen käytön tehostaminen. Tilojen yhteiskäyttöä lisätään ja uudet sekä peruskorjattavat tilat suunnitellaan entistä monikäyttöisemmiksi. Käytön tehokkuuden kasvaessa usein energiankulutus kasvaa ja pitkät käyttöajat voivat "rankaista" energiatehokkuuden tunnuslukujen ja mittaamisen näkökulmasta. Mittari fyysisen rakennuksen vertailuun ei välttämättä sovellu rakennuksen käytönaikaiseen seurantaan, sillä se ei huomioi rakennuksen todellista käyttöä.

Tämän väitöskirjatutkimuksen tavoitteena on lisätä ymmärrystä opetusrakennusten energiatehokkuuden arviointiin. Tutkimuksessa vastataan kolmeen tutkimuskysymykseen. Ensimmäinen tutkimuskysymys tarkastelee opetusrakennusten energiankulutuksen kokonaiskuvaa ja arvioi eri tekijöiden merkitystä siihen. Toinen tutkimuskysymys pyrkii selvittämään mikä on rakennuksen käytön merkitys energiatehokkuutta arvioitaessa. Kolmas tutkimuskysymys tarkastelee vaihtoehtoisten indikaattoreiden kykyä toimia vertailevina tunnuslukuina energiatehokkuuden parantamisessa.

Väitöskirja on yhdistelmätutkimus, jossa käytetään sekä numeerista että laadullista aineistoa. Numeerinen aineisto koostuu tutkittujen kiinteistöjen toteutuneesta, mitatusta energiankulutus ja energiakustannus sekä käyttöön liittyvästä datasta, laadullinen aineisto puolestaan energiatodistuksista ja energiakatselmuksista. Lisäksi kahdeksan tapaustutkimuksen avulla arvioidaan valittujen energiatehokkuusindikaattoreiden käytettävyyttä.

Tulosten perusteella tutkitun opetusrakennuskannan energiankulutus vaihtelee merkittävästi kaikkien tutkittujen tekijöiden suhteen sekä rakennustyyppien että yksittäisten rakennusten välillä tarkasteltuna. Tulosten mukaan tutkitut tekijät eivät yksinään selitä energiankulutuksen vaihtelua. Löydökset vahvistavat, että vaihtoehtoiset indikaattorit tuottavat erilaisia tuloksia energiatehokkuuden arvioimiseen ja soveltuvat erilaisiin käyttötarpeisiin. Tutkimuksessa annetaan ehdotus indikaattoreiden yhdistelmästä.

Tutkimuksessa ehdotetaan, että opetusrakennusten käyttövaiheen energiatehokkuutta arvioitaessa näkökulmaa laajennetaan siten, että fyysisen ominaisuuden lisäksi huomioidaan keskeisiä rakennuksen käyttöä kuvaavia parametreja kuten käyttäjämääriä, käyttöaikoja ja tilatehokkuutta. Löydösten mukaan teknisten parannusten lisäksi Espoon kaupungilla on mahdollisuus optimoida päiväkotien ja koulujen tilankäyttöä. Jotta energiatehokkuutta parantavia toimenpiteitä voidaan tulevaisuudessa huomioida kokonaisvaltaisemmin, tulee nykyistä energiansäästöön tähtäävää energiakatselmustapaa kehittää.

Avainsanat energiatehokkuus, energiankulutus, energiakustannus, energiatehokkuusindikaattorit, kiinteistön käyttö, päiväkoti, koulu

ISBN (painettu) 978-952-60-7359-0 **ISBN (pdf)** 978-952-60-7358-3

ISSN-L 1799-4934 **ISSN (painettu)** 1799-4934 **ISSN (pdf)** 1799-4942

Julkaisupaikka Helsinki **Painopaikka** Helsinki **Vuosi** 2017

Sivumäärä 123 **urn** http://urn.fi/URN:ISBN:978-952-60-7358-3

“Kaikki naiset älkööt tehkö käsitöitä”
-Minna Canth

Acknowledgements

It was just some rainy autumn workday when Arja Lukin came to my workroom and asked me a simple question: “How should energy efficiency be measured? Should there be different indicators in the facility strategy to accomplish building energy management more effectively?” It was the moment when my journey began and I could never have imagined that it would lead to a dissertation. I owe my deepest gratitude to Arja Lukin for support and confidence in my abilities to manage in my studies.

I wish to achnowledge the City of Espoo Premises Department and Education Services for offering their data and cases for investigation. There have been several persons from the City of Espoo who have helped me during this dissertation work. Especially, I wish to thank my “information sources” Visa Koivu, Jaana Hellinen and Pia Narikka, you made my studies possible! I wish to thank Tom Bremer and Jaana Saira for sharing your knowledge during this research, I appreciate the many advices you provided. I would like to express my gratitude to Juha Hovinen and Virpi Mattila from Education services for valuable input in the early stages of the reserch. Seppo Kallio, you have shown great appreciation for my work, special thanks to you. In addition, I wish to thank my co-workers from Espoo Sari Sahlberg, Tuula Haantaus and Elina Routto for taking care of my mental wellbeing during this journey.

I wish to thank my instructors Miimu Airaksinen and Arto Saari. Without Miimu Airaksinen’s support I would not have finished. I warmly thank Miimu’s efforts and valuable suggestions. I originally started my post-grad studies in Aalto University under the supervision of Professor Arto Saari. Between my studies, he decided to move to work at Tampere University. Not bad, because it is the City where I was born. Fortunately, our co-operation still continued and he took a position as an instructor. I wish to thank Arto for support and professional guidance throughout the research process.

I wish to thank my supervisor Professor Seppo Junnila for his time and guidance. In order to finish my dissertation at Aalto University, I also want to thank him for accepting me as a post-grad student into his research community.

I want to thank my pre-examiners Professor, Dr. Targo Kalamees and Business Area Manager, Dr. Kristiina Mjörnell for taking the time to carefully review my manuscript and giving me valuable feedback and improvement suggestions. I also wish to thank Professor, Dr. Juha Vinha for agreeing to act as my opponent.

During my worklife and academic studies, I have had the pleasure to work with excellent collagues and superiors. I want especially to thank my co-author and collegue Mia Andelin and collague Peggie Rothe, who have given me valuable advice in strengthening the logic and structure of the publications. I wish to thank all my bosses in my career, especially Erja Reinikainen and Satu Kankaala. I wish to thank my current co-workers Ulla Soitinaho, Katri Kuusinen, Jukka Forsman and the whole energy team at the City of Helsinki. And not forgetting an important mate, my native English speaker Marianna Tuomainen, who kindly revised and corrected the dissertation's language.

I would like to thank all my friends, especially my ex-Espoo-mates Robert Eriksson and Annina Stadius. I would also like to thank Robert for pre-reading and commenting on my dissertation before the examination.

Suvi, you have always been my great friend in troubles. I want to thank my parents and most important, my family for all the support during the studies. Vesa, Ville and Olli, you are my everyting.

It is a great honour to finalise my dissertation during the year when Finland celebrates its centenary of independence. The date of the defence will be the birthday of J.V. Snellman and the day of Finnish Identity. Snellman's idea was that the nation is composed of individuals and the nation, in turn, educates its individuals. My contribution has now been completed. My future work will focus on educating next generations.

Helsinki
Spring 2017

Tiina Sekki

This dissertation is based on research funded by:

Doctoral Programme of Aalto University School of Engineering
Espoon kaupunki, Tilapalvelut -liikelaitos
Espoon kaupunki, Sivistystoimi, Suomenkielinen varhaiskasvatus
Espoon kaupunki, Sivistystoimi, Tilat- ja alueet yksikkö
Aalto-yliopistokiinteistöt Oy
Helsingin kaupunki, Rakennusvirasto, HKR-Rakennuttaja
K.V. Lindholms stiftelse / K.V. Lindholmin säätiö

To support of all organisations is gratefully acknowledged.

List of Publications

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

1. Sekki, Tiina; Airaksinen, Miimu and Saari, Arto (2015), "Measured energy consumption of education buildings in a Finnish city", *Energy and Buildings*, Vol. 87, pp. 105-115.

2. Sekki, Tiina; Airaksinen, Miimu and Saari, Arto (2015), "Impact of building usage and occupancy on energy consumption in Finnish daycare and school buildings" *Energy and Buildings*, Vol. 105, pp. 247-257.

3. Sekki, Tiina; Andelin Mia; Airaksinen, Miimu and Saari, Arto (2016), "Consideration of energy consumption, energy costs, and space occupancy in Finnish daycare centres and school buildings" *Energy and Buildings*, Vol. 129, pp. 199-206.

4. Sekki, Tiina; Airaksinen, Miimu and Saari, Arto (2017), ”Effect of energy measures on the values of energy efficiency indicators in Finnish daycare and school buildings” *Energy and Buildings, Vol. 139, pp. 124-132*.

Author’s Contribution

Publication 1: “Measured energy consumption of education buildings in a Finnish city”

The author of this dissertation was responsible for collecting and analysing the data. The author wrote the paper. The second and the third author provided input on the theory and commented on the paper.

Publication 2: “Impact of building usage and occupancy on energy consumption in Finnish daycare and school buildings”

The author of this dissertation was responsible for collecting and analysing the data. The author wrote the paper. The second and the third author provided input on the theory and commented on the paper.

Publication 3: “Consideration of energy consumption, energy costs, and space occupancy in Finnish daycare centres and school buildings”

The author of this dissertation was responsible for collecting and analysing the data. The author wrote the paper. The second and the third author provided input on the theory and fourth commented on the paper.

Publication 4: ”Effect of energy measures on the values of energy efficiency indicators in Finnish daycare and school buildings”

The author of this dissertation was responsible for collecting and analysing the data. The author wrote the paper. The second and the third author provided input on the theory and commented on the paper.

Contents

1. Introduction

Debate on tangling climate change challenges has been ongoing for decades. It is widely acknowledged that climate change due to emissions of greenhouse gases is one of the major environmental challenges facing our globe today. Increasing energy efficiency constitutes one of the key actions reducing greenhouse emissions throughout the building lifecycle (IPCC, 2014; Perez-Lombarda et al., 2008) and energy efficiency in buildings is today a prime objective for energy policy at regional, national and international levels.

Buildings account for approximately 40% of the total energy use in Europe (EU Energy and Transpoint, 2008), and for about 36% of the EU's total CO2 emissions (IPCC, 2001; Commission of the European Communities, 2008). In December 2008, the European Commission implemented a strategy for Climate Action. According to the strategy, the European Union has set an indicative objective to reduce its primary energy consumption by 20% in relation to the projected 2020 energy consumption (EU, 2012). In addition, the Directive on energy performance of buildings (EU, 2010) outlines measures that require Member States to set minimum requirements and develop methods for determining the energy performance of buildings.

In Finland the built environment is estimated to count for 59% of the final energy use and 56% of the greenhouse gas emissions in 2007 (Finnish Government, 2009; Vehviläinen et al., 2010). Studies (Saari, A. et al. 1998; Saari, A. 2001a; Junnila and Horvart, 2003; Saari, A. et al. 2007; Sartori and Hestnes, 2007) showed that 80-90% of the environmental impacts of buildings are generated when in operation. Besides the impact on the emissions, the energy use in buildings represent a significant cost factor in the building operational phase. According to a survey of KTI Property Information Ltd (2013), the share of energy costs can be up to 50% of all operational costs.

Cities play a key role in mitigating climate change as most of the construction and transportation occurs in urban areas. Cities and municipalities have an important role in producing public services, meaning also construction and management of these services. In Finnish municipalities, municipal federations and public corporations owned by the municipalities possessed altogether 35471 buildings in 2005. The largest building type of public buildings in terms of floor area and volume are elementary schools and high schools which total 25% of the building stock. (Statistics Finland, 2010; Kuntaliitto, 2006) In Finland, in 2015 there were 1.5 million buildings which total 467 million of floor area (Statistics Finland, 2015).

Municipalities and property owners have been encouraged towards energy efficiency by educational and financial incentives, as well as by various energy surveys. During 2008-2012, Finnish municipalities have implemented 1.738 measures, with a total energy saving effect of 179.9 GWh/a. The investment costs of these measures were reported to be approximately EUR 43 million. The largest heating saving measures are related to implementing ventilation heat recovery, reducing indoor air temperature or designing demand controlled ventilation. In turn, the largest electricity saving measures are associated with lighting, power-saving computer equipment or updating building automation systems. The total amount of energy used in Finnish municipal buildings was circa 5600 GWh per year. (Motiva, 2012)

Finland's Energy Audit Programme (the EAP) is one of the oldest national energy efficiency grant schemes in place. The EAP started as a subsidy policy in 1992 and was developed into a programme level activity in 1993. During 2009-2011 over 3000 buildings have been audited in the municipal sector. In these audits the energy saving potential was circa 534 GWh. (Khan, 2006) These energy audits did not include any specific targets regarding the volumes of saving potentials or total energy savings. However, the target was that on the national level 80% of the building volume of the public service sector should be audited by 2010. In 2004, 50% of the building volume had been audited (Khan and Nordqvist, 2007). In addition, there is a need for increased implementation of the EU Directive on Energy Efficiency (EU, 2012) within the context of the public sector.

