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Smart Room Systems for Retrofitted Educational Buildings

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Abstract of master's thesis

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Smart technologies in buildings can improve user satisfaction, energy efficiency and the performance of technical systems. Demand-based ventilation and heating solutions are used to achieve great indoor environment quality energy efficiently. The European Commission has introduced a Smart Readiness Indicator in the new Energy performance of buildings directive, which aims at proving the added value that smart technologies bring to the building owners, users and tenants.

The objectives of the thesis are to evaluate how ICT-technology and services can be used in buildings through case examples and to integrate different systems to co-operate including building automation, HVAC and a mobile application. The measurements were conducted in seven rooms in Aalto University’s Undergraduate center. The main improvements were: the monitoring and controllability of the variable air volume ventilation- and water radiator heating-system through Aalto space – mobile app, occupancy measurements and the collection of user satisfaction feedback.

The VAV-ventilation system in the case rooms worked as designed. The CO_2 concentration varied with each room, but the temperatures were nearly identical and stable. Three different control strategies for the ventilation were tested, where the combination of both temperature and CO_2 concentration proved to be the best solution. The ratio between exhaust and supply air flows varied from room to room, best being 100% and worst 60%. This difference could be seen in the results of the pressure differences over the building envelope. This measurement was used to assess the performance of the ventilation system. All rooms were underpressured and there was a clear difference between day and night time pressures difference over the building envelope. During the night, the air handling unit of the zone serving the case rooms was not operating. Still during the nights, some general exhaust fan operating causing the greater underpressure.

Room occupancy was measured with image- and CO_2 concentration-based methods. Image-based methods provided varying results. The Kinect sensor had problems in identifying people, but the AXIS-3045 worked well with 95% accuracy. CO_2 concentration-based method was accurate to one person 66% of the time and 89% accurate in identifying if the room is occupied or not. The error is caused by the latency of change of the concentration in the rooms. Also, the CO_2 generation rates by humans and the accuracy of the supply and exhaust air flows can cause errors.

User satisfaction in the rooms was measured with a paper survey and through Aalto space – mobile app. The results indicate that people are quite satisfied with the rooms as through the paper survey 71% answered +/- 1 on the PMV scale and through Aalto Space 84% answered either four or five stars out of five. Nearly half rated the indoor temperature as slightly cool/cool or cold. The indoor temperature was considered to be acceptable by 69% and the air quality by 79% of the respondents.

Keywords Smart Readiness Indicator, User satisfaction, Variable air volume ventilation, Room occupancy, User controllability, Aalto Space

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Rakennusten älykkäät teknologiat parantavat käyttäjätyytyväisyyttä, energiatehokkuutta sekä rakennusten elinikää. Tarpeenmukaisen ilmanvaihdon ja lämmityksen ratkaisuilla saavutetaan energiatehokkaasti korkeatasoinen sisäilmaston laatu. Euroopan komissio on julkaissut uuden Smart Readiness indikaattorin, jonka tarkoituksena on korostaa älykkäiden teknologioiden tuoma lisäarvo rakennusten omistajille, käyttäjille sekä asukkaille.

Tämän työn tavoitteena on arvioida miten ICT-teknologiaa ja palveluita voidaan käyttää rakennuksissa esimerkkitapausten avulla sekä integroida eri taloteknisiä ja muita järjestelmiä, kuten rakennusautomaation ja LVI:n sekä mobiilisovelluksen yhteen. Mittaukset toteutettiin seitsemässä huoneessa Aalto-yliopiston Kandidaattikeskuksessa. Tärkeimmät parannukset olivat: muuttuvan ilmavirtasääteisen ilmanvaihdon sekä vesiradiaattorijärjestelmän seuranta sekä ohjaus Aalto Space-mobiilisovelluksella, huoneiden käyttöasteen mittaus sekä käyttäjätyytyväisyys palautteen kerääminen.

