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Improving energy performance of buildings through exploitation of available data

Rakennusten energiasuorituskyvyn parantaminen hyödyntämällä saatavilla olevaa dataa

Master's thesis
Espoo, October 3rd 2016

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Abstract of Master's thesis

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Title Improving energy performance of buildings through exploitation of available data

Degree programme Structural Engineering and Building Technology

Minor Construction Management and Economics **Code** IA3022

Thesis supervisor Assistant Professor Antti Peltokorpi D.Sc. (Tech.)

Thesis advisor Jaana Ihalainen M.Sc. (Tech.)

Date 03.10.2016 **Number of pages** 99+8 **Language** English

Abstract

The objective of this research is to find out how the energy performance of buildings can be improved effectively by exploiting available data in the operations and maintenance phase. In this research building automation systems, open data and Internet of Things are studied as value generating technological solutions. The research process is based on reviewing research literature, conducting interviews and analyzing measurement data recorded by the building automation system of a case office building.

The study identified 11 initiatives to close existing energy performance gaps. These initiatives belonged to categories of developing building services equipment control, increasing the extent of available data, observing the state of user experience and facilitating maintenance processes. Then the three most effective were chosen for a feasibility study. This effectiveness of an initiative was judged by evaluating it in the dimensions of *expected benefits* and *challenge to implement* in an indicative manner by 13 interviewees in four stakeholder groups. This simple evaluation method turned out to serve its purpose well: Vague evaluation dimensions covered both quantitative and qualitative aspects, while stakeholder groups had different perspectives on the initiatives. Thus the method is recommended for similar problems, as long as only indicative results are pursued.

Out of the 11 initiatives, the most effective ones were considered to be those that are simple and do not require any installation work, or at the most the installation of transmitters or sensors: 1) adaptive heating control, 2) user satisfaction measurement systems, 3) energy performance monitoring systems and 4) selected equipment group control interfaces. Feasibility studies suggested that adaptive heating control has the potential to increase energy performance with negligible installation work, user satisfaction measurement system would be sensible to pilot as a service, energy efficiency monitoring in small-scale would be convenient to purchase as a service and selected group control interfaces enable large savings with small trouble. The least effective initiatives were considered to be the ones that are complex, risk user satisfaction or require the integration of numerous systems.

Keywords energy performance, building automation, Internet of Things, open data

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Diplomityön tiivistelmä

Tekijä Tuomas Ruponen

Työn nimi Rakennusten energiasuorituskyvyn parantaminen hyödyntämällä saatavilla olevaa dataa

Koulutusohjelma Rakenne- ja rakennustuotantotekniikan koulutusohjelma

Sivuaine Rakentamistalous **Koodi** IA3022

Työn valvoja Apulaisprofessori, TkT Antti Peltokorpi

Työn ohjaaja DI Jaana Ihalainen

Päivämäärä 03.10.2016 **Sivumäärä** 99+8 **Kieli** englanti

Tiivistelmä

Tämän tutkimuksen tavoitteena on selvittää miten rakennusten energiasuorituskykyä voidaan parantaa tehokkaasti hyödyntämällä saatavilla olevaa dataa käyttö- ja ylläpitovaiheessa. Tutkimuksessa arvoa tuottavina teknologisina osaratkaisuina tutkitaan rakennusautomaatiojärjestelmiä, avointa dataa ja Esineiden Internetiä. Tutkimusmenetelminä käytetään kirjallisuustutkimusta, haastatteluja ja toimistorakennuksen rakennusautomaatiojärjestelmän tuottaman mittaustiedon analysointia.

Tutkimus tuotti 11 energiasuorituskyvyn ongelmakohtien korjaamiseen tähtäävää aloitetta. Näiden aloitteiden päämäärinä oli taloteknisten laitteiden ohjauksen kehittäminen, käytettävissä olevan datan lisääminen, käyttäjätyytyväisyyden tarkkailu tai ylläpidon prosessien helpottaminen. Aloitteista kolmelle tehokkaimmiksi arvioiduille tehtiin tarkempi toteutettavuustutkimus. Tehokkuusarviointi perustui neljään sidosryhmään jaetun 13 haastateltavan suuntaa-antavaan näkemykseen aloitteiden toimeenpanon hyödyistä ja haasteista. Tämä yksinkertainen arviointitapa osoittautui toimivaksi: Moniselitteiset arviointiulottuvuudet kattoivat sekä määrälliset että laadulliset näkökulmat, kun taas eri sidosryhmät painottivat aloitteiden eri ominaisuuksia. Näin ollen kyseinen arviointimenetelmä soveltuu samankaltaisiin ongelmiin, kunhan tulosten suuntaa-antava taso on riittävä tutkimuksen tavoitteisiin nähden.

Näistä 11 aloitteesta tehokkaimmiksi koettiin pääosin sellaiset, jotka ovat yksinkertaisia eivätkä vaadi laajaa asennustyötä: 1) adaptiivinen lämmityksen säätö, 2) käyttäjätyytyväisyyden mittausjärjestelmä, 3) energiatehokkuuden seurantajärjestelmä ja 4) laitteiden ryhmähallintaan perustuvat käyttöliittymät. Toteutettavuustutkimusten perusteella adaptiivinen lämmityksensäätö voisi parantaa energiasuorituskykyä pienellä asennustyöllä, käyttäjätyytyväisyyden mittausjärjestelmää olisi järkevää aluksi kokeilla palveluna, energiatehokkuuden seuranta pienessä mittakaavassa olisi kätevää ostaa palveluna ja ryhmäohjaukseen perustuvat käyttöliittymät voisivat säästää huomattavasti energiaa pienellä vaivalla. Tehottomimmiksi arvioidut aloitteet olivat monimutkaisia, vaaransivat käyttäjätyytyväisyyden tai vaativat useiden järjestelmien yhteensovittamista.

Avainsanat energiatehokkuus, rakennusautomaatio, Esineiden Internet, avoin data

Acknowledgements

I express my gratitude to the number of people and organizations who contributed to this Master's thesis.

This thesis is a part of the project "Improving the life-cycle value of buildings: Digitalization of performance-focused business" (DIGIBUILD). Within this framework the aim of the thesis is to use a case study to develop directions to design processes and systems to improve performance of buildings in the dimensions of user experience, use value, energy efficiency and maintenance efficiency, with open data and Internet of things as central elements.

I thank my supervisor Assistant Professor Antti Peltokorpi D. Sc. (Tech.) for his guidance during the research process. I am also grateful to my advisor Jaana Ihalainen M. Sc. (Tech.), Teppo Salmikivi Lic. Sc. (Tech.), Aimo Hämäläinen M. Sc. (Tech.), Jouni Poikkeus M. Eng. and Jussi Tuomola B. Eng. from Helsinki University for their counseling throughout this multidisciplinary work, and to the CEO Sampsa Laine D. Sc. (Tech.) from DataRangers Oy for allowing me to use their Louhin-platform for data analysis free of charge.

Similarly, I am thankful to all the people who went through the trouble to participate in the interviews and shared their insight, but whose names cannot be listed here due to ethical reasons.

Lastly, I appreciate Aalto University School of Science, Aalto University School of Engineering, Helsinki University Center for Properties and Facilities, TA-Yhtymä Oy, Granlund Oy and Fira Oy for committing to the DIGIBUILD project as sites of research, and to Tekes, Aalto University Foundation, TA-Yhtymä Oy, University of Helsinki Funds, Fira Oy and Granlund Oy for funding the project.

Helsinki, September 26th 2016

Tuomas Ruponen

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Appendices

Acronyms

P	[kW]	heating power of radiator network
$P_{exhaust}$	[kW]	electric power of an exhaust fan
P_{supply}	[kW]	electric power of a supply fan
SFP	[kW/(m^3/s)]	specific fan power
T_{11}	[°C]	exhaust air inlet
T_{21}	[°C]	supply air inlet
T_{22}	[°C]	supply air outlet
c	[kJ/(kg °C)]	specific heat capacity of water
q_{max}	[m^3/s]	the maximum of supply and exhaust air flows
$\frac{m}{\Delta t}$	[kg/h]	water flow through a heat exchanger
ΔT	[°C]	district heating water cooling
η	[-]	heat recovery efficiency ratio
ω	[%]	heat exchanger valve position

Abbreviations

AI	Artificial Intelligence
ANN	Artificial Neural Network
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BAS	Building Automation System
BEMS	Building Energy Management System
CBD	Central Business District
CPS	Cyber-Physical System
DDC	Direct Digital Control
EU	European Union
FDD	Fault Detection and Diagnostics
FK	Foreign Key
FMI	Finnish Meteorological Institute
GA	Genetic Algorithm
GHG	Greenhouse Gas
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
MBPC	Model-based Predictive Control
PBB	Performance-Based Building
PK	Primary Key
RFID	Radio-Frequency Identification
SFP	Specific Fan Power
WSN	Wireless Sensor Networks

1 Introduction

1.1 Research background

International action on climate change is increasing, and at the same time buildings are responsible for over 30% of the global energy consumption (IEA, 2015). This has led to emerging pressure from policymakers to increase the sector's energy efficiency. However as residential buildings account for over 40% of the building sector's carbon dioxide (CO_2) emissions (WBCSD, 2009), encouraging collective action is difficult. It is a typical "tragedy of the commons" (Lu, et al., 2010), as the financial incentive for individual homeowners to improve energy efficiency is negligible in comparison to the global motivation. For an average household in the United States for example, a 20-30% reduction in heating, ventilation and air-conditioning (HVAC) energy consumption would correspond to savings of around $15 per month, while the national savings would be $15 billion annually with 1.12 billion tons less pollutants in the atmosphere (Lu, et al., 2010). Yet, this is not the case with large property owners. Saving 10% in the heating expenses of a 6,000m^2 office building in Helsinki could translate to savings of 2,000-3,000€ annually, which would be enough to justify small scale investments. Thus, there is a stronger alignment of interests with large property owners and policymakers, rather than with individual homeowners and policymakers, which reduces the policy resistance of improving the energy performance of buildings.

However, it seems that self-interest has not been expected to be a sufficient driving force in the European Union (EU) that "… prefers to perceive itself as the frontrunner of environmental policy" (Korhola, 2014). This determination has materialized as the *2020 climate & energy package*, which in turn led to the *2010 Energy Performance of Buildings Directive*. This directive contains the requirement that all new buildings must be nearly zero energy buildings by the end of 2020 (European Commission, 2016a). However, in the wake of the Paris Agreement of December 2015 it has been observed that the current policy will not be enough to meet the 2030 reduction goals for greenhouse gas (GHG) emissions, so member states are given national reduction targets (European Commission, 2016b). For Finland, the current *Proposal for an Effort Sharing Regulation 2021-2030* includes a 2030 GHG reduction target of 39% (compared to 2005) for sectors outside Emission Trading System such as transport, buildings and agriculture (European Commission, 2016c). Based on the Climate Change Act 609/2015 of Finland it is evident that this target would reflect the national building codes (Finlex, 2015). Thus, property owners can expect more binding regulation driving towards increased energy performance.

Nonetheless, the energy performance of buildings cannot be prioritized over the health of building users. It is essential that building automation systems (BAS) control the building services equipment so that the criteria set for indoor environmental quality (IEQ) are met while making sure that the equipment are used energy efficiently to meet that goal. The philosophy behind this aspect of energy performance is demand-based control: Resources are used sparingly to meet the fluctuating demand. To enable computerized demand-based control, the demand must be estimated based on available data. This data is traditionally collected with a number of sensors deployed throughout the building and equipment, but can also include new technologies and open data. The energy performance of buildings can also be improved by ensuring that equipment are operating as intended. Undetected faulty equipment or suboptimal control can incur significant amounts of wasted energy over time.

To avoid this, building automation systems continuously process sensor data and generate alarms whenever undesired phenomena is detected. Sensor data can also be used to monitor and benchmark key figures such as specific resource consumptions of equipment.

The ability of the BAS to promote energy performance is always restricted, though. The capabilities of existing building services equipment and the realities of the construction market dictate to which extent it is feasible to strive towards a high level of performance that is based on computerization. If the ventilation system is incapable of purging rooms individually with different air flows, there is no way that a computer program could transform such a ventilation system into a highly demand-controlled one. Also, as a procurement, the BAS has a short life cycle in comparison with building services equipment in general, which means that all the automation-based investments leading to savings should have a short payback period. Moreover, large property owners can be cautious about giving up their ability to invite tenders from different providers: Any building automation solution that would unite the provider and customer to the foreseeable future is undesirable.

Research literature has presented many solutions that utilize computerization and available data in order to improve the energy performance of buildings. Some techniques presented in those solutions have also made their way through commercialization into specialized products or services. Yet, there seems to be a gap in the knowledge regarding the effectiveness of those solutions, or they have been found ineffective, for their adoption is not widespread at least in Finland. It could also be that some solutions have not even been granted a serious consideration due to policy resistance. If two of these options were the case, it would be unfortunate as the energy performance of buildings appears to be a global concern, and without self-driven improvement the industry will be forced to meet tightening policymakers' goals. Hence, this thesis is about exploring solutions to improve the energy performance of buildings in a low-threshold approach by exploiting available data, and investigating the effectiveness of those solutions.

1.2 Research objectives

The purpose of this research is to increase understanding on solutions that improve the energy performance of a building by exploiting available data. This objective is reformulated into the following research question:

- How the energy performance of buildings can be improved effectively by exploiting available data?

Before answering this question, the concepts *energy performance of a building* and *available data* need to be explored, which is done later in the thesis. Here, *effectively* refers to implications of a solution that suggest the largest benefits with the smallest trouble or costs associated to implementation and use.

The research question can be further divided into the three sub-questions:

1. What are the energy performance gaps of buildings?
2. What kind of solutions that are based on the exploitation of available data can close those gaps?
3. How effective are those solutions?

1.3 Research scope and structure

This thesis concentrates in detecting energy performance gaps in buildings, seeking solutions to fill them by exploiting available data and evaluating the effectiveness of those solutions. The research only includes factors of energy performance that can be enhanced with available data in the operations and maintenance phase of a building. This means that energy-efficient equipment control principles and methods to supervise and manage equipment so that they are operating energy-efficiently are included in the research as long as available data is being exploited. Such tasks are often executed with a BAS, for which those systems are also in the focus of research. Moreover, energy performance of a building cannot be improved in the operations and maintenance phase without considerations regarding indoor environmental quality. Therefore solutions that facilitate this aspect are also included in the research.

As the thesis is focused on the operations and maintenance phase of a building's life cycle, the energy performance aspects in the design of a building or its services equipment are excluded from research. Out of building types, the focus is on office buildings due to the high level of computerization and range of equipment. Furthermore, due to the multidisciplinary field of this research and often lack of relevant expertise available, the proposed performance-enhancing solutions are not described in high detail. Only the principles of the solutions are introduced so that the potential effectiveness can be estimated.

The thesis continues with chapter two, where the energy performance of buildings is discussed. Chapter three introduces briefly building automation systems in the context of the Internet of Things paradigm and advanced controlling strategies prevailing in research literature. In chapter four the research method and case study are presented. Chapter five includes the results of the complete research process: identifying energy performance gaps, suggesting potential solutions to close them, selecting the most effective solutions and studying their feasibility. In chapter six the research process is concluded and further research opportunities suggested.

2 Energy performance of buildings

2.1 Overview of the performance approach in buildings

The performance approach is “the practice of thinking and working in terms of ends rather than means” and suggested to be an effective way to promote innovation (Gibson, 1982, p. 4; Sexton & Barrett, 2005). In this approach the requirements for a building’s performance are articulated, but the means to achieve such performance are left for the suppliers to decide. It is argued that the current prescriptive codes reduce the motivation of businesses to innovate in the building sector. (Sexton & Barrett, 2005).

There are several technical challenges related to the performance approach. Firstly, formulating the target performance of a building is regarded difficult. It would include objectives, functional attributes and performance requirements that are not covered by building codes. So there is a need to create a framework of requirements for clients’ use. Secondly, the availability of tools to design, deliver or evaluate the performance of a given solution differ. Some performance areas have tools and some do not. Thirdly, the depth of knowledge is very uneven across the field of building technology. In some performance areas the formulation of quantified requirements is possible, while in other areas only qualitative requirements can be imposed. Finally, the interdependencies of performance requirements may not be comprehended resulting in exclusionary requirements. (Foliente, et al., 2005).

Furthermore, there are concerns regarding the situation of not relying on building codes. The code-based methods often deliver a cost-effective and a reliable solution, in other words, the performance of code-based methods is not thought to be a concern. If a transition to performance-based buildings (PBB) is made, routine designs become very laborious due to the burden of proof on the contractor about a building’s performance. (Sexton & Barrett, 2005). Yet, this very aspect can be regarded as the essence of PBB: Buildings can fulfil all the energy related building codes and meet low-energy certification requirements while performing poorly energy-wise. The energy consumption of Leadership in Energy and Environmental Design -certified buildings deviates by average more than 25% from design projections (Turner & Frankel, 2008, p. 32), while Finnish national building codes have not been observed to cover pressure differences over the building envelope adequately (Lindgren, 2012, p. 37; Katainen & Vähämaa, 2015, p. 90). To achieve a higher level of energy performance, the ends must gain importance over means. Also with PBB being widely accepted, maintenance contracts could specify the end result such as IEQ rather than defining the operation and maintenance work content itself (Ihasalo, 2012). Still, a prerequisite condition for PBB is that actors throughout the supply chain are able and interested in innovating individually and collectively, which may not be the case (Sexton & Barrett, 2005). In reality, sometimes innovation might mean the cannibalization of existing business which leads to reluctance to invest in such (Henderson, 1993).

Generally, the performance of a building is a multidimensional concept. As such it can be approached differently by each stakeholder (Ihasalo, 2012). From user’s viewpoint the main aspects of building performance may regard the satisfactory state of indoor microclimate and the functionality of space, whereas the owner may be more concerned with maintenance costs and energy consumption. Therefore it is essential to find ways to improve the performance of the building for all the actors rather than focusing on just one field of performance. For example advocating energy performance in an inappropriate manner could jeopardize the longevity of the tenancy agreement through degraded indoor environment. Depending on perspective, performance can then be evaluated quantitatively or qualitatively. Therefore it can be assessed by physical measurements, findings of an evaluator or surveys (Ihasalo, 2012).

Out of the performance indicators listed by Lavy et al. (2010) in Table 2.1, energy performance can be indicated by operating costs, utility costs, building maintenance costs, maintenance efficiency, building physical condition, health and safety, indoor environmental quality (IEQ) and resource consumption. More specifically, in this thesis the energy performance of a building is approached from three perspectives: 1) energy performance of building services equipment, 2) energy performance of equipment control and 3) quality of the indoor environment. Building automation systems (BAS) are a useful tool in evaluating performance in these dimensions, as they produce a large amount of continuous physical measurements.

Table 2.1 Performance indicators listed by Lavy et al. (2010).

Financial indicators	Functional indicators	Physical indicators	Survey-based indicators
• Operating costs • Occupancy costs • Utility costs • Capital costs • Building maintenance costs • Grounds-keeping costs • Custodial and janitorial costs • Current replacement value • Deferred maintenance, and deferred maintenance backlog • Capital renewal • Maintenance efficiency indicators • Facility conditions index • Churn rate and churn costs	• Productivity • Parking • Space utilization • Employee or occupant's turnover rate • Mission and vision, and Mission Dependency Index • Adequacy of space	• Building physical condition • Property and real estate • Waste • Health and safety • Indoor environmental quality • Accessibility for disabled • Resource consumption • Security • Site and location	• Customer/building occupants' satisfaction with products or services • Community satisfaction and participation • Learning environment, educational suitability, and appropriateness of facility for its function • Appearance

2.2 Improving the energy performance of buildings

In this thesis, the energy performance of buildings is approached from three different perspectives: 1) energy performance of building services equipment, 2) energy performance of equipment control and 3) quality of the indoor environment.

2.2.1 Energy performance of building services equipment

The proper functioning of building services equipment, particularly the HVAC systems, is an important energy performance criterion because it determines if a satisfactory indoor environment is even possible to attain economically. The energy performance of equipment can be ensured by monitoring key figures that depict whether the piece of equipment is operating optimally, and by having fault detection functionalities in place that monitor the processes within the equipment. These key figures can be target figures provided by suppliers or derived performance metrics, while fault detection systems range from simple threshold alarm functions to more complicated fault detection and diagnostics (FDD) tools.

Unfortunately "… most buildings do not work properly" (Wang, et al., 2013, p. 1382). Sometimes even simple abnormalities of the building services equipment such as simultaneous heating and cooling go long undetected and waste energy (Wang, et al., 2013). To detect and reduce such abnormalities, reviewing and benchmarking key figures can be an efficient approach. Comparing specific heating and cooling energy consumptions of properties should reveal if one of them had unsynchronized heating and cooling control. To extrapolate the idea of utilizing data to monitor performance, Ihasalo (2012) developed a HVAC performance metrics system that relies heavily on data generated by the BAS. For example in an air handling unit (AHU) the system measures the energy performance of time schedule and heat recovery, and the operational performance that is constructed by the system availability, pressure and temperature.

The metrics are based on performance targets that can include one or two target values. With one target value the metric is the actual measurement divided by the target value and with two target values it is the time when the measurements are between minimum and maximum values divided by the total measurement time. The energy performance of the time schedule of an AHU is based on comparing the schedule with an optimal one, while the performance of heat recovery is based on comparing the measured heat recovery efficiency ratio to a target value provided by the supplier. This measured efficiency ratio can be calculated with Expression 1. (Ihasalo, 2012, p. 121).

$$\eta = \frac{T_{22} - T_{21}}{T_{11} - T_{21}} \tag{1}$$

where

η = heat recovery efficiency ratio
T_{22} = supply air outlet (°C)
T_{21} = supply air inlet (°C)
T_{11} = exhaust air inlet (°C).

The operational performance metric is determined by the product of availability, pressure and temperature as shown in Expression 2 (Ihasalo, 2012, p. 124). Again an example of an AHU is used. Availability of the system is calculated by dividing the actual running time with the total duration of the time schedule. The pressure factor, that depicts whether the system is supplying the right amount of air into the building, is calculated by dividing the time period during which the pressure is within 5% of the pressure set point with the total measurement time. Finally, the temperature factor is calculated by dividing the time period during which the temperature is within 0.5 °C of the temperature set point with the total measurement time. (Ihasalo, 2012).

$$HVAC\ system\ metric = Availability \times Pressure \times Temperature \tag{2}$$

Another useful figure to derive metrics from could be the specific fan power (SFP) that represents the electric efficiency of a ventilation system, an AHU or a fan. According to the National Building Code of Finland, the SFP of forced supply and exhaust ventilation systems must not exceed 2.0kW/(m^3/s), which is the total electric power consumed by all of the fans, frequency converters and power control devices of the building divided by the design supply or extract air flow, whichever is the largest (Finnish Ministry of the Environment, 2012b). The SFP figure for an AHU is calculated according to Expression 3, and for a fan it is the electric power divided by the air flow (Muhli, 2012, p. 25). The target SFP figures are provided by the supplier.

$$SFP = \frac{P_{supply} + P_{exhaust}}{q_{max}} \tag{3}$$

where

SFP = specific fan power kW/(m^3/s)
P_{supply} = electric power of the supply fan (kW)
$P_{exhaust}$ = electric power of the exhaust fan (kW)
q_{max} = the maximum of the supply and exhaust air flows (m^3/s).

On the other hand, fault detection systems are an important part of ensuring energy-efficient operation of equipment. Those systems reduce the energy, water consumption and maintenance costs and improve the quality of the indoor environment and safety of users. The key to all this is the early detection of faults, which makes it possible to plan maintenance work beforehand and schedule it so that the inconvenience to users is minimized. (Hyvärinen & Kärki, 1996). Traditionally, fault detection in building automation systems is based on alarm limits on control variables. Such a system monitors for example the supply water temperature of an air heater, and if an upper threshold value is exceeded an alarm on the event is generated. When deciding upon the alarm limits there inevitably is a trade off with probability of false alarms and fast detection of irregularities. FDD tools on the other hand are more versatile. These tools collect data from a number of control variables and analyze it in order to detect and diagnose the reasons for abnormalities. By using data more extensively FDD tools can detect problems that simple threshold checks cannot. (Ihasalo, 2012).

The main methods in automatic FDD are top-down and bottom-up approaches, model-based methods, knowledge-based methods and process history –based methods. Top-down and bottom-up describe the direction of reasoning. (Ihasalo, 2012). A top-down reasoning process could start from elevated energy consumption of the building, lead to large amounts of energy consumed by the heating system and end with the detection of a problem in the heat recovery unit. Model-based methods rely on modelling mathematically the physical processes involved and comparing predicted measurements to the actual ones, while knowledge-based methods rely on expert if-then rules (Ihasalo, 2012). Obviously the application of these two methods is laborious. Process history –based methods use large amounts of historical data and categorize it to resemble different faults and normal operation (Ihasalo, 2012). The challenges related to the adoption of FDD systems include small incentives due to minor benefits with sometimes significant installation time and cost, inadequate sensor infrastructure and robustness of the tool (Ihasalo, 2012).

2.2.2 Energy performance of equipment control

Automatic and energy-efficient equipment control is an important factor of energy performance: Even though people are willing to conserve energy due to environmental and financial motives (Kim, et al., 2008), changing long-term behavior towards energy-saving can be difficult (Marchiori & Han, 2010). As a fundamental element in energy efficient control of artificial lighting, heating, ventilation and air-conditioning, user activity and behavior have long been used (Nguyen & Aiello, 2013). When a space is not occupied, the cooling set point can be elevated, heating set point lowered and lighting level set to minimum to conserve energy (Chen, et al., 2009). Another interesting approach into energy conservation is prioritizing passive cooling, heating and illuminance whenever possible by little energy consuming methods such as adjusting motorized shades and remotely opening windows (Kolokotsa, et al., 2009). Both methodologies fall into the category of *demand-based control* that is based on the principle that “for any given system, the energy use is minimized if the supply exactly matches the demand” (Gruber, 2012, p. 2). For example in artificial lighting control this could mean that in addition to occupancy, the controller takes into account the amount of available daylight (constant luminance control), or that the amount of fresh air supplied is controlled by occupancy and the CO_2 concentration of indoor air.

Yet, the objective of energy performance inevitably risks user comfort through degraded IEQ when occupancy detection is inaccurate. The often used motion-detection sensors are poor at detecting occupancy (Lu, et al., 2010): It is not unusual in areas where motion-controlled lighting is adopted that the workers find themselves waving their hands in the air in order to get the lighting switched back on. Therefore, researchers have developed more accurate methods in detecting user activity based on sensor data. These methods are presented in Chapter 3.5.3.

Simulation-based energy savings potential of user activity recognition based solutions can however be misleading. In a review carried out by Nguyen & Aiello (2013) the energy saving potential of solutions for HVAC systems, artificial lighting and plug appliances was charted. It was observable that the potential savings from actual experiments ended up being much lower than in simulations. Thus, real-world testbeds should be used to confirm saving potential of initiatives, as simulations are often based on a significant amount of idealization.

The challenges in demand-controlling HVAC systems mostly relate to the delay of conditioning and maintaining a decent indoor air quality (IAQ). The estimated energy savings through occupancy-based control of HVAC systems range from 10% to 40% (Nguyen & Aiello, 2013). What makes saving energy without loss of comfort problematic with the heating and cooling functions is that the conditioning of a room must commence before it is occupied (Erickson, et al., 2009). In research, this aspect is managed with various ways for different building types, sensor networks and activity recognition methods. Essentially, all the methods attempt to overcome the indeterminism of human behavior. On the other hand, the ventilation of buildings is important to manage well in order to reduce the energy load caused by it while maintaining a decent level of IAQ. By reducing the ventilation rate, however, there is a risk of introducing a so-called *sick building syndrome* to the users if the IAQ was to degrade. Demand-controlling ventilation systems are an efficient way to manage the pollutant concentration of indoor air energy-efficiently. (Dounis & Caraiscos, 2009). In such systems the ventilation rate is adjusted in real-time to keep the CO_2 concentration acceptable.

The concepts in efficient lighting control are occupancy-detection, controlled spaces and daylight harvesting. The potential savings achievable with the related solutions range then from 33% to 58% (Singhvi, et al., 2005; Delaney, et al., 2009). The concept of controlled spaces means that a large area can be partitioned into smaller, independent sections that can be managed separately, whereas daylight harvesting is simply optimizing the artificial lighting level with respect to the amount of natural light (Delaney, et al., 2009, p. 62). With innovative sensing algorithms, the energy consumption of the sensor networks can also be managed efficiently: Singhvi et al. (2005) developed an active sensing algorithm that enables the prediction of the daylight intensity throughout the day with just one observation per sensor. Overall, visual comfort is easier to satisfy than thermal comfort due to the immediate effect of the appliance on the surroundings. However, a challenge with lighting appliances, especially fluorescent lighting systems is considering the adverse effects of continuous state transitions. It is not a good idea to switch the lights on or off every time users enter and leave a room, as this would result in a shortened lifetime of the lighting equipment. The breakeven with the user absence period is estimated to be around 5-10 minutes. (Harris & Cahill, 2005). Another challenging area is the detection of glare in daylight harvesting systems (Kolokotsa, 2007).

Research with quantified energy savings potential regarding plug loads is not as extensive as with the other study areas. A prototype system developed by Marchiori & Han (2010) that controls irregularly used appliances based on occupancy, suggested energy savings between 7.1-14.6%. There are also second order effects introduced by running and idle appliances as they generate heat which in turn stresses the ventilation system (Harris & Cahill, 2005). Yet, what differentiates the management of plug loads from HVAC and lighting systems is the fact that appliances such as TV, microwave or printer may not be required to be on stand-by even if a room is occupied. Also a PC might experience a lot of idle periods during its operation. Therefore effective power management requires information on the user behavior in addition to his or her location (Harris & Cahill, 2005). When the power management system is unable to correctly predict the user's behavior it is possible that energy savings fade due to costs related to the state transitions of devices. These costs include the extra energy consumed during start-up and the reduced lifetime of the device (Harris & Cahill, 2005).

2.2.3 Quality of the indoor environment

Energy performance cannot be observed separately from IEQ. A number of standards are available that present guidelines for evaluating IEQ with physical measurements. Generally, indoor environments can be assessed by three parameters: thermal comfort, indoor air quality and indoor visual comfort. However, the American Society of Heating, Refrigerating, and

Air-Conditioning Engineers (ASHRAE) presents guidelines to measure IEQ even more comprehensively. ASHRAE guidelines cover measuring energy, water, IEQ, thermal comfort, indoor air quality, lighting and acoustics performance of commercial buildings. These guidelines are then divided into three protocol levels: basic, intermediate and advanced according to the accuracy of the metrics. (Hunn, et al., 2012).

On the other hand, in Finland three categories for indoor environment are used: S1, S2 and S3. S3 is satisfactory, S2 good and S1 a very good indoor environment. These categories are similar by description to the ones presented in SFS-EN 15251. In S1 indoor environment the operative temperature should be kept within 0.5 °C of the target value for 95% of the time the building is occupied. Also maximum and minimum indoor temperature limitations are imposed for different seasons, and the temperature must be adjustable by 1.5 °C by building users. The general principle is similar in S2 class, however a deviation of 1.5 °C is allowed for 90% of the time of occupancy. (Ihasalo, 2012). The classification also includes criteria for indoor air quality, acoustics and lighting that are specified for example in RT 07-10946 (Rakennustieto, 2008).

Thermal comfort can also be assessed differently from Finnish guidelines. It is influenced by temperature, humidity, indoor air velocity radiant temperature, metabolic rate and insulation of the clothing. (Kolokotsa, 2007). With quantified information on these parameters, a Predicted Mean Vote (PMV) index is calculated. This index is also introduced in EN ISO 7730:2005 (ISO, 2005; Oancea & Caluianu, 2013). This thermal environment can also be categorized into one of four categories of SFS-EN 15251 according to the variance of PMV (SFS, 2007). Indoor air quality is controlled by reducing pollutants or by the ventilation system. The principal pollutants in indoor air are CO_2 and volatile organic compounds. Indoor visual comfort is determined by illumination, brightness, contrast, glare and psycho-physiological aspects such as quantity, distribution and quality of light. (Kolokotsa, 2007).

3 Development of building automation systems to improve energy performance of buildings

3.1 Overview on building automation systems

Building automation systems (BAS) have a large influence on the energy performance of buildings by automating energy-saving functions such as switching lights off or adjusting ventilation rates. A BAS is a computerized control system that monitors, controls and manages building services such as HVAC systems, lighting systems and electrical systems (Shengwei, 2009). The main functions of BAS include switching equipment automatically on and off for example based on scheduling, observing and optimizing the operation of building services, collecting data on environmental conditions, providing information on energy consumption, managing electrical loads and enabling remote control of systems. These functions result in improved energy efficiency, substantial amounts of data on building performance and the possibility to centralize facility management operations. (Månsson & McIntyre, 1997). Thus, BAS is a central platform for improving energy performance with data.