The efficient use of facilities has been raised in the City of Espoo's facility strategy. Improving energy efficiency is achieved primarily for economic reasons. In the future, the buildings will offer more advanced services such as a youth clubs, sports facilities and library services or evening studies by the Finnish Espoo Adult Education Centre. The use of services is guaranteed by extending the operating times. Space efficiency is typically fixed already in the design phase and the building operating times are fixed based on the building's specific purpose of use. Today, many users are aware of the positive effects of good indoor air quality on productivity and learning. Therefore, they increasingly wish to have a better understanding of the environmental impacts of the buildings. It is very important to develop tools to collect real time data of both energy and occupancy since very often building users are encouraged to save energy based on measured energy consumption.

The energy efficiency is typically, and also in the specific case of the City of Espoo buildings the empirical environment of the study, is measured as energy consumption per unit of area, in this context in kWh/m^2. While this metric is useful when comparing the physical properties of buildings in the design phase, it can favor unsustainable ways of occupying buildings in the operational phase. In fact, lower usage of space in terms of m^2/person, shorter operating times of buildings (per day, per week, per year) or lower levels of occupant can lead to a situation in which one building seems more energy efficient in kWh/m^2 than another building with similar physical properties which is utilised more efficiently. There is a need to identify and develop indicators that can be applied to assess changes in energy consumption.

1.1 Research aims and questions

The aim of this study is to increase the understanding about the evaluation of energy efficiency in educational buildings. In addition, study provides information for guiding energy efficiency (indicators).

In Finland, energy efficiency has been taken into account in national building codes already for 20 years and Finnish building stock is relatively new. The public sector should be a frontrunner of energy performance of buildings and the leading role requires setting an example to other actors. Improved energy efficiency is achieved primarily for economic reason. Increasing the use of facilities often result higher energy consumption. For this reason, the targets i.e. energy savings and increased use of facilities may be partly contrary to each other. The research questions of the dissertation are:

How to evaluate energy efficiency of educational buildings?

This question is answered in this concluding part of the dissertation, which complies the findings of all papers and their perspectives of educational buildings energy efficiency. The dissertation approaches the research question through three sub-questions, which are following:

RQ1.1 How is the energy use (consumption) composed in educational buildings?

This question is answered in Paper I, which describes a study in which the energy use is measured in existing educational buildings and how it is divided into various forms of energy (heating, electricity). Paper I provides an overall picture of energy consumption and assesses factors, e.g. building age, primary energy factor and building shape factor, that are used in evaluating measured energy in building design phase.

RQ1.2. What is the connection between building occupancy, space efficiency and energy efficiency?

This question is answered in Papers II and III. Papers II and III explores ways in which building usage and occupancy influences the measured energy consumption and energy cost.

RQ1.3. What indicators can be used when evaluating energy efficiency measures?

This research question is answered in Paper IV. Paper IV examine further used indicators and how indicators can be combined so that the end result is user-driven and reflects the reality of building operational phase energy efficiency. The studied indicators express the annual energy consumption of a building with different functional units.

1.2 Structure of the dissertation

This dissertation consists of four appended peer-reviewed research papers, all of which have been published in academic journals, and a summary.

Paper I answer the first question. It provides an overall picture of energy consumption and assesses the factors that are used in evaluating measured energy.

Paper II and III contribute the second research question. Paper II explores ways in which building usage and occupancy influences the measured energy. Paper III assesses research question from the energy cost perspective. Paper II and III adopts existing energy efficiency indicators and introduces a new indicator for building energy efficiency which takes into account both space and occupancy efficiency.

Paper IV addresses the third research question by providing an insight how the energy efficient measures reflect the energy efficiency indicators and how they can be combined so the end result is user-driven and better reflects the reality of operational energy efficiency.

The relationship between the research questions and papers is presented in Figure 1.

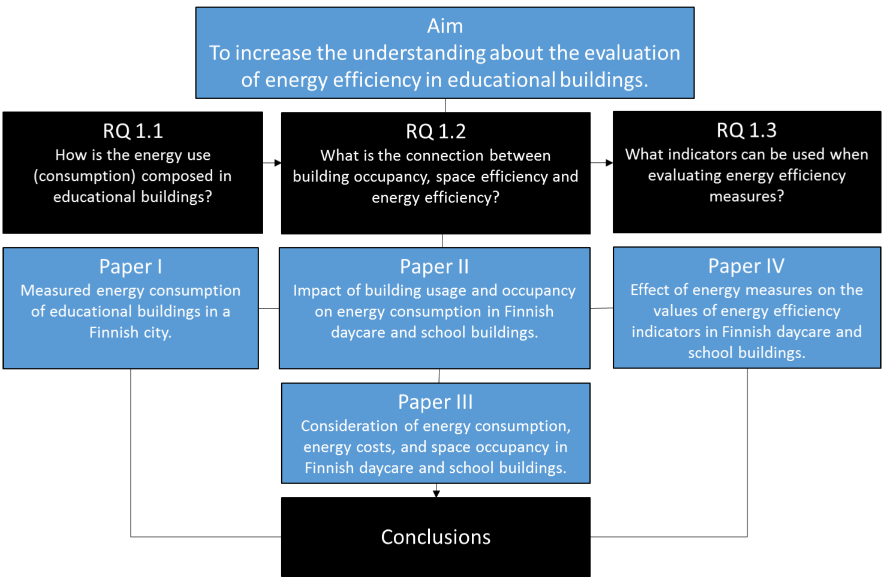


Figure 1. The structure of this dissertation.

This summary links the research together and discusses the contribution of the whole, demonstrating how the individual papers each contribute to the research questions of the dissertation and lead to a mutual conclusion, which is the argument of the dissertation. This summary is divided into three sections. First section introduces the research topic and sets out the research questions. The background and the methodology are presented in the first section. Second section summarises the appended papers. Finally, third section presents the conslusions, evaluation of the research and suggestions for further research.

1.3 Theoretical backgroud

Real-time energy monitoring and management is an increasing service in new buildings and in renovated buildings (European Commission, 2010). Typically, the energy consumption monitoring and management system covers electricity, heating and domestic water. Energy consumption data is obtained automatically by using remote reading and consumption monitoring system to collect metering data and offers consumption reports from hourly to annual level. In Finnish statistic (2012) the heating consumption include space heating, domestic hot water and heating of ventilation air. Electricity consumption includes all electricity used in a building, e.g. ventilation eguipment (engine and electrical preheating), appliances and lighting.

At present, more than 80% of the energy consumption in the City of Espoo public buildings is monitored at least on a monthly basis (Action Plan, 2010). In the newest buildings the energy reporting is integrated into the building automation system. Measurements from the building automation systems enable optimizing the indoor conditions and energy consumption (demand-controlled ventilation). Building automation system collects data such as outdoor and indoor temperature, humidity and information from the building technical performance. To be more specific measurement points provide information such as temperature and CO_2 (carbon dioxide) at zone level.

In the Energy Saving Agreement (2007), energy saving means reducing the current levels of energy consumption or preventing such future consumption as would result if no measures were taken. Thus, the energy savings can be achieved also by improving energy efficiency and not only reducing the absolute consumption. Improving energy efficiency involves the reduction of energy input, or specific consumption, required by municipal services so that the amount of energy required to, for instance, heat one square metre in a building, use electrical equipment, is reduced.

Energy efficiency can be defined as a ratio between an output of performance, service (such as one heated work space or one ventilated m^3 of air), goods, or energy, and an input of energy (European Commission, 2006). Energy efficiency is a term that is used in a variety of meanings in different contexts. Hence, there is no one unambiguous quantitative measure of energy efficiency for all cases (IAEA, 2005). The main issue of the formation of indicators should be for what purpose will the indicators serve. A different indicator will serve best when environmental, social, economic, or other aspects of energy efficiency are considered. This means that decision makers need methods for measuring and assessing the current and future effects of energy use on human health, human society, air, soil and water. They need to determine whether current energy use is sustainable and, if not, how to change it so that it will be. (IAEA, 2005)

Building usage, occupancy and energy consumption

In general, there is a close relationship between occupancy and energy consumption (Martani et al. 2012; Gul and Patidar 2015; Santin et al. 2009; Yun et al. 2012). Basically this means that when building is employed, they consume energy. Buildings consume energy directly for heating and cooling and indirectly through electricity i.e. for lights, ventilation, pumps and appliances.

The efficiency of building usage is affected by space efficiency measured in m^2/person and building occupancy. Building occupancy is impacted by the operating times (number of daily hours, week days and year days) and occupancy levels (percentage of occupants present at a given moment). Thus, building occupancy can be calculated as a multiplication of yearly operating times and average occupancy levels or by counting total person hours (sum of hours each building occupant has spent in the space studied).

The occupancy is influenced by space efficiency, which is affected by space design. The more effectively a given building is occupied, the less space is needed for a given number of people and, thus, the lower the space heating energy consumption per person. The same applies to the operating times of a building; it can have several purposes at different times of the day (e.g. organising leisure activities in a school after regular school hours).

The ways to approach energy efficiency

The experiences gained in the planning processes have proved that the early decisions have the greatest impact on the energy efficiency of a building. Hyartt et al. (1991) presented a procedure for estimating energy consumption and costs of building use in the programme stage of the project. The target consumption of heating and electricity was calculated for every space of the building taking into consideration the daily operating times. The study indicated that the differences in consumptions were caused by the space programme, operation time, local conditions, design solutions and the differences in the use of the building. The space programme identifies the needs of the building facilities and areas. During 1991-1993 the procedure was developed further (TKK, 1993). In this instance, it is essential that the targets of energy consumption and costs are project specific and set already in the programme stage. The targets are tested in the design phase and if needed, the design solutions can be developed.

Studies by Saari (Saari A. 2000; Saari A. 2001b) developed a method for controlling building design and bringing building design to an acceptable level as regards environmental loading. The use-phase energy consumption was chosen as the key environmental indicator. The procedure consists of three phases:

1. project programming,
2. building design phase and
3. implementation of construction works.

In the project programming phase, a limit for the annual energy consumption of the building operational phase is set. The limit is based on the space programme and the use schedule of spaces. In the building design phase, the operational energy consumption, based on the building design, is calculated. If the energy need based on the design solution exceeds the limit, the design is improved. The procedure offers a simple way for controlling the life-cycle environmental burdens of a building already at the building design phase. When a target is set, different design solutions can be compared. The procedure provides tools for bringing building design to a level that is acceptable in relation to the resulting environmental burdens.

The compactness of a building is on many occasions expressed using an indicator called the shape factor. When comparing architectural concepts or optional design solutions, the shape factor can be used for evaluating whether or not the shape of the volume supports energy efficiency. The study by Lylykangas (2009) showed that a simple indicator such as the shape factor could be used to evaluate the very first ideas and concepts, already before any energy calculation tools can be applied. In the sketch phase, a quick response and simple means of evaluation are needed for comparison of the optional ideas and architectural concepts. When the energy target is set after the sketch phase, it is too late to implement radical changes to the architectural concept. Lylykangas (2009) conducted that since architectural design is commissioned in square meters and the targets for heating energy demand are set per square meter, the ratio between the inside surface area of the building envelope and the heated floor area could be a more logical method for rough evaluations of the sketch phase design. In addition, the study by Ruusala (2015) has showed that when looking at the calculated energy consumption of schools and daycare centres, the effect of the ratio of the area of the envelope and the net area of the building on the consumption of heating energy can be recognised to some extent. However, when looking at measured consumption, the ratio of envelope area per net area does not have a significant relation to heating energy consumption.

In the operational phase, an approach to improve the quality and performance of buildings is continuous performance monitoring (Brambley et al. 2005; Haves and Hitchcock 2008; Ihasalo 2012). The approach aims at reducing energy use and improving indoor environmental quality by continuously tracking and analysing issues mainly related to heating, ventilation and air-conditioning (HVAC). The study by Ihasalo (2012) presented the solution that utilizes building automation data from real buildings and transforms the data into a set of performance metrics. The solution is capable of visualizing a building's performance from energy, indoor conditions and HVAC system perspectives. However, Ihasalo concluded that the main challenges to using the solution were related to accessibility and management practices. In addition to these, one challenge was the lack of trust of the users, since they did not entirely understand what the performance metrics meant or because the solution had limitations in regards to assessing building performance.

Traditionally energy efficiency is expressed in kWh/m^2. While this metric is useful when comparing the physical properties of buildings in the design phase, it can favor unsustainable ways of employing buildings in the operational phase. In fact, lower space efficiency (m^2/person), shorter operating times of buildings (per day, per week, per year) or lower levels of occupant can lead to a situation in which one building seems more energy efficient in kWh/m^2 than another building with similar physical properties which is utilised more efficiently. This is showed in studies by Dooley, K. (2011), Huovila et al. (2013), Martani et al. (2012) and Forsström et al. (2011).

The indicators are not merely data; rather, they extend beyond basic statistics to provide a deeper understanding of the main issues and to highlight important relations that are not evident using basic statistics (IAEA, 2005). For example, in recent literature Xia et al. (2014) compared energy efficiency in Chinese and American case office buildings and Zhao et al. (2009) studied the effect of supervision on energy efficiency on large-scale public buildings in China. In European, Boyano et al. (2013) estimated energy demands and energy savings potentials in case offices, Pikas et al. (2014) calculated cost optimal zero energy building solutions for office buildings in Estonia and Nunes et al. (2013) compared energy efficiency in two Portuguese case offices.

Two of these studies (Zhao et al., 2009; Nunes et al., 2013) included occupancy and space use in their scope. Nunes et al. (2013) attempted to take into account space efficiency in indicators by introducing what they call energy efficiency index per standard occupants, where the building energy use is divided with the normalized number of occupants in the building. In the City of Espoo, the children's activity space is dimensioned to be 7 m^2 per child and in schools the space requirements are based on the educational activities and their scale. However, all of these studies elected to use the specific energy consumption as the main indicator.

Currently, there are gaps of knowledge for estimating occupancy as a useful energy efficiency indicator to support the planning and benchmarking the usage phase. Such indicators are, however, required to obtain information regarding energy consumption and the cost factors. It is important to know that the indicator used to assess energy efficiency is truly guiding the building use towards sustainable energy use. To be useful, indicators must evolve over time to fit country-specific conditions, priorities and capabilities. The meaning will depend on the state of development of each country, the nature of its economy, its geography, the availability of indigenous energy resources and so on (IAEA, 2005).

In conclusion, when formulating the indicators, decisions on the collection must be taken into account on the interpretation of the results of the indicators. A small number of collected indicators can be interpreted quickly, however they can produce misleading results. For example, if vital information is lost in the collection. In turn, more detailed indicators may require more interpretation and evaluation of the results from the user. The choice of indicators should be based on thoughtful goal definition: why energy efficiency is measured? What decisions are taken based on the calculation of the indicators? The necessary data should be gathered and when the indicators are applied to the data, the results should be interpreted to understand the meaning of the figures.

The study by Ahtila et al. (2009) aimed to develop a common approach for measuring energy efficiency in buildings. Study propose that the choise of the indicators should attempt to strike a balance between the different aims of (1) coming as close as possible to an accurate description of the energy efficiency of a building while (2) satisfactorily covering the different aspects of energy efficiency important to the various stakeholders and making sure that (3) the indicators are practically applicable and (4) the necessary data is reasonably available. In addition to these, this study highlighted the objectives of:

1. Indicators are common used in evaluating energy efficiency of buildings
2. Indicators are suitable for educational buildings and suitable to use in building design and operational phase

1.4 Methodology

One type of nonexperimental quantitative research is causal-comparative research in which the researchers compares two or more groups in terms of a cause (or independent variable) that has already happened (Cresswell, 2013). Another nonexperimental form of research is the correlational design in which researchers use the correlational statistic to describe and measure the degree or association (or relationship) between two or more variables or sets of scores (Creswell, 2012). One of the quantitative approaches, the survey research, provides a quantitative or numeric description of trends, attitudes, or opinions of a population by studying a sample of that population. The data collection of survey research can include cross-sectional and longitudinal studies using questionnaires or structured interviews—with the intent of generalizing from a sample to a population (Fowler, 2008).

The approach of this study is a combination of quantitative and qualitative methods. This is in a wider methodological context called mixed methods research, which combines the benefits of both methods (Creswell, 2013). The background is for the most part quantitative and the research data is entirely quantitative. A statistical method was used in the interpretation of the results. The study started with a broad survey in order to generalize results to a building stock and then, in a second phase, focuses on qualitative, case studies to collect detailed views from building stock to help explain the initial quantitative survey. Thus, case study methodology is employed to deepen the numerical results of the quantative analysis.

An overview of how the research methods were applied is presented next. More detailed descriptions of the application of the research methods are presented in each of the papers.

Table 1. Research questions, methods and corresponding papers

Research question	Discussed in paper(s)	Research methods
1. How is the energy use (consumption) composed in educational buildings?	I	Quantitative (statistical data)
2. What is the connection between building occupancy, space efficiency and energy efficiency?	II	Quantitative (statistical data) Qualitative (multiple case study)
	III	Quantitative (statistical data)
3. What indicators can be used when evaluating energy efficiency measures?	II IV	Quantitative (statistical data) Qualitative (multiple case study)

Used indicators and units

The indicators used in this study express the annual energy consumption of a building with different functional units. The indicators are presented in Table 2.

Table 2. The indicators used in this study.

Indicator name	Unit
Specific energy consumption (SEC)	kWh/(m²,a)
Energy intensity of usage (EIU)	kWh/number of occupants (children, student, personnel) kWh/yearly operating times
Specific energy consumption adjusted for occupancy (SECo)	kWh/m^2o, $0 \leq o \leq 1$ o=the ratio of actual daily person hours to the highest daily person hours. In this study we use the highest possible person hour's value 24.
Specific energy consumption adjusted for usage and space efficiency (SECu.s)	kWh/m^2u, $u = nt_{avg}/((A/a_{ref})t_{ref})$ where the n is the actual number of student or children using the building, t_{avg} is the average number of hours present daily per person, A is the total area studied. The parameters a_{ref} and t_{ref} are normalising factors: a_{ref} is the amount of space per children or student and t_{ref} represent normal working hours, in this study we use the value 5,5 hours in schools and value 11,5 hours in daycare centres. For a_{ref} both actual and design figures from the City of Espoo's design guidelines were used.

To compare the energy consumptions of the studied buildings, this study used the gross heated floor area (m^2, including the exterior walls) as a benchmarking metric. The compactness of a building is in many occasions expressed using an indicator called the shape factor. The shape factor is most often calculated as the ratio between the outside surface area of the thermal insulation in the building envelope (A) and the heated volume (V). Since there were no detailed data on the studied buildings envelope area and the target was to make rough evaluations for the early decisions in planning processes, this study used A = gross heated floor area (m^2, including the exterior walls) per V = volume (m^3) as the shape factor.

In Paper I, the primary energy factors were based on the Finnish national building codes (2012) and the used factors were district heat = 0.7, electricity = 1.7, fossil fuels = 1.0 and renewable fuels = 0.5 for the primary energy assessments (Keto, 2010).

Process and data description

The first step in the process was to select and collect data. The research data were collected in 2012. The buildings were classified and described based on the construction year, the size, energy consumption, heat production, ventilation technology and energy class. Data were analysed using statistical methods. Descriptive statistics (mean, median, minimum, maximum, range) and linear correlations were statistically examined. Regression analysis was used to find out how the factors, e.g. building age, space efficiency and occupancy affected energy consumption and energy costs. The significance of the results was tested based on the regression analysis and the correlation coefficients p-value.

In Paper I, the energy consumption and occupancy data were collected from a total of 80 daycare centres, which represent 68% of the total number of Espoo daycare buildings, and 74 school buildings, which represent 82% of the school buildings in Espoo. In Paper III, where the focus was on running costs, the sample contains a total of 73 daycare centres which represent 62% of the total number of Espoo's daycare buildings and 69 school buildings which represent 75% of Espoo's school buildings.

The multiple case study was used to compare the alternative indicators of energy efficiency. The case study objects were buildings. Four buildings of the daycare centres and schools in Paper II and three buildings of the daycare centres and schools in Paper IV were selected. Paper IV was produced to test the usability of the indicators selected in Paper II and III.

Energy consumption data

The monitored sectors of energy consumption included heating (space heating and domestic hot water) and electricity. The energy measurement data were collected from consumption monitoring systems in the properties. The consumption data are obtained automatically by means of remote reading. Consumption monitoring systems collect metering data and offer consumption reports from an hourly to an annual level. Typically, the heating consumption is reported on a monthly basis. Billing of electricity consumption is based on the measured data. According to principles of Finnish Energy Industries (2010), the deviation of the energy consumption data from the consumption monitoring system is no more than ±2%. In addition, building automation system collects data such as outdoor and indoor temperature, humidity and information from the building technical performance. To be more specific measurement points provide information such as temperature and CO_2 (carbon dioxide) at zone level.

Using the normal year correction, the consumption of heating energy is standardised in order to compare the energy consumption of a building in different months or years as well as comparing buildings in different municipalities (Finnish Meteorological Institute, 2016). The studied buildings heating consumption data comprised of data from the one and the same year and the buildings are situated in the same locality. Thus, the heating consumption data was not standardised using the normal year correction. For reference, the heating degree day in Espoo (southern Finland) in 2012 was 3645°Cd and in Espoo during years 1981 to 2010 is 3723°Cd (The Finnish Meteorological Institute, 2013).

Occupancy data

The user profiles of daycare centres and schools were based on the data collected from the City of Espoo Educational Services. The data contain a number of occupants and a number of daily hours, weekly days and yearly days (yearly operating times). Schools number of user contain only educational activities. The City of Espoo's Sports and Recreation Department is responsible for the operation of sports facilities. The usage hours were obtained from the reservation system, called WebTimmi. (City of Espoo, 2014b). Schools' evening lessons usage hours were obtained from the Finnish Espoo Adult Education Centre. However, the number of evening users was not available. Occupancy data and data sources are presented in Table 3.

Table 3. Occupancy data and data sources.

	Number of yearly days	Number of daily hours	Number of users	Data sources
Daycare centres				
Daily use	229 d	building specific	building specific	City of Espoo Education Services
Evening	100-240 h/a	building specific	building specific	City of Espoo Education Services
Summer period 2.7.- 29.7.	22 d	building specific	building specific	City of Espoo Education Services
Schools				
Daily use	191 d	5.5 h/d	building specific	City of Espoo Education Services
Evening lessons	157 d	Mon.-Fri. 4 pm-9 pm	building specific	Finnish Espoo Adult Education Centre / WebTimmi
Sport facilities	157 d	Mon.-Fri. 6 pm-9 pm Sat. 10 am-5 pm Su. 9 am-9 pm	building specific	City of Espoo Sports Department / WebTimmi
Weekends (e.g. family events)	29 d	6 h	building specific	Finnish Espoo Adult Education Centre / WebTimmi

Running costs

In Paper III, distribution of the running costs were based on the definitions published in the Finnish Accounting Ordinance (1997). The running costs cover expence categories of 1. Operation, 2. Maintenance, 3. Consumption of utilities (heating, water and sewage, electricity), 4. Waste management and 5. Repair.

This study used the data which was collected in 2012 in respect of KTI Property Information Ltd. for the building operational cost benchmark study (KTI Property Information Ltd., 2013). In addition, energy costs data was specified from the consumption monitoring system and its energy costs data.

Energy audits

Energy audits were used to as a complementary source of information. The energy audits contain data such as the annual consumption for heating and lighting, the area of the building, the construction year of the building and the operating schedule. Especially, in the case studies, Paper II and Paper IV, information was obtained from the energy audits. Energy audits are based on the European Standard SFS-EN 16247-2 (2014). The European standard is applicable to specific energy audit requirements in buildings. The main steps of the energy audit process are described in the European standard (2014) and in The Energy Department of the Ministry of Employment and Economy (2015) and Motiva's guidelines (Motiva, 2016).

Energy (performance) certificates

Energy (performance) certificates have been used in Finland since 2008 (Finlex Data Bank, 2007). Certificates provides the proportionate gross number for energy efficiency and determine a building's energy class, graded between A-G. The energy certificate is compulsory for new buildings and a large proportion of existing buildings. In public buildings, the energy certificate must be displayed in a noticeable place to show the energy efficiency of the building in question.

In Paper I, the current energy certificates from 2012 were used. The certificates are valid until 2022. In the energy certificates, buildings are classified into classes according to their intended use. Educational buildings form their own class, which is shown in Table 4.

The current certificates include consumption of heating energy, the electric energy on the premises and the energy for cooling. The energy certificates used in the study are based on measured consumption and have been calculated when conducting an energy audit (Finlex Data Bank, 2007). The amount of domestic hot water and user appliances were based on the energy audits and if information was not available, the consumption was calculated (D5, 2012).

Table 4. Educational building classification into energy classes, graded from A to G. The classification and grades are based on energy certification.

Energy class	Number for Energy Efficiency (ET=kWh/(m^2,a))	
	Schools, University buildings	Daycare centres
A	ET ≤ 120	ET ≤ 140
B	121 ≤ ET ≤ 150	141 ≤ ET ≤ 180
C	151 ≤ ET ≤ 190	181 ≤ ET ≤ 230
D	191 ≤ ET ≤ 230	231 ≤ ET ≤ 300
E	231 ≤ ET ≤ 300	301 ≤ ET ≤ 390
F	301 ≤ ET ≤ 400	391 ≤ ET ≤ 500
G	401 ≤ ET	501 ≤ ET

Space desing guidelines

In Finland, the design of daycare centres and schools is based on national guidelines (RT 96-11003, 2010; FNBE, 2012).

However, the City of Espoo has own guidance for daycare centres design. In case of conflicts, the City of Espoo's own instructions for space programme overrides national guidelines. The space programme identifies the needs of the building facilities and areas. In the design of daycare centres, the term "structural design" is applied for dimensioning daycare places. In the design phase, the group size used for calculations is 21, despite the actual group size varying in operation time. In the City of Espoo, the children's activity space is dimensioned to be 7 m^2 per child. (City of Espoo, 2014a)

The design of schools is based on the guidelines of the Finnish National Board of Education. In the guidelines, the space requirements are based on the educational activities and their scale (Table 5).

Table 5. Key figures of space reguirements in schools (FNBE, 2012).

Number of students	Learning facilities m^2		School m^2	
	m^2/student	total m^2	m^2/student	total m^2
100	12,6	1 260	26,5	2 650
200	8,6	1 720	17,3	3 450
300	8,0	2 390	16,9	5 060
400	6,6	2 630	13,8	5 520
500	6,0	3 000	13,3	6 670
600	5,3	3 190	11,7	7 010
700	5,1	3 600	11,7	8 080
800	4,9	3 940	10,9	8 720
900	4,7	4 230	10,7	9 640
1 000	4,4	4 420	10,0	10 030

Characteristics of studied buildings

The oldest buildings in the sample were built in 1950 and the most recent ones in 2010. The buildings built after 1980 account for 68% of the sample. The university buildings were built mainly (54%) in 1960 when the university campus was established. Trend of annual growth of studied educational buildings gross area (m^2) are shown in Figure 2 and characteristics of the assessed educational buildings in Table 6.