There are many names for this kind of a system that essentially controls equipment in buildings: BAS, building energy management system (BEMS), energy management control system, building management system and facility management system (Ihasalo, 2012). The different expressions highlight different perspectives on the systems: For example BEMS communicate and use information at a larger scale than other systems to apply more developed algorithms in order to optimize the energy use (Månsson & McIntyre, 1997). One can also emphasize the management of user comfort along with energy performance by labelling the system as a building energy and comfort management system.

3.2 Traditional system architecture

The classic architecture of BAS does not strongly support decentralized execution of smart functions that are based on exploiting data collected elsewhere in the system. According to Soucek & Loy (2007) building automation systems traditionally have three levels in their hierarchy: field level, automation level and management level. The interaction with physical processes occurs at field level: Sensor data is collected by direct digital control (DDC) stations, which also send data to actuators. Actuators can be connected to DDC stations directly or through a bus communication system (fieldbus), which connects sensors to actuators. Examples of common fieldbus technologies are LonWorks, Konnex and BACnet. At automation level, data from field level is used to form logical connections and control loops. Server stations and building controllers implement automatic control sequences to operate the actuators appropriately. The server stations can also prepare field-level data for storing. The automation level entities are connected to the field level via the automation network, which can also use the LonWorks, KNX and BACnet technologies. At management level, servers monitor the overall functioning of the BAS. This task includes storing historical data for trending services, producing reports, observing system operation, alarming on malfunctions and enabling parameter-based operation such as scheduling. The management network uses Internet Protocol or other high-bitrate media. (Soucek & Loy, 2007). The hierarchical model of BAS is presented in Figure 3.1.

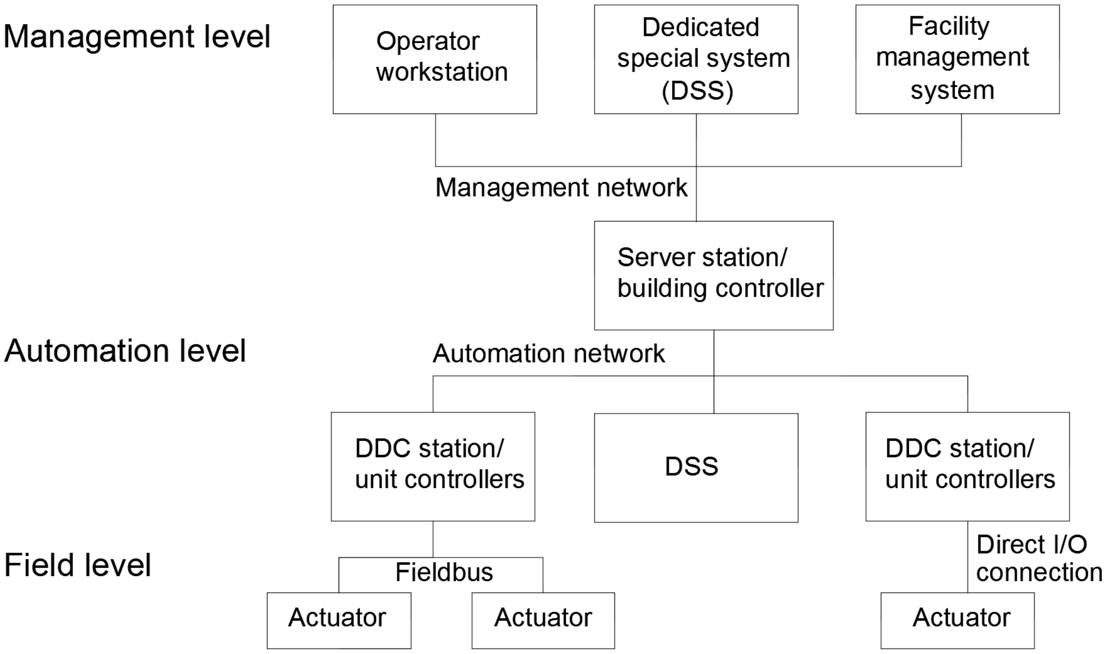


Figure 3.1 The hierarchical model of BAS. Based on Soucek & Loy (2007, p. 82).

3.3 Development of system architecture

3.3.1 Development in the context of Internet of Things paradigm

BAS are the solution pursuing the value drivers of Internet of Things (IoT) in buildings context. Also the development of BAS seems to aim towards similar goals to the IoT paradigm. IoT is about the ability to connect at any time and from anywhere to anything (Atzori, et al., 2010). Conceptually IoT consists of three aspects on smart objects: Anything is identified, anything communicates and anything interacts (Miorandi, et al., 2012). The value drivers of IoT are automatic proximity and sensor triggering, automatic product security and extensive user feedback. These factors support the development of applications belonging to the categories of *information and analysis* or *automation and control*. Information and analysis applications apply to tracking, situational awareness and sensor-driven decision analytics whereas automation and control concerns process optimization and optimized resource consumption. (Coetzee & Eksteen, 2011).

Both of the application categories of *information and analysis* and *automation and control* are highly relevant in improving the energy performance of built environment and are mainly covered by building automation systems. However, the conceptual aspects on smart objects are not met in a traditional model. Even though all the control points are identified, not everything can communicate or interact. Therefore, it may be more appropriate to involve the concept of a Cyber-Physical System (CPS) rather than IoT with a traditional BAS. CPS integrates computation, communication and control with emphasis on closed-loop information exchange and feedback while IoT highlights networking and interconnectivity of all things (Ma, 2011). However, the next described development of the BAS architecture towards a service-oriented network model seems to aim towards such.

3.3.2 Development towards a service-oriented model of building automation

In order to allow for more complicated building services in building automation, more data needs to be made available to subsystems of building controllers. Also the aspiration towards developing reliable systems calls for more decentralized services, which are an effective way to reduce single points of failure. Therefore the former layers and boundaries of the hierarchical model are not appropriate in a service-oriented model of BAS. (Soucek & Loy, 2007).

Soucek & Loy (2007) present four aspects in this integration: flat network model, service distribution, protocol convergence and new protocols to integrate BAS with IT systems. In a flat network model the same network domain may include automation, management and the fieldbus level. This means that special fieldbus media are tunnelled through control network/IP routers to IP-based transport, thus bringing the I/O points directly to management level. By gaining access to data point services of field devices from management-level systems, the execution of those services can be done closer to the field. Thus the services are executed in smaller autonomous units rather than in a building controller. Those data services include browse, data point, trending, alarming, scheduling and security. Conversely, the area of protocol convergence is focused on enabling communication between systems in different control network technologies. Traditionally such has been achieved with gateways, but the matter can also be managed by including other network protocol stacks in devices. The BAS integration with IT systems on the other hand is driven by demand for Web-based interfaces. Setting up a Web service interface requires servers, and to avoid a single point of failure it is suggested that there could be small Web servers distributed in the field level in room controllers or control network/IP routers. (Soucek & Loy, 2007).

3.4 Energy performance with available data

3.4.1 Traditionally collected data

Building automation systems need large amounts of data to monitor and operate processes of HVAC systems. Sensors measuring temperature, pressure and humidity are necessary as parts of control loops that produce actuator output for each HVAC process state. These actuators can be for example valves in heat exchangers and pipework, pumps with frequency converters and fans. To monitor a process, it is essential that the BAS also makes the control signal of each actuator available for analysis together with physical measurements.

3.4.2 Deployment of Internet of Things related technology

To increase the energy performance of buildings beyond properly operating equipment, more contextual information is needed. This information can be acquired with IoT related technologies that enable identification and sensing. For example, lighting can be switched off when sensors do not detect user activity and user-preferences can be retrieved with tag identification procedures. The deployment of these technologies in existing buildings has been greatly facilitated by the introduction of low-cost wireless sensing technologies. Without the need for additional wiring for each device the installation costs decrease, and wide deployment is more likely to be feasible (Agarwal, et al., 2010).

Central technologies of IoT include radio-frequency identification (RFID) and wireless sensor networks (WSN). RFID technology is based on tags and readers. Every tag possesses a unique identifier which is transmitted to the reader when a reader sends a query for tags in the environment. The tag can be very small and it often resembles an adhesive sticker. Passive tags do not have their own power source whereas active ones do, which obviously affects the radio signal coverage. Passive tags get their power from the query signal through induction. All in all, RFID technology makes it easy to track objects without seeing them. (Atzori, et al., 2010).

On the other hand, sensors are more suitable when context-awareness is required. With wireless technology it is easy to reconfigure and extend sensor networks, and position the sensors in places where it previously has not been possible because of the aesthetic, conservatory or safety issues related to the cabling (Reinisch, et al., 2007). Challenges associated with wireless technology include supplying power, managing with the communication range, dealing with problems in data exchange and ensuring the security of information (Ihasalo, 2012). When choosing the type sensors of a wireless sensor network, important factors to consider are practicalities such as cost, size and ease of use, data quality, ethical issues, data type and level of intrusiveness (Keeling, et al., 2013).

A hybrid approach to these two technologies is a passive RFID sensor network, where the sensing and computation devices are in fact RFID tags while the readers are data sinks and the power supply of the network (Atzori, et al., 2010).

3.4.3 Open data

To accumulate data that could be used for control purposes, open data programs deliver a cost-effective opportunity. Open data is available for the use of everyone and may freely be used to improve the energy performance of buildings. The definition of open data and content is that it "…can be freely used, modified, and shared by anyone for any purpose" (Open Definition, 2016). Generally, the aim of the open data movement is to make data, especially publicly acquired, obtainable via Web in electronic form (Gurstein, 2011).

3.5 Development in building automation control systems

3.5.1 Overview of building automation control

The task of a control system is to decide the appropriate output for an actuator to meet the predefined objectives based on its input data. When a control task is simple also a more straight-forward control method is appropriate. On the other hand, whenever there is a non-linear process to be optimized and an abundance of sensor data to be analyzed, also a more sophisticated control method may be required.

The controlling task can be divided to sub-tasks that all are performed differently. For example the conventional control methods introduced next are mainly associated with process control: The output is adjusted based on an input signal that can be the error from a target value. Other control methods introduced below relate in part to process control, but also to increasing contextual awareness based on sensor data. The task for context-based control can then be to judge the demand for process control.

3.5.2 Conventional control

Here, proportional, integral and derivative (PID) and adaptive control are regarded as conventional, as those are common in a BAS. In a proportional control system, the input is the deviation from the target value: The error between indoor temperature and the temperature set point, for example. The main idea of proportional control is to set a high output when the error is large, and a low output when the error is small. Proportional control cannot completely eliminate offset without instability, however. This offset is the steady-state deviation from the target value. (Shengwei, 2009).

To tackle this issue it is possible to add integral action into the control system. The principle of integral control is illustrated in Figure 3.2. With such action, the control system reacts to an accumulating steady-state error by altering its output until the error has been eliminated, given that the working condition and disturbances remain the same during this process which is not often the case. The weakness of integral control is its slow responsiveness to sudden and large errors. (Shengwei, 2009). These two first terms of PID control (proportional and integral) are the most widely used combination in building automation control.

To enable fast responsiveness, derivative action can be introduced in the control loop. Derivative control takes into account the rate of change of error in its response, while it has no effect on steady errors. (Shengwei, 2009). This last term of PID control is less common in building automation control, as it requires fast responsiveness from the controlled process itself. However, it can be used for example in the control of service water.

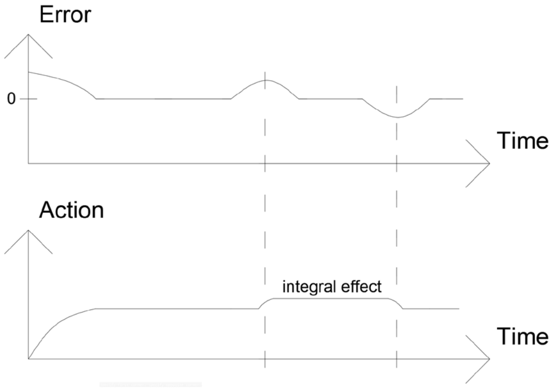


Figure 3.2 Principle of integral control. Based on Shengwei (2009, p. 121).

An adaptive controller can be regarded as “a controller with adjustable parameters and a mechanism for adjusting the parameters” (Shengwei, 2009, p. 132). Typical adaptive control applications are auto-tuning, gain scheduling, self-tuning regulator, model-reference adaptive system and stochastic adaptive control. Only auto-tuning is briefly introduced to shed light on the principles of adaptive control. The main idea of relay auto-tuning is to create a system that is able to adjust the parameters of a PID controller every time tuning is demanded. When the tuning is demanded by operating a switch, relay feedback is enabled and the PID controller is disconnected from the process. After the relay feedback stabilizes the system, the PID parameters are computed and the controller resumes normal operation. (Shengwei, 2009).

3.5.3 Occupancy detection methods

Occupancy detection methods range from motion-detection to probabilistic models. In occupancy detection the most common method is to use a passive infrared (PIR) sensor that is cheap, consumes little energy, produces data that is easy to interpret and does not enable privacy violations. However, PIR sensors have their limitations: When a PIR sensor does not detect movement, it is difficult to deduce based on PIR sensor data alone whether the space is unoccupied or the user is remaining still. Therefore many innovative and complementary sensing ways are developed.

As a very straight-forward approach Agarwal et al. (2010) installed a magnetic reed switch door sensor. By doing so, it became much easier to isolate different occupancy transition scenarios with the door opening and closing, thus improving accuracy of occupancy detection. Still, there were some scenarios that the system could not infer correctly. Other method introduced by Hagras et al. (2004) is to use pressure pad sensors on furniture to detect people sitting, or installing software that informs the control system about user activity on computers.

A camera in comparison to a PIR sensor produces more comprehensive information on the state of a space. Erickson et al. (2009) installed a wireless camera sensor network that uses an algorithm to classify every pixel of a frame into background, object or shadow. Then the object pixels are merged to a blob that is tracked throughout the frame. The main goal of the study was to quantify the number of occupants in rooms as an input for HVAC system control. (Erickson, et al., 2009). With the use of cameras, however, ethical issues and a feeling of intrusiveness must be considered. Clear principles for data collection, accessibility and usage should then be defined and applied to avoid conflicts.

Radio-frequency identification (RFID) technology can also be used to accurately locate people in buildings (Keeling, et al., 2013). The use of such technology requires the occupants to keep tags with them in order to get the rooms they occupy conditioned, which means that the system causes inconvenience for example when the tag is forgotten or when visitors do not possess any. A strong advantage of RFID-based occupancy detection is that the users and thus their preferences can be identified and stored in a database, enabling tailored service (Chen, et al., 2009).

As a comprehensive occupancy detection method, Dong & Andrews (2009) present a procedure for constructing an occupancy model from sensor event patterns. They experimented with a conference room that was equipped with acoustics, illumination, motion, CO_2, temperature and relative humidity sensors. These sensors would obviously produce a lot of data during their deployment. First step of the model development was to use a data mining technique called Episode Discovery, which filters the most notable and frequent event sequences. Some of these sequences can then be identified as meaningful events, such as someone entering or leaving the room. Next, all the sequences are treated as states in a semi-Markov model, so that they form a network of transition probabilities between states, with each state having an expected duration. (Dong & Andrews, 2009). The network is illustrated in Figure 3.3. In the figure X~(*a*) is the expected duration *a* of a state and the number below a transition is the probability of the transition. The letter sequences depict sensor event patterns: G denotes users entering the room, A, B and H notate different sensor sequences that indicate a user staying in the room, D and I indicate users leaving the room and F means that the HVAC is running.

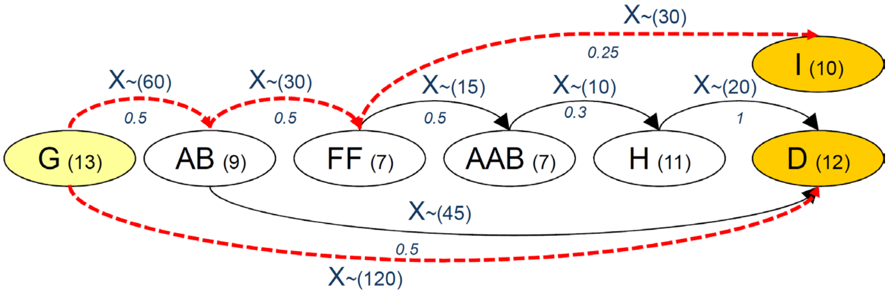


Figure 3.3 Semi-Markov model of discovered patterns (Dong & Andrews, 2009, p. 1448).

There is great strength in such an approach, as it tackles issues that purely motion-detection based systems cannot. This detection method reduces the likelihood of the system being fooled into deducing that the room is empty when it is not, or reacting to events that would not require conditioning of the space. For example the system would not start conditioning the space when someone entered the room just to make a phone call, whereas it would do so when a meeting commenced. (Dong & Andrews, 2009).

3.5.4 Model-based predictive control

Under a range of idealized assumptions that their study was based on, Gyalistras et al. (2010) found predictive control automation systems especially promising when it comes to saving energy. Even though the saving potential is only a theoretical estimation, the authors are confident that their assumptions are on the conservative side. The importance of prediction seemed to increase the higher the solar heat gains were on the building in their several thousand simulations. (Gyalistras, et al., 2010).

Model predictive control or model based predictive control (MBPC) is an algorithm that is used to control dynamic systems by predicting changes in dependent variables. The goal of the algorithm is minimizing a so-called cost function for a given time horizon. The cost function depicts the interrelatedness of system inputs and overall objectives in terms of acceptable boundaries. A strong advantage of the algorithm is using a receding horizon strategy: The calculations to predict the future trajectory of the system are based on the current state of the system which keeps shifting forward.

Freire et al. (2008) conducted simulations with MBPC strategy, where indoor temperature and relative humidity were used to determine the appropriate output for a HVAC device. The challenge was to optimize energy consumption without violating the thermal comfort sensation of occupants with respect to a psychometric chart or predicted mean vote index. In their simulations they were able to reduce energy consumption in varying weather without violating thermal comfort boundaries once.

Similar benefits were observed by Kolokotsa et al. (2009). In addition to temperature and relative humidity, they included observing CO_2 concentration and illuminance in their predictive control model. The study environment was a 125m^2 laboratory, where they taught the system the relationships between the current state of the space and environmental factors such as outdoor temperature, window opening or air-conditioning operating. As a result, the system was able to closely predict the development of a given set of environmental parameters. Energy-optimization was performed by a minimization of a weighted function that resembles the electricity consumption of control measures. Over 90% of users assessed the overall comfort good or very good. (Kolokotsa, et al., 2009).

3.5.5 Artificial intelligence based control

Artificial intelligence (AI) techniques are useful when the objective is to integrate aspects of learning, reasoning and optimizing into control. There are several artificial intelligence (AI) techniques, but only artificial neural networks, fuzzy logics and genetic algorithms are introduced here. Describing the AI aspect of information processing to this extent is considered adequate, as the techniques focus on separate areas of intelligence and they are extensively used in the related research. In human-intelligence terms it can be said that artificial neural networks relate to learning, fuzzy logics relates to capacity of reasoning with uncertainties and genetic algorithms relate to improving performance based on previous experience (Oancea & Caluianu, 2013).

Artificial neural network (ANN) is a technique that tries to simulate the learning process of human brain. ANN models the input-output relationships of a system based on history data and exploits this ability to predict the outcomes of new combinations of inputs (Kalogirou, 2006). An application of an ANN could be to use it to predict the optimum moment to start heating a building after the night setback in order to have the indoor temperature at a comfortable level by 8 o'clock in the morning. Some of the input parameters in this case could be the outside air temperature and wind speed, while the output of the ANN will be the indoor temperature. (Oancea & Caluianu, 2013). Moreover, ANN is a so-called black box model, meaning that it does not need any information about the system it is learning (Kalogirou, 2006). In other words, ANN is able to learn causalities between given inputs and outputs within a system without any other knowledge about the system. An illustration of an ANN structure is presented in Figure 3.4.

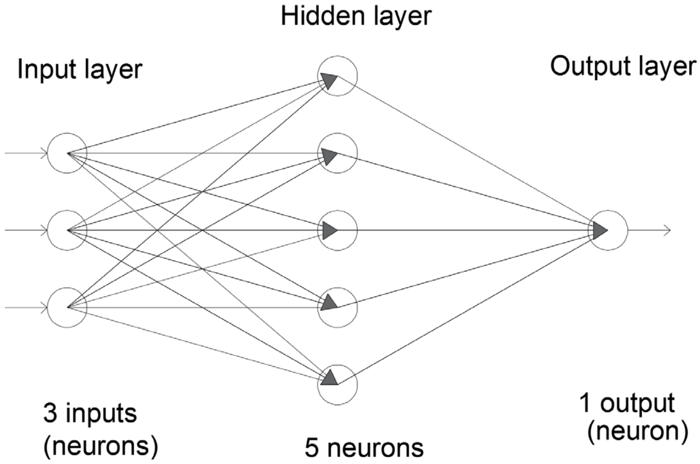


Figure 3.4 An artificial neural network. Based on Oancea & Caluianu (2013, p. 99).

The neural network has three layers of neurons: an input layer, a hidden layer and an output layer. A neuron is a basic element of the network that processes its input with summation and activation functions to produce its output, which is the input of the neurons in the next layer. Additionally, each input and output have a corresponding neuron. The amount of hidden layers and neurons in them is problem-specific. Based on training data the network then learns the relevant relationships between neurons and determines the corresponding weights of every neuron's output. The most common learning algorithm is called the Back-Propagation algorithm, which reduces the error of the network by varying the weights along its gradient until an acceptable tolerance is reached. (Kalogirou, 2006; Oancea & Caluianu, 2013).

In order to solve problems with ANN one must select suitable learning rate, number of hidden neurons and activation functions. What makes ANN a strong technique is that it is fault tolerant, robust and immune to input noise. (Kalogirou, 2006). Still, there are some challenges related to the technique: The learning process of ANN needs reliable training data and the self-learning algorithms are limited to their experience (Kolokotsa, et al., 2009). Therefore the system cannot take intelligent action if it has not *experienced* the situation before.

Fuzzy logics is a powerful approach when managing systems with humanistic aspects (Kolokotsa, 2007). It is a way to get the reasoning process of computers closer to the way human brain does it (Oancea & Caluianu, 2013). Fuzzy logics requires some computational tricks to illustrate the ambiguity of thinking, but as a great advantage the inference logic is very easy to understand and evaluate. Fuzzy logic consists of fuzzy rules and fuzzy sets. Fuzzy sets are the input of the reasoning process, which is in the form if-then as fuzzy rules. Every item of a fuzzy set belongs to that set to a degree, and the rules take those partially true facts and determine to what degree they are true (Oancea & Caluianu, 2013). This degree of membership is determined with membership functions. These functions are chosen based on their perceived fit on the fuzzy set in question. An example of fuzzy membership functions for categories of thermal environment is illustrated in Figure 3.5. In the figure the horizontal axis (thermal sensation) corresponds to PMV index values. With such membership functions, thermal sensation index of value +2 belongs to the fuzzy set of hot with a degree of 0.4 and to the fuzzy set of warm with a degree of 1 (Oancea & Caluianu, 2013). These degrees of memberships within fuzzy sets are the foundation of the fuzzy reasoning process.

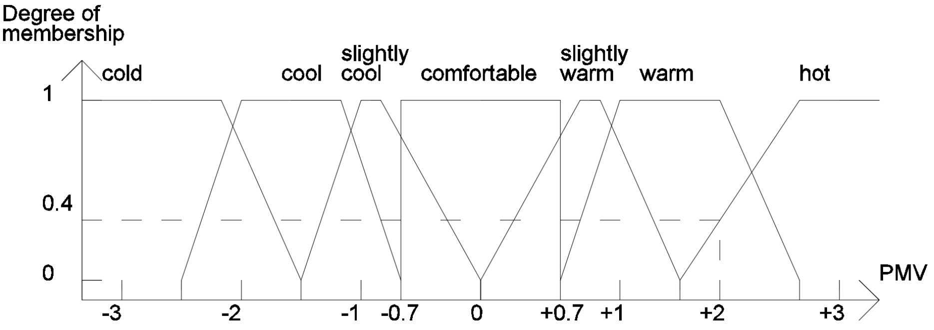


Figure 3.5 Fuzzy membership functions for categories of sensation of thermal environment. Based on Oancea & Caluianu (2013, p. 97).

To clarify the concept of fuzzy logic, consider the following example. A cooler is equipped with a temperature sensor, and the comfort temperature is considered to be 21°C. A measured temperature of 28°C could then belong to a predefined fuzzy set of warm with a membership degree of 0.5, to the set of hot with 0.8 and to the set of comfortable with a degree of 0. The deviation from the temperature set point and changes in cooler output would then also be given linguistic representations. A fuzzy rule could state that if *the temperature is hot and the deviation is growing* then *increase the cooler output*. Now in this case the cooler would add more output the warmer it is and the more the deviation is growing. The strength of such logic is that the controlling rules can contain ambiguity and cover many different situations (Paiho, et al., 2002).

Genetic algorithms (GA), which are a form of evolutionary computing, are good at optimizing solutions. The algorithm mimics the selection process of nature by producing an initial population of chromosomes (solutions) and evaluating their fitness. The best candidates are selected as *parents* and their *offspring* is generated by recombination of their parents' qualities, and the process goes on and on until the required fitness is achieved. The fitness of the chromosomes is assessed with a fitness function and an objective function. Also a number of constraints can be imposed on the selection process. (Oancea & Caluianu, 2013).

Let us consider an example of optimization with genetic algorithms. In energy consumption and thermal comfort management the objective function can be defined with the predicted mean vote index and a formula connecting energy consumption with the HVAC operation. Whenever the room temperature set point is changed, the mean radiant temperature (radiators), air velocity and relative humidity (humidifiers and ventilation system) need to be optimized with respect to the comfort index and energy consumption. This is when the GA starts the evolutionary computation and evaluation of candidate solutions. Ultimately the algorithm produces the optimum combination of system outputs to achieve the best level of thermal comfort with the least energy consumption. (Oancea & Caluianu, 2013).

3.6 Summary of the theoretical background

Based on the theoretical background, the relationships of energy performance and available data are illustrated in Figure 3.6 By reinforcing aspects of open data, BAS and IoT technology, the ability of building service equipment to achieve a higher level of equipment performance, control performance and indoor environmental quality is enhanced. This improvement is not necessarily completely attributable to BAS, but also to a property manager working with the BAS. Also instead of relying exclusively on sensor data to evaluate IEQ, feedback could be collected from building users with IoT technology.

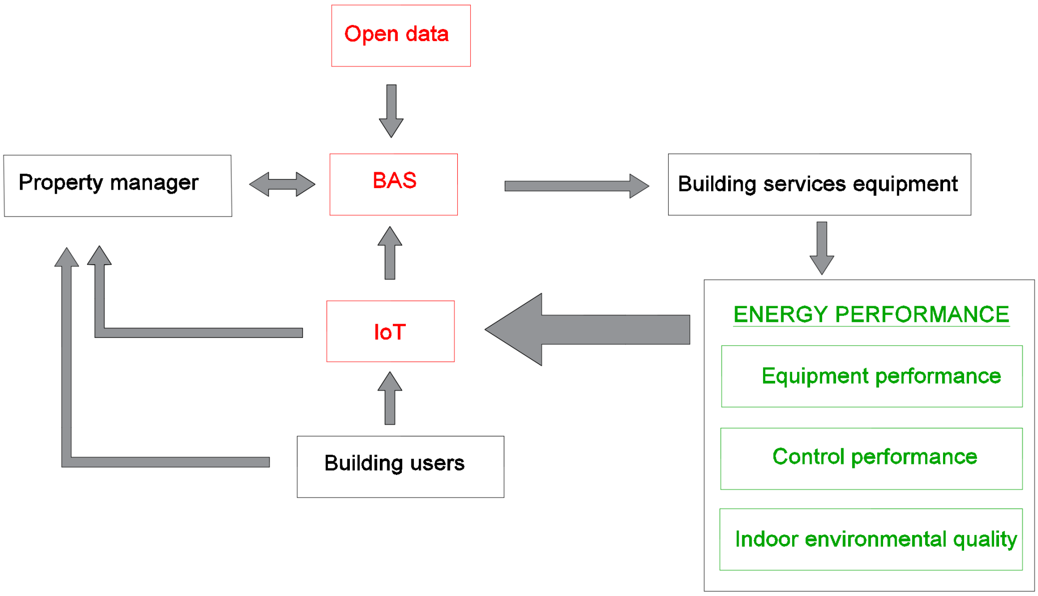


Figure 3.6 Relationships of energy performance and available data.

4 Research method

The objective of the empirical study is to provide practical evidence and understanding on solutions that improve the energy performance of buildings by exploiting available data. This is done by answering to the three research sub questions in a real-life context:

- What are the energy performance gaps of buildings?
- What kind of solutions that are based on the exploitation of available data can close those gaps?
- How effective are those solutions?

4.1 Overview of the research method

The research method of this thesis is a case study on a property maintenance organization and an office building in Helsinki, Finland. Case study was chosen as the research method because it allows the research to take place within a real environment, which is convenient for detecting existing energy performance gaps and methods to close them, while the theory-building process itself verifies the results (Eisenhardt, 1989, p. 547). Still, it is important in case studies to collect evidence from multiple sources to capture the richness of the research environment and phenomena (Yin, 2009, p. 2). The overall approach was constructive: Focus was not on what has been done to close energy performance gaps, but on what could be done to close the current ones.

4.2 Description of the case study

4.2.1 Case organization

Helsinki University Center for Properties and Facilities is responsible for tasks related to owning, developing and managing properties that are owned by Helsinki University. The center also executes the university's capital expenditure plan and construction projects. The building portfolio ranges from warehouses and offices to chemical laboratories and medical facilities. The turnover is 140 million euros and the amount of staff is 430. (University of Helsinki, 2013; Helsinki University Intranet, 2014). The total of 300 buildings are distributed over 33 regions with a clear majority in Helsinki. (Helsinki University Intranet, 2014). Out of the 300 buildings, 30 are remotely managed from a control room in Helsinki.

Being responsible for property maintenance, the case organization is well-equipped to make informed decisions regarding building services engineering in the construction phase. In their decisions they emphasize usability, modifiability, adjustability and serviceability of buildings throughout their lifecycle. Additionally, with such a large amount of properties, there is an incentive to consider the energy efficiency of buildings. Therefore the case organization is interested in automating energy conservative functions in building services equipment and increasing energy awareness among building users.

4.2.2 Case building automation system

The case organization uses six different building automation system controller software. These are Visonik and Desigo from Siemens, Trend, Deos OPENweb ControlPanel, Fidelix and Regin. The one studied the most was OPENweb ControlPanel by Deos. It is a web-based BACnet BMS software capable of integrating systems that use standardized interfaces, therefore allowing for data exchange via SQL, OPC, M-bus and Modbus. OPENweb also supports control of KNX systems for lighting and shading control. An Event Control Center modular expansion was used for handling alarms and messages. Another modular expansion that Deos provides is a Fidelio hotel booking system which makes Check-In, Check-Out and Pre-Check-In available as BACnet objects. The software providers also promise that the open architecture allows for individual expansions if any special application is required. (Deos, 2016). Also Desigo, Fidelix and Regin systems were studied a little for benchmarking purposes, however the less intuitive interfaces or half-completed sensor infrastructure resulted in the decision to focus on Deos.

4.2.3 Case building

The building studied in this thesis is an office building in Helsinki central business district (CBD). The original purpose of this thesis was to study both offices and laboratories that were controlled in Deos software. Laboratories are very intensive in their energy consumption in comparison to offices, which is mainly attributable to research needs: Large volumes of air flow, strict temperature tolerances and energy intensive equipment such as particle accelerators. Much of the potential savings can be attributed to making research equipment more energy efficient, which did not quite fit well with the scope of the thesis.

Therefore the most attention is given to a recently renovated office building that is referred to OfficeOne in this thesis. It has the most comprehensive sensor infrastructure of all the buildings managed by Helsinki University Properties and Facilities. OfficeOne has eight storeys and its gross internal area is 6100m^2. It is connected to the district heating and cooling network, has 16 air handling units and produces well over 600 measurement streams from its sensor infrastructure. The later suggested improvements that include sensor data utilization are mostly generic, so that they are applicable to both laboratories and office space unless some research needs are violated.