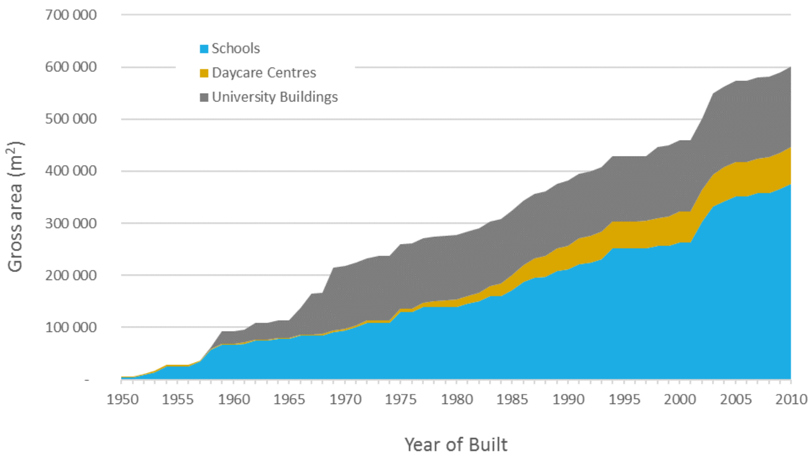


Figure 2. Trend of annual growth of studied educational buildings gross area (m^2).

Two-thirds of the daycare centres' (68%) have a gross area (m^2) ranging from 700m^2 to 900m^2. 64% of the school buildings have a gross area (m^2) that ranges from 3000m^2 to 7000m^2. The majority (62%) of the university buildings have a gross area of less than 9000m^2.

In general, the construction of the educational buildings has complied with the minimum requirements. All of the measured buildings have insulation at the envelope. In the new buildings, the insulation corresponds to 0.25–0.17 W/(m^2K). In addition, nearly all of the building stock has double windows corresponding with a minimum U value of 2.7 W/(m2K).

The old building stock typically employs mechanical exhaust or natural ventilation. As a rule, ventilation with heat recovery is adopted in buildings built after the 1990s when the ventilation requirements were added to legislation. In the 1970s and 1980s, the typical ventilation system was a mechanical exhaust or recirculation damper.

The daycare centres were in use for an average of 11 hours from Monday to Friday, 6:30 am to 5:30 pm. Two daycare centres have around-the-clock schedules and they are in use 24 hours. One daycare centre offered extended daycare service (16 hours per day). Fifteen daycare centres were in use in the summer, during the period 2.7-29.7.2012, when others were closed. In addition, two daycare centres had some activities also on weekends and three centres in the evenings, from 5 pm to 9 pm.

The schools under examination operated approximately five and a half hours per weekday. In 45% of the schools, lectures were arranged in the class areas in the evening on weekdays, from 4 pm to 9 pm. Sport facilities were in use on weekdays from 6 pm to 10 pm, on Saturdays from 10 am to 5 pm and on Sundays from 9 am to 9 pm. Eight schools have no sports facilities. Further, five schools have some activities also during the weekends, i.e. celebrations or other family events.

Table 6. Characteristics of the assessed educational buildings.

Built, completion Daycare centres (80 pcs.)	1950s 3 Buildings			1960s 2 Buildings			1970s 9 Buildings			1980s 37 Buildings			1990s 15 Buildings			2000s 14 Buildings		
	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max
Gross Area (m^2)	601	690	1082	720	767	813	845	940	1221	584	838	1225	342	913	1574	421	1034	1853
Volume (m^3)	2018	2700	4660	2200	2510	2820	2840	2975	4510	2090	2980	4400	1150	3579	5920	1420	4140	7819
Heat consumption (MWh)	107	179	194	196	322	448	137	182	361	44	156	236	78	129	231	73	167	310
Electricity consumption (MWh)	39	42	100	37	55	73	35	59	78	32	59	217	27	58	100	33	73	108
Heat production	100% District heating			50% Didtrict heating 50% Oil			100% District heating			84% District heating 16% electric heatimg			100% District heating			100% District heating		
Ventilation, heat recovery (in general)	Natural ventilaiton			Natural ventilation or mechanical exhaust			Mechanical exhaust recirculation damper			Mechanical exhaust recirculation damper			Mechanicalsupply and exhaust with heat recovery			Mechanical supply and exhaust with heat recovery. Indoor climate requirement S3 and 20% option for increased ventilation		
Energy class (pcs.)	D (2), E (1)			F (1), G (1)			C (1), D (3), E (4), G (1)			B (1), C (9), D (15), E (8), F (2), G (2)			C (3), D (6), E (5), F (1)			C (3), D (8), E (3)		
Energy audit in 2011 (completed %)	0%			50%			56%			27%			47%			50%		

Built, completion	1950s			1960s			1970s			1980s			1990s			2000s		
Schools (74 pcs.)	12 Buildings			7 Buildings			9 Buildings			18 Buildings			11 Buildings			17 Buildings		
	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max
Gross Area (m^2)	1319	4004	11726	2605	4047	6561	1012	8192	9836	1883	3714	6826	4192	5085	10985	1348	7179	13520
Volume (m^3)	5000	15033	51174	7400	13965	26180	3270	33195	44628	7794	14192	33727	15940	20680	30100	3970	34820	71200
Heat consumption (MWh)	363	800	1419	415	944	1447	199	1195	1920	167	530	1380	234	717	2651	416	1000	1652
Electricity consumption (MWh)	95	221	603	136	254	630	356	496	632	89	205	664	47	263	417	60	442	1094
Heat production	100% District heating			86% Didtrict heating 14& oil			100% District heating			100% District heating			100% District heating			100% District heating		
Ventilation, heat recovery (in general)	Natural ventilaiton			Natural ventilation or mechanical exhaust			Mechanical exhaust recirculation damper			Mechanical exhaust recirculation damper			Mechanicalsupply and exhaust with heat recovery			Mechanical supply and exhaust with heat recovery. Indoor climate requirement S3 and 20% option for increased ventilation		
Energy class (pcs.)	A (1), B (1), C (1), E (4), F (1), G (4)			B (1), E (1), F (2), G (3)			D (1), E (5), F (1), G (2)			A (2), B (1), C (5), D (2), E (5), F (2), G (1)			C (5), D (5), F (1)			A (3), B (1), C (3), D (2), E (4), F (2), G (2)		

80% of school buildings have been audited between year 1998 and 2001. Newer information not found.

Built, completion	1950s			1960s			1970s			1980s			1990s			2000s		
University buildings (13 pcs.)	3 Buildings			7 Buildings			1 Buildings			-			1 Buildings			1 Buildings		
	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med	Max
Gross Area (m^2)	3497	5109	15799	1479	8553	41419		4567						12990			18112	
Volume (m^3)	12500	16095	45000	3935	26000	140133		17731						55000			60000	
Heat consumption (MWh)	474	511	2528	150	1642	8104		442						108			1486	
Electricity consumption (MWh)	268	365	3099	251	1039	4474		560						1007			2043	
Heat production	100% District heating			100% District heating			100% District heating						100% District heating			100% District heating		
Ventilation, heat recovery (in general)	Natural ventilaiton			Natural ventilation or mechanical exhaust			Mechanical exhaust recirculation damper						Mechanicalsupply and exhaust with heat recovery			Mechanical supply and exhaust with heat recovery. Indoor climate requirement S3 and 20% option for increased ventilation		
Energy class (pcs.)	E (1), G(2)			C (1), E (2), G (4)			C						C			F		
Energy audit in 2013	57%			67%			0%						100%			100%		

Characteristics of selected cases

The cases were selected to represent the versatile nature of the City of Espoo daycare centres and schools building stock. The cases shared similar characteristics compared to the whole building stock, such as the size (gross floor area and volume), the age of buildings and the operating times. Thus, daycare centres and schools are homogeneous nationwide in their spaces and operating times. Operational and technical characteristics of selected case studies are shown in Table 7 and Table 8.

Table 7. Operational characteristics of selected case studies.

	Construction Year	Volume m^3	Gross floor m^2	Person-nel	Child./ Stud.	Usage	Other	Energy Audit
1.Daycare centre	1969	2 820	813	14	75	Mon. to Fri. 7 am to 5:15 pm	Condition assessment in 1996 Energy calculation in 2013	-
2.Daycare centre	1977 renovation in 1998	3 027	866	14	83	Mon. to Fri. 6 am to 4 pm	Open in summer period	6.1.2012
3.Daycare centre	1989	3 360	821	25	95	Every day 24h	Open always	4.1.2012
4.Daycare centre	2008	5 260	1 311	14	94	Mon. to Fri. 7 am to 5 pm	Open in summer period	17.1.2012
5. School	1970 renovation in 2006	33 195	5 730	43	482	Mon. to Fri. 8 am to 3 pm	Use of gym till 10 pm Lectures till 8 pm Ktchen 1140 meal/day	14.1.2011
6. School	1975	19 590	4 300	48	554	Mon. to Fri. 6 am to 3 pm	Use of gym till 10 pm Lectures till 9 pm Also weekend use	13.9.2001
7. School	1994 extension in 2004	22 110	5 258	26	324	Mon. to Fri. 6 am to 6 pm	-	14.1.2011
8.School	2004	36 740	7 945	50	498	Mon. to Fri. 8 am to 4 pm	Use of gym till 11 pm Lectures till 11 pm Ktchen 1000 meal/day	14.1.2011

Table 8. Technical characteristics of selected case studies.

	Heating consumption (MWh)	Electricity consumption (MWh)	Wall U (W/(m^{2}K))	Roof U (W/(m^{2}K))	Building component against the groud U (W/(m^{2}K))	Window U (W/(m^{2}K))	Tightness n50** (1/h)	Ventilation heat recovery efficiency (ηa)	Ventilation, general
1.Daycare centre	448	73	0.81	0.41	0.47	1.4	5	-	Mechanical exhaust recirculation damper
2.Daycare centre	186	65	0.28	0.22	0.36	2.1	6	60%	Mechanical supply and exhaust with heat recovery
3.Daycare centre	192	76	0.28	0.22	0.36	2.1	6	50%	Mechanical supply and exhaust with heat recovery
4.Daycare centre	154	73	0.24	0.15	0.24	1.4	4	70%	Mechanical supply and exhaust with heat recovery
5. School	897	356	0.24	0.15	0.24	1.4	4	30- 70%	Mechanical supply and exhaust with heat recovery
6. School	1 920	498	0.4	0.35	0.4	2.1	6	-	Mechanical exhaust recirculation damper
7. School	612	299	0.28/ 0.25*	0.22/ 0.16*	0.36/ 0.25	2.1/ 1.4*	6/ 4*	70%	Mechanical supply and exhaust with heat recovery
8.School	1 139	570	0.25	0.16	0.25	1.4	4	50- 70%	Mechanical supply and exhaust with heat recovery

* values are for the new part of the school

** n50 expresses airtightness in numbers, and indicates how often the air volume of the building concerned is éxhanged per hour at a pressure difference of 50 Pa.

2. Summaries of the research papers

This chapter presents a brief summary of each research paper. The summaries highlight the main findings relevant to this dissertation. Each of the four publications approaches the research problem from a specific perspective. The papers reinforce one another, providing an encompassing response to the research questions.

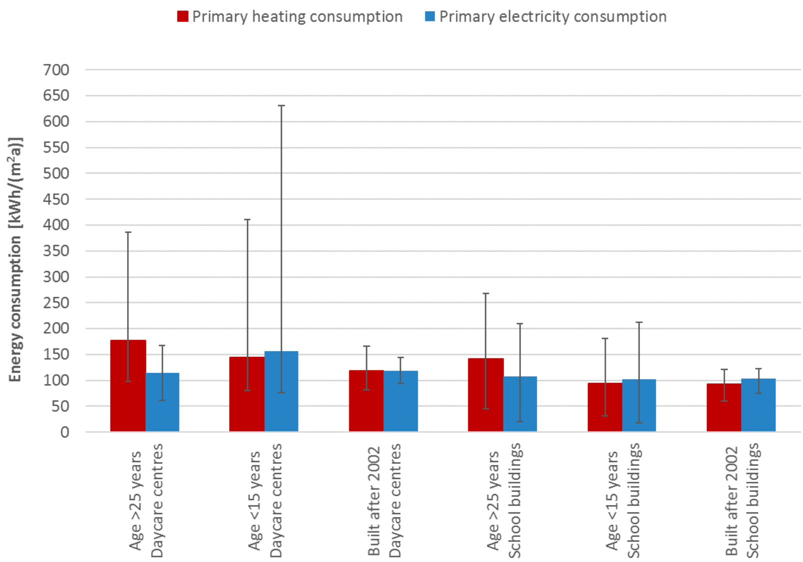
2.1 Paper I: Measured energy consumption of education buildings in a Finnish city

The first paper focused on studying the energy consumption and the primary energy consumption in existing educational buildings. The aim was to findout differences between heating consumption and electricity consumption. The first paper provides an overall picture of energy consumption and assess the factors that are used in evaluating measured energy. The studied factors were number for energy efficiency in energy certificas and the building shape factor (A/V ratio, where A = gross heated floor area (m^2, including the exterior walls) and V = volume (m^3)).

The evaluation was taken from the actual measured energy consumption. The energy measurement data was based on consumption monitoring systems in properties. Collected database were basis for all studied papers. The heating consumption includes space heating, domestic hot water and heating of ventilation air. Electricity consumption includes all electricity, e.g. ventilation, appliances and lighting.

The results showed that the variation in energy consumption and primary energy consumption of studied buildings was high between the buildings regardless of the age and the building type. The results showed that heating consumption was higher than electricity energy use in daycare centres and school buildings. A decreasing heating consumption could be seen in newer buildings. On the other hand, electricity consumption slightly increased as newer buildings consume more electricity.

In general, in the studied daycare and school buildings, the primary heating consumption clearly decreased in newer buildings. In turn, the primary electricity consumption rose. In both building types, daycare centres and schools, the primary heating and electricity consumption varied significantly between the buildings. A more detailed analysis of energy consumption as a function of age results no statistically significant correlation. However, a significant negative correlation was revealed for over 25-year-old daycare centres and electricity consumption. The primary electricity consumption was higher than primary heating in daycare centres built after 2002, whereas, in schools built after 1988. This means that in the design phase, there is a need to find ways to influence the electricity consumption in particular. Also, the European Union has set an indicative objective to reduce its primary energy consumption by 20% in relation to the projected 2020 energy consumption. Therefore, the use of electricity will have a more significant role in achieving these goals.



	Age >25 years Daycare centres		Age <15 years Daycare centres		Built after 2002 Daycare centres		Age >25 years School buildings		Age <15 years School buildings		Built after 2002 School buildings	
	Heating	Electricity	Heating	Electricity	Heating	Electricity	Heating	Electricity	Heating	Electricity	Heating	Electricity
Mean	153,8	104,7	144,8	18,5	118,4	19,0	141,1	15,8	94,4	13,9	92,1	14,2
Median	129,9	101,7	50,8	18,6	42,7	18,3	31,4	14,4	33,6	13,4	30,9	14,3
Minimun	98,1	62,1	81,0	77,1	82,1	94,0	44,5	20,2	31,4	17,8	60,6	75,7
Maximum	385,7	167,5	411,1	631,7	166,5	144,5	267,8	210,1	180,9	212,5	121,5	122,0
Range	287,6	105,4	330,1	554,6	84,4	50,5	223,3	189,9	149,5	194,7	60,9	46,3
Linear correlation coefficients R	$0,22^{(n.s.)}$	$0,27^{(*)}$	$0,29^{(n.s.)}$	$0,33^{(n.s.)}$	$0,33^{(n.s.)}$	$0,34^{(n.s.)}$	$0,21^{(n.s.)}$	$0,20^{(n.s.)}$	$0,08^{(n.s.)}$	$0,22^{(n.s.)}$	$0,19^{(n.s.)}$	$0,05^{(n.s.)}$
R-squared	-0,0479	-0,0727	-0,0841	-0,1084	-0,1083	-0,1144	-0,0451	0,0391	-0,0068	-0,0483	-0,0354	-0,0028

Level of significance/error of probability: P ≤ 0.1%, high significant (***);0.1% < P ≤ 1.0%, very significant (**); 1.0% < P ≤ 5.0%, significant (*); P > 5.0%, not significant (n.s.).

Figure 3. Comparison of the primary energy consumption [delivered energy multiplied by primary energy factors, kWh/(m^2,a)] between over 25-year-old, retrofitted and new daycare centres and school buildings in the City of Espoo. Statistical values of the primary consumptions in studied buildings are shown in figure.

The effects of the reforms in Finnish building regulations can be seen in the decreased heating consumption in newer building. The rise in primary electricity consumption and the difference between the electricity consumption of the buildings is assumed to be the consequence of the increased use of the premises and improvement of the indoor air quality. The differences are also affected by the variation of electrical equipment. In daycare centres the trend in the primary energy consumption is due to the fact that all six electrically heated daycare centres were built in the 1980s. Even though they represent only 16% of the total number of the buildings (37 buildings) built in the 1980s, their role in the primary energy consumption of the entire daycare building stock is significant.

However, the effect of the reforms in Finnish building regulations cannot be seen clearly in the number for energy efficiency, which are showing the energy efficiency during the building operational phase. Deviations in the number for energy efficiency were great especially in the educational buildings that were constructed before the 1980s. The largest deviation between the numbers for energy efficiency could be seen in the schools and daycare centres constructed in the 1980s, where the difference between the highest and lowest was 75% (daycare centres lowest 171 and highest 635, schools lowest 156 and highest 508). In turn, the energy consumption and the number for energy efficiency had clear connection.

The correlation A/V decreased in all educational building types. This paper also showed that the building volumes have increased during the past decades. The results reflect that even though the volumes of daycare centres and schools have increased in recent years, this does not have a clear impact on energy consumption (Figure 4). However, it is assumed that the ratio A/V (envelope area per volume) have an high impact on the energy consumption (heat losses) of the buildings.

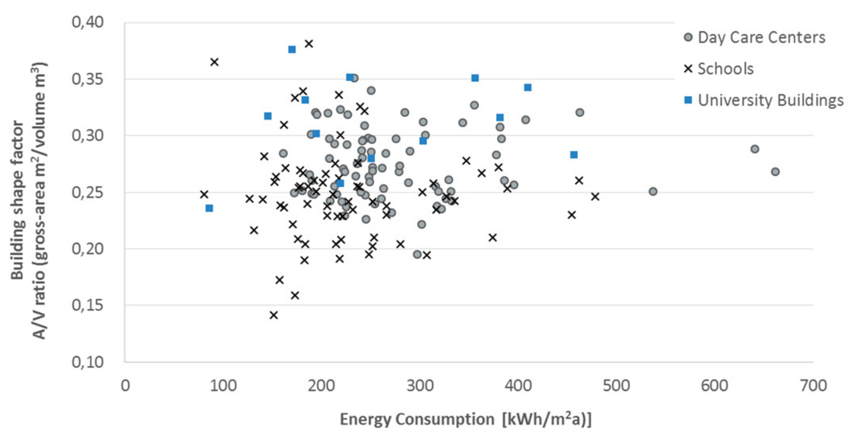


Figure 4. Energy consumption [delivered energy, kWh/(m^2,a)] in comparison with the building shape factor (A/V ratio) in the studied educational buildings in the City of Espoo.

However, at present it is challenging to obtain detailed information regarding how much of the energy consumption is due to users, equipment or the property. The great differences in energy consumptions of studied buildings cannot be explained only with technical reasons such as insulation and air tightness. Also the ways and methods of building services have a great effect on energy consumption.

2.2 Paper II: Impact of building usage and occupancy on energy consumption in Finnish daycare and school buildings

The purpose of the second paper was to find out how building usage and occupancy influence on the measured energy consumption. In addition, Paper II evaluated the different possibilities to indicate energy efficiency.

The study in the Paper II was divided into two phases:

- In the first phase, where the influence of building usage and occupancy on the overall measured energy consumption was analysed.
- In the case studies section, where the alternative indicators for energy efficiency were compared with respect to the measured energy consumption. The indicators were tested in eight case studies.

The findings in the Paper II indicated that the newest buildings have slightly longer operating times. In addition, in the studied daycare centres and schools, the space in m^2 per child or student grew as the newest buildings have more space per user. A similar result can be found in Paper I, which showed that the building volumes have increased during the past decades.

Paper II demonstrated that daycare centre buildings have similar user profiles, with only minor variation between the profiles. However, schools have clearly identifiable user profiles and thus the variation between the buildings is greater. In addition, these user profiles can be seen in the results when analysing the dependence of the measured energy consumption and energy consumption adjusted for occupancy.

Over 93% of the daycare centres examined were in operation between 2000 and 3000 out of total 8038 hours per year, with an average of 2600 hours. 40% of the schools were in use approximately 2200 hours a year and 45% were in use 3000 hours or more per year.

The three indicators, EIU, SECo and SECu,s were designed to take into account the efficiency of space usage. Results showed that in the studied daycare centres and school buildings, there were no clear connection when comparing energy consumption and space use (m^2/child or student). In addition, results indicated that when comparing energy consumption and yearly operating times, the energy consumption follows no evident trend. However, analysis of the dependence of the measured energy consumption and energy consumption adjusted for occupancy revealed a connection, although some deviations appeared. In school buildings, an evident connection and three kinds of profiles emerged. This was due to the different types of occupation hours; in this context, the deviations have longer operating times compared to the average. This means that the school buildings provide sports and learning facilities in the evenings.

Results showed that the dependence of the measured energy consumption and energy consumption adjusted for usage and space efficiency in the studied daycare centres and school buildings, a clear connection and trend emerged. In daycare centres, energy consumption adjusted for usage was higher based on space values in design guidelines than when calculated based on actual building use. In daycare centres, the U[1] values were on average 39% lower (0,6) in design guidelines than in actual operation (1,0). The results showed that the actual space use (on average 12.2 m²/child) was higher compared to the demand estimated in the design guidelines space programme (City of Espoo, 2014a).

In school buildings, the results were closer to each other than the results in the daycare centres. However, the U[2] values and space use were the opposite. In schools, the U[3] values were on average 9% higher in design guidelines (2.6) than in the actual operation (2.4). The results indicated that actual space use (on average 16.1 m²/stud) was slightly lower compared to the demand in the design guidelines (on average 15.3 m²/stud).

In Paper II, the three indicators, EIU, SECo and SECu,s were designed to take into account the efficiency of space usage. Results showed that the values in different indicators vary considerably between the studied case buildings. Figure 5 summarises the results from the different cases. To allow easier comparison, the values for energy intensity of usage, EIU (unit: kWh/number of occupants), were indexed so that the value 1.000 represents the Case 1. Daycare Centre value 6.947.

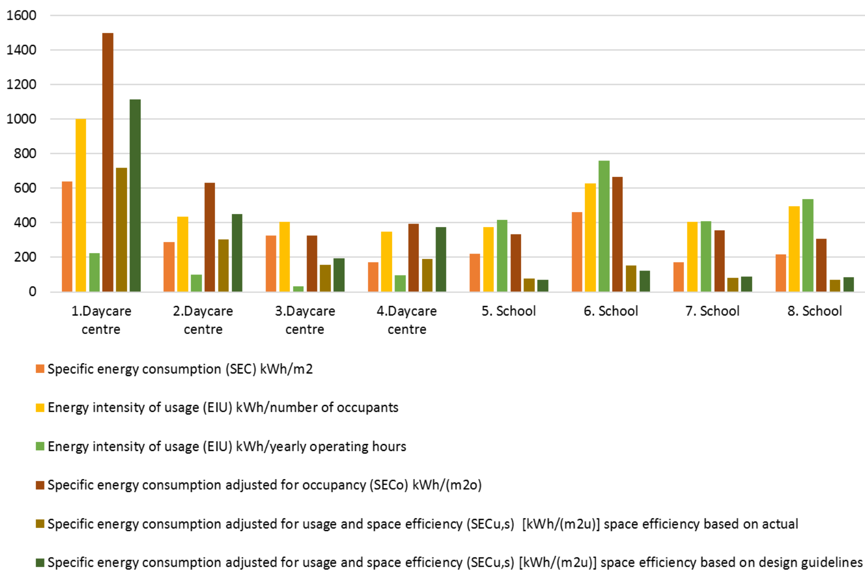


Figure 5. Summary of different indicators in studied cases. Energy consumption (kWh) is delivered energy.

With the traditional indicator of energy efficiency (kWh/m²), Case 4 in daycare centres and Case 7 in schools were the most energy efficient. However, when the efficiency in the number of users (kWh/personnel+children +students) was compared, Case 4 in daycare centres and Case 5 in schools were the most energy

[1,2,3] $u = \frac{n t_{avg}}{\frac{A}{a_{ref}} t_{ref}}$

efficient. Contrastively, when the usage profiles (yearly operating times) were compared, Case 3 in daycare centres was the most efficient (day and night care center) and therefore the indicator (kWh/ yearly operating times) seemed the most energy efficient. Cases 6 and 8 in schools were most efficiently used (3189h/a) but the most efficient case based on the indicator kWh/yearly operating times was Case 7.

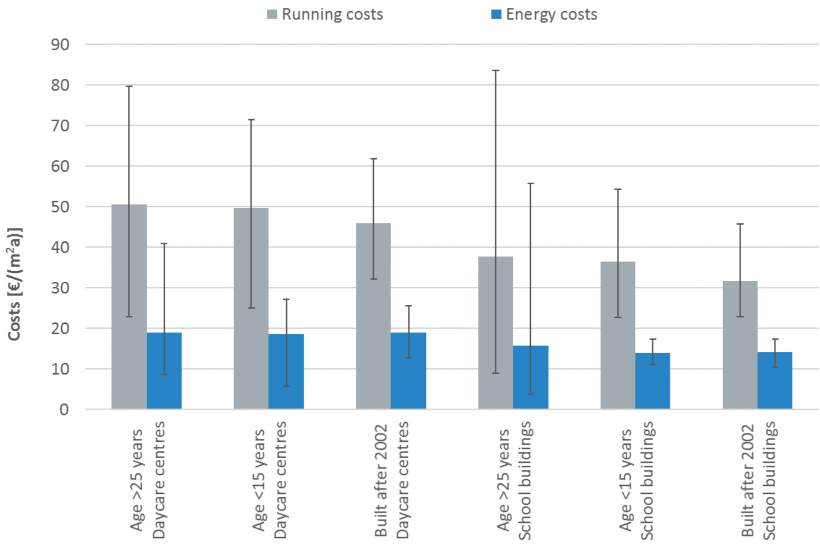
An indicator of energy efficiency that includes building occupancy as a parameter in denominators like kWh/yearly operating times rewards a building with efficient space usage. The results showed that indicator SECu,s combines the area and occupancy into one indicator, as both are highly relevant causal factors for energy consumption in buildings. It produces a reasonable synthesis of the technical energy efficiency, as measured by SEC, and energy efficiency derived from efficient use of space. Scalar factor u as the denominator produces comparable results regardless of the size or population present in the building examined.