4.3 Research process, data and analysis

4.3.1 Research process and data collection

The research is conducted in the following phases:

1. **Identifying energy performance gaps**. This phase is based on analyzing historical sensor data available in the building automation system and semi-structured interviews of key personnel in the case organization. The sensor data used in the analysis was recorded in Deos OPENweb ControlPanel between 1st February 2016 and 26th September 2016. This time window was chosen because the final sensor infrastructure of the later introduced case building OfficeOne was completed in the end of January 2016. There were four key personnel that were interviewed: The people responsible for property maintenance, building automation, building services engineering and the case building. The themes explored in the interviews were energy consumption of properties, sources of energy waste, adjustability of HVAC systems, energy efficiency by building automation, energy management and the stakeholders in energy saving activities. The interviews were recorded and transcribed.
2. **Seeking solutions to close the gaps.** Existing ideas and solutions that eliminate or reduce the identified inefficiency were sought from research literature and commercial providers. If no existing solutions were found, such was suggested.
3. **Evaluating solution initiatives.** These ideas and solutions were introduced to experts of property management, building automation, building services engineering and property maintenance in separate workshops of various group sizes from one

expert to four experts at a time. These experts belonged to the case organization or its interest groups, and are listed in Table 4.1. They were asked to share thoughts and evaluate the proposed solutions in the dimensions of *challenge to implement* and *expected benefits* in the scale of 1-10. Such a method was chosen to roughly group the suggestions into groups of *low hanging fruits*, *continuous improvement*, *strategical development projects* and *lemons* according to an organizational change initiative evaluation framework presented by Peltokorpi et al. (2008). The grouping was used to support later decision making, and the complete evaluation results are presented in Appendix 1. The fourfold evaluation table is presented in Figure 4.1: The plotted dots resemble the averages of evaluations per respondent group, while the ellipse axis depicts the standard deviation of evaluation in both dimensions. If the respondent was unable to evaluate *challenge* or *benefits*, it was plotted as *5* but not taken into account in the average or standard deviation calculation. Descriptions of the four groups are as follows (Peltokorpi, et al., 2008):

- "Low hanging fruits are changes that lead to assured results with only minor effort."
- "Continuous improvement means an ongoing series of minor intervention which creates steady, but marginal, growth."
- "Contrary to continuous improvement, strategic development projects require the managers' attention. The project's results are breakthrough improvements …"
- "Lemons are projects when assessed in detail prove to be impossible or too labor intensive to implement for the expected results, and thus must be dismissed."

4. **Studying the feasibility of selected improvements.** The project steering group chose three most effective solutions for further examination to provide estimates on their monetary costs and benefits. This selection was based partly on the evaluation results and partly on their own judgment.

Table 4.1 Experts evaluating proposed improvements.

Expertise area	Background	Total amount
Building automation	Contractor (2) and designer (2)	4
Building services engineering	Designer (3)	3
Property management	Manager (3)	3
Property maintenance	Plumber (3)	3

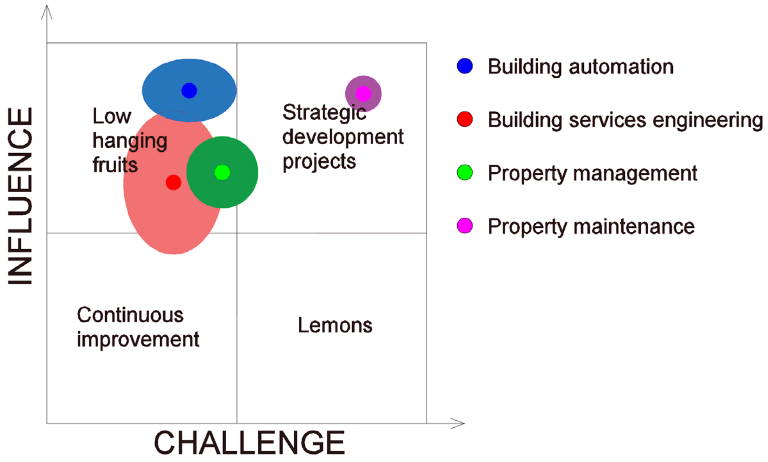


Figure 4.1 The fourfold table for evaluation results.

4.3.2 Data analysis tools

The data analysis tools and software used in the process are presented in Table 4.2.

Table 4.2 Tools and software used in data analysis

Purpose	Software/Tool name	More information from:
Provider: Deos		
Exporting sensor data. (Phases 1 and 4 of research.)	OPENweb ControlPanel	(Deos, 2016)
Provider: DataRangers		
Creating self-organizing maps and a user survey. (Phases 1 and 2 of research.)	Louhin	(DataRangers, 2016a)
Building analyses and managing large amounts of sensor data. (Phases 1 and 2 of research.)	DataMiner	(DataRangers, 2016b)
Provider: Microsoft		
Data clustering. (Phase 2 of research.)	SQL Server Data Tools for SQL Server 2014	(MSDN, 2016a)
Excel add-in for data clustering. (Phase 2 of research.)	SQL Server Data Mining Add-Ins for Office	(MSDN, 2016b)
Visualizing data and fitting trend lines (Phases 1 and 4 of research.)	Excel	(MSDN, 2016c)
Creating reports that are based on dimensional data modelling. (Phase 2 of research.)	Power BI Desktop	(Microsoft, 2016)

4.3.3 Limitations in the research method

The research was limited by the existing sensor infrastructure of the case building, unfinished tuning of building services equipment and the subjective evaluation method of initiatives aimed to close energy performance gaps. Due to unavailability of relevant sensor data, some naïve assumptions were made regarding causalities and processes to estimate the significance of energy consumption sources. These assumptions are always stated in the text.

Additionally, the HVAC equipment were partly in tuning phase due to recent renovation in the case building OfficeOne. This means that some of the systems operated temporarily in a way that may cause higher energy consumption by purpose and thus mislead the energy efficiency analysis, however these sources of energy inefficiency were acknowledged in the text whenever identified. OfficeOne was still chosen to be the case building due to its most extensive sensor measurements and a user-friendly interface.

Grouping the proposed improvements according to their attractiveness was thought to be convenient to base on subjective expert knowledge, because test results in other parts of the world, simulation results or product brochures were not considered adequate sources of information, nor the wide scope supported real-world testing. Although, the evaluation meetings of proposed improvements were heterogeneous. The number of participants varied and a meeting is never identical to another. Hence there is a social aspect to the evaluation process and unavoidable misunderstandings may lead to distorted and incomparable evaluation grades. Anyway, same information content on the idea of an improvement, expected benefits and identified challenges was provided and a short discussion followed to specify unclear aspects of the subject if necessary.

5 Results

5.1 Identified energy performance gaps

5.1.1 Current approach to managing energy performance

The case organization deals with buildings from construction to maintenance, which is why they emphasize usability, modifiability, adjustability and serviceability of buildings throughout their lifecycle. This manifests as distributed systems, loose sizing of equipment and light integration of hardware into the building to facilitate replacements and upgrades. The distributed system architecture can be accomplished with appropriate air handling unit zoning with variable air volume systems and allocation of cooling units, whereas loose sizing of equipment can mean for example reserve capacity in heating and cooling power of equipment or in ventilation system components and ducts. It was suggested that in the future the philosophy of distributed systems would lead to integrated panel heating and cooling solutions to better meet area specific indoor conditions and allow for comprehensive recycling of return water heat content.

The energy saving goals of the case organization are in part externally motivated. There are long-term energy efficiency and sustainability objectives imposed by the management and obligations regarding energy auditing based on the law on energy efficiency 1429/2014 of Finland (Finlex, 2014). In the past, energy has mostly been saved by basic and effective things rather than complicated control systems: Making sure that the time-scheduling of equipment operation times is appropriate, heat recovery of exhaust air is functioning and occupancy-based lighting control is working. If automation-based solutions are introduced, they cannot be prioritized over the controllability of systems. The lack of excess funds however is an impediment to upgrading the energy performance of the case properties, which is why most investments are timed to coincide with building modernizations.

It should also be made sure that the energy costs remain within budget in the short-term. Ensuring this requires continuous consumption monitoring. If an increase in energy consumption is detected by an energy manager company with whom the case organization has a contract, the underlying causes are determined and action is taken with the organization’s own resources if necessary. These resources extend all the way to own maintenance-men that replace actuators in the field. There are however too often problems associated with poor tuning of control loops of building systems, and the reason for this is suggested to be the instalment schedules in building automation contracts that leave no financial incentive for the contractor to finish the work properly. The contractors are mainly involved with the case organization through maintenance contracts that concern server and sub-distribution board aspects of building automation systems. Anyhow, there is reluctance to move towards solutions provided by energy service companies, because all the necessary special expertise is already in-house. Energy service professionals are however considered appropriate for occasional consulting purposes.

5.1.2 Existing energy performance gaps

The interviewees identified multiple needs for improvement with regard to building automation system functionalities, energy consumption metering and systems integration to be met in the future. None of the improvements should include extensive electrical work or large amounts of equipment replacements, however. When it comes to building automation, there are goals of reducing energy consumption when the building is not in use and eliminating overheating of spaces. Currently no system exists that contains the opening hours and holiday periods of the property portfolio, on which the operating times programming of equipment could be based on. With a large number of properties it is impossible to keep up with the programming task, as every piece of equipment needs to be programmed separately. It was suggested that a system that contains this information and automatically programs the time schedules for equipment should be developed, an interface between building automation and room reservation systems should be created or at least that the equipment could be controlled in purposeful groups. Group control in general was thought to facilitate tasks as supply water temperature programming adjustments according to seasons, supply air temperature control and air handling unit operating times. Falling behind in doing these tasks manually was considered to lead to energy waste.

A few issues were brought up concerning the overheating of spaces: Forgotten radiator heating compensation curve adjustments, poor adjustability of radiator heating, lack of protection from heat loads and the fact that weather forecasts are not utilized in any way. With the older building automation systems that represent a vast majority, supply water temperature of radiators is defined with a two point compensation curve. These curves tend to get shifted upwards during cold winters to supply warmer water into the system, but unfortunately it often is forgotten to make the shift back after the cold period is over. Large benefits were thought to be expected should those system adjustments be automated reliably. On the other hand, most of the case buildings have a single radiator network which impedes area specific heating optimization. If the cellar and façades had their own networks, heating could be optimized better with respect to heat loads caused by the sun for example. Moreover, Finland was thought to be behind in protecting buildings from solar radiation according to an interviewee. Automatically operating motorized sun blinds could reduce heat loads when they are not desired and utilize them when needed. Additionally, the fact that the heating system does not use weather forecast data can lead suboptimal performance when facing a very cold night or a sharp temperature rise.

The case organization is aiming towards a role in energy leadership in the future to increase energy awareness among building users. Energy consumption measurement infrastructure and reporting are central aspects of this goal. Currently energy consumption is reported inconsistently across buildings and much thought is given to the matters of what to measure and how should the information be managed. Identified needs however are user friendliness, information content that serves maintenance, automated and detailed energy monitoring and reporting capabilities that enable drilling through to the underlying equipment operation, and monetary feedback to motivate short response times of the staff. The needs of user friendliness and maintenance serving information content highlight the fact that the system would be used by staff with various backgrounds and tasks. Only the relevant information should then be produced for each user.

There were two more energy performance gaps, but those were based on observation rather than interviews: User complaints that were received in personal e-mails inboxes and single value threshold alarms. User complaints are a problematic area as the indoor environment is not likely to ever satisfy everybody. In the case building users in the same room feel cold and hot. With more knowledge on the relative numbers of satisfied and unsatisfied occupants the interventions through the BAS could be better informed. Also the feedback channel could be more efficient: Gathering feedback could be systematic and the satisfaction rate could be made visible to the whole maintenance organization. Conversely, with single value threshold alarms there is inevitably a trade-off with the amount of false positives and early detection of faults. If the detection accuracy was better, the amount of false positives could be reduced.

5.1.3 Summary of identified energy performance gaps

The identified energy performance gaps are listed in Table 5.1. Next, measurement data available through the BAS is used to verify identified energy performance gaps and detect new ones.

Table 5.1 Summary of identified energy performance gaps.

Performance area	Description
Heating	• Poor area-specific adjustability of heating • Reactive essence of heating control • Need for shifting the compensation curves to adapt the heating power to seasonal needs
Cooling	• Lack of protection from heat loads
Processes	• Manual input intensive processes • Inability to control actuators in groups • Inefficient channels for feedback from building users • Lack of knowledge on the relative numbers of satisfied and unsatisfied building users • Inaccurate single-value threshold alarms in BAS • Inconsistent energy consumption reporting

5.2 Overview and limitations of available data

There is a large amount of measurement data generated and recorded by the building automation system of OfficeOne, but in some cases the constraints in sensor infrastructure make it difficult to evaluate the energy performance of equipment control. The data is collected in Deos OPENweb ControlPanel building automation system controller software that monitors the state of spaces and equipment extensively. The most common measurement point types are listed in Table 5.2. These measurement types include over 600 measurement streams which are gathered and recorded in 25 sub-distribution boards. The measurements can be downloaded as a comma separated value file in which the first column states the date, the second states the time and the remaining columns state the measurement values for a given sensor.

Table 5.2 Available sensor data in OfficeOne.

Parameter/actuator name	Parameter units or alternative states	Recorded (X)	Actuator (X)
ROOM			
Temperature	°C	X	
Temperature set point	°C		
CO_2 concentration	ppm	X	
CO_2 concentration set point	ppm		
Motion detection state	Detected/Not detected		
Chilled beam valve opening	0% - 100%		X
Supply air damper state	Minimum/Normal/Augmented air flow	X	X
Exhaust air damper state	Minimum/Normal/Augmented air flow	X	X
FLOOR			
Plug load of the northern or southern half of the floor	kW	X	
Lighting load of the northern or southern half of the floor	kW	X	
AIR HANDLING UNITS			
Energy consumption per a switchgear	kWh	X	
Inlet air temperature	°C	X	
Pressure difference over the air inlet filter	Pa	X	
Air temperature after heat recovery	°C	X	
Return water temperature in the heating radiator circuit	°C	X	
Pump state in the heating radiator circuit	Running/Not running		X
Valve opening in the heating radiator circuit	0% - 100%	X	X
Valve opening in the cooling coil circuit	0% - 100%	X	X
Electronically commutated supply air fan	0% - 100%	X	X
Inlet pressure	Pa	X	
Inlet pressure set point	Pa	X	
Supply air temperature	°C	X	
Supply air humidity	0% - 100%	X	
Exhaust air temperature	°C	X	
Terminal pressure	Pa	X	
Terminal pressure set point	Pa	X	
Pressure difference over exhaust air filter	Pa	X	
Pressure difference over heat recovery	Pa	X	
Heat recovery disc	0% - 100%	X	X
Outlet air temperature	°C	X	
Electronically commutated exhaust air fan	0% - 100%	X	X
Bypass damper	0% - 100%	X	X
HEATING SYSTEM			
Energy consumption	MWh	X	
District heating water usage	m^3	X	
Inbound district heating water temperature	°C	X	
Outbound district heating water temperature	°C	X	
Outdoor temperature	°C	X	

Parameter/actuator name	**Parameter units or alternative states**	**Recorded (X)**	**Actuator (X)**
Service water heating			
Service water usage	m^3	X	
Heat exchanger valve of the warm service water system	0% - 100%	X	X
Service water temperature	°C	X	
Circulated warm service water pump state	Running/Not running		X
Radiator system			
Heat exchanger valve of the radiator system	0% - 100%	X	X
Radiator system supply water temperature	°C	X	
Radiator system supply water temperature set point	°C	X	
Radiator system pressure	Pa	X	
Radiator system pump	Running/Not running		X
Radiator system return water temperature	°C	X	
Floor heating system			
Heat exchanger valve of the floor heating system	0% - 100%	X	X
Floor heating system supply water temperature	°C	X	
Floor heating system supply water temperature set point	°C	X	
Floor heating system pressure	Pa	X	
Floor heating system pump	Running/Not running		X
Floor heating system return water temperature	°C	X	
Air heater			
Heat exchanger valve of the air heater network	0% - 100%	X	X
Air heater supply water temperature	°C	X	
Air heater supply water temperature set point	°C	X	
Air heater system pressure	Pa	X	
Air heater system pump	Running/Not running		X
Air heater return water temperature	°C	X	
COOLING SYSTEM			
Energy consumption	MWh	X	
District cooling water usage		X	
Inbound district cooling water temperature	°C	X	
Outbound district cooling water temperature	°C	X	
Cooling convector system			
Heat exchanger valve of the convector system	0% - 100%	X	X
Convector system pump	Running/Not running		X
Convector system supply water	°C	X	
Convector system supply water set point	°C	X	
Convector system pressure	Pa	X	
Convector system return water	°C	X	

Parameter/actuator name	Parameter units or alternative states	Recorded (X)	Actuator (X)
Air cooler			
Heat exchanger valve of the circuit formed by air cooler and chilled beam system	0% - 100%	X	X
Air cooler supply water temperature	°C	X	
Air cooler supply water temperature set point	°C	X	
Air cooler system pressure	Pa	X	
Air cooler circuit pump	Running/Not running		X
Air cooler return water temperature	°C	X	
Chilled beams			
Valve of the beam circuit	0% - 100%	X	X
Chilled beam system pump	Running/Not running		X
Chilled beam system supply water temperature	°C	X	
Chilled beam system supply water temperature set point	°C	X	
Chilled beam system pressure	Pa	X	
Chilled beam system return water temperature	°C	X	

The controller software also collects data regarding the state of separate systems such as street lighting, special outlet fans and fire safety systems, and manages events and alarms based on threshold values and rules.

There are some issues with the produced data that pose challenges to its utilization:

- **Bulk measurements.** Energy consumption measurements often represent more than one separate system: The electricity consumption of 16 air handling units is measured in bulks in 4 switchgears which results in noise in the data depending on the operating schedules. For example in the occupied zone the consumption may be cyclical whereas in toilets it is not. Additionally, the heating and cooling energy consumption metering covers multiple separate systems. This complicates system-specific energy consumption analysis.
- **Limitations in hardware.** Not all systems can be controlled digitally. Mechanical radiator thermostats are self-operated unit controllers that cannot be connected to building automation. Nonetheless, the radiator valve position for each room is vital information when assessing the effect of the heating system on room temperature.
- **Missing target values.** Room temperature and carbon dioxide content of air set points are not recorded. This means that it is impossible to know what conditions the chilled beams and supply air dampers were trying to achieve in historical analysis.
- **Locally controlled systems.** Lighting systems are not connected to building automation with the exception of corridor lighting and outdoor lights. The functionality of the lighting system cannot therefore be assessed remotely. Also the information produced through lighting control regarding daylight availability and lighting state are not available.

5.3 Evaluation of current control systems and their energy performance

5.3.1 Heating system control

Heating is controlled with the BAS. The source of heat in OfficeOne is the water in the district heating network. The heat of this water is used in four systems: Radiator network, air heater, service water heating and floor heating. The required temperature of supply water flowing into the radiator network is determined by outdoor temperature with a compensation curve that is presented in Figure 5.1, where the vertical axis corresponds to supply water temperature and the horizontal axis corresponds to outdoor temperature. To reach the appropriate supply water temperature with the heat content of district heating water, a heat exchanger valve is controlled in the radiator network. The control target of the supply water temperature of air heating and floor heating is also defined with an outdoor temperature compensation curve, whereas warm service water temperature is being kept constant regardless of the outdoor temperature.

The amount of supply water used for the actual heating is adjusted with separate valves. The air handling units have their own valves that heat the intake air if heat recovery is not able to warm it up sufficiently. Radiators also have their own valves that adjust the water flow and thus the heat that is transferred. This valve is controlled by a mechanical thermostat that can only be adjusted manually within a small range. The purpose of mechanical thermostats is to reduce the heating power of radiators when free heat is available.

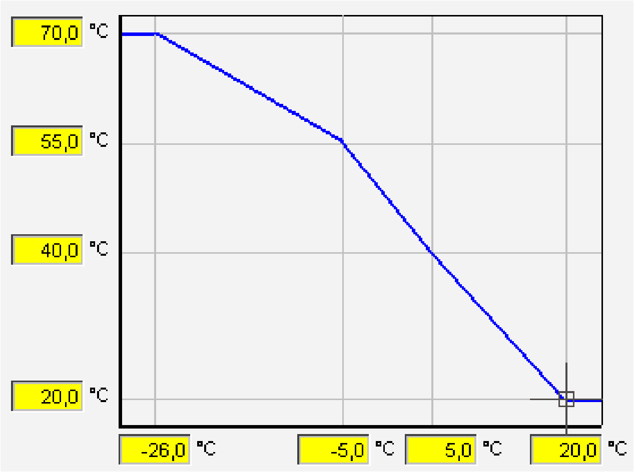


Figure 5.1 The outdoor compensation curve of the radiator heating system.

OfficeOne is heated constantly to keep the rooms in uniform temperature regardless of the cyclical occupancy patterns, however around half of the air handling units (AHU) are supplying a minimum air flow until midnight and then turned off for the rest of the night. The reason why all AHUs are not on minimum air flow is that the building was recently renovated and the night time ventilation is used to reduce smells. As a reminder, the heating system energy consumption metering covers radiator heating, air heater, floor heating and service water heating. During winter the energy consumption is quite static around the clock, though there are some night time spikes as observable in Figure 5.2. Based on Figure 5.3 it can be suggested that those spikes are caused by some air handling units running and radiators heating more during lowering outdoor temperatures (the temperature dropped towards the 4th and 6th of February). The midnight drops may have something to do with the respective drops in AHU operation that can be seen later in Figure 5.11. Still, it is suspicious how the consumption profile stays rather static with such dynamic overall operation.

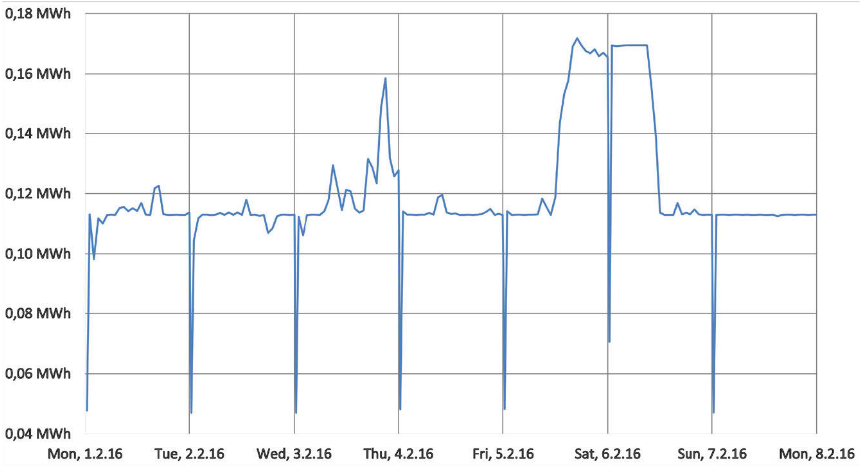


Figure 5.2 Hourly energy consumption of the heating system during winter. The consumption profile stays quite static with occasional night time spikes.

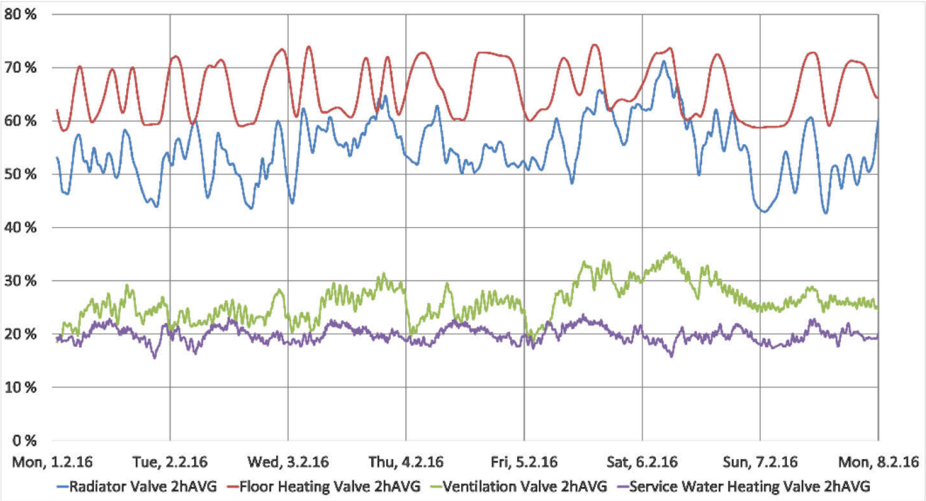


Figure 5.3 Heating system heat exchanger valve opening trends as two hour averages to reduce oscillation of the data. The consumption spikes seem to be explained by increasing demand for radiator and air heating.

During warm spring days heating energy is mainly consumed outside office hours, as can be seen in Figure 5.4. This is explained by heating system valve opening trends in Figure 5.5 as radiators and the ventilation system do not require as much energy during the daytime. Also the almost zero energy consumption during warm days suggests that service water heating and floor heating are negligible. However, the frequent and sharp drops from 110kWh to 0kWh in hourly heating energy consumption occurring within the span of two hours can be a performance concern. The thermal mass of a building can cause undesirable situations: Cold structures may cause thermal discomfort in the building after heating is lowered due to rising outdoor temperatures, and warm structures may induce inertia after cooling is commenced. Therefore information on future heat loads may help in anticipating situations when cooling systems are battling the thermal mass, or heating systems are fighting cold structures with reduced output. The mechanical radiator thermostats do handle the situation reactively so that radiator heating is stopped after a certain room temperature is reached, but with predictive capabilities free heat could be utilized to save purchased energy.

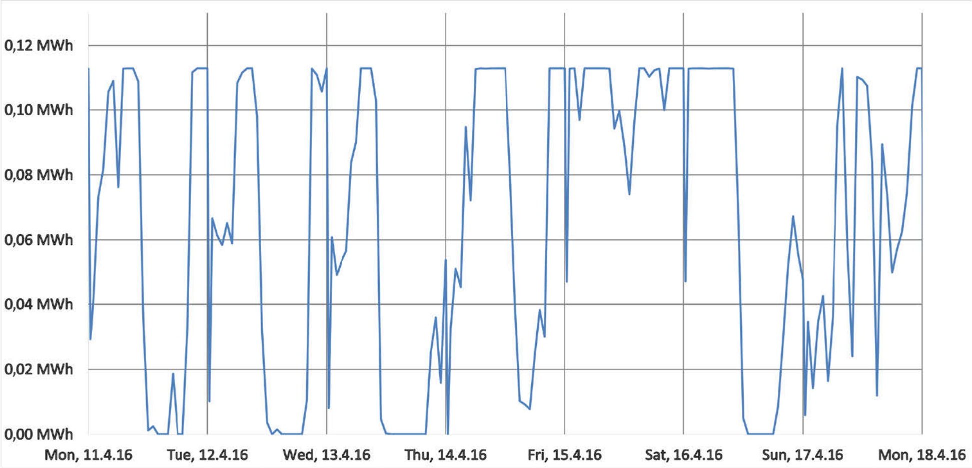


Figure 5.4 Hourly energy consumption of the heating system during spring. There are occasional daytime drops.

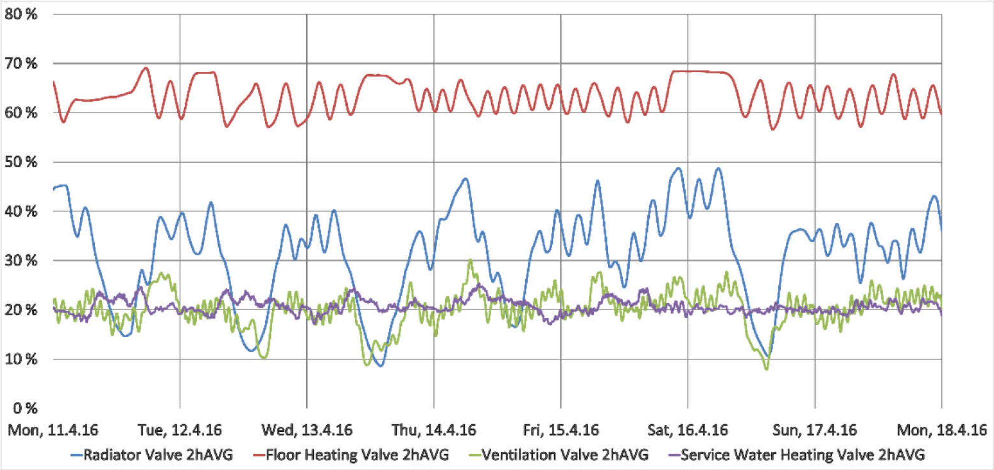


Figure 5.5 Heating system heat exchanger valve opening trends as two hour averages to reduce oscillation in data. The daytime drops seem to be caused by reduced radiator and air heating.

The effect of heat loads on overheating the building, indicated by the chilled beam network valve opening in the cool distribution system, was explored by studying the correlation between outdoor temperature and chilled beam network valve, plug loads and chilled beam network valve, and produced solar energy and chilled beam network valve. The data sets were recorded between 12th April and 12th August 2016 between 10:00 and 15:00 on working days to assume a relatively stable occupancy and thus utilization of chilled beams. Chilled beam valve signals were aggregated into hourly averages. Plug loads were assumed to correlate with the amount of users, and the electricity produced in the solar panels was assumed to correlate with the solar radiation heating the building that is quite evenly exposed to sunlight from the East, South and the West.

Based on the coefficients of determination it seems that the most valuable information (out of the three observed sets) for predictive control would be the future outdoor temperature, which is quite trivial. This correlation is seen in Figure 5.6. Plug loads and solar radiation did not correlate with cooling demand at all. The correlations are compiled in Table 5.3.

With conditional estimation methods the data on produced solar energy and plug loads could prove useful too, though. This is illustrated by data sets presented in Figure 5.7 and Figure 5.8. Within segments of the more defining variables the previously irrelevant variables gain significance, which is suggested by the increased coefficients of determination. This finding implies that techniques of predictive analytics may be able to increase control performance.

Table 5.3 Correlations of heat loads and cooling demand.

Description	Conditions	Trend line	Coefficient of determination
Outdoor temperature vs. Cooling demand	None	y = 0.7912 x + 2.6109	$R^2 = 0.2317$
Plug loads vs. Cooling demand	None	y = 0.4191 x + 10.405	$R^2 = 0.0566$
Solar radiation vs. Cooling demand	None	y = 0.3148 x + 15.09	$R^2 = 0.0698$
Plug loads vs. Cooling demand	Outdoor temperature above 23°C	y = 1.6263 x + 5.5926	$R^2 = 0.3536$
Solar radiation vs. Cooling demand	Outdoor temperature above 20°C and plug loads between 16kWh and 19kWh	y = 0.7285 x + 13.035	$R^2 = 0.3333$

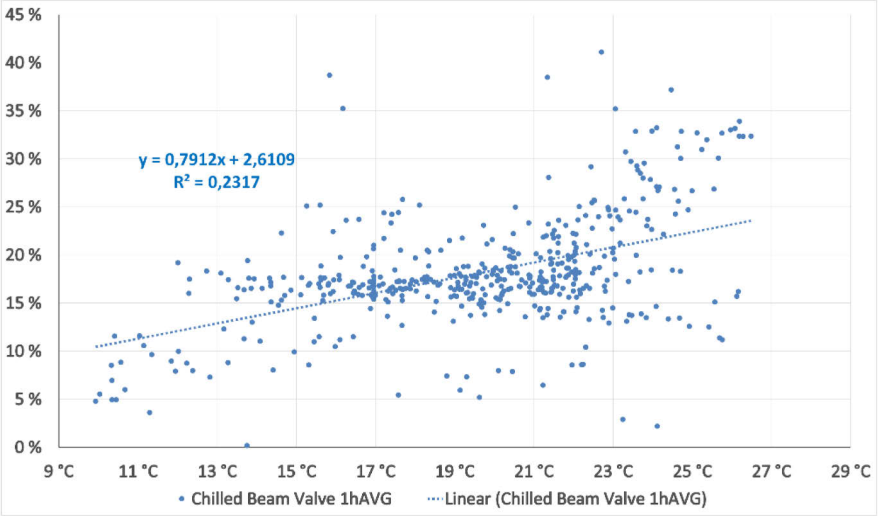


Figure 5.6 Outdoor temperature vs. cooling demand. Outdoor temperature was the most defining variable.