2.3 Paper III: Consideration of energy consumption, energy costs, and space occupancy in Finnish daycare centres and school buildings

The third paper focused on evaluating the different possibilities to indicate energy efficiency and energy costs in existing daycare and school building. The aim was to examine the connection between different building energy efficiency indicators and the energy cost. The evaluation was based on the buildings actual energy consumption and real costs, yearly usage and occupancy data. The studied buildings comprised 62% of the daycare centres and 75% of the schools in the City of Espoo area.

The results showed that the variation in costs of studied buildings was high between the buildings regardless of the age and the building type. In the studied daycare centres the running costs ranged from 22.7 €/m^2 to 79.7 €/m^2. The share of the energy costs was an average 39%. In the studied schools the running costs ranged from 9 €/m^2 to 83.6 €/m^2 and the share of the energy costs was an average of 45%.

In both building types, the share of energy cost for running costs varied significantly between the buildings. Variation of energy costs decreased in newer buildings. As shown in Figure 6, the energy costs ranged from 5.9 €/m^2 to 41 €/m^2 in the studied daycare centres. In the studied schools, the energy costs ranged from 4 €/m^2 to 55.7 €/m^2 (Figure 6). A more detailed analysis of running and energy costs as a function of age resulted in no statistically significant correlation. However, a significant correlation between costs and over 25-year-old schools was revealed. The running and energy costs were clearly higher in school buildings built in the 1960s. None of these buildings have undergone major renovation.



	Age >25 years Daycare centres		Age <15 years Daycare centres		Built after 2002 Daycare centres		Age >25 years School buildings		Age <15 years School buildings		Built after 2002 School buildings	
	Running Costs	Energy Costs	Running Costs	Energy Costs	Running Costs	Energy Costs	Running Costs	Energy Costs	Running Costs	Energy Costs	Running Costs	Energy Costs
Mean	50,6	19,0	49,7	18,5	45,9	19,0	37,8	15,8	36,4	13,9	31,7	14,2
Median	50,3	18,8	50,8	18,6	42,7	18,3	31,4	14,4	33,6	13,4	30,9	14,3
Minimun	22,9	8,7	25,0	5,8	32,1	12,7	9,1	3,8	22,8	11,1	22,9	10,5
Maximum	79,7	41,0	71,5	27,2	61,9	25,5	83,6	55,7	54,4	17,4	45,8	17,4
Range	56,8	32,4	46,5	21,3	29,8	12,8	74,5	51,9	31,6	6,3	22,9	6,9
Linear correlation coefficients R	0,14$^{(n.s.)}$	0,05$^{(n.s.)}$	0,02$^{(n.s.)}$	0,07$^{(n.s.)}$	0,65$^{(*)}$	0,30$^{(n.s.)}$	0,46$^{(***)}$	0,42$^{(**)}$	0,33$^{(n.s.)}$	0,28$^{(n.s.)}$	0,62$^{(**)}$	0,53$^{(**)}$
R-squared	0,0189	-0,0025	0,0006	-0,0045	-0,4230	-0,0898	-0,2125	-0,1726	-0,1095	0,0783	-0,3839	-0,2807

Level of significance/error of probability: P ≤ 0.1%, high significant (***);0.1% < P ≤ 1.0%, very significant (**); 1.0% < P ≤ 5.0%, significant (*); P > 5.0%, not significant (n.s.).

Figure 6. Comparison of the building running costs [€/(m^{2}a)] between over 25-year-old, retrofitted and new daycare centres and school buildings in the City of Espoo. Statistical values of the running and the energy costs in studied buildings are shown in figure. Energy costs are based on delivered energy consumption (kWh).

The results showed that in daycare centres, the newer buildings heating costs were lower. In turn, such a clear correlation not found for the electricity costs. However, in schools, the heating costs was higher in schools built before 2004 and the share of heating and electricity costs are almost equal in schools built after 2004. However, in both building types, the energy costs €/m^2 varied significantly e.g. in daycare centres variation was 86% and in schools 93% between the buildings.

On average, estimation of one m^2/number of occupants' addition increases the cost of energy 3.8% in daycare centres and 6.9% in school building. However, results indicated that actual use of space was profiled in the operational phase where the energy costs variation was great. Therefore, in the planning phase, the results of square meter addition increasing cannot be directly utilised.

This study also demonstrates that there is a connection between occupancy and energy costs. However, some deviations appear. Significant reason for deviations in the studied buildings was higher energy consumption compared the average. In addition, deviations in due to the different types of occupation hours; in this context the deviations had longer operating times compared the average. Estimation of one actual daily person hour addition increased the yearly cost of energy on average 5% in daycare centres and on average 5.3% in school building. In turn, estimation of the energy costs when the building is empty of users is average 9.8 €/m^2 in daycare centres and average 8.2 €/m^2 in schools.

This study revealed a connection when compared energy costs and energy consumption adjusted for usage and space use. However, the connection was not as strong as Paper II stated between the energy consumption.

In daycare centres, results of energy consumption adjusted for usage was higher based on space values in design guidelines than when calculated based on actual building use. However, in school buildings the results were quite close to each other. Although actual use of space is profiled in the operational phase and the planning phase is full of uncertainties, studied indicators can be utilized already in the planning phase from the perspective of energy costs.

2.4 Paper IV: Effect of energy measures on the values of energy efficiency indicators in Finnish daycare and school buildings

In Paper II, the three indicators, EIU, SECo and SECu,s were designed to take into account the efficiency of space usage. The findings in the Paper IV indicated that energy efficiency can be measured by using different indicators and confirmed that different indicators have a different impact on the results showing efficiency. EIU is a measure of energy use per occupant and energy use per yearly operating times, but does not consider the physical floor area of the building. The two remaining indicators include building occupancy as a parameter in denominators and rewards a building that implements efficient space usage.

Results showed that, when the building age is compared, the newest daycare centre (Case 3) were the most energy efficient. However, renovated schools, e.g. Case 4, were performing well in comparison with newer buildings. When the building size was compared, in daycare centres Case 2 was the least efficient with the indicator of kWh/(m^2,a). However, Case 2 was the most efficient when the usage profiles were compared. In turn, school Case 5 was the most efficient with the indicator of kWh/(m^2,a). However, in Case 5 the daily operating times was shorter compared to the others.

Results in Paper IV showed that if the case buildings were to be retrofitted, it will be possible to invest in energy efficiency improvements. The total energy saving potential reached 15 kWh/(m^2,a) whereas the heating saving potential was 10.4 kWh/(m^2,a) and 4.3 kWh/(m^2,a) in terms of electricity saving potential. However, the energy saving potential varied in the different Cases. Significant saving potential was found in building services which reflected that the automation system does not control the service systems correctly or the initial automation system is somehow underdeveloped. This means that there is need for increasing demand controlled ventilation or updating building automation systems.

Paper IV studied the impact of energy savings measures on different energy efficient indicators. Summary of different energy efficient indicators before and after energy saving measures in studied cases are shown in Table 9 (kWh include both heating (space heating and domestic hot water) and electricity).

Table 9. Summary of energy consumptions before and after energy saving measures in studied cases. (The consumption is delivered energy (kWh) and include both heating (space heating and domestic hot water) and electricity)

Indicator	**Heating consumption** kWh/(m²,a)			**Electricity consumption** kWh/(m²,a)		
Energy saving measures	Before	After	%	Before	After	%
1.Daycare centre	215	203	-6	75	73	-3
2.Daycare centre	234	204	-13	93	88	-5
3.Daycare centre	117	102	-13	55	50	-10
4. School	157	140	-11	62	60	-3
5. School	116	115	-1	57	57	0
6. School	143	134	-6	72	63	-12

The study showed that even if the buildings are equipped with different kinds of ventilation technology and built to meet different levels of construction requirements that affect energy efficiency, the alternative indicators of energy efficiency produced roughly similar results. The impact of energy savings on the energy intensity of usage indicators is shown in Table 10.

Table 10. Summary of different energy efficient indicators before and after energy saving measures in studied cases. (The consumption is delivered energy (kWh) and include both heating (space heating and domestic hot water) and electricity)

Indicator	**kWh/ personnel+child/stud**			**kWh/ child/stud**			**kWh/ yearly operating times**		
Energy saving measures	Before	After	%	Before	After	%	Before	After	%
1.Daycare centre	2 588	2 462	-5	3 024	2 877	-5	99	94	-5
2.Daycare centre	2 233	1 997	-11	2 821	2 522	-11	33	30	-11
3.Daycare centre	2 102	1 852	-12	2 415	2 128	-12	95	84	-12
4. School	2 387	2 180	-9	2 600	2 374	-9	416	380	-9
5. School	2 603	2 582	-1	2 812	2 790	-1	409	405	-1
6. School	3 119	2 866	-8	3 432	3 153	-8	536	492	-8

In this instance, alternative indicators refer to energy consumption adjusted for usage and space use. An analysis of energy consumption adjusted for occupancy, SECo, revealed average 7.4% impact when comparing values before energy saving measures. As shown in Table 11 when savings in energy consumption were analysed, based on actual use of buildings, a clear change was revealed. The average impact of the indicator was 7.3%. The order of the most efficient cases remained the same after energy saving measures as before energy saving measures.

Table 11. Summary of different energy efficient indicators before and after energy saving measures in studied cases. (The consumption is delivered energy (kWh) and include both heating (space heating and domestic hot water) and electricity)

Indicator	**SECo kWh/(m^2o)**			**SECu,s [kWh/(m^2u)] space efficiency based on actual**			**SECu,s [kWh/(m^2u)] space efficiency based on design quidelines**		
Energy saving measures	Before	After	%	Before	After	%	Before	After	%
1.Daycare centre	632	602	-4,7	303	288	-5,0	452	430	-4,9
2.Daycare centre	326	293	-10,1	156	140	-10,3	193	173	-10,4
3.Daycare centre	395	348	-11,9	190	167	-12,1	377	332	-11,9
4. School	333	304	-8,7	76	70	-7,9	68	62	-8,8
5. School	356	353	-0,8	82	81	-1,2	88	87	-1,1
6. School	309	284	-8,1	70	65	-7,1	85	78	-8,2

The indicator SEC (kWh/m^2) is reliable as a measurement of the technical properties of a building, especially during the design phase. This could be seen from the results of the indicator SEC, where all cases consumed less energy per square meter after energy saving measures. However, for space efficiency no difference is expected.

Results confirmed that there is need for advanced and reliable monitoring of the life cycle energy efficiency of buildings. Actual and real time utilisation could be used to adjust building automation in real time based on the real utilisation of spaces.

3. Discussion

3.1 Evaluation of the main findings

This dissertation evaluates the different possibilities to indicate energy efficiency. The research was conducted by exploring issues in existing educational building. The energy efficiency was examined in a statistical and multiple case study approach. The study started with a broad survey in order to generalize results of a building stock. The case study methodology was used to compare alternative indicators of energy efficiency.

The starting point of the study was that the property owner does not have means to use and process information related to energy consumption, energy efficiency and energy saving measures. The aim of the facility strategy is the increased use of premises, which means i.e. improving space efficiency and increasing operating times. However, energy audits aim at energy savings. In turn, the energy efficiency indicators aim at measuring effectiveness.

RQ1: The first research question focused on producing the overall picture of energy consumption in the different building types studied.

There is great variation in energy consumption regardless of the factors that are used for evaluating measured energy. The majority of the school and daycare centres in this study were built between years 1980-1990. For this reason, energy efficiency has been taken into account already in the design phase decisions. This is showed in Paper I, where in general, the newer buildings consumed less heating energy. However, such a clear correlation was not found for electricity consumption. The study showed that daycare centres built after the 1980s consumed on average 6% less heating energy than the entire daycare building stock, and those built after the 2000s consumed on average 14% less. In turn, schools built after the 1980s consumed on average 16% less heating energy than the entire school building stock and those built after 2004 consumed on average 22% less.

Changes in the building shape factors did not have clear impact on energy consumption. In turn, the energy consumption and the number for energy efficiency had a clear connection (Table 12). For that reason, the energy certificates can provide guidance for reducing consumption. The deviations in the number for energy efficiency were great especially in the educational buildings that were constructed before the 1980s, which was probably due to the different kind of level of building services, space use and occupation hours. In addition, when comparing the difference between the electricity consumption, higher rates of premise use and indoor air quality improvements might increase energy consumption.

Table 12. Linear correlation coefficients R between dependent and independent variables.

Linear correlation coefficients R between dependent (yi) and independent (xi) variables			
		Number for energy efficiency [kWh/(m^2,a)]	A/V ratio (gross-area m^2/volume m^3)
		X_1	X_2
Daycare centres			
Energy consumption [kWh/(m^2,a)]	y1	0,99 (***)	0,02 (n.s.)
Schools			
Energy consumption [kWh/(m^2,a)]	y1	0,81 (***)	-0,07 (n.s.)

Level of significance/error of probability: P ≤ 0.1%, high significant (***);0.1% < P ≤ 1.0%, very significant (**); 1.0% < P ≤ 5.0%, significant (*); P > 5.0%, not significant (n.s.).

RQ2: The second research question focused on understanding the connection between building occupancy, space efficiency and energy efficiency. This was examined from both perspectives, energy consumption and energy cost.

The study showed that the connection between occupancy and energy consumption was not strong (Table 13). In addition, there were great variations between the buildings. When comparing schools and daycare centres on the basis of usage, the heating consumption in daycare centres was much higher than the electricity consumption. However, in schools the variation of heating consumption was stable. Daycare centre buildings had similar user profiles, with minor variation between profiles. However, schools had strong user profiles but the variation between the buildings was higher.

The share of energy costs can be up to 50% of all running costs in Finland. Paper II showed that the average energy costs for running costs were 39% for daycare centres and 45% for schools. The results indicated that the actual use of space is profiled in the operational phase where the energy consumption and energy costs variation is remarkable.

Results indicated that the running costs of newer buildings were lower (Table 13). This is due to the fact that there is no need for repairs in newer buildings. In the studied daycare centres and schools, heating costs were dominant in comparison with the electricity costs. However, in schools built after 2004 the share of heating and electricity costs were almost equal. This is supported by the results which showed that heating and electricity consumption of new buildings were quite close to each other (see in Paper I). In addition, the two core forms of energy in Espoo are district heating and grid electricity and the cost for heat and electricity is different.

The oldest daycare centres and the oldest school buildings had exceptionally high energy costs in comparison with other studied buildings. The comparison of the energy costs showed great variation in daycare centres and school buildings built before the 1980s. Most of these buildings are in near-original condition, i.e. have not undergone major renovation.

The newest buildings had slightly longer operating times, which means that new facilities were used more efficiently and had longer operational hours. In general, longer operational hours can drive the energy consumption higher. However, results showed that the energy consumption and costs were not higher in those buildings. This is probably because in newer buildings, especially built after the 2000s, energy efficiency solutions have been taken into account already in the design phase decisions and buildings are more energy efficient. In addition, this could be seen from the results in Paper I, which showed that in the newest buildings energy consumption was lower.

Table 13. Linear correlation coefficients R between dependent and independent variables.

Linear correlation coefficients R between dependent (yi) and independent (xi) variables						
		Building age X_1	m²/student, child X_2	Number of users X_3	Yearly operating times X_4	Use of schools' gym and learnig facilities in the evenings X_5
Daycare centres						
Heating consumption [kWh/(m²,a)]	y1	-0,28 (**)	-0,14 (***)	0,03 (n.s.)	0,08 (n.s.)	
Electricity consumption [kWh/(m²,a)]	y2	0,01 (n.s.)	-0,22 (*)	0,09 (n.s.)	0,06 (n.s.)	
Primary heating consumption [kWh/(m²,a)]	y3	-0,25 (*)				
Primary electricity consumption [kWh/(m²,a)]	y4	0,02 (n.s.)				
Running costs [€/(m²,a)]	y5	-0,01 (n.s.)				
Heating costs [€/(m²,a)]	y6	-0,15 (n.s.)	-0,04 (n.s.)		0,12 (n.s.)	
Electricity costs [€/(m²,a)]	y7	0,09 (n.s.)	-0,14 (n.s.)		0,08 (n.s.)	
Schools						
Heating consumption [kWh/(m²,a)]	y1	-0,42 (***)	-0,19 (n.s.)	0,04 (n.s.)	0,03 (n.s.)	0,07 (n.s.)
Electricity consumption [kWh/(m²,a)]	y2	0,04 (n.s.)	-0,35 (**)	0,06 (n.s.)	0,02 (n.s.)	0,05 (n.s.)
Primary heating consumption [kWh/(m²,a)]	y3	-0,47 (***)				
Primary electricity consumption [kWh/(m²,a)]	y4	0,04 (n.s.)				
Running costs [€/(m²,a)]	y5	-0,30 (*)				
Heating costs [€/(m²,a)]	y6	-0,44 (***)	-0,30 (**)		0,09 (n.s.)	
Electricity costs [€/(m²,a)]	y7	-0,06 (n.s.)	-0,23 (*)		0,08 (n.s.)	

Level of significance/error of probability: P ≤ 0.1%, high significant (***);0.1% < P ≤ 1.0%, very significant (**); 1.0% < P ≤ 5.0%, significant (*); P > 5.0%, not significant (n.s.).

Correlations between traditional (kWh/m²) and alternative energy efficiency indicators showed that energy efficiency can be measured by using different indicators (Table 14). The results from the Case studies confirmed that different indicators make a different impact on results showing efficiency. This indicates that the indicators serve different purposes and interests depending on the needs of the indicator user. Although actual use of space is profiled in the operational phase and the planning phase is full of uncertainties, studied indicators can be utilised already in the planning phase from the perspective of energy consumption and energy costs.

Table 14. Linear correlation coefficients R between dependent and independent variables.

Linear correlation coefficients R between dependent (yi) and independent (xi) variables					
		EIU (kWh/number of student, children) X_1	EIU (kWh/yearly operating hour) X_2	SECo (kWh/m^{2}o) X_3	SECu,s [kWh/(m^{2}u)] X_4
Daycare centres					
Energy consumption [kWh/(m^2,a)]	y1	0,7 (***)	0,66 (***)	0,94 (***)	0,94 (***)
Energy costs [€/(m^2,a)]	y2	Not analysed	Not analysed	0,67 (***)	0,66 (***)
Schools					
Energy consumption [kWh/(m^2,a)]	y1	0,23 (*)	0,26 (*)	0,63 (***)	0,63 (***)
Energy costs [€/(m^2,a)]	y2	Not analysed	Not analysed	0,27 (*)	0,27 (*)

Level of significance/error of probability: P ≤ 0.1%, high significant (***);0.1% < P ≤ 1.0%, very significant (**); 1.0% < P ≤ 5.0%, significant (*); P > 5.0%, not significant (n.s.).

RQ3: The third research question looked at how selected indicators can be used in evaluating energy measures and how energy measures can be combined so that the end result is user-driven and better reflects the reality of the building operational phase energy efficiency.

It is important to improve the energy efficiency by technical measures e.g. improve ventilation heat recovery, increase demand controlled ventilation or update building automation systems. Especially this occurs in the building construction or renovation process. In those processes, the indicator kWh/m² is reliable as a measurement of the technical properties of a building during the design phase. This could be seen from the results of the indicator SEC, where all cases consumed less energy per square meter after energy saving measures.

Traditionally the energy efficiency in buildings is measured by means of units of kWh/m^2, specific energy consumption SEC, which enables comparisons nationally and internationally. However, it has weaknesses, such as the exclusion of usage and economic factors which would be beneficial to consider in addition for gaining more knowledge on improvement potential. From the perspective of evaluation, it is appropriate to use different indicators in different phases, i.e. one indicator in the design phase and another indicator during the operational phase. Findings indicated that in the building operational phase, an indicator of energy efficiency should promote the use of facilities. In example, when the space use is increased by 5-12%, the improvement effect on the indicator of specific energy consumption adjusted for usage and space efficiency is 9%. Especially, when the schools evening use is increased and the indicator of energy intensity of usage is used, that improvement in users' presence improves also energy efficiency by 26% and with the indicator of specific energy consumption adjusted for occupancy the improvement is 26-75%. The study by Airaksinen (2016) showed that when the occupancy levels increased by 18%, decreased energy efficiency by 7% with the indicator of specific energy consumption.

In summary, this dissertation proposes that an indicator of energy efficiency should promote the use of facilities. However, the size of the effect depends on different factors. The summary of different energy efficient indicators is shown in Table 15.

Table 15. Summary of different energy efficiency indicators.

	Specific energy consumption	Energy intensity of usage	Specific energy consumption adjusted for occupancy	Specific energy consumption adjusted for usage and space efficiency
Indicator unit	kWh/m²	kWh/number of occupants (children, student, personnel) kWh/yearly operating times	SECo kWh/(m²o)	SECu,s kWh/(m²u)
Based on	Physical properties of the building	Energy use divided per occupancy	Energy use divided per relative occupancy	Combines the area and occupancy into one indicator
Indicates	Technical energy efficiency	The efficient use of facilities	The efficient use of facilities	Technical energy efficiency and efficient use of space
Usability	- Indicator is reliable as a measurement of the technical properties of a building during the design phase, but inappropriate when the building occupancy and space efficiency are considered in the building operational phase. - Enables comparisons nationally and internationally. - Relatively easy to obtain and also easy to understand. - It is recommended that it remains in use, in combination with other indicators, to ensure temporal and regional comparability of data. Especially, in the case of energy audit and conservation	- Rewards a building with efficient space usage. - Only takes into account people and operating times but completely ignores the physical floor area of the building. - Ilustrative when usage efficiency is considered and when the building space is fixed. This is typical in existing buildings. - Indicator is also rather easy to calculate. - This study addresses only the number of daytime occupants, there should also be a way to measure the number of evening users.	- Yields the relative occupancy. - Takes into account operating times and ignores the physical floor area of the building - Does not consider the real use of the building.	- Relatively complicated to calculate in existing buildings. - When more sensors are installed and the data for real-time usage and occupancy information are available, the calculation of SECu,s will be easier and more accurate.

The required data sources for energy efficient indicators are shown in Table 16. The building owner systematically utilises consumption monitoring data in order to maintain a high level of energy efficiency and avoid unnecessary energy consumption. The energy consumption data can be combined and assessed with building automation systems data, thus ensuring the energy-efficient control of the property while maintaining the target values of indoor air quality.

Technologies for the real-time utilisation of data are becoming accessible, and many knowledge work organisations are interested in applying this data for workplace design purposes. Direct links between building automation and access control systems create an alternative purpose for using this data and the possibility to calculate the savings that could be achieved with this information.

Table 16. Required data sources for energy efficient indicators.

Required data sources	Specific energy consumption	Energy intensity of usage	Specific energy consumption adjusted for occupancy	Specific energy consumption adjusted for usage and space efficiency
Area				
Gross-area	x		x	x
Energy consumption Data based on consumption monitoring system				
Heating consumption	x	x	x	x
Electricity consumption	x	x	x	x
Building occupancy Data based on: - sensors - collection from the users - survey				
Number of occupants		x		x
Yearly operating times		x		x
Daily person hours			x	x
Normal working hours				x
Space efficiency				x

Different energy efficiency indicators serve different purposes and interests depending on the needs of the indicator user. Measuring energy efficiency in buildings is complicated because the various stakeholders have differing interests regarding energy efficiency. Every indicator should be developed keeping in mind the specific use and objective that it is intended for. Therefore, no single indicator can be devised that could serve all needs. Rather a set of indicators is suggested, whereby the right combination of indicators can be chosen for each purpose. The summary of suggested indicators for different purposes is shown in Table 17.

Table 17. Summary of suggested indicators for different purposes.

Purpose chosen for	Specific energy consumption	Energy intensity of usage	Specific energy consumption adjusted for occupancy	Specific energy consumption adjusted for usage and space efficiency
Usability				
Space Programme	x	x		
Design phase	x	x		x
Operational phase	x	x	x	x
Tenancy agreement	x	x		
Energy Audit	x	x	x	x
Evaluate				
Energy efficiency	x	x	x	x
Energy savings	x	x		x
Energy measures	x	x		x

3.2 Contribution of the research

Increasing energy efficiency constitutes one of the key actions in reducing greenhouse gas emissions throughout the building lifecycle (Vehviläinen et al., 2010). As many studies (Junnila and Horvart, 2003; Sartori and Hestnes, 2007; Cabeza et al., 2014) showed, 80-90% of the environmental impacts of buildings are generated when in operation. Studies have emphasized that it is important to improve the energy efficiency by technical measures (Harvey 2009; Tuominen et al. 2013; Heljo and Vihola 2012; Airaksinen and Vainio 2012). However, previous studies have focused on technical improvement measures instead of examining the effects of building occupancy. Several studies have indicated that occupancy has a high impact on the energy consumption (Airaksinen, 2011; Thewes et al., 2014). The importance of building occupancy in energy efficiency has already been brought up by many authors (Dooley, 2011; Huovila et al., 2013; Forsström et al., 2011).

This research builds on the previous studies, but is one of the first to combine the building usage and occupancy with real measured energy consumption and cost. This provides new perspectives for the evaluation of energy efficiency. The occupant perspective expands the contribution of evalution even further, as usually building users are often encouraged to save energy based on measured energy consumption and ignoring the use of the building.

The great differences in the energy consumptions of the studied buildings cannot be explained only by technical reasons. In addition, the variation of energy consumption can not be explained only by building age and occupancy. On an annual basis, lower occupancy can lead to higher energy efficiency when the indicator kWh/m^2 is adopted. In general, in cases where 1) the amount of users is increased, 2) the operating times of the building are increased, 3) the building space efficiency is increased, or 4) the building users are more often present in the building, the building seems less energy efficient when the indicator of energy consumption per floor area is applied.

In this study, the higher number of users in daycare centres and schools does not explain the higher level of consumption i.e. energy consumption does not rise in relation to number of users. As such, we may not argue that building age or occupancy (i.e., one level of the independent variable) increases (i.e., causes an increase in) energy consumption (i.e., the dependent variable).