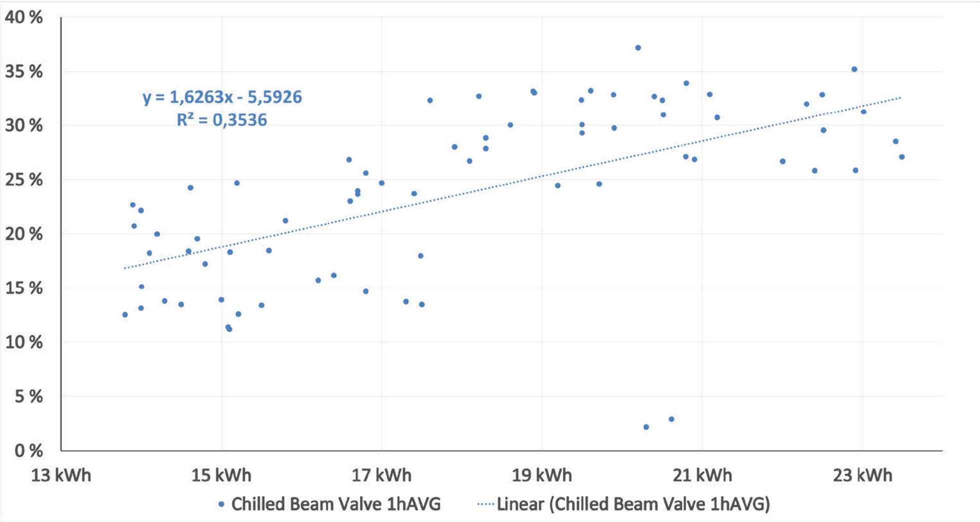


Figure 5.7 Plug loads vs. cooling demand when data is filtered with outdoor temperature. Plug loads gained significance with a limited outdoor temperature interval.

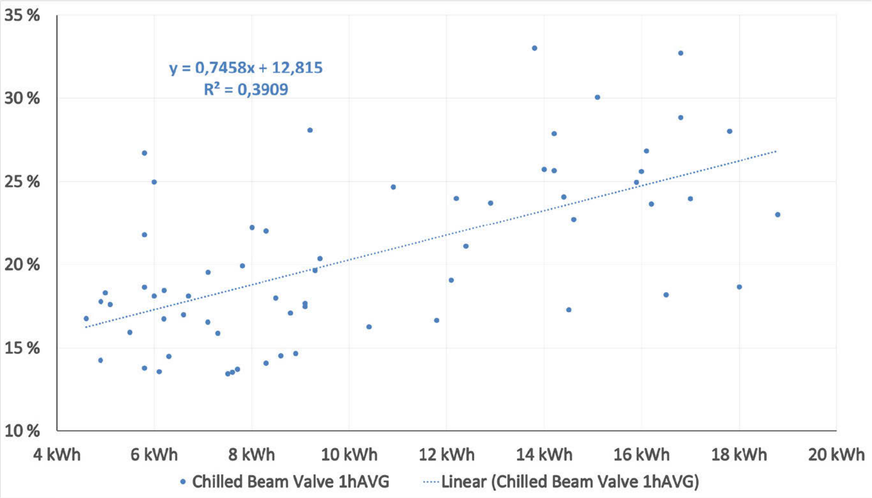


Figure 5.8 Solar energy vs. cooling demand when the data has been filtered with outdoor temperature and plug loads. Solar radiation then gained more significance.

Anyhow, these observations suggest that the largest energy savings could result from demand-controlling ventilation and radiator heating, of which ventilation system is covered in Chapter 5.3.3. Demand-controlling radiator heating would mean reducing heating while users are not present and when free energy is available. Reducing heating while users are not present is also known as using night setback temperatures, which means that the room temperatures are lowered by a few degrees for the night. Decreasing heating when free energy is available means that the controller calculates the forecasted heat loads and estimates an appropriate level of heating output, respectively.

The energy performance of heating control is then considered satisfactory: Heating demand is estimated based on outdoor temperature and overheating is eliminated with self-operated unit controllers (mechanical radiator thermostats) in a reactive manner. This kind of control is reliable and affordable. A problem however is that these mechanical unit controllers cannot be adjusted remotely, which means that they cannot be synchronized with cooling control either. The energy performance could be enhanced by adding predictive capabilities, allocating heat output to periods of occupancy and enabling digital control.

5.3.2 Cooling system control

Cooling is controlled with the BAS. The principle of cooling is also heat exchange with district network water however in reverse to heating. The cool water is used in three circuits: Convectors, air coolers and chilled beams. The convectors and air cooler have a single set point for the supply water temperature while chilled beam network has an interval of a few degrees with a fixed raise to the current dew point temperature. The cooling demand is determined by room temperature measurements and intake air temperature. The cooling valve of convectors and chilled beams starts opening once a room temperature set point is exceeded. Utility service rooms are equipped with convectors, whereas spaces in the occupancy zone are equipped with chilled beams. The beams are active meaning that supply air is distributed through them. The total chilled air supplied by chilled beams consists of conditioned supply air by 30% and recycled indoor air by 70%. Conversely, AHUs start cooling the intake air whenever the supply air set point is not reached with zero usage of both the heat recovery and air heater.

The chilled beam operation is limited exclusively to the periods when there is a user present in the room and the temperature set point is exceeded, which means that control is based on demand. Likewise, the air cooler starts functioning only when the air is too warm. Therefore there is little to do to save energy other than adjusting set points. The energy consumption profile and valve openings of the heat exchangers in the cooling system are presented in Figure 5.9 and Figure 5.10. It can be inferred that the energy consumption of the convector system is negligible with its hourly energy consumption of approximately 1kWh.

The energy performance of cooling system control is therefore considered excellent. Cooling energy is consumed exclusively during periods of demand: Chilled beams operate only when users are present in an overheating room and air coolers operate only when the intake air is too hot. The only sensible way to improve cooling performance is then to decrease cooling demand by protecting spaces from heat loads.

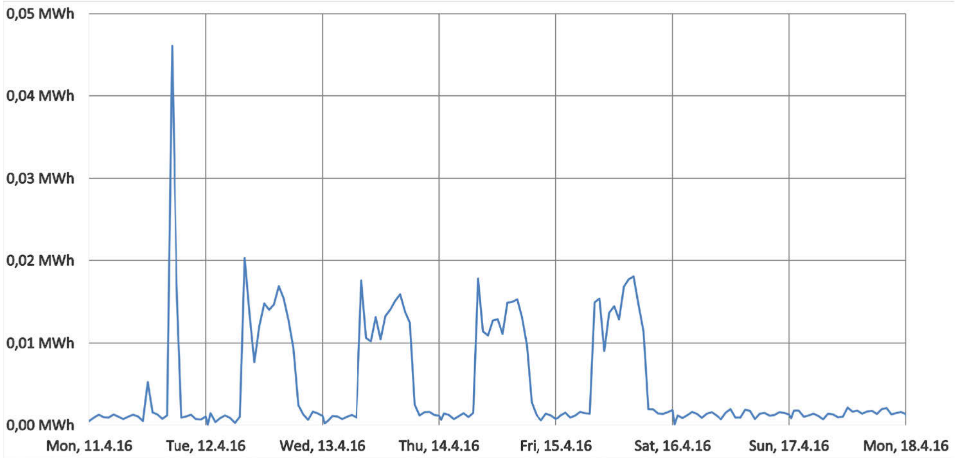


Figure 5.9 Hourly energy consumption of the cooling system during a spring week. Consumption occurs exclusively during periods of occupancy.

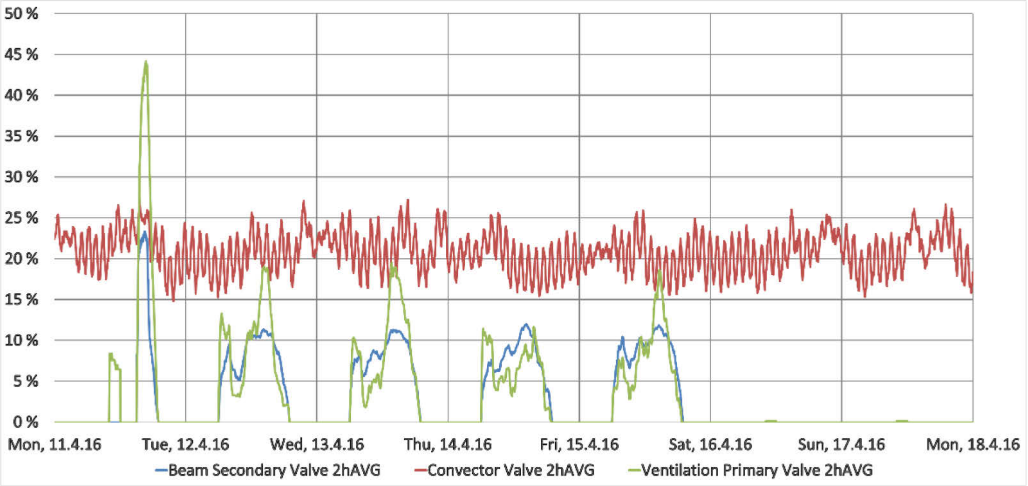


Figure 5.10 Cooling system valve opening trends as two hour averages to reduce oscillation in data. It is apparent that the total consumption is defined by chilled beams and air coolers.

5.3.3 Ventilation system control

Ventilation is controlled with the BAS. The ventilation system consists of 16 air handling units (AHU) that are mainly concerned with conditioning the intake air into supply air of appropriate temperature and upholding a pressure in the supply and exhaust duct network. The amount of air supplied and exhausted from the room is then controlled by dampers. A typical AHU in OfficeOne consists of a supply damper, filters, a heat recovery unit, an air heater, an air cooler, a supply fan, an exhaust fan and an exhaust damper. The AHUs operate according to time schedules, and with less power during weekends. In OfficeOne the operating schedule is from 6.30am to 11.59pm. The desired supply air temperature is defined with a compensation curve with respect to the exhaust air temperature, and that temperature set point is achieved with heat recovery that transfers heat from exhaust air to intake air if necessary. If the effect of heat recovery is not sufficient, air heater valve is opened until the desired air temperature is reached. If cooling is necessary then the air cooler valve is opened respectively. The system also monitors that the supply air is not too humid.

The dampers have three states: minimum, normal and augmented air flow. The appropriate state is defined by occupancy detection and the CO_2 concentration of indoor air as follows: A minimum air flow is maintained when the room is empty, a normal air flow is maintained during occupancy and an augmented air flow is provided if an upper limit of CO_2 concentration is reached.

As mentioned earlier, some AHUs operate around the clock due to smells from renovation. Also some exhaust fans are running constantly in toilets and stairways. This causes noise in some of the energy consumption data that obscures the cyclicity of the AHUs serving the occupancy zone. The electricity consumption of the groups of AHUs in different switchgears is presented in Figure 5.11. In the figure the spike on the early afternoon of Thu 12th May is caused by a break exercise session in one area. It is important to note that this data does not include the air heater and air cooler energy consumption.

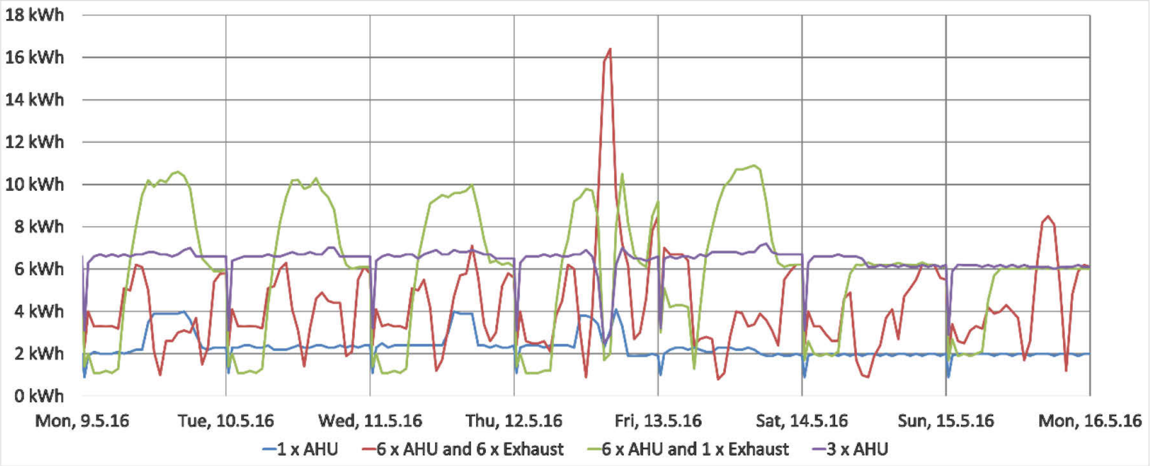


Figure 5.11 Electricity consumption of the ventilation system. The trends are largely obscure.

The cyclicity according to occupancy patterns is apparent in the green curve *6xAHUand1xExhaust*. That group consists of three AHUs serving offices, two AHU serving cafeterias and one AHU serving a stairway. The blue curve *1xAHU* consists of a single AHU serving a seminar room and utility room, which explains the irregular daytime spikes. The purple curve *3xAHU* is rather constant due to the needs imposed by renovation. It serves various areas but mainly the lobby, meeting rooms in the cellar and toilets. The red curve *6xAHU6xExhaust* is the one with the noisiest profile. It consists of three AHU serving office areas, one AHU serving meeting rooms, one AHU serving toilets and one AHU serving a stairway. The six exhaust fans serve utility rooms.

Yet, there is cyclicity hidden in the obscure trends too as observable in Figure 5.12. The trends show the fan and related damper operation for office space, which is very cyclical. The principles of ventilation system control can be seen from those trends as well: operating schedules of the fan, less power on weekends, morning purges after the downtime and occupancy detection based damper state. Note that the average value for damper state consists of almost 30 dampers, so the augmented air flows in individual rooms have limited effect on the average value.

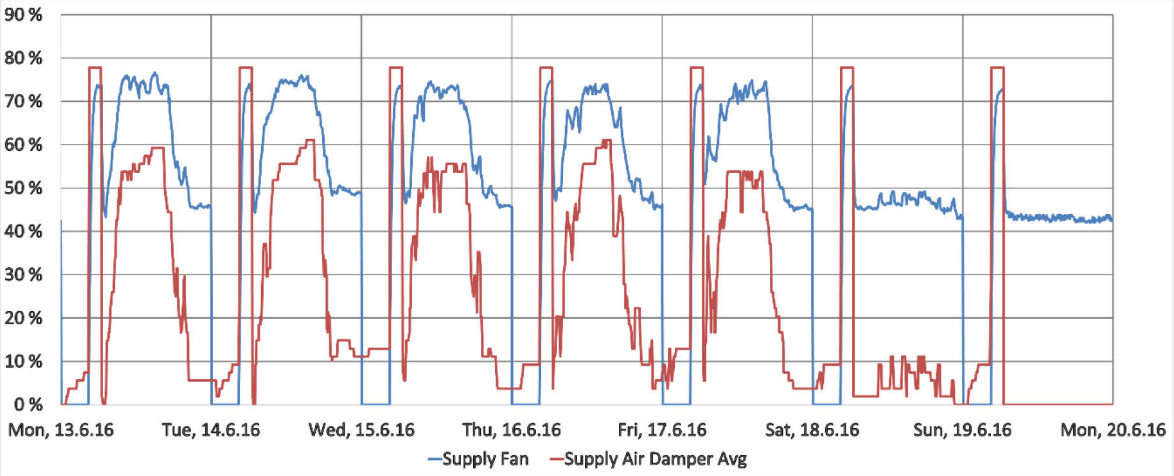


Figure 5.12 Single AHU supply fan and related damper operation.

The energy performance of ventilation control is considered excellent as well. The electricity consumption is mainly allocated to time periods of occupancy and heightened demand for fresh air. Even though the control is by nature reactive it is not that much of a concern because the inertia of the ventilation process is small in comparison to heating: Rising CO_2 concentrations can be quickly and effectively managed by temporarily augmenting the supplied air flow. The only concern in ventilation control is that AHU downtimes may have adverse effects on the pressure differences over the building envelope.

5.3.4 Lighting system control

The lighting is controlled locally separately from the BAS, except for corridor and outdoor lighting that are based on schedules and outdoor illuminance. Room lighting is controlled by occupancy detection with a time-out period and a daylight harvesting setting. The artificial lighting intensity does not adjust gradually, so there is a single daylight illuminance threshold when the lights switch off. As data used in lighting control is unavailable through the building automation system, only high level observations can be made. The electricity consumption of the lighting system of OfficeOne versus the produced solar energy (assumed to correlate with daylight availability) at the rooftop during a week is shown in Figure 5.13 and in larger scale in Figure 5.14. The data in the figure was collected between 1st February and 1st July 2016 daily from 9:00 to 17:00 in order to focus on periods of occupancy.

Without knowledge on the operation permissions given by the lighting controller it cannot be stated whether the reduced electricity consumption is attributable to user behavior or the daylight harvesting function, whereas the efficiency of occupancy detection is evident judging by the cyclicity of the consumption profile. The lighting controller's operation should be scrutinized to see to which extent daylight is really harvested. If the reduction of around 5.6kWh in hourly electricity consumption can be attributed to a daylight harvesting function, it is saving 3.8€ every sunny day with a price of electricity of 8.4c/kWh.

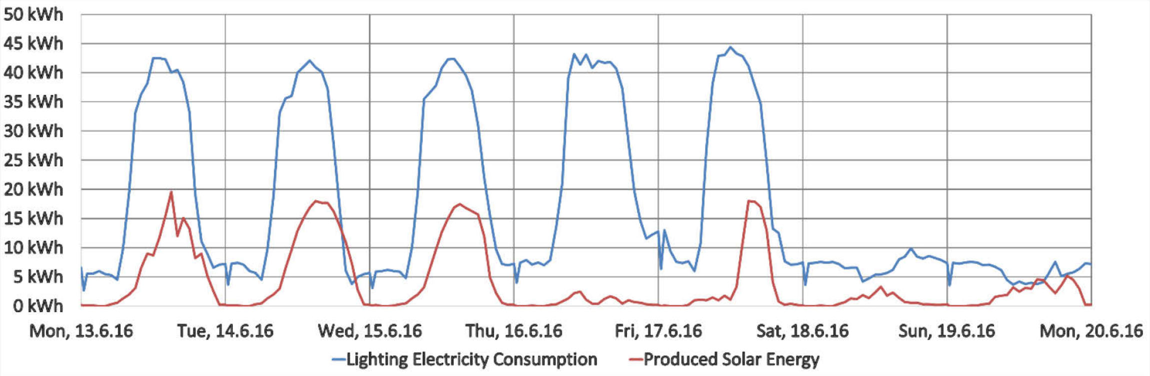


Figure 5.13 Hourly electricity consumption of the lighting system in comparison to hourly produced solar energy during a week. The consumption is focused on periods of occupancy.

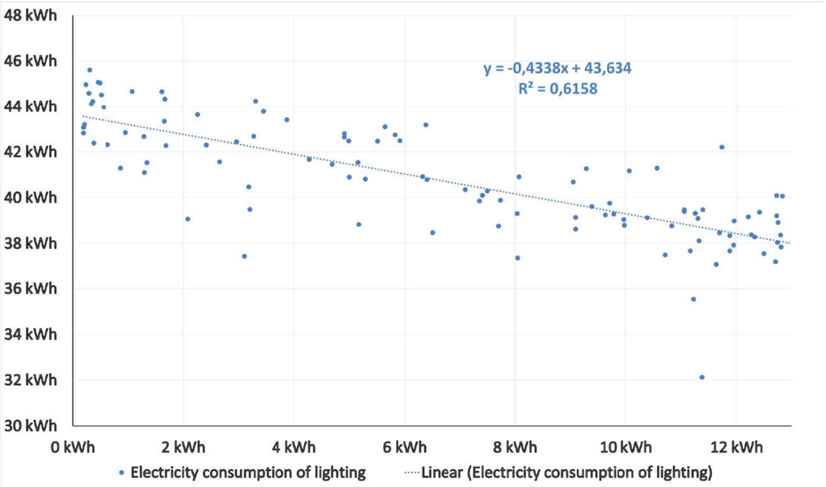


Figure 5.14 Daylight availability vs. lighting electricity consumption. The consumption is reducing towards increasing daylight availability.

The energy performance of lighting control is considered good. The electricity consumption concentrates to periods of occupancy, however it is unclear how well the daylight harvesting function is operating. Even if it is operating as intended by switching lights off when a threshold is exceeded, the performance could be increased by constant luminance control: Adjusting artificial lighting level gradually according to available daylight to keep a constant luminance.

5.3.5 Summary of all energy performance gaps

All energy performance gaps identified in the research are listed in Table 5.4.

Table 5.4 Summary of all energy performance gaps.

Description	Identified by interview	Identified by observation
Heating		
Poor area-specific adjustability of heating	X	X
Reactive essence of heating control	X	X
Heating control not being founded on the cyclical demand		X
Need for shifting the compensation curves to adapt the heating power to seasonal needs	X	
No synchronization with cooling		X
Cooling		
Lack of protection from heat loads	X	
Ventilation		
Potentially harmful implications on pressure differences over the building envelope due to air handling unit downtimes		X
Lighting		
Potential lack of daylight harvesting		X
Processes		
Manual input intensive processes	X	
Inability to control actuators in groups	X	
Inefficient channels for feedback from building users		X
Lack of knowledge on the relative numbers of satisfied and unsatisfied building users		X
Inaccurate single-value threshold alarms in BAS		X
Inconsistent energy consumption reporting	X	X

5.4 Identified solutions to close the energy performance gaps

Eleven potential solutions were identified based on energy performance gaps covered in interviews or observed in measurement data. These solution initiatives and their evaluations are presented next.

5.4.1 Installing electronic radiator thermostats with smart heating functions

Mechanical radiator thermostats are cheap and reliable, but have some drawbacks. The temperature set points of mechanical radiator thermostats and chilled beams may differ from one another. Radiators may be set to a higher room temperature than what the cooling system is trying to achieve without any remote means observe or control the situation. Moreover, mechanical thermostats measure room temperature right next to the radiator. This may cause trouble as curtains or furniture right next to the radiator distort the temperature measurement. If the measured temperature is much higher than the temperature in the occupancy zone, the radiator valve may be closed even when the room temperature is lower than desired.

The situation can be improved by installing electronic radiator thermostats that could also be connected to the building automation system via radio:

- The thermostats can be given an offset according to the distorted temperature measurement, which means that the valve is operated as if the measured temperature was higher or lower than the measured value next to the radiator.
- The radiator valve operation can be determined by a temperature measurement from the occupancy zone.
- The radiator valve operation can also be linked to occupancy detection through different modes: When nobody is around an economy mode is assumed, and when occupancy is detected a comfort mode is resumed. This allows for a slight daytime room-specific optimization of heating.
- Controlling logic can be applied regarding the synchronized operation of the chilled beams and radiators to minimize the simultaneous cooling and heating while preventing draft from windows.
- By enabling remote control over radiator valves the imperfections of valve functions can be compensated (Salama, 2014, p. 52).
- Open windows are detected and valve is closed for a set period to minimize heat loss (Salama, 2014).
- Valve operation can be optimized when using room temperature setbacks or predictive heating control. For example during morning setback recoveries radiator valves with mechanical thermostats tend to be completely open. This causes uneven water flow in radiators and thus uneven heating if the network is out of balance. (TA, 2011, p. 9).
- The valve can be programmed to regularly close and open completely to prevent calcification.

There are also some drawbacks related to the installation of electronic radiator thermostats:

- The hardware and installation cost a lot in large scale.
- Electronic thermostats require a power source, which means battery replacements every one to three years or electrical wiring.

- The cost of building automation programming work that depend on the amount of logic integrated to the functioning of the valves.

The remote operation of radiator valves requires communication between the building automation system and the electronic thermostat. This can be done wirelessly over radio, which is supported by KNX, LON, Modbus and BACnet protocols (Ylitalo, 2012; Morris, et al., 2012; Martocci, 2008). Some commercially available electronic thermostats are operated by a central controller over radio mesh network technology, but essentially the requirement for wireless communication is a radio transmitter connected to the thermostat. If the radiator thermostat operation in OfficeOne is desired to be determined by a separate room temperature sensor or chilled beam state, it is possible through building automation where that information is available. This improvement would lead to a lot more data generated into the building automation system (over 300 points of control). Therefore considerations must be given to the graphical representation of this new data.

The evaluation results for this proposition are presented in Figure 5.15. Respondents with building automation background mainly consider this proposition to pose minor difficulties, however the estimated benefits vary a lot. Connecting the electronic thermostats to building automation was considered easy, but the associated costs troubled. Some valued the increased controllability of heating radiators high, while others did not see large benefits to be expected from this. Respondents with building services engineering background mainly saw this proposition as beneficial, however the assessed challenge of implementation diverged. In general the ability to synchronize heating and cooling was considered valuable. Respondents with property management background did not agree on the challenge but generally the improved heating control was welcomed. Respondents in property maintenance estimated the challenges of implementation to be medium, and the positive influence to be large. The positive influence was mainly attributed to the ability to adjust the heating power of radiators with regard to the actual room temperature rather than the temperature measured right next to the radiator. The necessity of changing the batteries did not trouble them.

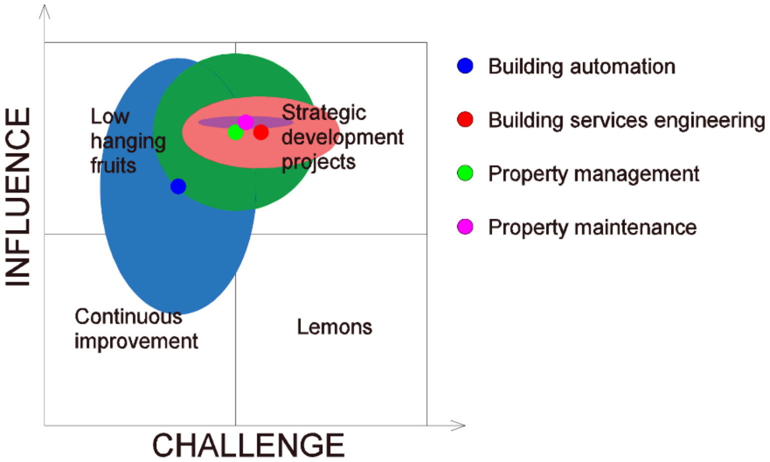


Figure 5.15 Evaluation results of the initiative of installing electronic radiator thermostats. The ellipse axis length corresponds to the standard deviation of answers, while the dot is the average.

5.4.2 Adaptive outdoor temperature compensation for heating

The vast majority of the buildings of the case organization have a radiator heating system where supply water temperature set point is determined by a compensation curve that is a straight line, which is a suboptimal heating control method. A straight line is not an ideal shape for a compensation curve as the required heating power is not linearly dependent on the outdoor temperature nor the heating power of radiators is linearly dependent on the supply water temperature (Paiho, et al., 2002). Therefore the curve placement or steepness often needs adjustment after users complain about thermal discomfort. A typical case is that during winters users complain about coldness and the curve is shifted upwards. Yet, after outdoor temperatures rise it is easy to forget to shift the curve back to its original position. This results in the radiator supply water being often warmer than necessary.

The automatic adjustment of the compensation curve requires only programming effort if room temperature measurements are available through the building automation system. An example of such a fuzzy logic based program is presented by Paiho et al. (2002, p. 69). The idea is to adjust the radiator supply water temperature according to outdoor temperature and room temperatures. The domains of these three parameters are divided into fuzzy sets that are used in control with fuzzy rules that are presented in Table 5.5. The configuring process begins by moving the original compensation curve to coincide with the current outdoor temperature and supply water temperature. Then the fuzzy reasoning is done twice: Late in the evening and in the early hours. If the result of both reasoning processes is similar in means of need and direction of change, a new point is recorded accordingly. Every point that is recorded in the future overwrites the existing point that is the closest, and so the compensation curve is updated by connecting the points. (Paiho, et al., 2002). This process is illustrated in Figure 5.16. By constantly checking for the need to update the compensation curve it is ensured that the supply water temperature is kept at an optimal level. The defuzzification method of the program was not specified.

Table 5.5 Rule base for the fuzzy controller. Translated from Paiho et al. (2002, p. 69).

1. IF room temperature is “cold” AND if the outdoor temperature is “cold” THEN “raise” the supply water temperature
2. IF room temperature is “cold” AND if the outdoor temperature is “mild” THEN “raise a lot” the supply water temperature
3. IF room temperature is “hot” AND if the outdoor temperature is “cold” THEN “drop” the supply water temperature
4. IF room temperature is “hot” AND if the outdoor temperature is “mild” THEN “drop a lot” the supply water temperature
5. IF room temperature is “suitable” AND if the outdoor temperature is “cold” THEN “don’t change” the supply water temperature
6. IF room temperature is “suitable” AND if the outdoor temperature is “mild” THEN “don’t change” the supply water temperature

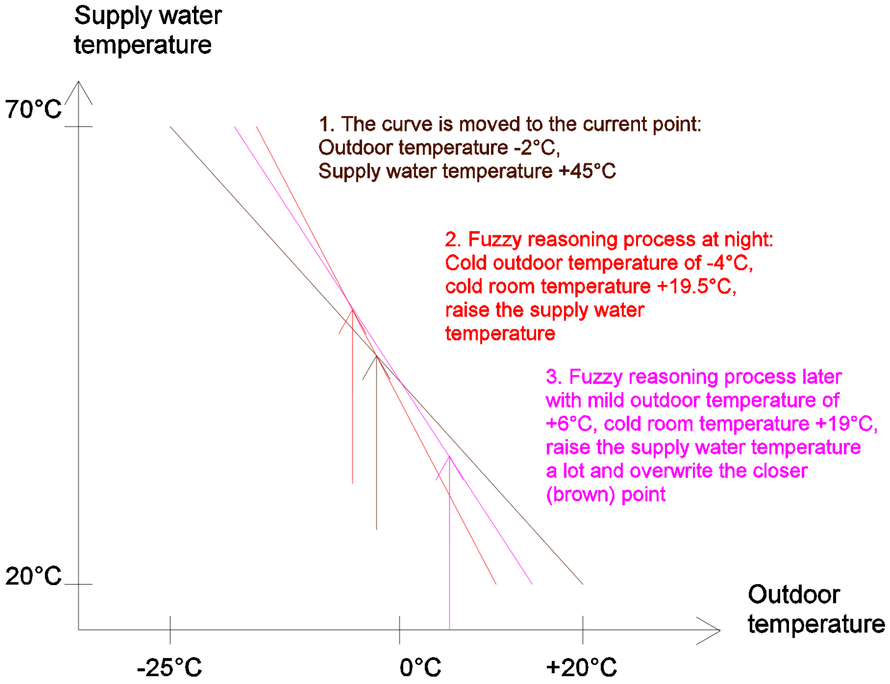


Figure 5.16 The principle of compensation curve modification process. Based on Paiho et al. (2002, p. 69).

The potential benefits of applying this program include smaller deviations from desired room temperatures, reduced energy consumption and a decrease in the workload of maintenance personnel. Naturally the extent to which heating can be optimized depends on the physical radiator network, whether it is the same for the whole building or if it is façade-specific. With façade-specific radiator networks other parameters can be utilized to a larger extent such as solar radiation. This increased adjustability has been found to enable savings of 8% in heating expenses (Laaksonen, 1995, p. 629). Anyhow, with adaptive heating control in a 20,000m^3 residential building with an annual heating energy consumption of 600MWh and a room-specific heating power of 184kW, Paiho et al. (2002, pp. 93-94) estimated the following benefits if the average room temperatures decrease by 1°C and maintenance workhours decrease by 5 hours a year:

- annual energy savings of 3.3% with a total heating energy consumption of 600MWh (800€ with 40€/MWh),
- savings of 170€ due to reduced workhours and
- smaller deviations in room temperatures.

There are some risks and drawbacks associated to the implementation of the program, too. First of all, the program cannot perform well if the measured room temperatures do not represent the temperature in the occupancy zone. For example if the temperature sensors are located inside a chilled beam problems are likely to arise. The decision on which room temperature measurements to include and how is building-specific. Secondly, the program requires constant monitoring by a property maintenance professional for a year to ensure its proper functioning. For property managers it is more likely a matter of resources than additional staff, however. Lastly, some precautionary measures must be taken to ensure the appropriate functioning of the heating system when room temperature measurements are temporarily distorted or unavailable. Such can include a default compensation curve when an abnormal situation is detected.

The prerequisites for the implementation of this program are easily met. Radiator supply water temperature control and outdoor temperature measurements are basic points of control and available through building automation. Also the room temperature measurements are often produced, but if that is not the case, retrofitting some wireless temperature sensors is not too big of a task.

The evaluation results for this proposition are presented in Figure 5.17. Respondents with building automation background considered this proposition to be highly beneficial with the dominant opinion being that the implementation would be easy, too. The main arguments were that efficient adjustment of heating could save a lot of energy, and often no added infrastructure would be required, or at least it would be easy to install. Respondents with building services engineering background mainly considered the application to be easy, however the benefits were estimated mainly to be medium. The person that estimated the challenge of implementation (and also the benefits) to be high was concerned that in Finland during periods of large daily temperature changes the program's performance may be suboptimal. Respondents with property management background estimated both the challenge and benefits to be medium, while respondents in property maintenance thought uniformly that the positive influence is high but challenging to obtain. They thought that successfully automating the shifts of compensation curves would save a lot of energy and time, but choosing the right room temperatures for input would be difficult.