This clearly shows how complicated the relationships in energy consumption and the factors affecting it are. The building can only be compared with itself, which indicates a change of direction. In turn, comparison with itself is not enough to indicate on which level the building is, e.g. compared to the other buildings. This study aimed to develop a common approach for measuring energy efficiency in buildings. Based on the findings of the studied indicators, buildings can be compared in a more versatile way and this strikes a balance between the different aims of measuring energy efficiency.

The aim of the Espoo City facility strategy is that in the future the same building can offer several services. For example, a school building provides also library services and sports facilities. In this study, the growing use of facilities and longer operating times was observed in the newest buildings. The results of this study support the achievement of the objectives of the strategy. However, when the buildings' operational phase energy efficiency is considered, it is illustrative to use an indicator that takes into account occupancy and space efficiency. If occupancy is measured in order to understand energy consumption, specific energy efficiency criteria need to be defined to allow sustainable decisions to be made and to achieve the target values. Furthermore, if occupancy is measured, then this knowledge can also be used to turn on or turn off the energy-consuming systems that are directly related to people present. This requires that the building's automation and control systems are based on demand control.

In daycare centres the results showed that the actual space use was higher compared to the demand estimated in the design guidelines space programme. Over 93% of the daycare centres examined were in operation between 2000 and 3000 hours per year, with an average of 2600 hours. 40% of the schools were in use approximately 2200 hours a year and 45% were in use 3000 hours or more per year. In schools, typical operation profiles identified with considerable variation in energy consumption and cost in and between profiles. On average, in school buildings the estimation of one square meter addition per user increases the yearly cost of energy more than one actual daily person hour addition. Therefore, from the view of efficient use of facilities it is preferable to increase efficiency by adding yearly operating hours within the programme framework rather than expanding spaces. In turn, daycare centres have an average high space use and have a limited possibility to increase the yearly operating hours. In daycare centres, the addition of m^2 per user is not as critical in terms of energy costs. In the design phase there should be a method to more accurately predict the future use and number of users in daycare centres.

This study demonstrated that especially daycare centres have similar user profiles, with only minor variation between the profiles. In Finland, the total energy approach was introduced in the new building code after 2012. Energy performance regulations also give user profiles, as well as other initial values for use of appliances' electricity. In regulations, educational buildings i.e. daycre centres and schools form their own class which determines same user profiles for both building types. User profiles are presented with daily use from 8 am to 4 pm and weekly use 5d/7d. When comparing these user profiles between the studied buildings, the regulations' user profiles can lead to too optimistic estimates of the target consumption in design phase. At least this should be taken into account when the differences between the design phase and the actual energy consumption are analysed. In addition, when the electricity consumption of schools' appliances are compared, an estimation based on measured consumption is on average 35% higher than the calculated consumption which is based on the initial values of the regulations.

The shape factor is most often calculated as the ratio between the outside surface area of the thermal insulation in the building envelope (A) and the heated volume (V). It is known that a building with a lot of extensions and annexes can have a higher shape factor and also a higher energy demand than a compact building. In addition, there are also other indicators for the compactness of the building volume. Some of these methods take into consideration the different heat losses through the floor, walls and roof. This study used A = gross heated floor area (m^2, including the exterior walls) per V = volume (m^3) as the shape factor. This approach would be simple if the aim is to set a target value for architectural concepts in sketch phase design. However, results showed that the correlation of A/V did not have clear impact on measured energy consumption and the approach cannot be directly utilised.

3.3 Evaluation of the research

Each appended paper contains its own discussion of the quality of research, applicable for the particular study. In this section, the quality of the dissertation is discussed as a whole. The quality of research is usually evaluated by the validity and reliability of the research.

Validity

Validity in quantitative research refers to whether one can draw meaningful and useful conclusions from outcomes on given indicators (Creswell, 2013). Commonly, the validity is divided into two perspectives, the internal validity and the external validity.

Internal validity is a concern for causal or explanatory research (Eisenhardt, 1989), where the researcher tries to determine whether one event led to another. In general, literature provides sufficient qualitative information on both causal relations, and relevant indicators regarding energy efficiency.

The energy measurement data is based on the consumption monitoring systems of the properties and the user profiles of schools and daycare centres based on the data collected from the users. The realised yearly costs in different running cost categories (Paper III) is based on the data which was collected for the KTI Property Information Ltd. building operational cost benchmark in 2012. From the accuracy perspective, there are factors that decrease the accuracy of the results. For example, the energy consumption data isn't comprehensive if the consumption metering is incomplete. The reason to this might be that buildings with different types of usage use the same consumption meter, e.g. a school building with a gym, library and/or kitchen. However, the reference period is a whole year, therefore it contributes to removing fluctuations in individual months. In addition, the study by Airaksinen (2011) showed that the normalized heating energy consumption was quite similar in all the buildings studied during many years, indicating that the consumption is rather stable. However, electricity consumption varied substantially amongst daycare centres and the study assumed that one of the reasons might be the different service levels of the buildings (more equipment).

External validity refers to whether the study's findings can be generalized (Yin, 2009), i. e. we want to know if our findings from the sample can be generalised to the building stock. The data represents 82% of the total number of Espoo's school and 68% of the daycare buildings. In Paper I, all of the university buildings in the Espoo area were also included. The method, with such a high number of studied buildings assessed in the dissertation, provides a high degree of external validity (Eisenhardt, 1989). In this research, the building sample shared similar characteristics to the whole building stock, such as the size (gross-floor area and volume), the age of buildings, the operating times and building running costs. In this study, the case studies do not aim at statistical generalization, but rather at analytical generalization, so that the findings provide a base to understand a broader theory. Being limited to the daycare centres and schools of only one city, research lacks a holistic view on the situation nationwide. However, in Finland, the design of daycare centres and schools is based on national guidelines (RT 96-11003 2010; FNBE 2012). Thus, daycare centres and schools are homogeneous nationwide concerning their spaces and operating times.

Reliability

Reliability refers to demonstrating that the operations can be repeated, with the same results. The objective of reliability is that if another researcher follows the same procedures and conducts the same case study again, the same findings and conclusions could be made (Yin, 2009). This requires that the research process is well documented.

In this research, the research process and the activities in the research process have been organised and all data has been stored. This includes the research plan, data collection and the collected data.

The research data was collected in 2012. The energy measurement readings for year 2012 were revised and are reliable. The deviation of the energy consumption data from the consumption monitoring system is no more than ±2% (Finnish Energy Industries, 2010). Also the weather conditions of year 2012 corresponds with the weather conditions of the comparison period of the years 1981-2000 (Finnish Meteorological Institute, 2013).

3.4 Future research

In addition to the indicators defined in this dissertation, the use of other indicators that may be more appropriate in some specific cases is encouraged. It would be interesting to investigate other types of buildings to examine whether the findings of this research apply to them. More indicators for use in buildings and building components have been presented for instance in the RET project (Heljo, 2005). When defining energy efficiency (European Commission, 2006; IAEA, 2005), a ratio between an output and an input (in this study energy consumption) is essential. This study uses intermediate indicators (occupancy, efficiency of use) as an output indicator. Thus, this study does not use the actual final outcome indicators, such as children's satisfaction with daycare or student learning or graduation.

In addition to energy efficiency, the quality of the indoor environment (e.g. thermal comfort and CO_2) could be measured at the same time, as it is not factored in the indicators. Energy consumption for space heating also depends on indoor temperature. Temperature data can be collected by the building automation system. It is well known that there is a relationship between energy use and indoor temperature. However, details of different building components were not analysed in this study.

In this dissertation, the user profiles of schools and daycare centres were based on the data collected from the users. Hence, the schools' user data contain only educational activities. In the future, instruments should be devised to calculate the number of evening users in premises. This is important in order to maintain comparable indicators that take into account also the evening use of the premises.

As the results of this research, the great differences in the energy consumptions of the studied buildings cannot be explained only with technical reasons. Also, the practices and methods of building services have a great effect on energy consumption. Määttänen (2014) pointed out that the sustainable operation of buildings is not hindered by a lack of technologies. Another interesting aspect is, that energy costs in offices are low when compared to the personnel costs of office work, e.g., Wargocki and Seppänen (2006). This means that from the economic perspective, it is more importance to provide productive work environments and less important to save on energy costs. More information is however needed on the different roles of the different actors in the area.

In the procedures (Hyartt el. al., 1991, TKK, 1993; Saari A., 2001b; Saari A. 2000) estimating energy consumptions and costs, results indicated that the differences in real consumptions were caused by the space programme or different design solutions. It would be interesting to investigate procedures for evaluating also efficiency.

4. Conclusions

The public sector should lead the field in of energy performance of buildings and the leading role requires setting an example to other actors. Energy efficiency has been taken into account in national building codes already for twenty years. In addition, the City of Espoo has participated more than 20 years in projects and signed agreements to conserve energy in its operations and to encourage energy conservation.

Improved energy efficiency is achieved primarily for economic reasons. The facility strategy of the City of Espoo emphasises improvements in the energy efficiency and efficient use of buildings, which means i.e. improving space efficiency and increasing operating times. It is assumed that increasing the use of facilities often increase in energy consumption. For this reason, the targets i.e. energy savings and increased use of facilities may be partly contrary to each other if individual buildings are considered. In turn, the City of Espoo does not have means to use and process information related to energy consumption, energy efficiency and energy saving measures. In order to encourage relevant efficiency efforts, it is essential to know how to measure energy efficiency, especially in the building operational phase. In some instances, the importance of building occupancy (space efficiency and operating times) for energy efficiency can be even higher than the technical improvement.

The study examines the influence of occupancy on energy efficiency evaluation and suggests indicators for evaluating energy efficiency. Traditionally the energy efficiency in buildings is measured by means of units of kWh/m^2, specific energy consumption, SEC. This indicator indicates technical energy efficiency and is suggested to use during the design phase as a measurement indicator. Indicators of energy intensity of usage and specific energy consumption adjusted for occupancy indicate the efficient use of facilities. Those are illustrative when usage efficiency is considered and when the building space is fixed. This is typical in existing buildings. Specific energy consumption adjusted for usage and space efficiency, SECu,s, is an indicator that takes into account both relevant aspects, technical energy efficiency and efficient use of space. Currently, this indicator is relatively complicate to calculate in existing buildings. The calculation of this indicator needs technical development of collecting real-time usage and occupation data.

Results showed that both energy consumption and energy costs vary a lot between different energy efficiency indicators. In general, the newest buildings have slightly longer operating times. However, the results showed that the energy consumption and costs were not higher in those buildings.

Energy efficiency can be measured by using different indicators and different indicators make a different impact on the results showing efficiency. Measuring energy efficiency in buildings may be complicated, because various stakeholders have differing interests regarding energy efficiency. However, to gain a holistic picture of the energy efficiency of a building it is necessary to adopt a combination of indicators. It is appropriate to use different indicators in different phases, i. e. one indicator in the design phase one indicator and another indicator during the operational phase. If the aim of the facility strategy is the increased use of premises, the indicator of operational phase energy efficiency should promote the use of facilities.

Indicators for measuring energy use are available, but indicators are needed to measure both current energy efficiency and improvement potential. In addition, the City of Espoo can also optimise the need of spaces. In the future, energy audits should begin to evaluate measures which are also related to building use. The audits should not only measure energy savings, but also energy efficiency. There is a major need for an energy efficiency measures audit method.

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Errata

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Evaluation of Energy Efficiency in Educational Buildings
School of Engineering
Aalto University publication series DOCTORAL DISSERTATIONS 57/2017
Date of Errata: 29.11.2016

Publication 1, page 109, Table 3

Table 3 Educational building classification into energy classes, graded from A to G. The classification and grades are based on energy certification.

Energy class	Number for Energy Efficiency (ET=kWh/(m^2,a))	
	Schools, University buildings	Daycare centres
A	ET ≤ 120	ET ≤ 140
B	121 ≤ ET ≤ 150	141 ≤ ET ≤ 180
C	151 ≤ ET ≤ 190	181 ≤ ET ≤ 230
D	191 ≤ ET ≤ 230	231 ≤ ET ≤ 300
E	231 ≤ ET ≤ 300	301 ≤ ET ≤ 390
F	301 ≤ ET ≤ 400	391 ≤ ET ≤ 500
G	401 ≤ ET	501 ≤ ET

Publication 2, pages 250 and 255, Table 2 and 5

5.School Gross floor (m^2) should be 5 730.

Publication 2, page 255, Table 5

Values of the studied daycare centres SECu,s should be the other way around.

Aalto-DD 57/2017

The facility strategy of the City of Espoo emphasises improvements in the energy efficiency and efficient use of buildings. Increasing the use of facilities often increases energy consumption. In order to encourage relevant efficiency efforts, it is essential to know how to measure energy efficiency, especially in the building operational phase. The aim of this dissertation is to increase knowledge about the evaluation of energy efficiency in educational buildings. The dissertation demonstrates that energy efficiency can be measured by using alternative indicators and confirmed that different indicators make a different impact on results showing efficiency. However, to gain a holistic picture of the energy efficiency of a building it is necessary to adopt a combination of indicators. In the future, the assessment of the energy efficiency of the operational phase should include, beside physical characteristics, parameters describing building use such as occupant levels, operating times and space efficiency.

ISBN 978-952-60-7359-0 (printed)
ISBN 978-952-60-7358-3 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)

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