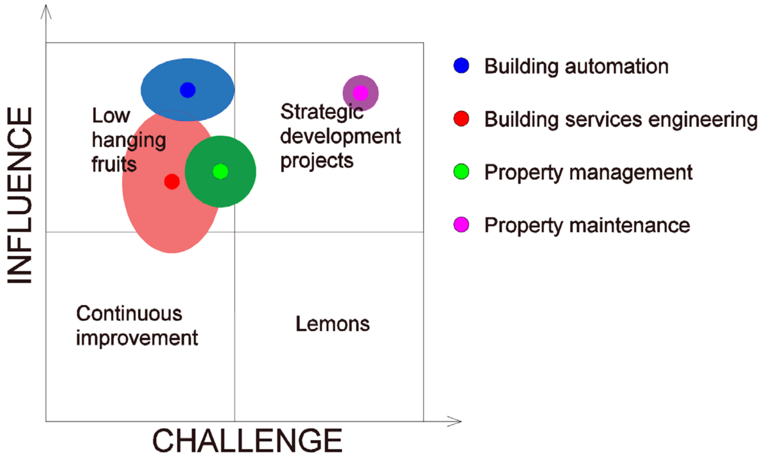


Figure 5.17 Evaluation results of the initiative of programming adaptive outdoor temperature compensation for heating control.

5.4.3 Room setback temperatures outside office hours

Unlike with the ventilation system, cooling system and plug appliances, the energy consumption of the radiator heating system of OfficeOne is not cyclical. Radiator heating output is kept at a level determined by the outdoor temperature regardless of the time and occupancy. By adopting setback temperature schedules for nights and weekends some energy could potentially be saved by lowering room temperatures temporarily by 1-3°C.

There are many ways to use setback temperatures. Setback schedules and depths can be given as fixed values based on safe side expert knowledge, or those can be the outputs of an algorithm that calculates optimal setback depths and likely reheating times so that overall energy consumption is minimized. Moreover, the existing equipment defines how the setback can be implemented. With radiators that have mechanical thermostats setbacks can only be applied by lowering the supply water temperature or reducing the water flow in the network. If the system was equipped with remotely controllable electrical thermostats, the setbacks could also be executed by controlling individual radiator valves. Anyhow, the limitations of the equipment should be considered before implementing setback temperatures. For example in the case organization's buildings the heat exchanger valves of the radiator network have usually been sized to meet the requirements of a cold winter, which means that with temperatures from -5°C to +10°C the control is rather coarse and the system is not precise in its adjustments.

Regardless of the method it is important to correctly determine the setback schedules to minimize user inconvenience but also maximise savings. To facilitate this aspect, a self-learning algorithm to learn and store reheating rates is presented next. The algorithm has been developed by Paiho et al. (2002, p. 127) to control a building's air supply based heating system in relation to building occupancy patterns. It was applied in a low-energy office building that consumes approximately 60% less energy than offices in average (Paiho, et al., 2002, p. 116).

The algorithm is based on the idea that the setback recovery rate is dependent on outdoor temperature alone. Then the time in minutes that it takes to raise the room temperature by 1°C is recorded for each outdoor temperature and used for control, as in the future this information can be used to derive the required advance to start reheating. The initial values for reheating rates are generated with test runs and the assumption of linear relationship between outdoor temperature and reheating rates. Also a boundary condition is applied: The reheating rates with indoor temperatures of 21°C and above are 0 min/°C. By using this information, a straight line can be fitted that contains all the initial values. (Paiho, et al., 2002). Yet, it may be wise to rule out setback temperatures during very cold periods when the excess heating power of radiators is used up.

The learning process modifies the initially linear curve based on true setback recovery durations. If the reheating duration is overestimated by let us say 20 minutes for a 2°C setback depth, a new point is inserted corresponding to that outdoor temperature with the initial reheating rate subtracted by 20 min / 2°C = 10 min/°C. On the other hand when the estimated reheating duration of 200 minutes is underestimated by let us say 30 minutes and the difference to the suitable room temperature is 0.6°C, then the new point corresponds to that outdoor temperature and the initial reheating rate increased by 0.6°C * 200 min/°C = 120 min/°C. Then this new point is connected to the nearest points. For the first learning event the point is connected to the initial curve's end points. This learning process is visualized in Figure 5.18. To impose restrictions to learning Paiho et al. (2002) used a 0.5°C deviation limit for resulting indoor temperature to differentiate between a successful reheating and a failed one, and the maximum allowed change to the initial reheating rate was limited to 50% to reduce the effect of errors. The effect of errors could also be effectively managed by the method of ordinary least squares. (Paiho, et al., 2002).

As the radiator heating system is more likely to experience long lags between control measures and room temperatures compared to air supply based heating, forecasted outdoor temperatures may become a necessary input to make better control decisions. Additionally it may be appropriate to integrate learning of the cooling times versus outdoor temperatures to enable better timing.

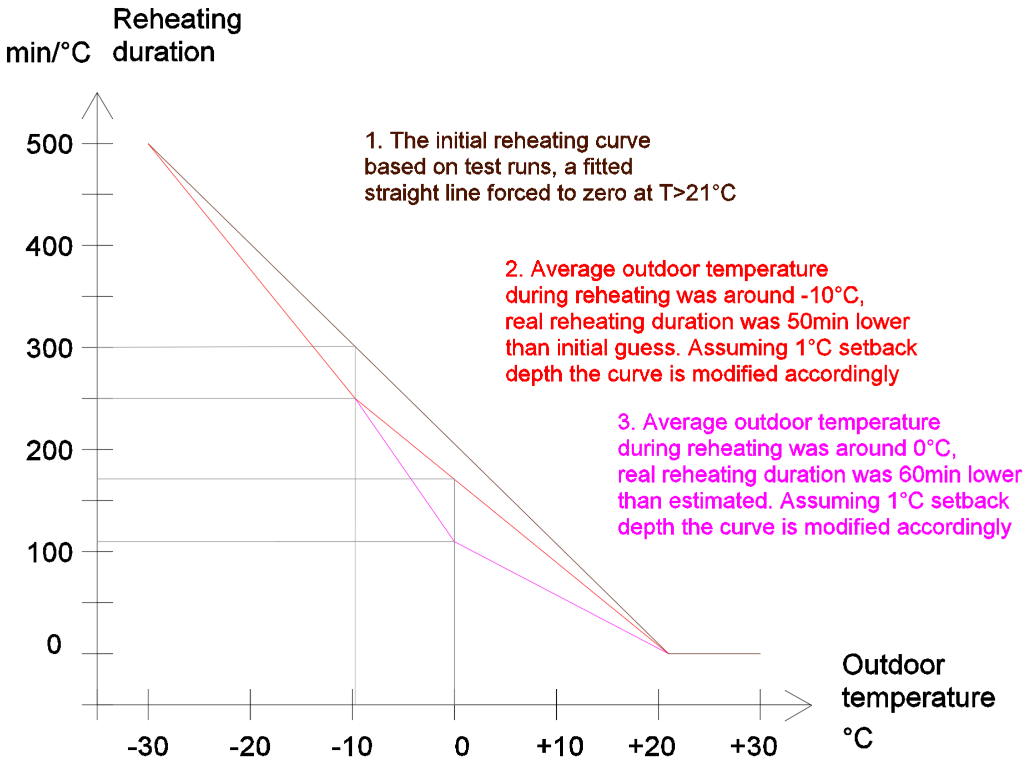


Figure 5.18 The learning process. Based on Paiho et al. (2002, p. 132).

Simulations on room setback temperatures suggest a decent amount of savings. In his Master's thesis Salama (2014) simulated 3°C night setbacks in radiator heating. In simulations that were based on a mathematical model of room thermodynamics in Python language the expected energy savings were 4.3% with the air-conditioning switched on for the night, and 22.5% with air-conditioning turned off for the night. The outdoor temperatures corresponded to temperatures in March in Finland. If the setback depth and length were optimized with regard to outdoor temperature the savings were 8% with average outdoor temperature corresponding to Southern Finland's annual average of 6.5°C. With an IDA simulator of VTT Technical Research Centre of Finland the simulated 3°C night setbacks resulted in energy savings of 12.6% between December and February in Finland. (Salama, 2014). To estimate the scale of the savings consider an office building in Helsinki with a surface area of 6100m^2. The consumed district heating energy during the past year was roughly 600MWh. If half of it is assumed to go towards radiator heating, a let us say 10% decrease in energy consumption would then equal to annual savings in money of 1200€ or 0.20€/m^2 with the price of 40€/MWh for district heating energy.

There are some problems associated with the implementation of setback temperatures: Setback recoveries can use up more energy than what was saved during the lower temperature period, the desired temperature may not be reached by the time users arrive and the feasibility of the method is situation-specific. In the reheating phase of a setback period the required heating power exceeds the power required in a normal situation. This fact leads to a building-specific break-even for the setback duration that determines whether any energy is saved. Moreover, the change in the heat content of the radiator network water uses up energy. For example in a 40,000m^3 educational facility the radiator network has 3m^3 of water. In fixed 5°C setbacks of supply water temperature the simple action of reheating the network water changes the water's heat content every time by 17.5kWh, and annually by 4.4MWh if the heating season is assumed 250 days long. This amount of energy corresponds to 1.1% of the total estimated radiator heating energy consumption of 400MWh in that building if the losses during heat exchange are not considered.

If the algorithm fails in estimating the duration for the reheating process and rooms remain chilly when users arrive, complaints can be expected. It is important to note that with mechanical radiator thermostats all the radiator valves are often completely open during the setback period. This leads to uneven water flow and so uneven heating in the setback recovery phase if the network is out of balance. (TA, 2011). Therefore it is possible that some rooms remain chilly longer than others causing thermal discomfort. If this problem cannot be solved quickly with the current resources it is more likely that the whole setback function is disabled rather than an external expert is summoned. Furthermore, an important notion is that temperature sensors often measure air temperature instead of operative temperature, on which the Finnish indoor environment categories S1-S3 and user's thermal comfort are based. Therefore successful implementation of setback temperatures requires constant monitoring by a property maintenance professional and knowledge on the building's characteristics to minimize the amount of dissatisfaction within the users and maximize the longevity of the setback temperature function.

The last major drawback of the implementation of setback temperatures is that its feasibility is very context-specific. First of all, to even consider its implementation the building should have periodical use patterns and the user's operations should not be harmfully affected by the temperature drop. Secondly, the function should adapt to the surrounding conditions. With temperatures much below zero the building's heating system is struggling to maintain a constant room temperature and there is not enough heating power to raise the room temperature rapidly. On the other hand, the setback depth should be optimized: Whenever there is much excess heating power available and room temperature can be raised quickly, the temperature drop can be deeper. Thirdly, it is often the case that the excess heating power has been minimized in a district heating based radiator heating system. Up to 30%-50% of the heating bill can consist of a payment that reserves a desired heating power capacity for the ultimate heating situation (Laaksonen, 1995, p. 581), however by average it is around 16% (Göös, 2012). This means that there is inherently a trade-off with the savings achievable by night setbacks and the costs of the required heating power.

The requirements of the implementation of setback temperatures on sensor and actuator infrastructure depend on the method. If temperature drops are carried out based on expert knowledge with mechanical radiator thermostats by lowering supply water temperatures, the existing automation systems are sufficient with data on outdoor temperature and control over supply water temperature. If setback lengths and depths are optimized, room temperatures and possibly weather forecasts are needed. As mentioned in Chapter 5.4.2, room temperatures are often available in the building automation system and if this is not the case, retrofitting a few wireless sensors is not a major issue. Weather forecast data can be acquired from commercial providers like Foreca or for free from Finnish Meteorological Institute, if such is not done already. Finnish Meteorological Institute's open data program is explained in more detail in Chapter 5.4.4. Importing weather data requires constant queries from the building automation system to a web feature service and partitioning the resulting file into exploitable parameters. If control over every radiator's valve position and temperature set point is desired, electronic thermostats with wireless control from building automation system is required as explained in Chapter 5.4.1.

The evaluation results for this proposition are presented in Figure 5.19. Respondents with building automation background considered the implementation of setback temperatures easy, however the expected benefits varied a lot. For some it was unclear how much of the saved energy would be used up in the reheating phases of setback periods, and whether anything would be saved at all. The programming part was not thought to be a problem, though. Respondents with building services engineering background mainly thought the proposition to be challenging, while the potential benefits were mainly estimated medium. It was emphasized that the balance of radiator networks should be verified before applying night setbacks. Respondents in property management did not see much benefits and considered the temperature setbacks to be a challenging area. The fact that the available excess heating power has been minimized does not strongly encourage the implementation of this proposition. Respondents in property maintenance estimated the benefits to be large, but also the challenge. They thought that with careful implementation setback temperatures would be a viable way to save heating energy.

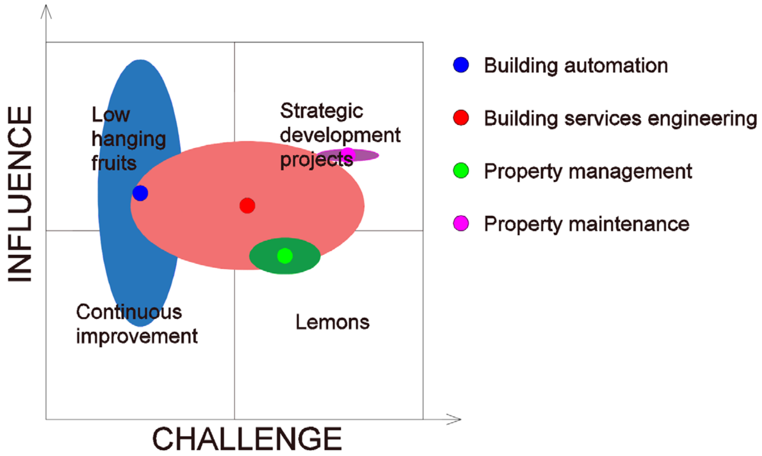


Figure 5.19 Evaluation results of the initiative of using room setback temperatures.

5.4.4 Optimizing heating with weather forecast data

During spring and autumn the changes in outdoor temperature can be large between the day and the night, which may lead to suboptimal heating control: Compensating the supply water temperature with outdoor temperature in real time is poor at taking into account the thermal inertia of the building. For example if outdoor temperatures suddenly rise in the spring after a long and cold period, the heating power is cut down instantly and users may consequently experience thermal discomfort due to the still cold structures. On the other hand in energy saving perspective, free energy is unharnessed when the building is heated during the early morning only to stop heating completely and start cooling a few hours later.

The solutions to utilize predicted heat loads vary. A simple approach is to use an average of outdoor temperatures of a certain time frame to adapt to fluctuating conditions. The challenge then is to determine that appropriate time frame for every building. Another type of a solution is based on Roger Taesler’s (2007) concept of equivalent temperature. Equivalent temperature is a transformed outdoor temperature that can be used to control the supply water temperature directly so that expected heat gains and heat losses are taken into account to maximize the use of free energy and minimize the use of purchased energy. (Taesler, 2007). It is essentially a mathematical model derived from a building’s heat balance that relies on technical building characteristics, site characteristics and weather forecast parameters. A commercially available product called eGain forecasting™ uses equivalent temperature in heating control (eGain, 2016). A more decentralized solution is the control of every radiator equipped with an electronic thermostat individually. Salama (2014) developed a neural network based solution that is used to control the room temperature set point based on weather forecast. The idea is to lower the room temperature in advance so that the changing outdoor temperature elevates it to the desired level. The neural network is found by a genetic algorithm that runs simulations. The inputs of the neural network are 11 different second time derivatives of outdoor temperature and the output is the deviation with the room temperature set point. In his Python language –based simulations of a thermal model of a room the achieved energy savings were 9% with the average outdoor temperature corresponding to Southern Finland's annual average of 6.5°C. The simulations were a part of the product development of the smart thermostat of Fourdeg. (Salama, 2014; Fourdeg, 2016). To estimate the scale of the savings consider an office building in Helsinki with a surface area of 6100m^2. The consumed district heating energy past year was roughly 600MWh. If half of it is assumed to go towards radiator heating, a 9% decrease in energy consumption would then equal to annual savings in money of 1080€ or 0.18€/m^2 with the price of 40€/MWh for district heating energy.

The main risks and drawbacks associated to continuous model-based predictive heating control are related to user dissatisfaction, difficulties in problem diagnosis and costs of installation. Similarly to the use of setback temperatures, user dissatisfaction leads quickly to the disconnection of the smart predictive control system, and to the situation when money has been spent for nothing. Additionally, the case organization's property managers are reluctant towards the installation of systems where problem diagnosis can only be done by external consultants. Whenever the parameters of a mathematical model are wrong, the maintenance personnel will face major difficulties trying to diagnose the problem, which also leads to the previously mentioned situation if the service provider is not accommodating. Anyhow, all of the predictive methods require constant supervision by a property maintenance professional for at least a year to ensure appropriate operation, which absorbs resources of the maintenance organization. Drawbacks of the installation of electronic thermostats have been discussed earlier in Chapter 5.4.1.

Again the required information and control infrastructure depends on the amount of operations included, though weather forecasts must be imported to the system in all of the cases. Those forecasts can be received from a number of providers, however the Finnish Meteorological Institute (FMI) provides them for free as a part of their open data program. By querying the web feature service of FMI one has continuous access to weather data. These queries can be made single point and parameter-specifically. It however is necessary to register for the service and obtain a user-specific API key that is used in the construction of a query. There are also limitations imposed to the number of requests made by a single API key in different time windows, however these limits are reasonable. (Finnish Meteorological Institute, 2014). The following findings were made based on FMI weather forecasts and subsequent observation data:

- By average the forecasted outdoor temperature was 2.0°C lower than the observation.
- By average the forecasted cloud cover exceeded the observation by 2.4 units on a cloudiness scale of 0-8.
- By average the forecasted wind speed exceeded the observation by 1.5 m/s.
- By average the forecasted air humidity was 5.4% higher than the observation.

The findings were based on 888 hourly forecasts between 20.5.2016 5:00:00 - 20.7.2016 7:00 with scopes up to 24 hours. Observations were not available coordinate-specifically, so the values are weather station (suburb) specific. The forecast coordinates belong to that suburb though. Also cloud cover observations were limited to a scale of 0-8 whereas forecasts were on a scale of 0-100 (requiring conversion to 0-8).

The web service queries can be made with a web browser that opens a XML file containing time and parameter stamped forecast values. For example a query to obtain the temperature, total cloud cover, wind speed, wind direction, dew point and accumulated solar radiation forecasts for a randomly chosen point in Åland Island would be of form:

```
http://data.fmi.fi/fmi-apikey/<API-
key>/wfs?request=getFeature&storedquery_id=fmi::forecast::hirlam::surface::point::timevalue
pair&latlon=<Latitude and longitude, for example:
“60.2,20”>&parameters=temperature,totalcloudcover,
windspeedms,dewpoint,winddirection,radiationglobalaccumulation
```

After the forecast provider has been chosen, it is only a matter of creating the software interface to import the data into building automation. The rest of the information and control related challenges with regard to supply water temperature, outdoor temperature, room temperatures and electronic radiator thermostats have been discussed earlier in Chapters 5.4.1 and 5.4.2. Still it should be emphasized that the room temperature measurements need to be representative of the conditions in the occupancy zone. Neglecting this and operative temperature considerations could lead to user complaints and disconnection of the whole function. Operative temperature can be well below the room temperature for example when the windows are large, and heating power is too low to eliminate the cold draft.

The evaluation results for this proposition are presented in Figure 5.20. Respondents with building automation background considered the challenges in weather data utilization primarily minor. Weather data is available from a number of sources and importing it is straight-forward. The expected gains differed, though. The usage of weather data directly in radiator heating control raised suspicion, however more confidence was placed on the benefits in special heating control such as snow melting. According to a respondent these savings can be significant when the warm weather of the next day is used to melt the snow instead of electricity. Respondents with building services engineering background considered weather data utilization to be easy as well, with mainly large benefits to be expected. After all it is about harvesting free energy. Respondents in property management estimated the benefits to be medium, but thought that predictive heating optimization would be difficult without compromising thermal comfort. Respondents in property maintenance regarded this field as both challenging and rewarding. They thought that at best this improvement would help in keeping the indoor thermal conditions more stable with dynamic weather.

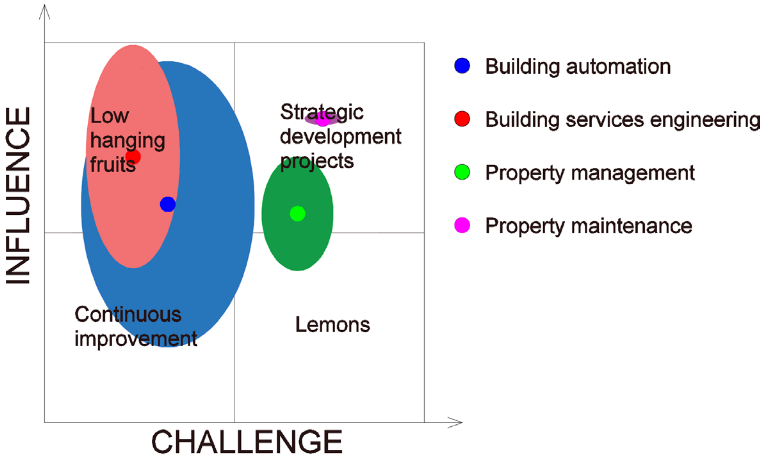


Figure 5.20 Evaluation results of the initiative of utilizing weather forecast data in heating control.

5.4.5 Intelligent lighting and blind control with daylight harvesting

Occupancy detection is utilized extensively in lighting control, however available daylight is not. The disregard of users can easily undermine the attempts to harvest the daylight, too. When the sun is shining strong and low the blinds are often closed by the user, but after the sun has risen the blinds remain closed and lights on even if the daylight would be enough to illuminate the space. It is impossible to know currently how well the daylight harvesting function is working in OfficeOne based on Chapter 5.3.4, but it can be suggested that gradually adjusting artificial lighting could make more use of the available daylight than a simple on-off switch.

To make the most of the available daylight and to automate energy conservative behavior it would be necessary to integrate blinds and lighting control. The idea is to let daylight into the room whenever there is no risk of glare, and correspondingly adjust the artificial lighting level. Doing so would obviously require motorized blinds. Moreover, the controller requires information on the available outdoor illuminance, which can be provided by illuminance sensors. The sensors can be placed in rooms or on the outside wall to detect the space-specific daylight intensity. Then with information on solar position the likelihood of glare can be inferred. Next the outlines of two solutions are presented.

Two solutions developed around the latitude of Finland shared a number of similarities. Paiho et al. (2002, p. 211) developed a fuzzy control system that is based on vertical surface daylight intensity, sun altitude and the azimuth as inputs, and blind angle together with artificial lighting level as outputs. The fuzzy rules are essentially based on the notion that glare is likely when the sun's altitude is low and the vertical surface illuminance level is over 20klx. (Paiho, et al., 2002). The glare is then eliminated by adjusting the blind angle. A similar system was developed and tested by Bülow-Hübe (2007). The idea is to keep the slat angle equal or greater than the cut-off angle of the present effective solar altitude when the vertical surface illuminance threshold of 20klx is exceeded. The effective solar altitude takes into account the latitude and orientation of the building, and the cut-off angle is the angle that prevents direct sunlight. In the case of negative cut-off angles the blinds remain horizontal to eliminate a direct view of the sky. On the other hand, with a long period of little available daylight the blinds will be raised to maximize daylight intake (Bülow-Hübe, 2007). Some cut-off angles for effective solar altitudes are presented in Figure 5.21.

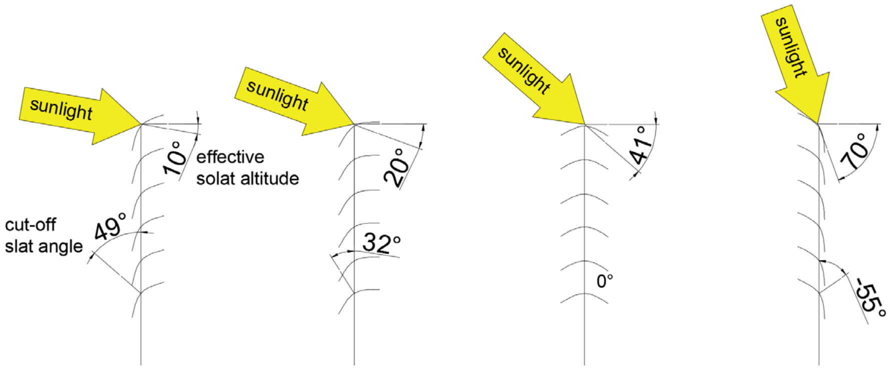


Figure 5.21 Cut-off angles for effective solar altitudes. Based on Bülow-Hübe (2007, p. 16).

The solar altitude angles for each time of day change constantly in the latitudes of Sweden and Finland. This makes the blind angle control more complicated than in countries closer to the equator. Bülow-Hübe (2007) solved this problem by using three different slat angles during the day that are listed for each month. Solar position can also be calculated with an algorithm. In one presented by Reda & Andreas (2004) the solar azimuth and zenith angles can be determined with an accuracy of around ±0.0003° and validity from the year -2000 to 6000. The required parameters for the solar position calculation are date, coordinated universal time, the fraction of a second that is added to the coordinated universal time to adjust for Earth's irregular rotational rate. The predicted values for these fractions of a second are reported weekly for example by the United States Naval Observatory. Other necessary parameters are longitude, latitude, elevation and annual local pressure and temperature. The coordinated universal time is based on universal time, also known as Greenwich civil time, and is kept within 0.9 seconds of universal time by one second steps. These steps are reported based on observation. Also the slope and azimuth rotation for the observation surface are required to determine the angles of incidence from the solar angles. Note that the solar azimuth angle is measured from north towards the east, and the solar zenith angle is measured from up towards the horizon in this application as depicted in Figure 5.22. (Reda & Andreas, 2004).

An important objective is to avoid inconvenience to the users due to fluctuating control. For example consider the situation when a cloud moves in front of the sun that causes glare: Before the event the blinds were closed and lighting level was high, and after the cloud blocks some of the sunlight, blind angle is lowered and lighting level decreased. Soon afterwards as the cloud moves away, the blinds are closed and lighting level increased again. To avoid such annoyance there should be a sufficient delay of around 15-30 minutes integrated to the action of opening the blinds, however the action of closing the blinds should be swift. The delay length could also depend on the amount of fluctuation in the measured daylight illuminance. (Paiho, et al., 2002).

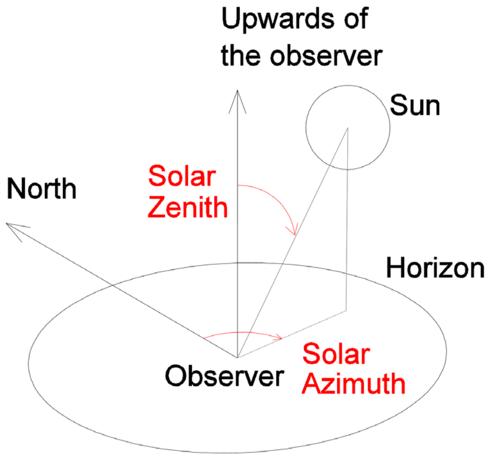


Figure 5.22 The two solar angles: the zenith and the azimuth.

The benefits of integrated blind and lighting control include reduced electricity consumption of artificial lighting and reduced cooling energy consumption. These benefits can be attributed to decreasing heat loads and visual discomfort with blinds while maximizing the use of available daylight. In their simulations Paiho et al. (2002, p. 224) achieved average lighting energy savings of 44.3% in comparison to the situation when lights are constantly on at their nominal output during working hours. Therefore these savings are not comparable to occupancy detection based lighting control situation. Similar results were observed by a real test bed in Sweden with average annual savings of approximately 50%. The savings were however really seasonal due to available daylight: 77% in May and 5% in November, respectively. Also if working desks are located far from the windows the expected savings reduce to around 25%. (Bülow-Hübe, 2007). When estimating the scale of these savings, consider an office building in Helsinki with a surface area of 6100m^2. The average amount of electricity used for lighting is 400kWh daily which in money corresponds to 33€ daily and about 12 152€ annually with the price of electricity of 8.4c/kWh. The potential savings are then annually 6076€ or 1.0€/m^2 in comparison to the situation when lights are constantly on at nominal output during working hours.

The drawbacks of integrated blind and lighting control include the investment and lifecycle costs of motorized blinds, and the annoyance of users especially if the system is not working properly. Motorizing the blinds costs and even though the blinds can be wirelessly controlled, they need a power supply and thus electrical wiring. This adds to the installation cost. The tuning process of the system on the other hand can be annoying for users. Even the fluctuating artificial lighting level can be a distracting element, but when blind movement and angle adjustment is added the whole system risks becoming an inconvenience. Anyhow, as there is little experience of motorized blinds in Finland some policy resistance is only natural.

Lighting systems are challenging in the information and control infrastructure sense. In the case organization’s buildings lighting control is often implemented locally with DALI protocol. This means that the lights are not connected to building automation, and all the programming must be done on the spot. Many building automation control software support the inclusion of systems operating on DALI protocol, but doing so requires expertise in that field from the building automation contractor. In OfficeOne for example, corridor lights and lights in the outdoor areas that are operating based on time schedules are connected to OPENweb ControlPanel, but room lighting is left out. It is perhaps because of the specialized nature of the lighting field: There are lighting management solutions such as Helvar Imagine (2016) commercially available that can be integrated to building automation, and systems such as Houm (2016) that are completely cloud-based and do not emphasize integration with building automation. Anyway, the decision on whether to integrate these systems or not is not straight forward. Integration always requires maintenance when systems update or are replaced, and if both of the systems enable remote problem diagnosis and system supervision separately, there may not be enough grounds to integrate them. The decision will nevertheless determine whether the sensor data used in lighting control will be available in the control of other devices through building automation.

Other information availability and control infrastructure problems relate to illuminance inference and blind control. Installing illuminance sensors is not a major task, however if daylight availability estimation is based on a vertical surface illuminance measurement and solar position calculations, some astronomical parameters need to be imported to the program. The shading devices on the other hand can be controlled with building automation for example by installing commercially available controlling solutions such as Somfy Animeo (2016) product family that supports IP, KNX and LON protocols.

The evaluation results for this proposition are presented in Figure 5.23. The respondents with building automation background did not have similar opinions on neither the challenge nor the benefits of a daylight harvesting blinds and lighting control system. Daylight harvesting as a lighting control principle was generally seen as a desirable goal, whereas including motorized blinds was not. Respondents with building services engineering background considered the proposition to be challenging with varying estimated benefits. Respondents with property management background estimated diverging benefits, and the challenge of implementation was considered above medium. This can be attributed to previous experience: Motorized blinds were installed in a building and the users were not satisfied because of inconvenient blind movement. Respondents in property maintenance regarded this field as both challenging and rewarding. They thought that currently the available daylight is not utilized sufficiently.

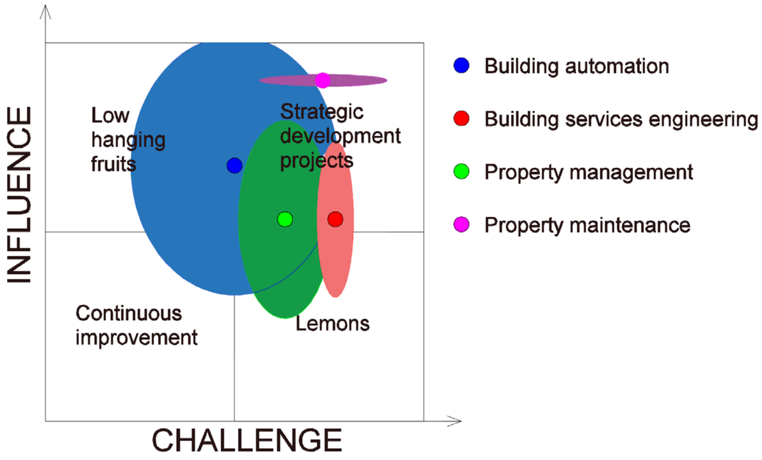


Figure 5.23 Evaluation results of the initiative of daylight harvesting with motorized blinds and constant luminance lighting control.

5.4.6 Improving the manageability of large amounts of sensor data and actuators

Large amounts of sensor data nor actuators can be managed well without case-specific definitions. Forming a control group of snow melting heaters of all the buildings in the same suburb would require programming effort, or querying the efficiency of all the heat recovery units would require manual gathering of all the relevant measurements. There are no hierarchical system- and location-specific attributes for actuators or sensor data that would ease the work of the maintenance organization. Note that OfficeOne alone produces continuously over 600 different measurements.

On the other hand, allowing property managers to create refined data streams and views based on their needs would facilitate their supervisory task and benchmarking. These refined data streams could include SFP figures, heat recovery efficiencies and other HVAC system metrics. If the software allows the creation of user's own views, these figures can be laid out on the same page across different buildings. Attributes would be of great help in the process of key figure definition, as all the relevant measurements could be easily referred to as their attributes rather than sensor network nodes. Moreover, if better alarm event management is desired, the attribute-based data modelling philosophy should be extended there. Also the ability to define triggers and data fields in alarm events such as Boolean alarm criteria, traffic lights to visualize status, response time calculation and cumulative costs of maintenance negligence the alarm event management could produce more useful figures to an active property manager. The matter of alarm events with attributes is not considered here further, however.

The basic idea is to add attributes to sensors and actuators that describe its location and the measurement or actuator type. Moreover, these attributes should be structured hierarchically when possible. An example of this procedure with room temperature measurements is presented in Table 5.6. By utilizing the properties of relational databases, repetitive attributes can be input only once with primary and foreign key relationships. In the tables below, the ID column higher in the hierarchy is the primary key (PK) to which the tables lower in the hierarchy refer to with their case-specific foreign key (FK) column.

Table 5.6 Normalization of sensor data.

BEFORE NORMALIZATION

Point-wise measurements

Date	Time	Room 101 Temperature (°C)	Room 102 Temperature (°C)	Room 201 Temperature (°C)	Room 202 Temperature (°C)
1.4.2016	07:00:00	20	21	20.3	20.7
1.4.2016	07:05:00	20.5	21.3	20.6	21.1
…	…	…	…	…	…

AFTER NORMALIZATION

Floor table

ID (PK 1)	Floor Name
1	1st floor
2	2nd floor
…	…

Room table

ID (PK 2)	Room Name	Floor ID (FK 1)
1	101	1
2	102	1
3	201	2
4	202	2
…	…	…

System table

ID (PK 3)	System name
1	Room measurements
2	Radiator heating system
…	…

Measurement type table

ID (PK4)	Measurement type	Measurement unit	System ID (FK 3)
1	Temperature	°C	1
2	Indoor air CO_2 concentration	ppm	1
3	Illuminance	lux	1
4	Supply water temperature	°C	2
…	…	…	…

Fact table

Date and Time	Measurement	Room ID (FK 2)	Measurement ID (FK 4)
1.4.2016 07:00:00	20	1	1
1.4.2016 07:00:00	21	2	1
1.4.2016 07:00:00	20.3	3	1
1.4.2016 07:00:00	20.7	4	1
…	…	…	…

The example above is meant only for introductory purposes, as in reality the database design task is much more complex. Such a database structure would face problems with measurements that are not limited to a single room, but are distributed across several areas such as in an AHU. Therefore it is necessary to develop a more flexible database structure so that areas can be defined. It may also be a good idea to allow for relationship definition between systems and locations in the database structure, even if that is not utilized immediately in applications. This matter is further illustrated in Appendix 2.

The benefits of attributes in measurement data and actuator control are indirect. These attribute-based features would allow for faster routine operations such as switching seasonal heaters on and off, user friendlier measurement data management by data slicing functionalities and easier monitoring through refined information and benchmarking. These features would not save energy alone, but only through active harnessing of a property manager. A lot of energy is wasted because of failures in simple things that go long unnoticed, such as forgetting those seasonal heaters on or by having the heating power unnecessarily high. With a better data model and user interface the property manager could easily define the key figures that reflect his concerns, and drill from abnormalities through to the underlying problems.

By focusing in attributes in application development the hardware gradually loses its importance in programming sense. All references in applications can be made through attributes rather than network addresses. Also, adding or replacing sensors is only a matter of adding rows in tables rather than a data structure affecting operation. Extrapolating the database thinking of sensor data and attribute-based controls leads to many cross-platform possibilities as every measurement and actuator could be linked to a location in a building information model for example. Acquiring attribute-based control capabilities can be problematic as it either is a fundamental element of a building automation system or then it is not. The development of such features can be expensive, and so it would require sufficient demand in the market.

When it comes to adding attributes to sensor data the problems are easier to overcome. Measurement data can be imported from a building automation system to an external server that then writes a database with every piece of measurement data containing attributes. Anyhow, software development and database management is not free. Properties produce huge amounts of data that require processing capabilities, data transfer, server rooms with cooling and database maintenance.

The evaluation results for this proposition are presented in Figure 5.24. Respondents with building automation background considered the challenges of implementation in improving the manageability of large amounts of sensor data and actuators to be medium with medium to high benefits to be expected. Some of the controller software already support user-defined attributes to an extent. Group control of some previously defined actuator groups was generally considered desirable with a large amount of properties to manage, but everyone did not see the benefits in an interface enabling arbitrary control groups. The estimated challenge and benefits diverged dramatically among respondents with building services engineering background. Two of them thought that time could be saved a lot making sensor data and actuator management more efficient, whereas one person did not see these benefits. This person is not involved with a similar stock of properties every day, though. Respondents in property management regarded the proposal to be somewhat of a *low hanging fruit*. In their perspective the natural direction of controller software development should include a data model to better manage with the huge amounts of data. Also benchmarking views were thought to be desirable for energy management purposes. Respondents in property maintenance were frustrated with the current snow melting control. Currently it is based on outdoor temperature limits so that the heaters are on during most of the heating season. Stricter limits have not served their purpose as the heaters have then been off when they have been needed. The property maintenance respondents therefore thought it best to have a single switch to stop snow melting altogether within a sensible area when there clearly is no need, and thought that this would save a significant amount of energy. Also the ability to define time schedules of equipment in groups was desired.

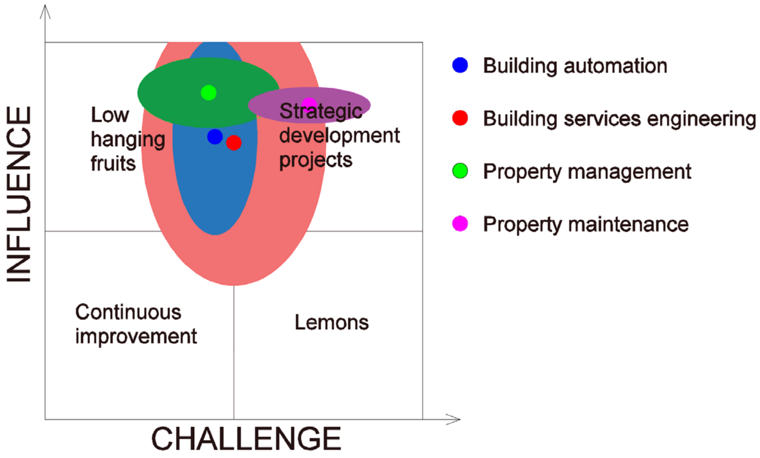


Figure 5.24 Evaluation results of the initiative of improving the manageability of large amounts of sensor data and actuators.

5.4.7 Enabling communication between building automation and room reservation systems to reduce energy consumption and manual input

Energy is wasted when empty rooms are being conditioned. With multi-user office space in the case properties this is not much of an issue because the rooms are rarely completely empty during office hours. Yet, with irregularly used rooms such as lecture halls or meeting rooms the energy inefficiency can become more of a concern. In some of the case properties' lecture halls, air handling unit operation times are set by hand according to teaching timetables. Air supply can also be based on a fixed schedule or occupancy detection. None of these solutions alone is optimal: Manual input is laborious, fixed schedules disregard empty rooms and occupancy detection requires time-out periods to compensate for inaccuracies in detection. On the other hand, there is a discrepancy between meeting room bookings and true usage due to last minute cancellations and over-estimated time needs. Empty rooms that are free for use may then appear to be reserved when looked up through the system.

A solution is to enable communication between the user, room reservation system and building automation system. A system that does this has been developed by Padmanabh et al. (2009). It monitors the state of meeting room with wireless sensors and compares it to the actual bookings. The system consists of an application server, database server, SMS server and a sensor cloud. Their system operates as a proxy between Microsoft Outlook booking system and the user. To use the system, the user is required to give their phone number. If a user is trying to book a room that is currently unavailable for the desired time, an option becomes available to be put on a waiting list that can be room or zone specific. The system keeps track of chances made in the bookings, and if a meeting is cancelled and there is someone in the waiting list, they are alerted through SMS and e-mail to book the room. If 60 minutes have passed without any bookings from the person first in the waiting list, the next person is given a chance. Additionally, if a room has been booked and five minutes have passed since the meeting start time without any activity detected by sensors, the meeting organizer receives a SMS telling them to cancel their booking. Once the booking is cancelled, the waiting list gets serviced. The system also alerts the meeting organizer if they have left lighting or air conditioning on after a meeting. (Padmanabh, et al., 2009).

Implemented with the case buildings the system would be slightly different from the one presented above as observable in Figure 5.25. The application would require an interface with building automation to gain access to sensor data, whereas the previously introduced system had its own sensors. Moreover, if it is desired that the application can directly control equipment, some security concerns may have to be tackled. Still, essentially the system would be very similar to the one presented by Padmanabh et al. (2009), except that lecture hall reservations are given as an input rather than booked through the system. It would monitor the reservations of meeting rooms in Microsoft Outlook and also the reservations of lecture halls. Based on this information supply air unit operation schedules and room temperature set points are imposed with sufficient advance to the event starting time. If occupancy sensors do not detect any activity within 5 minutes of starting time, the lecture or meeting organizer is asked with a SMS if anything will take place at all in the room. If not, the conditioning will be stopped. If the user answers *yes* or no answer is received at all, conditioning of the room continues. The system can be notified about the premature end of an event by a SMS, and if no movement is sensed for 15 minutes the organizer is asked through a SMS if the event has ended. It is noteworthy that the system does not make a decision to degrade the indoor environment's quality unless a confirmation is made with a SMS.

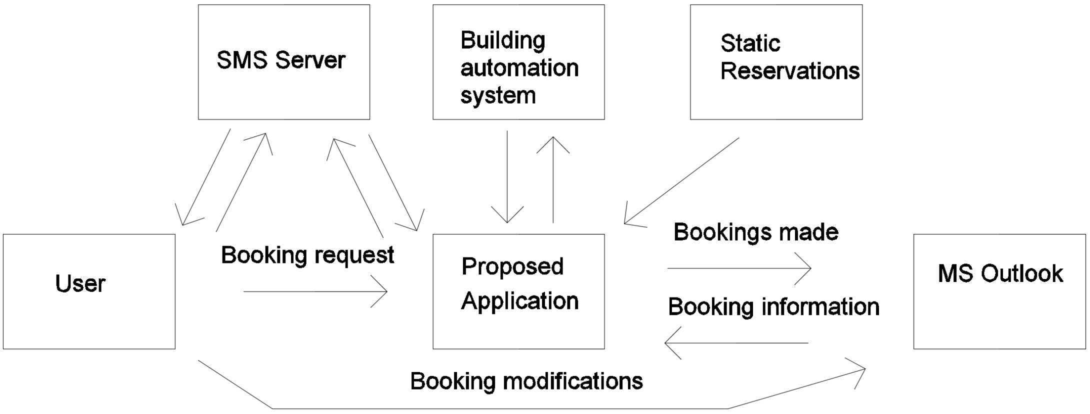


Figure 5.25 Architecture of the proposed system cluster.

The benefits of the application are reduced energy consumption, increased room utilization and reduced manual input. Padmanabh et al. (2009) tested their application during 60 days in one of the buildings of their company in India. The company has more than 100,000 employees and approximately 2,700 meeting rooms in total. They were able to elevate the utilization of the meeting rooms from 67% to 90%. For their working hours this equals to about 2 extra hours per day in a conference room. If the utility is extrapolated to their whole stock of meeting rooms, the improved utilization corresponds to a utility of 583 new conference rooms. With their alerting mechanisms on air conditioning or lighting being accidentally left on they were able to save 13% of the electricity consumption.

The application communicating with reservation systems, Outlook and building automation systems will be difficult to upkeep due to many integration interfaces. Problems may arise every time any of these systems updates, thus incurring maintenance costs and downtime. The situation when some of the systems is replaced is completely another issue. Another drawbacks are that majority of the energy savings are achievable simply by occupancy-based control of air supply and lighting, and the building automation system can produce reports on room occupancy if the discrepancy between bookings and true usage is suspected to be high. These undesired habits can then be mended with organizational policy. The feasibility of this application however rises together with the number of meeting rooms and the demand for them. The main technical challenges relate to enabling the communication between software, and if the application is allowed to control any equipment, the security of the whole. The integration would require a lot of coordination between experts of different software to come up with a properly functioning entity. The readiness of software to integrate with anything and the interests of the organization to co-operate can vary a lot adding to the difficulties. Nonetheless, occupancy sensor data of the meeting rooms needs to be available in the building automation system.

The evaluation results for this proposition are presented in Figure 5.26. Some respondents in property management, building services engineering and building automation that have been involved in software development projects saw the integration of a number of systems as both too expensive and laborious when much of the benefits can be gained simply by occupancy detection. The other respondents generally considered the challenge of implementation to be lower for this proposition. Respondents in property maintenance and building automation who evaluated the benefits high justified this by the present amount of daily manual work that could be eliminated, while the others generally estimated the benefits to be smaller.

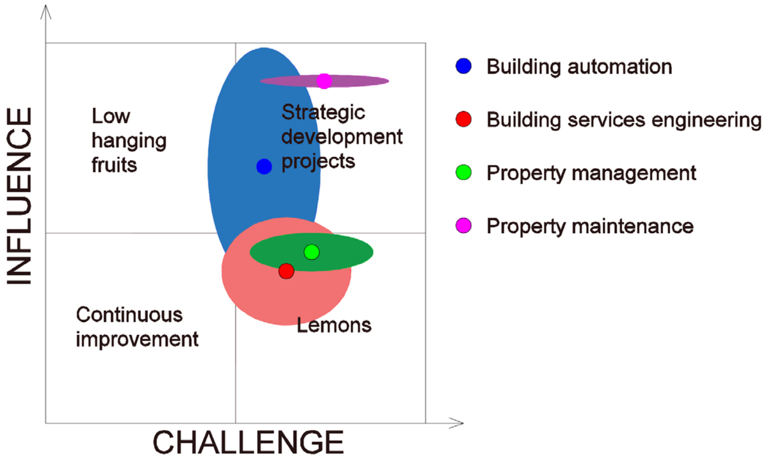


Figure 5.26 Evaluation results of the initiative of utilizing room reservation data on equipment control and managing the discrepancy between bookings and true occupancy.

5.4.8 Satisfying the dynamic demands of users with artificial intelligence based control of equipment

Building users are not always able to adjust indoor conditions towards their liking which can be a factor that leads to complaints. These complaints can then cause a large amount of work for property managers who try to fix the situation, as every change in room conditions could lead to new complaints from other users. If the users were given the ability to tell a computer what conditions they want and where, and the computer could satisfy these demands to a reasonable extent, this work would be reduced greatly.

Artificial intelligence (AI) can be a useful framework to tackle these kind of issues because of capabilities in learning, reasoning and optimizing. If predictive capabilities are desired in control, a possible approach is to create a decision unit that uses measurement data to analyze situations and determine interventions to meet previously defined objectives. These objectives can be anything that is measured or possible to derive from measurements, such as room temperature, carbon dioxide content of air, deviations from target values, illuminance and energy consumption. In other words, the decision unit could perform any optimization tasks, even non-linear ones, if inputs and outputs are measured. The building users could then tell the decision unit what they want, and the unit will control the equipment accordingly within appropriate boundaries. The decision unit could basically be a functionality of a room controller, however the heavy processing tasks such as machine learning could be done on a separate server.

There are two essential functionalities of the decision unit: predictive capabilities and efficient optimization. Examples of these are presented next. Predictive capabilities can be gained with data mining models such as neural networks, whereas optimization can be done with a genetic algorithm where fitness of an individual can be weighed to favor energy efficiency or comfort. The data mining model would require extensive training data including every possible control situation in every possible context to achieve a satisfactory level of predictive accuracy, because the optimization technique will only be as good as the predictive model due to its usage in the solution optimization. Including energy consumption optimization in every control action by a weight that the user has approved and giving users more control could result in energy savings and reduced complaints. Also the less time is used in dealing with complaints the more resources are available for other tasks.

Still, these positive aspects also embody a negative side, and there are many downsides in the implementation of AI based control. First of all, gathering the training data can be a very long task especially with systems that have long delays between inputs and outputs such as radiators. Also the number of systems adds to the training time as every state of system operation in every context needs to be trained. Historical data from normal operation is unlikely to be suitable for training, especially if the control targets have always been the same. It is virtually impossible to completely train a predictive model, which leads to the problem of unreliable predictions in situations that have not been experienced before. On the other hand, giving users control over the room's conditions may cause larger problems with the thermal functionality of the area as a whole. Having separate areas of a large room trying to achieve completely different thermal conditions leads to a high energy consumption. Also the amount of statistical intelligence in control makes it extremely difficult to diagnose the reason for upcoming problems, and an external consultant is likely to be needed every time the system is not working properly. Perhaps the largest problem of all is that once any of the building systems controlled by AI is replaced, the model needs to be trained again.

A predictive analytics model will require all relevant contextual information, control signals and outcomes as direct measurements or derived values. For example in OfficeOne such control would require electronic thermostat valves in heating and as much recorded data as possible. The required data depends on the application, but could include occupancy detection, radiator valve positions, chilled beam valve positions, lighting output, available daylight and illuminance at every workplace. As described in Chapter 5.4.5 the act of integrating lighting control in building automation is a challenge itself. Also to tackle the problem of bulk energy consumption measurements devices would need to be run separately in the training phase, or this information would need to be derived based on some other data.

The evaluation results for this proposition are presented in Figure 5.27. Respondents with building automation background considered the challenge of implementation of AI based control to be high with varying benefits to be expected. The weight of expected benefits was below medium, indicating a slight orientation towards a *lemon* proposition. This can largely be attributed to the reduced manageability of systems: Among these respondents there was a desire to be able to know exactly what each actuator is doing and why. Two respondents with building services engineering background expected large benefits with challenging implementation. The reasoning behind the benefits was the potential ability to save energy whenever users permit it, but accomplishing this would need significant tuning, dividing space appropriately for control and sufficient resources for the unit's upkeep. The outlier of small benefits and challenge considered AI more appropriate in smaller nonlinear optimization tasks, such as choosing an ideal starting time for heating setback recovery. Respondents in property management expected medium benefits with medium to high challenge, while respondents in property maintenance expected both medium benefits and challenge. There was no discussion regarding these evaluations.

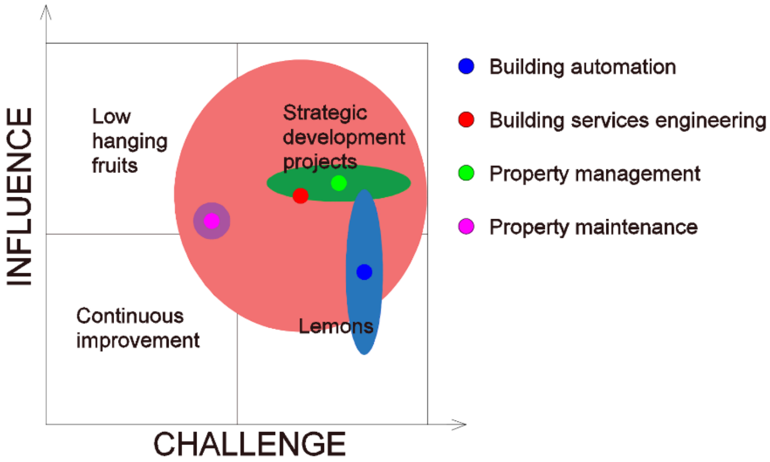


Figure 5.27 Evaluation results of the initiative of using artificial intelligence in equipment control.

5.4.9 Utilizing context-aware alarm thresholds in fault detection

In the case study it was observed that most of the alarm events on HVAC processes are based on a single value threshold. With single value thresholds there is a trade off with early detection of faults and false alarms: If thresholds are very strict, faults can be detected early with the cost of many false alarms and if the thresholds are not strict, faults may not be detected before the system stops working completely. Some reduction in false alarms could be achieved if the fault detection tool could learn to distinguish between normal operation and a fault.

Such functionality can be realized by statistical models that group sensor measurements automatically into different situations. This idea is visualized with self-organizing maps in Figure 5.28 where each cell in a field corresponds to the same situation between fields. For example the top right corner of every field is the same situation, and the usual parameter value is shown on the bar to the right of every field. The statistical model has information on the typical value and the usual deviation range of every parameter for every situation. Therefore the distance from a situation that is considered normal is not measured in one dimension as it is done currently, but in as many dimensions as there are measurements. With a group of measurements as an input, the outputs of for example Microsoft Clustering are the nearest cluster, distance from the nearest cluster, probability that the measurements belong to a cluster or that these measurements are included in the model at all. These outputs can be used to detect faults after normal operation has been shown to the model. A clustering model was used to detect a manually inserted heat recovery malfunction in Appendix 3.

With more accurate fault detection the upcoming alarm events would be taken more seriously, as maintenance personnel would experience that by default an alarm is likely to require action (although this attitude can be reinforced by prioritizing fault events too). This can incur major benefits to the maintenance organization as every fault has implications on user inconvenience, maintenance costs and energy consumption if not detected in time. The statistical models could also provide alarm-specific feedback on the usual energy consumption of that situation versus normal operation to encourage early involvement. The model cannot produce anything that is not measured, however.

The drawbacks of statistical models are that they need extensive and reliable training data, or at least supervised learning where an expert specifies normal operation to the model while it is observing the measurements. Regardless of the means of the training, there is need for expertise in statistical tools and building systems during the tuning process of the model, which is costly. Also no matter how well the training is done, eventually the model will face a situation that has not been trained, and then its performance will be poor. Therefore if some accuracy in fault detection is gained, it comes with the price of dependence on consultants that help in tuning the model.

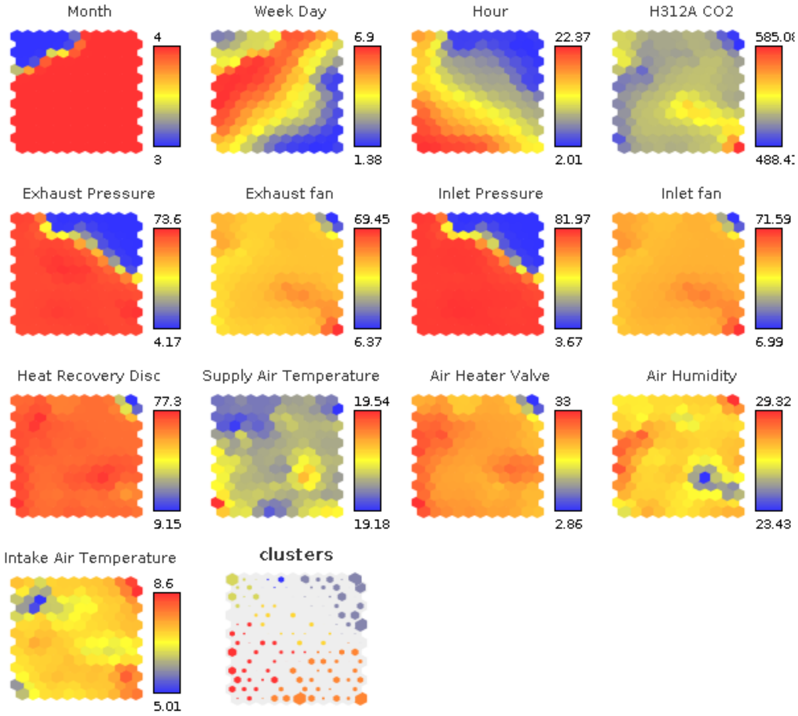


Figure 5.28 Self-organizing map of air handling unit sensor data.

The evaluation results for this proposition are presented in Figure 5.29. Respondents with building automation background mainly regarded the challenge of implementation of context-aware alarm thresholds to be medium and the benefits to be small, with a slight overall orientation towards a *lemon* proposition again. It was mostly difficult to see what there was to gain by eliminating some false alarms, and the tuning process of the tool was considered laborious. It was suspected that the tool would not be able to capture all the states of normal operation, which could lead to even more false alarms than currently. The evaluations of respondents with building services engineering and property management background diverged without much discussion on the reasons for the grades. They would not have to deal with alarm events in their work. Respondents in property maintenance, however, considered the ability to differentiate between regular abnormal situations and true faults desirable. They regarded the challenge of implementation from medium to high.

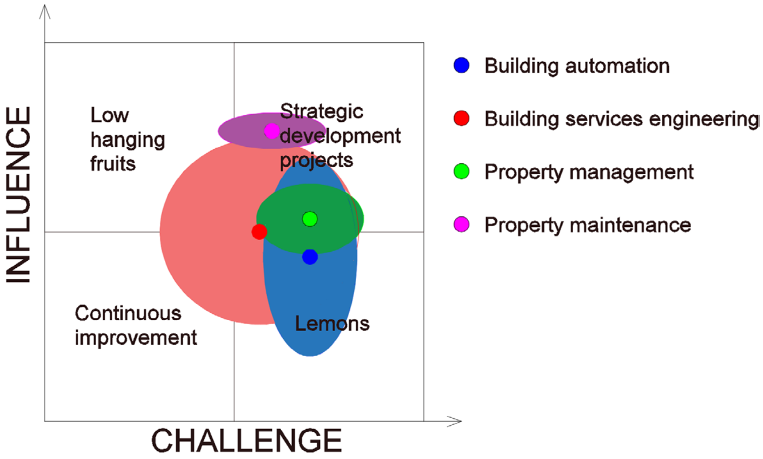


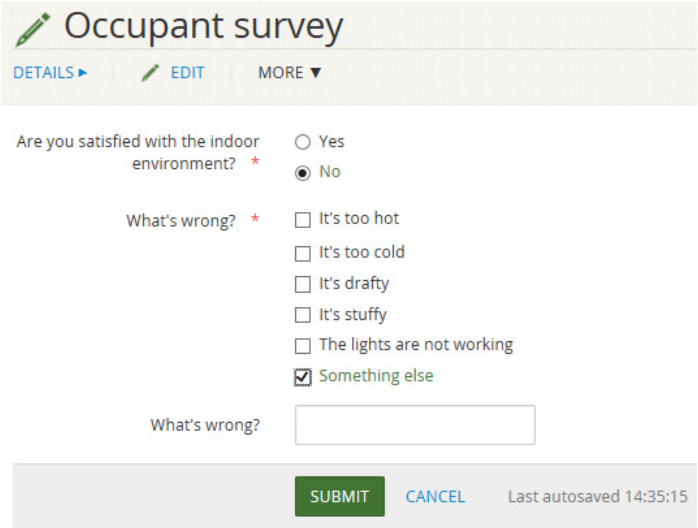
Figure 5.29 Evaluation results of the initiative of utilizing context-aware alarm thresholds.

5.4.10 Introducing mobile applications to collect sensing data on the indoor environment from building users

There is currently a large amount of inefficiency within the process of submitting user feedback that is consequently used as basis for BAS interventions. User complaints are currently received through e-mail. The messages do not always contain accurate information regarding the location of the problem which leads to more messages and delays with the problem handling, nor does it on the amount of satisfied people in the same room. Additionally, e-mail inboxes of different people in the maintenance organization are not the best place to store user feedback, as the feedback is not visible to anyone else and it may be difficult to look up old feedback. On the other hand, user satisfaction metrics are hard to derive from separate messages.

Today the majority of people carry smart phones, which are a convenient platform for collecting feedback. There are hardware and applications commercially available that enable gathering location-specific user input from mobile phones to a server in the cloud. For example Bluetooth low energy proximity transmitters broadcast a device-specific ID which may correspond to a particular location in the building by a definition in the server, and this identification by the server will trigger a push-notification that invites the user to give feedback through an application in the phone. An example of a survey created with the Louhin platform of DataRangers (2016b) that supports those functionalities is shown below in Figure 5.30. The process of giving feedback should be fast and easy, yet produce all the necessary information and allow users to give text-form feedback if necessary. If the user is satisfied, ticking *yes* and submitting ends the survey, but if something is wrong then the survey expands just enough to drill through to the exact problem. After the survey has ended, the user could be informed on the current satisfaction rate and room condition measurements from that location.

The feedback data could also be used in maintenance processes. By importing this location-specific feedback to the building automation control software and visualizing it for example in a floor plan or room view the maintenance personnel can observe both the room conditions and user feedback at the same time. With time stamps of feedback events it is possible to compare conditions to the trend in user satisfaction to diagnose problems. After set points have been adjusted, the submitter of the feedback can be notified that action has been taken and another survey can be sent later to see if the situation has improved. On the other hand, this feedback module should enable forwarding messages with location information to maintenance-men should the problem require a visit. Anyhow, it is vital to notify the sender of the feedback on interventions to ensure their commitment on giving feedback.



Are you satisfied with the indoor environment? *
○ Yes
● No

What's wrong? *
☐ It's too hot
☐ It's too cold
☐ It's drafty
☐ It's stuffy
☐ The lights are not working
☑ Something else

What's wrong?

Figure 5.30 An example of an occupant survey created with Louhin platform.

This method of collecting user feedback prevents the system from becoming a channel for complaining only, as users are invited to give feedback according to preprogramming. Therefore the feedback should represent the room conditions better than in the situation when feedback is given solely because something is wrong. The programming can also include smart functions such as verifying surveys when abnormal feedback is given.

The benefits of collecting sensing data from users regularly include reduction of waste in user complaint handling, more comprehensive data on user satisfaction and charting effects of maintenance interventions. Such benefits are hard to estimate in currency, however by attaining a better understanding on user satisfaction some energy could be saved by avoiding unneccessary interventions and reducing excess output. For example the philosophy of the *WarmEnough* concept developed by Granlund and Nomenal is to increase comfort and productivity by optimizing heating based on collected location-specific feedback data (Dooley, 2016). The results could then occasionally indicate an opportunity to reduce heating output. A screenshot of the *WarmEnough* application is presented in Figure 5.31.

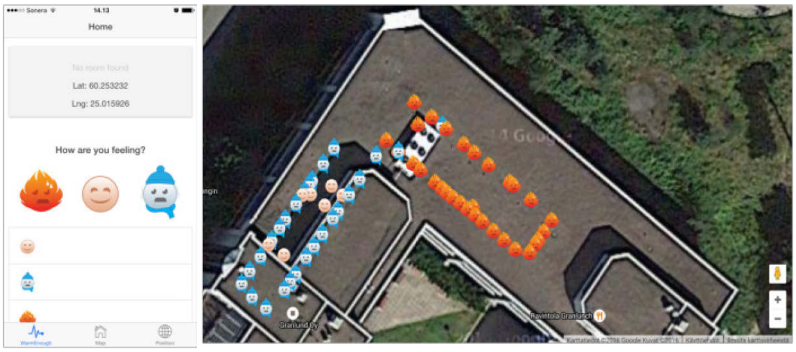


Figure 5.31 A snapshot of the location-specific temperature feedback view (Dooley, 2016).

The challenges and drawbacks associated with this proposition are the fluctuating interests of building users to give feedback, battery replacements of bluetooth transmitters and integrity of the feedback data. Especially keeping up the interest of building users seems to be difficult: In an interview it was mentioned that a feedback system was piloted in the past, and within a span of a few months the users stopped giving feedback completely. Therefore it is imperative to ensure the commitment of users by fortifying their perception on the feedback leading to action whenever there are reasonable grounds for that. Complementarily by making the process of giving feedback more fun, some users might become more eager to participate. For example Ken Dooley (2016) in Granlund is experimenting with PlaySign how user experience can be improved with playable surveys. A snapshot of such a survey is presented in Figure 5.32. There are no results published from this experimentation.

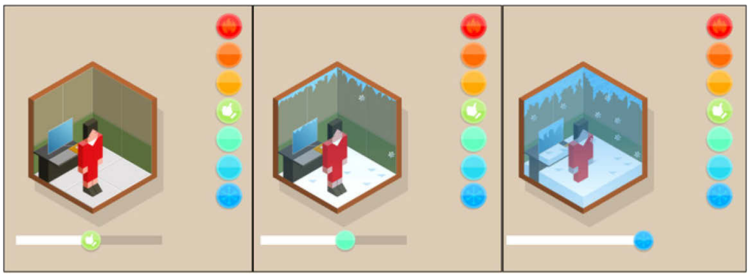


Figure 5.32 A snapshot of a playable user feedback survey (Dooley, 2016).

If bluetooth or any other transmitters are used in the infrastructure, battery replacements are required every few years. Conversely, the sensation of thermal comfort can be affected by a number of psychological factors in addition to the actual room temperature, which is why the integrity of feedback data should be ensured by verification procedures when abnormal input is received. For example when the temperature is 22°C and a user is feeling very cold, the feedback should be verified by sending the survey to other users in the room or the next user entering the room.

When feedback data is collected to a server of a separate service provider from the building automation contractor, a software interface is required to enable a feedback module within the controller software. As discussed earlier, such integration requires upkeep in the case of software updates and replacements. Another option is to use a completely separate feedback platform, which imports room condition data from separate sensors or building automation.

The evaluation results for this proposition are presented in Figure 5.33. The majority of respondents with building automation background considered the proposal to be a *low hanging fruit* as the necessary technology is available and the produced data could prove valuable whenever adjusting set points. Respondents with building services engineering background estimated the challenges of implementation to be medium with mainly high gains to be expected, essentially for the same reasons as above. Respondents in property management thought the benefits to be above medium with diverging opinions on the associated difficulties. There was varying optimism regarding the interests of users to participate in the surveys, but the produced data on user satisfaction was considered valuable. Respondents in property maintenance evaluated the gains to be high, but also the challenges of implementation. After all the suggested transmitter infrastructure needs maintenance, and the users must be committed to giving feedback. The awkwardness of dealing with user complaints was highlighted particularly by property maintenance staff: It is not uncommon that a person feeling cold has someone sitting next to them that is feeling hot. The situation cannot therefore be resolved successfully if both are complaining. Not adjusting set points due to a single complaint could be better justified if everyone else was happy with the room conditions.

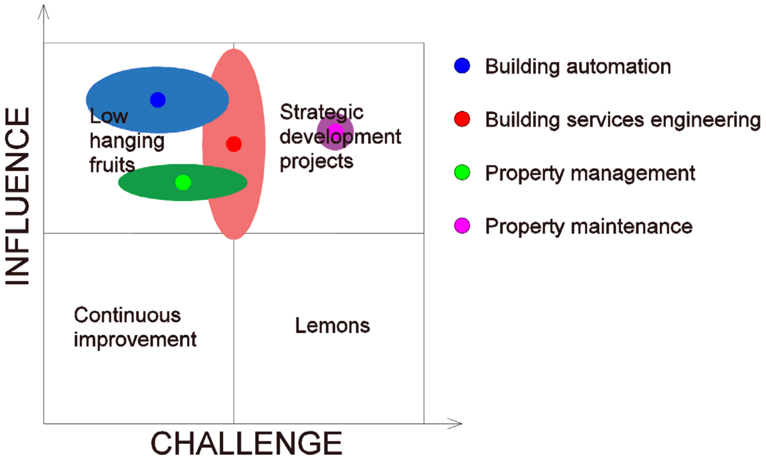


Figure 5.33 Evaluation results of the initiative of collecting sensing data from building users.

5.4.11 Optimizing pressure differences with ventilation

Current saving activities in ventilation may induce adverse effects on IAQ. Air supply is often minimized for the nights for saving purposes, but some exhaust fans for example in stairways, kitchens and toilets keep running. These actions have effects on the pressure differences of the building that are hard to evaluate without separate studies. In Finland the indoor air of the building should be in a slight vacuum of 0-10Pa in comparison to the outdoor air (Seppänen, 2010, p. 18). Slight vacuum is considered best, as positive pressure would cause long term moisture stress on the building envelope and high vacuum would risk the indoor air quality through suction of impurities from the holes and cracks of the structures. The vacuum should therefore not exceed 30Pa (Finnish Ministry of the Environment, 2012a, p. 19). Field study results on pressure differences can be distorted in many ways, as the pressure difference is influenced by ventilation system, wind, fluctuating outdoor temperatures and user activities of for example opening doors and windows. Therefore conclusions regarding the pressure differences of a building should be based on long term monitoring. (Katainen & Vähämaa, 2015).

The solution is to install sensors measuring the pressure difference between indoor air and outdoor air. As pressure differences not only depend on air supplied and exhausted but also on wind speed and temperature differences, some refined information should be supplied in order to detect potentially harmful time periods from the oscillating data. The refined data could simply be hourly averages on pressure differences, wind speed and temperature difference between outdoor and indoor air. The visual representation of pressure difference data should include schematics of areas of different air handling unit.

By optimizing ventilation system operation schedules the energy consumption could rise to compensate for the exhaust fans running around the clock, but in proportion the risks on indoor air quality can be better managed. The drawbacks are the large amount of sensor installation work and the necessity of expert resources to manage the ventilation system effectively based on the produced information. It is noteworthy that the air-tightness of the building must be sufficient, and the ventilation system must allow for space-specific purging if the measurement data was to be utilized. In other cases the measurement data could only indicate underlying reasons of problems without much means to resolve them. Therefore the issue should be considered already in the design phase of a construction project, for example by allocating separate air handling units for the toilets, kitchens and stairways.

The evaluation results for this proposition are presented in Figure 5.34. This proposal was included in the initiative portfolio later on by the project steering group, so the number of respondents is smaller (N=9). There was a single evaluation by a person with building automation background. He estimated the benefits to be high and the challenge to be small, because the provided information might help in indoor air quality problem diagnosis simply with sensor data. The two respondents with building services engineering background considered the produced data beneficial, but the sometimes poor adjustability of the ventilation system could mean that the identified problem would not be possible to resolve effectively. The three respondents with property management background estimated high benefits for the same reason as above with diverging estimated challenge. The required amount of sensors and drilled holes was a concern. The three respondents with property maintenance background considered both the benefits and challenge to be high for the same reason.

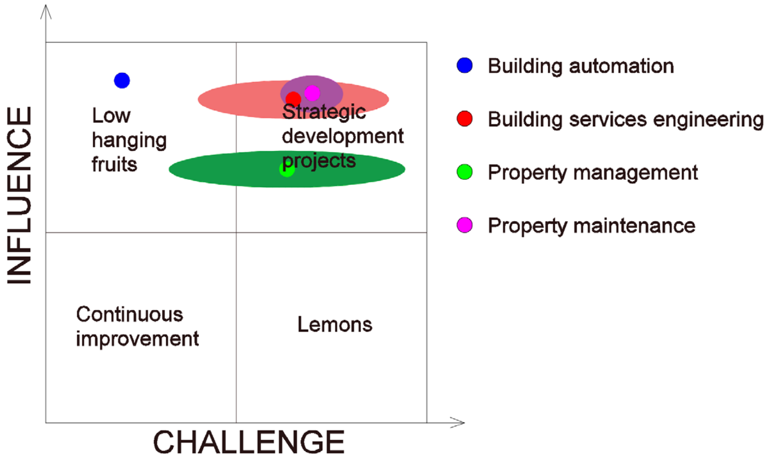


Figure 5.34 Evaluation results of the initiative of collecting long-term sensor data on pressure differences over building envelope.

5.4.12 Summary of the initiatives

The initiatives to close the energy performance gaps are summarized in Table 5.7. In the last column the distribution of evaluation result categories among the stakeholder groups is shown. If an evaluation result happened to be exactly at the boundary of a category, then half a stakeholder group was appointed to both categories, respectively.

Table 5.7 Summary of the initiatives.

Initiative	Benefits	Challenges	Category
1. Installing electronic radiator thermostats with smart heating functions	• Better area-specific adjustability of heating	• Installation costs • Power supply	• *Strategic development project (2.5/4)* • *Low hanging fruit (1.5/4)*
2. Adaptive outdoor temperature compensation for heating	• Automatic adjustments of heating power to meet seasonal needs	• Choosing the appropriate room temperature as the adaptive variable • Requires supervision to ensure proper functioning	• *Low hanging fruit (3/4)* • *Strategic development project (1/4)*
3. Room setback temperatures outside office hours	• Allocating heating power to better meet the cyclical demand	• Lack of excess heating power during cold periods • Uneven reheating with unbalanced radiator networks • Elevated energy consumption during reheating • Risking thermal comfort	• *Strategic development project (2/4)* • *Low hanging fruit (1/4)* • *Lemon (1/4)*
4. Optimizing heating with weather forecast data	• Predictive control of heating	• Difficult problem diagnosis • Cost of installation with electronic thermostats • Risking thermal comfort	• *Low hanging fruit (2/4)* • *Strategic development project (2/4)*
5. Intelligent lighting and blind control with daylight harvesting	• Daylight harvesting • Protection from heat loads	• Cost of installation • Risking visual comfort • Power supply	• *Strategic development project (3.5/4)* • *Low hanging fruit (0.5/4)*
6. Improving the manageability of large amounts of sensor data and actuators	• Ability to control actuators in groups that are based on their attributes • Ability to create key figures with references to attributes	• Actuator control requires commitment of BAS software providers • Database development project for sensor data • Database maintenance	• *Low hanging fruit (2.5/4)* • *Strategic development project (1.5/4)*
7. Enabling communication between building automation and room reservation systems to reduce energy consumption and manual input	• Automatic equipment operation scheduling based on room bookings • Room booking management to improve utilization	• Many interfaces between software	• *Strategic development project (2/4)* • *Lemon (2/4)*
8. Satisfying the dynamic demands of users with artificial intelligence based control of equipment	• AI satisfies users' demands while optimizing energy consumption	• Acquiring training data • Need of new training after replacements • Need of better adjustability of heating • Difficulties in problem diagnosis	• *Strategic development project (2/4)* • *Low hanging fruit (1/4)* • *Lemon (1/4)*

Initiative	Benefits	Challenges	Category
9. Utilizing context-aware alarm thresholds in fault detection	• Alarm thresholds adjust for each situation	• Need of training data • Need of supervision and tuning	• *Strategic development project (2.5/4)* • *Lemon (1.5/4)*
10. Introducing mobile applications to collect sensing data on the indoor environment from building users	• Comprehensive knowledge on the relative numbers of satisfied users to unsatisfied ones • Feedback data available for anyone in the maintenance organization to review	• Committing users to give feedback • Costs of procuring and/or licensing • Battery replacements for transmitters	• *Low hanging fruit (2.5/4)* • *Strategic development project (1.5/4)*
11. Optimizing pressure differences with ventilation	• Comprehensive knowledge on the long-term behavior of pressure differences over building envelope to help diagnose potential IAQ problems	• Cost of installation • Required expertise to act on the produced data • The ventilation system may not enable energy efficient resolving of identified issues	• *Strategic development project (3/4)* • *Low hanging fruit (1/4)*

5.5 Feasibility study of selected improvements

5.5.1 Selection rationale

The project steering group familiarized with the evaluation results and selected three of the most promising and different initiatives for further evaluation. This means that information on costs of implementation and potential monetary benefits were sought. Moreover, the ends were emphasized over the means according to performance philosophy, so some of the feasibility studies included different options to find the most cost efficient way to close performance gaps.

The selection process was based partly on the evaluation results and partly on the steering group's judgment. The initiatives were scored by weighing the benefits by 70% and challenges by 30% according to Expression 4, after which they were ranked. Influence was weighed over challenge in the scoring due to larger uncertainty in the latter dimension. Then the highest scoring and most heterogeneous initiatives were chosen for further study. The ranking is shown in Table 5.8. The ranks are numbered from I to XI with the top three highlighted green, bottom three red and the rest yellow, respectively.

$$Score = 0.7 \times Influence + (1 - 0.7) \times (10 - Challenge) \qquad (4)$$

Table 5.8 Score-based ranking of proposals by respondent background.

Proposal/Background	Building automation	Building services engineering	Property management	Property maintenance	All
2. Adaptive outdoor temperature compensation for heating	III	VI	IV	VII	I
10. Collecting sensing data from users	II	V	III	IX	II
6. Improving the manageability of large amounts of sensor data and actuators	IV	IV	I	V	III
11. Optimizing pressure differences	I	II	V	IV	IV
1. Electronic radiator thermostats	VI	III	II	III	V
4. Utilizing weather forecast data in heating control	VIII	I	VII	VIII	VI
5. Daylight harvesting with blinds and lighting control	VII	X	VIII	I	VII
3. Room setback temperatures	V	VII	X	X	VIII
7. Communication between room reservation systems and BAS	IX	XI	XI	II	IX
9. Context-aware alarm thresholds	X	IX	IX	VI	X
8. Artificial intelligence based control of equipment	XI	VIII	VI	XI	XI

As a result, *2. Adaptive outdoor temperature compensation for heating*, *6. Improving the manageability of large amounts of sensor data and actuators* and *9. Collecting sensing data from users* were chosen for further study. *9. Collecting sensing data from users* was reformulated into *measuring user satisfaction* to better capture the identified value driver. Moreover, for the same reason the proposition *6. Improving the manageability of large amounts of sensor data and actuators* was split in two: *Group control of actuators* and *energy efficiency monitoring*.

5.5.2 Measuring user satisfaction

The project steering group considered the main benefit of collecting sensing data from users with mobile applications to be the information on user satisfaction, which is an intrinsic value as it fosters the longevity of tenancy agreements. Therefore in addition to the solution described in Chapter 5.4.10 some services that provide user satisfaction measurements and information on indoor air quality are studied.

Two courses for implementation were identified: One is to simply purchase everything as a service, while the other is to design the infrastructure and user interfaces yourself and acquire a license for data collection and handling. The latter option leaves more freedom in generating functions that support maintenance operations, however. Another benefit, if user dissatisfaction could be reduced with the designed functions, would be the decrease in the workload related to handling complaints. A person in the case organization estimated that complaints from a very problematic building cause 2-3 hours of work every week, which corresponds to roughly 7,800€ of resources annually (salary costs of 60€/h). Next the costs of options are considered: Providers A and B are service providers, whereas Provider C is a license and consultation provider.

The service provided by Provider A is piloted in one of the buildings of the case organization. The piloted service includes indoor air quality measurements visualized to users on screens: Relative humidity of air, temperature, total volatile organic compound content of air and CO_2 content of air. There was an option to include particulate matter (PM_1, $PM_{2.5}$ and PM_{10}) and noise sensors for an additional fee. The tablets also let users to submit feedback. All the measurements and feedback results can then be reviewed on a web page. The pricing is based on fixed annual costs for sensors, gateways, tablets and routers with installation included, while the license fee is surface area based. The total cost of the piloted service is 11.4€/m^2 annually with an area of 450m^2. Particulate matter and noise measurements would have added 4.7€/m^2 each. For an office building with a room area of 5,000m^2 the service fee would then be 57,000€ annually.

Provider B offers a service that measures user satisfaction. Feedback is given with a browser (computer or mobile phone) and with separate button pairs that can measure for example overall satisfaction, thermal comfort or indoor air quality. The feedback is not location-specific within the building unless the submitter provides it in text-form. The running costs are based on the amount of users and buttons. The running costs would be 2,520€ annually with a service allowing over 300 users and including seven button pairs per building. The initial costs are 400€ per measured entity (for example a building). The feedback results can be reviewed on a webpage.

Provider C offers a cloud environment to conduct mobile surveys and report the results. The environment supports a low energy Bluetooth transmitter infrastructure and has capabilities to easily export data to, and import data from other servers. This option seems fit if sensing data is to be utilized in controller software and maintenance operations. Based on an estimate given by the service provider, the fixed costs of the cloud environment are approximately 10,000€ annually, while the one-time consultation costs for a first-time setup are estimated to be another 10,000€. The required in-house resources for setup would then be 6,000€ per building (derived from the consultation costs above with 60€/h). Based on a case building floor plan the transmitters would cost 0.22€/m^2 (around 20€ each), while the recurring battery replacement costs every three years would be 0.03€/m^2 annually (1 hour per floor every three years à 40€/h). So for a single 5,000m^2 office building the costs would be 27 100€ first year and 10 150€ annually thenceforth. A comparison of the costs between suppliers is summarized in Table 5.9 over five buildings and a five year period.

Table 5.9 Benefits and costs of user satisfaction measurement systems

Description	Costs		Present value
	First year	Following years	
Provider A			
• Information on user satisfaction • Potential to reduce complaints by visualizing room conditions	228,000€	228,000€	-987,240€
Provider B			
• Information on user satisfaction	14,600€	12,600€	-56,462€
Provider C			
• Information on user satisfaction • Potential to reduce complaints by informing on room conditions • Potential to utilize the system in maintenance operations	56,250€	10,750€	-89,864€

The options over five 5,000m^2 buildings and a five year period. The interest rate for present value estimation was chosen to be 5%. The resultant discount factor for periodical payments is 4.33.

It seems that the most economical option is to use the service provided by Provider B, if data on user satisfaction is the only thing that is desired. Also due to the lowest initial costs, it may be a good idea to determine the interest of users to give feedback with the service of Provider B. However, if two-way feedback and area-specific satisfaction data are going to be required, then those features can be included with an approximated additional 5-year contribution of 30,000€.

5.5.3 Group control of actuators

The benefits of group control are largely attributable to facilitating routine processes. On one hand time is saved and on the other hand energy is saved because some adjustments cannot simply be made currently quickly enough due to the large amount of manual work involved. It is however not realistic to assume that a building automation controller would support attribute-based group control introduced in Chapter 5.4.6 without sufficient demand in the market, so the feasibility of group control is studied by examples of predefined control groups. Two examples are considered as sources of benefits: AHU time schedule programming and snow melting control.

Facilitating AHU time schedule programming is a simple example of saving time. Let us consider an upcoming holiday period in the university, and to save energy the air handling units are programmed to operate on half power and minimum air flow except for the utility services rooms. As starting information let us assume 30 buildings, eight AHUs per building of which two serve spaces with fixed ventilation demand and five minutes of programming per AHU (includes looking up the closing period and occasionally the AHU operating area; the time estimate is based on observing this work in the control room briefly). In the first scenario every AHU is programmed separately which leads to 15 hours of work. This work is to be done before and after the holiday period, and occasionally during the holiday should some unexpected use of the building occur. Still, let us assume 30 hours of work in total. In the second scenario all the AHUs in a building can be controlled in groups to holiday mode and back with a single click according to an interface presented in Figure 5.35. In the same interface it is possible to edit the holiday period time schedules and check the operating areas. This would essentially save all the 30 hours work once the settings have been defined. With a salary of 40€/h that equals to 1,200€ annually. A contractor that was asked about the costs of developing such a feature told that the idea could be implemented in a different way to the one presented here (changing time schedules), and a cost estimate cannot be provided without a thorough study.

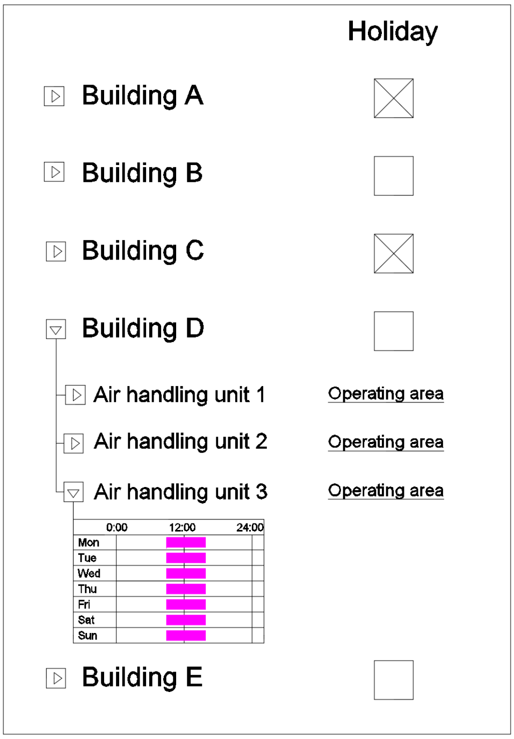


Figure 5.35 AHU group control interface.

The other example is the control of electric snow melting in gutters and spouts, which has long been a concern for the case organization. The purpose of snow melting cables is to keep the gutters and water spouts clear of ice and snow in metal-sheeted gable roofs. The ideal situation would be that the heaters are only on when there is snow on the roof and the snow is melting or it is raining. The heaters also require a time-out period to let the rainwater system dry. On some of the roofs there are sensors detecting snow, rain and humidity, but problems may arise when snow is melting in other parts of the roof undetected by the sensors. If the gutters get clogged by ice, the water that has melted starts to dam up, and the risk of moisture damage grows. Another risk is that the water starts to overflow the gutters instead of flowing through the water spouts, which easily results in icicles that need to be cleared in the CBD area. Also because AHUs are often located on the top floor there is a significant amount of heat radiating from underneath the roof. With a thick layer of snow on the roof and the lowest layer melting, the pressure can cause the water to leak through the metal sheet seams. Based on the experience in the case organization, even the smallest water leakage costs 5,000-10,000€ to treat while a larger water damage costs 10,000-100,000€ to repair. Therefore the reliability of the controlling method is extremely important.

However, on the vast majority of the roofs the heaters are controlled by the outdoor temperature so that heating is on when the temperature is between -5°C and +5°C. Subzero temperatures have been included because snow can melt with temperatures below zero when it is sunny or with buildings that have a lot of heat leakage through the roof. Obviously purely outdoor temperature based control is not optimal, and next the wasted electricity is being estimated.

Between 1st September 2015 and 1st September 2016 the heating criteria was satisfied for 2964 hours according to measurement data collected by an outdoor temperature sensors in Helsinki CBD. This corresponds to 34% of the whole year. Based on data collected from technical drawings in Table 5.10 snow melting power is roughly 10kW per 1,000m^2 flat projected roof area. It is important to note that in some buildings the heating cables are self-adjusting the heating power, which reduces the electricity consumption when there is no need for full output. Still, the nominal output is used in the following calculations.

Table 5.10 Snow melting power and projected roof areas for four buildings in Helsinki CBD.

Building	Snow melting power [kW]	Projected roof area [m^2]	Ratio [W/m^2]
A	9.6	1035	9.3
B	9.2	946	9.7
C	5.6	434	12.9
D	5.6	540	10.3

Let us consider an imaginary roof with 700m^2 projected roof area and 7kW of snow melting power. If the heaters are on with full power for 2964 hours, 20.7MWh of electricity is consumed. This equals to a bill of 1743€ annually with the price of electricity of 84€/MWh. If that roof area is the average among the 30 buildings that are remotely managed by the case organization in Helsinki CBD, the total bill is then 52,285€.

The savings potential can be estimated in two stages: Firstly by eliminating the days without snow and rain, and secondly by eliminating the days when there is snow or it rains, but melting is not needed. The estimates are based on an outdoor temperature sensor in Helsinki CBD and FMI observation data on daily snow depth, cumulative 24 hour precipitation, daily minimum temperature and daily maximum temperature between 1st September 2015 and 1st September 2016. This weather data can be downloaded for Helsinki CBD once an API-key is provided[1].

The idea is to compartmentalize the runtime of the snow melting heaters into different states that are either waste or not, and have durations based on the weather and sensor data. This concept is illustrated in Figure 5.36. In the figure observation data on daily snow depth, cumulative 24 hour precipitation, daily minimum temperature and daily maximum temperature are used to compartmentalize the snow melting runtime (determined with an outdoor temperature sensor) into states with durations. These states are ultimately labeled into waste of electricity or not waste of electricity.

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[1] http://data.fmi.fi/fmi-apikey/<APIkey>/wfs?request=getFeature&storedquery_id=fmi::observations::weather::daily::timevaluepair&fmisid=100971&parameters=snow,rrday,tmin,tmax&starttime=2015-09-01T00:00:00Z&endtime=2016-09-01T00:00:00Z

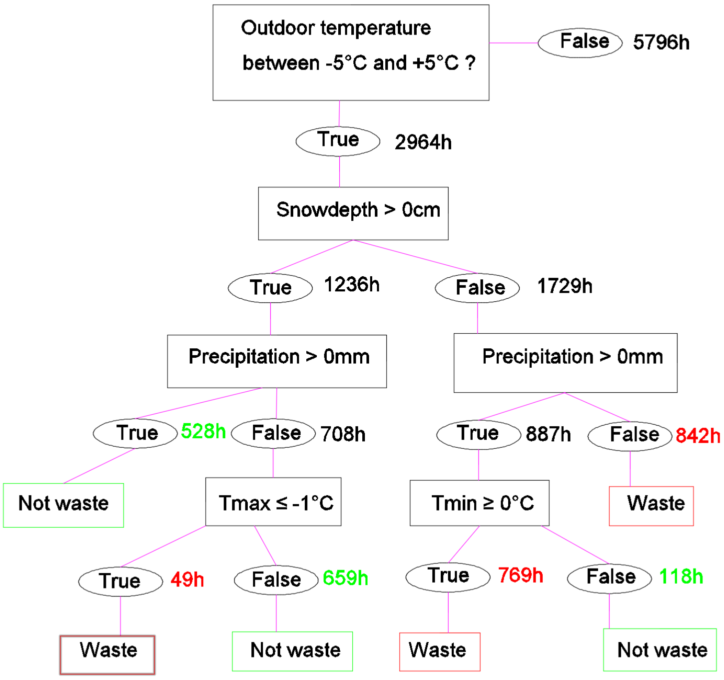

Figure 5.36 Snow melting waste estimation method.

In the first stage the duration is calculated when temperature is between -5°C and +5°C but there is no snow and it has not rained. According to Figure 5.36 this duration is 842 hours. It was suggested by the technical managers that there should be one switch for all of the snow melting heaters within the same suburb, so that the heaters could be turned off whenever there is clearly no need for heating. When the switch is turned back on, the building specific controller operation is resumed. By eliminating the duration without snow or rain in this way, 5.89MWh of electricity could be saved per building (assuming 7kW output). A contractor that was asked about the costs of creating such a switch told that it is quite easy and does not require much work as long as the heaters are connected to BAS, however no cost estimate was provided.

The second stage is to eliminate the time periods when there is snow, it has not rained and the temperatures are well below zero (but above -5°C) so that snow is unlikely to melt (in total 49 hours) and when there is no snow, it has rained but the temperatures are not freezing (in total 769 hours). The total duration meeting this criteria is then 818 hours according to Figure 5.36. This corresponds to additional savings of 5.73MWh per building. To eliminate this runtime, one must rely on automation, and a number of sensors would need to be installed on the roofs with different orientations. The cost of procuring a controller and the sensors (snow, temperature and humidity) for a building with roof area of 700m^2 is estimated to be 5,000€ based on a previous contract. The estimate is subject to uncertainty as it is based on a lump-sum from memory from which the portion of heating cables has been removed based on the cost of another contract. Yet, the cost is not far-fetched as a controller costs 1,000€ (Taloon, 2016a), four temperature and humidity sensors 800€ (Taloon, 2016b), and a power supply 170€ (Talotuote, 2016), adding up to 1,970€ without installation costs. The prices are not wholesale prices, though.

Another option is to install self-adjusting cables that halve the heating output whenever the surroundings are dry or rainwater is unlikely to freeze (approximated as 842 hours plus 769 hours plus 49 hours). The costs related to this option per building are estimated below:

- 200m of self-adjusting cable à 8€/m (Finnparttia, 2016), and
- cost of installation of 1,650€ (based on a historical contract).

The savings potential of different actions is then compiled in Table 5.11 assuming 30 buildings with average roof area of 700m^2, heating power of 7kW and price of electricity of 84€/MWh.

Table 5.11 Compiled snow melting savings potential versus costs for 30 buildings.

Description	Savings			Cost
	Energy	Money	Percent	
Option 1				
Creating a single switch for all the snow melting cables within a suburb	176.8MWh	14,853€	28.4%	-
Option 2				
Automating snow melting successfully	348.6MWh	29,282€	56.0%	150,000€
Option 3				
Installing self-adjusting melting cables	174.3MWh	14,641€	28.0%	97,500€

Group control is clearly a feasible tool to take into use immediately, as large benefits are possible to reap with a minimal cost. Moreover, the savings potential of advanced snow melting controllers should be verified with appropriate consumption metering. If the savings estimate above can be validated, it would be sensible to install such controllers at least whenever replacing the old snow melting systems.

5.5.4 Energy efficiency monitoring

The main value driver in improving the manageability of sensor data is the ability to observe large amounts of data of interest across different buildings in a single view. This data of interest can be specific consumptions of properties, specific powers of equipment or other key figures such as heat recovery efficiencies. This value could be captured by a software and database development project that covers the principles presented in Chapter 5.4.6 and Appendix 2, but the costs of such a project were not possible to estimate accurately within the limits of this thesis. The costs depend highly on naming policies of control points throughout the building automation systems, and the capabilities of the systems to export and import data, though. Instead two service providers who offer web-based energy management tools are presented as options. The options are compiled in Table 5.12.

Provider A offers a web-based energy management tool that is used globally. Assuming that all the measurements they need are specified in a .csv file at the customer side, the pricing is as follows: 3€ a month per measurement and a 2,000€ initial cost per building for basic reporting. If 50 resource consumption and key performance indicator measurements were included, the total annual cost would then be 3,800€ for the first year and 1,800€ the following years. If a lot more measurements were included, the price per measurement would start to decrease towards 2€ a month per measurement, while the initial costs would rise to accommodate for the more in-depth reporting.

Provider B offers a web-based performance monitoring tool that converts sensor data, control signals and alarms into performance metrics. The performance of a building is then visualized on various dashboards. The initial costs are 2,200€ and annual costs 2,400€ when procuring the tool for an average office building with around 10 AHUs and 150 room measurements. If the BAS is a Visonik, Desigo or Deos the initial costs may elevate slightly.

Table 5.12 Options for an energy management tool.

Description	Costs	
	First year	Following years
Provider A		
• Visualizations and reports are tailored to meet user's needs	3,800€ per building	1,800€ per building
Provider B		
• Sensor data is converted into performance metrics • The performance of a building is visualized on various dashboards	2,200€ per building	2,400€ per building

Due to the amount of ongoing costs it may be more feasible to develop one's own system if all the buildings were monitored. However, if the biggest consumers of the building stock were the only ones monitored, it could be more sensible to purchase the system as a service instead of developing one's own.

5.5.5 Adaptive outdoor temperature compensation for heating

The energy performance gap being closed by adaptive outdoor temperature compensation is automating the changes in heating power to meet the demands of different seasons while maintaining thermal comfort. It was not possible to test such a program on the case building, so the potential benefits from adaptive outdoor temperature compensation are estimated based on simulated situations of excessive heat content in radiator supply water. In other words, radiator supply water temperature is raised temporarily and the implications on energy consumption are studied. It is important to note that the capability of the presented program to close this gap has not been verified, so the following is estimating the gap itself.

There is an option in OfficeOne to use 5°C shifts in radiator supply water temperature during cold periods. These shifts were then made for testing purposes during weekends of the mild period when nobody was present in the building (to avoid inconvenience), and the energy consumption was compared to a normal situation. Unfortunately this thesis took place mainly outside the heating season, so it was not possible to gather extensive test data for analysis. Some preliminary results could be obtained, however.

The shift periods were 26th August 15:00 – 28th August 16:30, 2nd September 15:00 – 4th September 15:00 and 9th September 15:00 – 11th September 15:00 (year 2016) while the complete data set was recorded from 1st February 00:00 to 11th September 23:59 (year 2016). Because of bulk energy consumption measurements and around the clock running AHUs it was impossible to differentiate between air heater and radiator energy consumption, so the estimates were based on thermodynamic calculations. First, the specific heat capacity of water is converted to watt-hours per kilogram degrees Celsius according to Expression 5. Then the water flow through the heat exchanger is estimated based on average hourly valve position and the design flow of the exchanger ($0.49 dm^3/s$) according to Expression 6. This number is subject to uncertainty due to hysteresis. Finally, radiator heating power is calculated as the heat divided by the time interval of one hour according to Expression 7. That number is also subject to uncertainty due to losses of heat exchange, mixing outbound district heating water and the fact that district heating water is used in preheating service water after heating the radiator water. The cooling of district heating water was calculated based on hourly averages of temperatures, with the outbound district heating water temperature being a mix of the return district water temperatures of all the four heat exchangers. Additionally, the portion that was used to preheat service water was impossible to estimate because the temperature of district heating water was not measured after the radiator network heat exchanger. However, this uncertainty slightly loses importance because of the fact that it is the difference in heating power that is being analyzed.

$$c = 4.19\ \frac{kJ}{kg \times °C} = 4.19 \times 0.000278\ \frac{kWh}{kg \times °C} \tag{5}$$

where
c = specific heat capacity of water (kWh/kg°C)

$$\frac{m}{\Delta t} \approx \frac{\omega}{100\%} \times 1764\ \frac{kg}{h} \tag{6}$$

where
$\frac{m}{\Delta t}$ = water flow through the heat exchanger (kg/h)
ω = heat exchanger valve position (%)

$$P \approx c \times \frac{m}{\Delta t} \times \Delta T \tag{7}$$

where
P = total heating power of the radiator network (kW)
ΔT = district heating water cooling (°C)

The resulting data on radiator heating power in a normal situation and in a shift situation is presented in Figure 5.37. The data suggests that heating power is higher in a shift situation with outdoor temperatures ranging between 17-21°C.

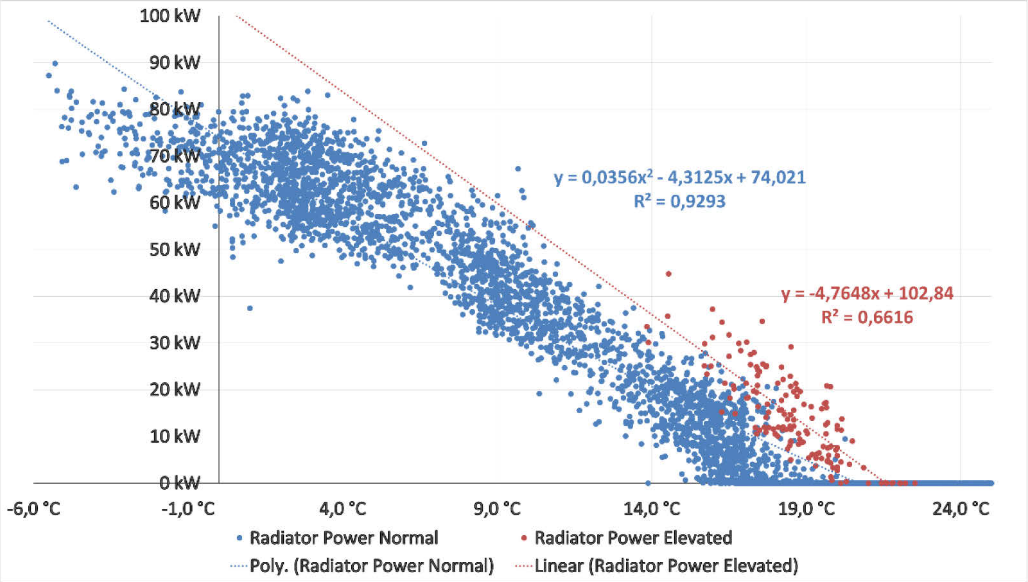

Figure 5.37 Radiator heating power with normal and elevated supply water temperature.

At the design temperature of -26°C the trend line of the normal situation would suggest a heating power of 210kW, while technical drawings state a design power of 144kW. Thus, the validity of these calculations is very unclear before data near design temperatures have been acquired. Yet, some preliminary results can be obtained for outdoor temperatures between 17-20°C. The average difference of radiator heating power with normal and elevated supply water temperature is 7.67kW while the duration within that temperature interval is 1360 hours, respectively. This indicates an annual energy performance gap of 10.4MWh, if 5°C warmer water was supplied throughout the year. More durations are compiled in Table 5.13 to facilitate the possible utilization of further tests.

However, due to these experimentations occurring during weekends, this estimation method does not take into account how much of the elevated heating power can be attributed to the absence of heat loads caused by user activity. If only weekends were observed, the heating power was still 6.64kW more by average in the elevated supply water temperature scenario. This aspect contributes also to the margin of error, but does not reverse the findings.

Table 5.13 A sheet to estimate the total benefits with further study.

Interval [°C]	]-∞,-5[	[-5,+0[	[+0,+8[	[+8,+17[	[+17,+21[	[+21,+∞[
Duration	569h	556h	3123h	2365h	1360h	789h
Hourly gap	No excess power assumed	Requires tests	Requires tests	Requires tests	7.32kW	Negligible water flow assumed
Annual gap					9.96MWh (398€)	

Based on the preliminary results it can be suggested that if a control program of adaptive outdoor temperature compensation is able to eliminate or narrow this gap without any installation work, its implementation could be beneficial. Unfortunately no cost estimates for the installation of adaptive heating control program were obtained, even though two contractors were asked.

6 Conclusion

6.1 Discussion of the findings

The objective of this thesis was to investigate how the energy performance of buildings could be improved effectively by exploiting available data. This objective was subsequently formulated into three research sub-questions:

1. What are the energy performance gaps of buildings?
2. What kind of solutions that are based on the exploitation of available data can close those gaps?
3. How effective are those solutions?

The research process was based on reviewing research literature, conducting interviews and analyzing measurement data recorded by the building automation system of a case office building. The research only included factors of energy performance that could be enhanced with available data in the operations and maintenance phase of a building's lifecycle. This means that energy-efficient equipment control principles, and methods to supervise and manage the energy performance of equipment were included in research. Additionally, being the main tool for computerized intervention, building automation systems were within the scope of the thesis. Also solutions that facilitate the management of satisfactory indoor environmental quality were included.

The identified energy performance gaps of buildings related to 1) inadequate heating adjustability and control, 2) suboptimal utilization of free energies, 3) uncharted implications of existing saving measures, 4) insufficient knowledge on the satisfaction of building users and 5) inefficiency of processes. The initiatives to close these gaps were based on acquiring new equipment to enhance adjustability, installing new sensors and transmitters to collect more data, programming new control methods or developing new information systems. Out of these initiatives the most effective were considered to be the ones that are simple and do not require any installation work, or at the most, the installation of transmitters or sensors. The least effective initiatives were considered to be the ones that are complex, risk user satisfaction or require integration of numerous systems.

To increase feasibility, some compromises were made with regard to the originally proposed top three initiatives: Instead of studying the costs and benefits of those three initiatives as such, four more commercially realistic entities and options within them were studied. Those four entities were *measuring user satisfaction*, *group control of actuators*, *energy efficiency monitoring* and *adaptive outdoor temperature compensation for heating*. Based on the feasibility studies it is suggested that adaptive heating control has the potential to increase energy performance with negligible installation work, user satisfaction measurement system would be sensible to pilot as a service, energy efficiency monitoring in small scale would be convenient to purchase as a service and selected group control interfaces would enable large savings with small trouble.

6.2 Theoretical contribution

The results of this research produce feedback from an end-user organization (and its stakeholders) to the research community and support some findings made in earlier research.

The findings increase understanding on the perceived effectiveness of energy performance enhancing initiatives from the perspectives of professionals in the fields of building automation, building services engineering, property management and property maintenance. Even with such a small sample size, the perceived challenges and benefits can be utilized to clarify the value propositions of solutions that rely on the same technologies. By harnessing the identified value drivers while minimizing the impact of drawbacks, the policy resistance regarding the adoption of those solutions is likely to decrease.

There are also results that support findings and statements made in earlier research:

- The findings of this research verified that adaptive outdoor temperature compensation would reduce the workload of maintenance, therefore confirming the suggested benefits by Paiho et al. (2002, p. 94). Moreover, their control method was considered highly effective.
- Forming half of the initiative *6. Improving manageability of large amounts of sensor data and actuators* that ranked third among all the initiatives in effectiveness, *energy efficiency monitoring* was considered very beneficial. This supports the notion of Ihasalo (2012, pp. 2, 137) that there is a need for tools that monitor performance. Moreover, based on a semi-structured interview the monitoring dashboards should be tailored to user-specific needs.
- The limitations of available data confirmed that training data required by artificial neural networks may not be available as suggested by Kolokotsa et al. (2009, p. 1850). The historical data available through the BAS is deterministic due to control objectives and limited due to sensor infrastructure: For example the resultant room temperature with different actions and contexts cannot be taught with historical data because control always has had the same goal, and not all inputs are measured.
- Based on the evaluations it was observed that the initiative *9. Utilizing context-aware alarm thresholds in fault detection* was not perceived beneficial enough versus the development costs. This finding supports the statement of Ihasalo (2012, p. 42) that FDD tools are not widespread because of little quantified information about the benefits with sometimes large costs of installation. The only stakeholder group that saw clear benefits in improving fault detection was property maintenance.

6.3 Practical implications

The results of this thesis have implications regarding the design guidelines of heating systems, ventilation systems and lighting systems, and the requirements for building automation systems: Decisions made then by building owners, property managers, building automation contractors and building services engineering designers may have a huge impact on energy performance and the applicability of the presented initiatives later on. These implications are listed below:

- In heating system design, the exposure of the building to heat loads such as sunlight should be considered based on window size, façade type and immediate protective environment. If it is likely that the heat loads are going to be large at a façade at a time during the heating season, then a separate radiator network for each façade could improve heating control performance significantly. Also allocating a separate network for spaces with constant heating demand would serve the same purpose.

- In ventilation system design, the division of operating areas and decentralization of ventilation is essential to attain a good level of energy performance. To an extent, areas with constant ventilation demand and areas serving different functions or occupants should have their own AHUs to increase adjustability.
- In lighting system design, the availability of natural light in working areas should be scrutinized based on window area and floor layout. If there is large availability of natural light due to large windows and working areas mainly near the windows, constant luminance control with motorized blinds may introduce large savings of electricity.
- In requirements for a building automation system, attention should be given to the naming policy of control points and capabilities to export and import data, if a database project for sensor measurements was being considered. Such a database project would face problems if control points were not named in a standardized and unique way, or if importing data from the BAS was difficult. If the BAS had interfaces requiring only credential, link and refresh interval specification from the database server, this aspect would be greatly facilitated. Additionally, snow melting heaters should be connected to building automation.

6.4 Research limitations

The findings made from this research are subject to limitations of the case study. The limitations of the case study were caused by the occasional unavailability of relevant sensor data, unfinished tuning of building services equipment, the subjective evaluation method of initiatives aimed to close energy performance gaps and the small sample of evaluators (N=13). Consequently, let us recall the three research sub-questions:

1. What are the energy performance gaps of buildings?
2. What kind of solutions that are based on the exploitation of available data can close those gaps?
3. How effective are those solutions?

The case study limited the answers to the first research question especially with respect to lighting control performance due to unavailability of *cause* level data. All the findings in this area were made based on *effect* level data. In other aspects of energy performance, there was *cause* level data available supported occasionally by statements made in the semi-structured interviews. Unfinished tuning did not limit the research, as it was possible to isolate equipment still in tuning phase from analysis.

Answers to the second research question were limited by the lack of experience of the author about the field of research. The effect of this limitation was reduced by a literature review before commencing the research, multidisciplinary steering within the case organization and information provided by experts during the evaluation interviews.

Answers to the third research question were subject to limitations caused by the small amount of experts that evaluated the initiatives and occasionally the unavailability of relevant expertise. Not many of the respondents were familiar with artificial intelligence or database development, which reduced the input or its degree of certainty especially in the *challenge to implement* dimension. Therefore, the results occasionally answer a question: *How effective are those solutions perceived to be?* Still, the effect of the small sample size was reduced by interviewing people from different organizations.

6.5 Further research

Identified needs for further research relate on one hand to clarifying the value proposition of some of the potential solutions and on the other hand to monitoring the influence of the selected solutions should they be implemented.

There was vagueness in the value proposition of installing electronic thermostats and motorized blinds. Even though the installation of electronic radiator thermostats was considered beneficial, the quantitative influence of smart heating functions on the energy performance of the heating (and cooling) system remained unclear. By applying the solution to a part of a building, deploying the radiator pipes with sensors measuring water flow and recording chilled beam operation (if any) the outcome could be compared quantitatively to the situation with mechanical thermostats. Similarly with daylight harvesting, the referred test results did not state the benefit of including motorized blinds in constant luminance controlled lighting system. Constant luminance control is much simpler to implement without motorizing blinds, thus the value proposition of including them should be scrutinized.

The capability of the selected solutions to improve energy performance in real-world testbeds is also an interesting study area. Especially the commitment of building users to giving feedback and the ability to utilize it in BAS interventions, and the capability of adaptive heating control to reduce excess output are intriguing areas of study.

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Appendices

Appendix 1. Evaluation results. 2 pages.
Appendix 2. Sensor data modelling. 4 pages.
Appendix 3. Data clustering. 2 pages.

Appendix 1

Evaluation results

The interviewees are listed in Table 0.1 and evaluation results in Table 0.2, respectively.

Table 0.1 Interviewees.

Interviewee	Interview date	Supplementary interview for proposal 11	Expertise	Background
I	27.5.2016	-	Building automation	Contractor
II	30.5.2016	-	Building services engineering	Designer
III	6.6.2016	12.8.2016	Building services engineering	Manager
IV	6.6.2016	12.8.2016	Property management	Manager
V	6.6.2016	12.8.2016	Property management	Manager
VI	6.6.2016	12.8.2016	Building services engineering	Designer
VII	15.6.2016	-	Building automation	Designer
VIII	15.6.2016	-	Building automation	Designer
IX	13.7.2016	-	Property maintenance	Plumber
X	13.7.2016	-	Property maintenance	Plumber
XI	13.7.2016	-	Property maintenance	Plumber
XII	2.8.2016	-	Building automation	Contractor
XIII	17.8.2016	-	Property management	Manager

Table 0.2 Evaluation results.

Interviewee / Proposal		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
1	Influence	10	7	9	8	5	7	2	4	8	8	8	9	10
	Challenge	7	8	6	8	4	3	2	3	7	4	5	2	3
2	Influence	10	5	9	6	6	5	8	8	9	9	8	9	8
	Challenge	8	1	7	4	6	2	3	2	9	8	8	2	4
3	Influence	10	4	8	4	4	5	2	3	7	7	7	9	5
	Challenge	1	1	8	7	7	7	2	4	7	8	9	3	5
4	Influence	10	3	10	7	4	8	2	2	8	8	8	9	null
	Challenge	7	1	2	8	6	4	2	3	7	7	8	1	6
5	Influence	10	5	8	3	4	3	2	5	9	9	9	10	9
	Challenge	1	8	7	8	6	8	8	7	8	5	9	4	5
6	Influence	10	2	10	8	8	10	4	6	8	8	9	10	10
	Challenge	6	2	8	3	7	null	4	5	7	5	9	3	3
7	Influence	10	5	5	5	4	2	2	6	9	9	9	9	null
	Challenge	5	4	8	7	5	7	8	6	8	5	9	4	9
8	Influence	null	1	8	6	6	9	2	3	5	6	5	7	7
	Challenge	null	2	9	9	5	9	9	8	4	4	5	8	9
9	Influence	null	2	8	4	6	null	3	2	7	8	8	8	6
	Challenge	null	2	8	8	5	7	null	8	5	5	8	6	8
10	Influence	10	4	8	6	7	10	8	8	8	7	8	8	6
	Challenge	1	6	5	3	6	4	2	3	8	7	8	6	2
11	Influence	null	null	8	6	7	9	null	null	8	9	9	9	7
	Challenge	null	null	9	2	9	4	null	null	8	6	7	2	8

Appendix 2

Sensor data modelling

Below there are three figures visualizing the functionalities of attribute-based modelling of measurement data and one figure demonstrating an interactive user view. The visualizations were made with Microsoft Excel and Microsoft PowerBI.

In Figure 0.1 the multidimensional data cube has not been sliced in any dimension. On top of the page there are functions that enable slicing the cube:

- All fact data (both room and equipment measurements) can be sliced in two dimensions: Time and location.
- Room measurements can be sliced further in the dimension: Measurement type.
- Equipment measurements can be sliced further in two dimensions: Equipment and Measurement type.
- It is also the dimensions that can be sliced with one another: Choosing a physical location removes all the irrelevant equipment and vice versa.

In Figure 0.2 the cube has been sliced in the location dimension by choosing the room H312B. This removes all the measurements that are not related to that room: For example air handling unit 204 can be chosen but not 203. Also plug loads and lighting electricity consumption measurements are only available for that portion of the floor.

In Figure 0.3 the cube has been sliced in the location dimension by choosing the room H123. The data is further sliced with measurement types.

The dimensions can be hierarchized in many different ways but the idea is that the data model itself contains information on what measurements are relevant in which physical location, so there is no need to go through drawings when analyzing measurement data.

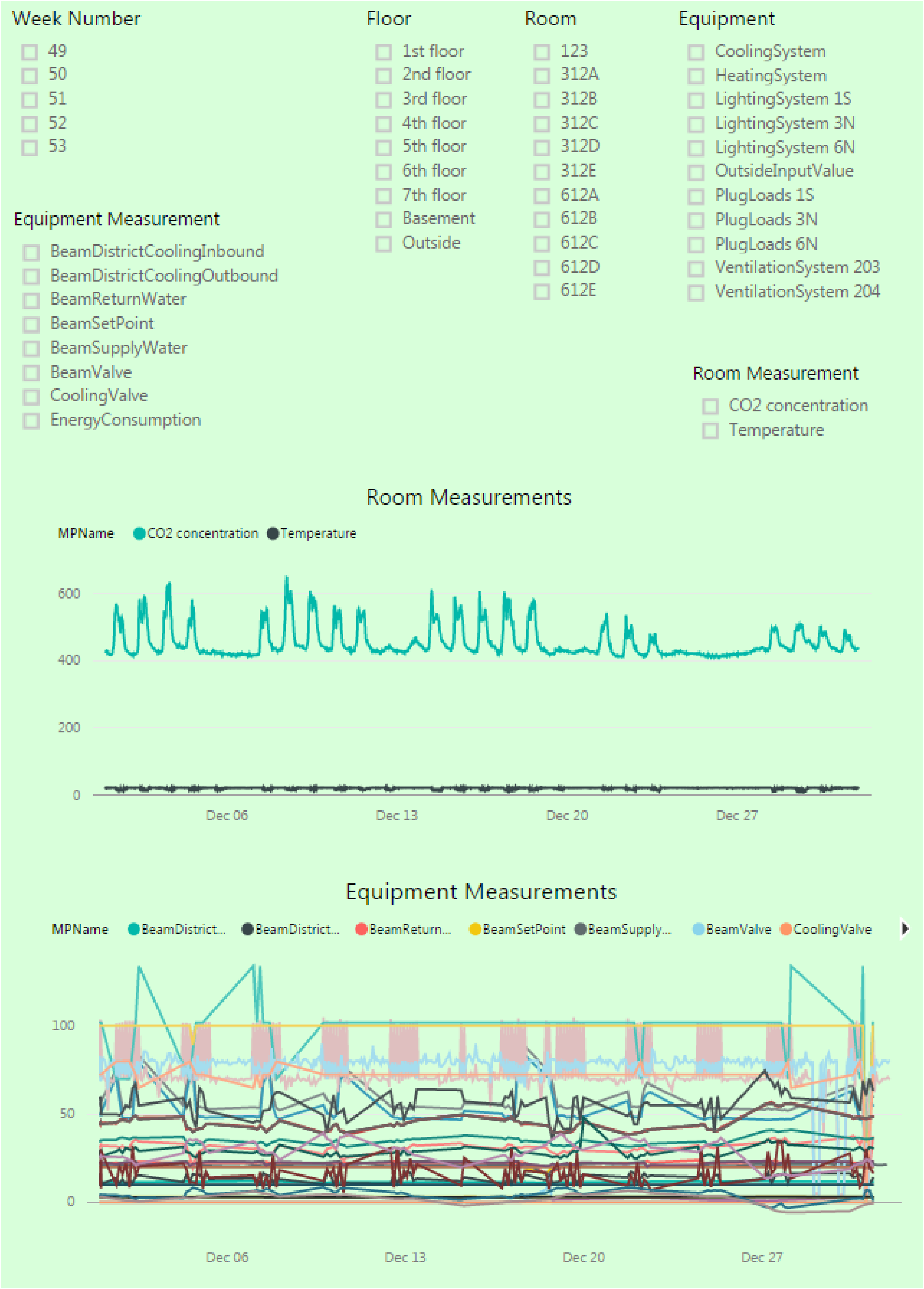
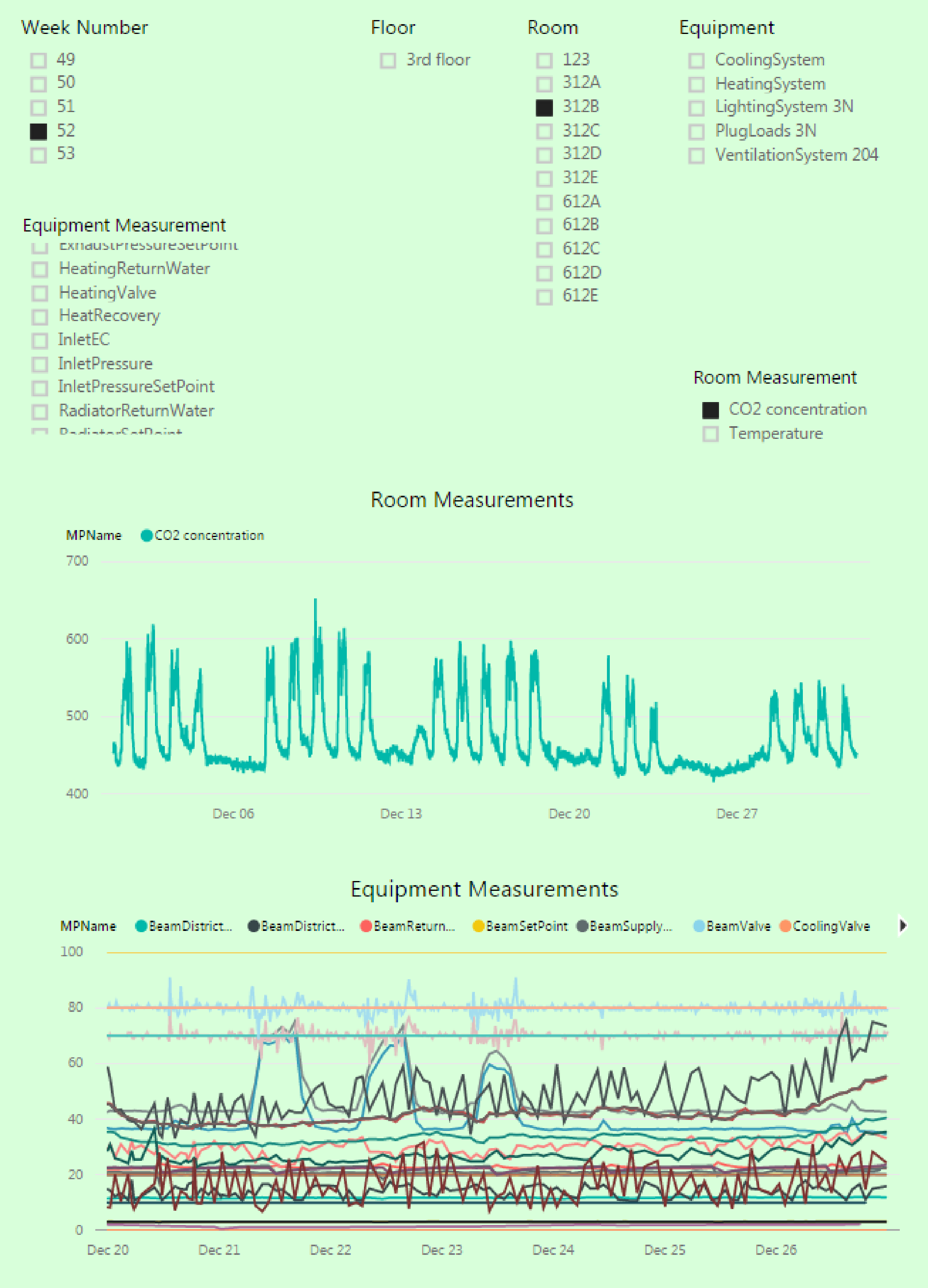


Figure 0.1 Unsliced sensor data view. All fact data (both room and equipment measurements) can be sliced in two dimensions: Time and location. It is also the dimensions that can be sliced with one another: Choosing a physical location removes all the irrelevant equipment and vice versa.



Week Number
☐ 49
☐ 50
☐ 51
☒ 52
☐ 53

Floor
☐ 3rd floor

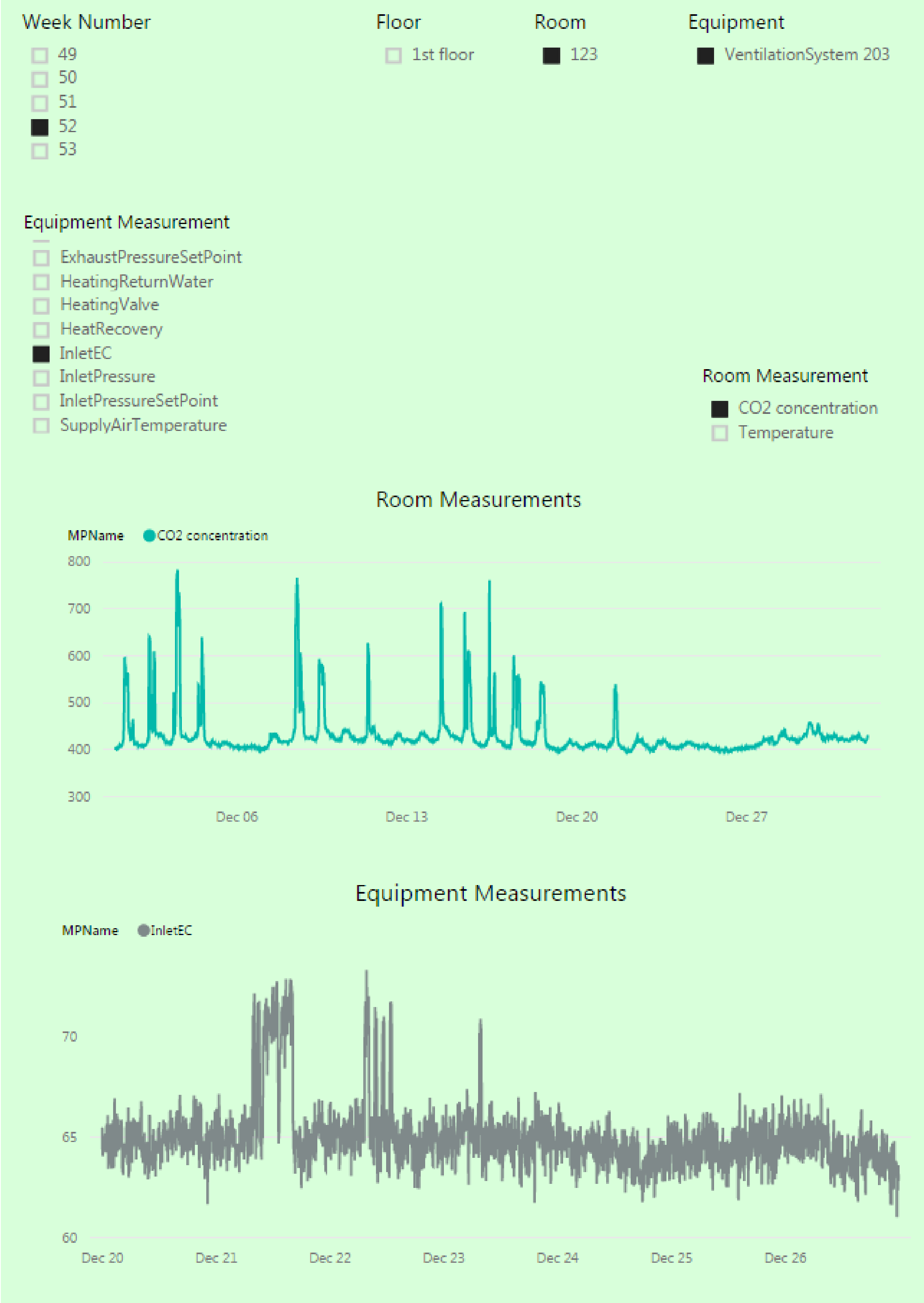
Room
☐ 123
☐ 312A
☒ 312B
☐ 312C
☐ 312D
☐ 312E
☐ 612A
☐ 612B
☐ 612C
☐ 612D
☐ 612E

Equipment
☐ CoolingSystem
☐ HeatingSystem
☐ LightingSystem 3N
☐ PlugLoads 3N
☐ VentilationSystem 204

Equipment Measurement
☐ HeatingReturnWater
☐ HeatingValve
☐ HeatRecovery
☐ InletEC
☐ InletPressure
☐ InletPressureSetPoint
☐ RadiatorReturnWater

Room Measurement
☒ CO2 concentration
☐ Temperature

Figure 0.2 Sensor data sliced with room 312B. The data model includes the information that it is the air handling unit 204 serving that area.



Week Number

☐ 49
☐ 50
☐ 51
☒ 52
☐ 53

Floor

☐ 1st floor

Room

☒ 123

Equipment

☒ VentilationSystem 203

Equipment Measurement

☐ ExhaustPressureSetPoint
☐ HeatingReturnWater
☐ HeatingValve
☐ HeatRecovery
☒ InletEC
☐ InletPressure
☐ InletPressureSetPoint
☐ SupplyAirTemperature

Room Measurement

☒ CO2 concentration
☐ Temperature

Room Measurements

Equipment Measurements

Figure 0.3 Sensor data sliced with the room H123. The data model includes the information that it is the air handling unit 203 serving that area.

Appendix 3

Data Clustering

A Microsoft Clustering model was created with SQL Server Data Tools for SQL Server 2014 and SQL Server Data Mining Add-In for Office to group sensor data sets into clusters. The model was trained with air handling unit measurement data between 1st January 2016 and 30th March 2016 that consists of

- Month,
- Weekday,
- Hour,
- Room air CO_2 concentration,
- Exhaust pressure,
- Exhaust pressure set point,
- Exhaust fan,
- Inlet pressure,
- Inlet pressure set point,
- Inlet fan,
- Heat recovery,
- Supply air temperature,
- Supply air temperature set point,
- Air heater valve,
- Air heater return water,
- Air cooler valve,
- Air humidity and
- Intake air temperature.

The resulting clusters were named according to their favored occurrence times and outdoor temperatures.

Then the model was given data from 11th April to produce four outputs: cluster, cluster distance, cluster probability and model inclusion likelihood. There was an inserted malfunction at 6.50am: The heat recovery disc stopped operating while the air heater was operating. That row is bolded and underlined in Table 0.3.

At 6.50am the model inclusion likelihood drops to 0.08 indicating that the combination of operating air heater and non-operating heat recovery disc is abnormal, which it is.

Appendix 3 (2/2)

Table 0.3 Air handling unit measurements in clusters.

Time	Room CO2	Heat Recovery	Supply Air Temperature	Air Heater Valve	Intake Air Temperature	Cluster	Cluster Distance	Cluster Probability	Inclusion Likelihood
11.4.16 4:40	430,7	0,0	19,4	0,4	10,3	Temperate Night	0,00	1,00	1,00
11.4.16 4:45	427,5	0,0	19,4	0,7	10,3	Temperate Night	0,00	1,00	1,00
11.4.16 4:50	430,1	0,0	19,4	0,0	10,2	Temperate Night	0,00	1,00	1,00
11.4.16 4:55	430,4	0,0	19,4	1,1	10,3	Temperate Night	0,00	1,00	1,00
11.4.16 5:00	428,6	0,0	19,4	1,9	10,3	Temperate Night	0,00	1,00	1,00
11.4.16 5:05	433,3	0,0	19,4	3,2	10,3	Temperate Night	0,00	1,00	1,00
11.4.16 5:10	431,2	0,0	19,4	8,6	10,3	Temperate Night	0,00	1,00	1,00
11.4.16 5:15	431,5	0,0	19,4	16,3	10,3	Temperate Night	0,00	1,00	1,00
11.4.16 5:20	427,0	0,0	19,4	22,9	10,3	Temperate Night	0,00	1,00	1,00
11.4.16 5:25	418,7	0,0	19,4	8,6	10,2	Temperate Night	0,00	1,00	1,00
11.4.16 5:30	418,7	0,0	19,4	0,1	10,2	Temperate Night	0,00	1,00	1,00
11.4.16 5:35	431,2	0,0	19,4	0,1	10,2	Temperate Night	0,00	1,00	1,00
11.4.16 5:40	430,1	0,0	19,4	0,0	10,2	Temperate Night	0,00	1,00	1,00
11.4.16 5:45	421,3	0,0	19,4	0,5	10,1	Temperate Night	0,00	1,00	1,00
11.4.16 5:50	426,9	0,0	19,4	0,5	10,2	Temperate Night	0,00	1,00	1,00
11.4.16 5:55	425,5	0,0	19,4	0,9	10,2	Temperate Night	0,00	1,00	1,00
11.4.16 6:00	429,1	0,0	19,4	1,9	10,1	Temperate Night	0,00	1,00	1,00
11.4.16 6:05	430,8	100,0	19,7	21,9	7,1	Early hours	0,00	1,00	1,00
11.4.16 6:10	423,4	100,0	20,0	21,1	5,8	Early hours	0,00	1,00	1,00
11.4.16 6:15	426,5	100,0	19,7	22,5	5,4	Early hours	0,00	1,00	1,00
11.4.16 6:20	429,6	100,0	19,6	24,6	5,1	Early hours	0,00	1,00	1,00
11.4.16 6:25	424,4	100,0	19,6	26,7	4,9	Early hours	0,00	1,00	1,00
11.4.16 6:30	424,4	100,0	19,7	28,6	4,9	Early hours	0,00	1,00	1,00
11.4.16 6:35	427,0	100,0	18,5	27,4	4,9	Early hours	0,00	1,00	0,65
11.4.16 6:40	424,1	100,0	17,9	36,5	4,8	Early hours	0,00	1,00	0,86
11.4.16 6:45	435,4	100,0	18,3	41,9	4,8	Spring evening	0,02	0,98	1,00
11.4.16 6:50	**437,9**	**0,0**	**18,6**	**44,8**	**4,7**	**Spring evening**	**0,00**	**1,00**	**0,08**
11.4.16 6:55	430,6	100,0	18,9	45,6	4,6	Early hours	0,08	0,92	0,51