Muuttuva ilmavirtasääteinen ilmanvaihto toimi huoneissa kuten se oli suunniteltu. Sisäilmaolosuhteet vaihtelivat huoneiden välillä hiilidioksidipitoisuuden osalta, mutta lämpötila oli lähes identtinen jokaisessa huoneessa. Huoneissa testattiin kolmea eri ilmanvaihdonohjausstrategiaa, joista lämpötilan ja hiilidioksidipitoisuuden yhteisohjaus osoittautui parhaaksi ratkaisuksi. Myös tulo- ja poistoilmavirtojen suhde vaihteli huoneissa. Muutamissa huoneissa ilmavirrat olivat noin 100 % tasapainossa ja joissakin huoneissa suhde oli jopa 60 %. Tämä ero näkyi esimerkiksi huoneiden paine-eroissa rakennuksen vaipan yli. Paine-ero mittauksia tehtiin arvioidakseen ilmanvaihtojärjestelmän toimivuutta. Kaikki huoneet olivat alipaineisia. Alipaine oli selvästi suurempi öisin kuin päivisin. Tämä muutos johtuu siitä, että huoneiden ilmanvaihtokone on öisin pois päältä, mutta rakennuksessa on muita poistoilmanvaihtokoneita päällä.

Käyttäjätyytyväisyyttä mitattiin kuudella kysymyksellä paperisena sekä Aalto Space -mobiilisovelluksen avulla. Tulokset osoittavat, että ihmiset ovat melko tyytyväisiä huoneiden sisäilmastoon, sillä paperikyselyiden kautta 71 % vastasi +/- 1 PMV-asteikolla ja Aalto Spacen kautta 84 % vastasi joko neljä tai viisi tähteä viidestä. Lähes puolet vastaajista kertoi sisälämpötilan olevan hieman viileä, viileä tai kylmä. Hyväksyttävänä sisälämpötilaa piti 69 % ja ilmanlaatua 79 % vastaajista.

Avainsanat Smart Readiness Indicator, Käyttäjätyytyväisyys, Muuttuva ilmavirtasääteinen ilmanvaihto, Huoneen käyttöaste, Käyttäjäohjaus, Aalto Space

Foreword

This master's thesis has been carried out within the RealGO project between November 2017 and May 2018. RealGO is a project funded by STEK ry, STUL ry, Foundation for Quality of Construction Products and Aalto University. The project is carried out in co-operation between research groups from Aalto Real Estate Business Unit, Aalto HVAC, Aalto Computer Science and Aalto IT. The aim of the project is to find the added value that smart technologies in buildings can bring to the relevant stakeholders. The project was done in co-operation with Fidelix, Fourdeg and Integral.

I want to thank both my thesis supervisor Professor Risto Kosonen and my thesis advisor D.Sc. Juha Jokisalo for guiding the thesis process and providing me with constructive feedback throughout the process. Their help has been invaluable considering this thesis.

I would also like to thank the whole HVAC research group and especially Simo Kilpeläinen and Petteri Kivivuori for their help on my measurements. Especially Simo has provided me with help in the practical side of how each measurement should be conducted and I am very grateful for the help.

From the first day of University I was always told to study hard and participate in Teekkariculture. I have followed this advice throughout my time here in Aalto. This thesis was even a part of a Jäynä as papers asking people to rate the outdoor air were put on walls in the campus. The paper said that it was part of the Jukka-project. The experiences and memories I have gotten from Otaniemi will stay with me for the rest of my life and I will always wear my Teekkarilakki with pride.

Last, I want to thank my family for all their support and help through the years and Leena for all the love and laughter that we have shared and will share in the future.

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Jukka Kopra

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Abbreviations

ACRE	Aalto Campus and Real Estate
AHU	Air-Handling Unit
API	Application Programming Interface
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
BACS	Building Automation and Control System
Bq	Becquerel
CAV	Constant air volume
CO_2	Carbon Dioxide
DH	District Heating
EED	Energy Efficiency Directive
EPBD	Energy Performance of Buildings Directive
EU	European Union
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communications Technology
IEQ	Indoor Environment Quality
IoT	Internet of Things
nZEB	nearly Zero Energy Buildings
O-MI	Open Messaging Interface
O-DF	Open Data Format
PIR	Passive Infrared detection systems
$PM_{2.5}$	Particulate matter with a diameter of 2.5 micrometers or less
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
ppm	Parts per million
REHVA	Federation of European Heating, Ventilation and Air Conditioning Associations
RFID	Radio Frequency Identification
SRI	Smart Readiness Indicator
VAV	Variable Air Volume

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1 Introduction

In the European Union (EU), buildings accounted for 40 % of the final energy consumption and 36% of the greenhouse gas emissions in 2017 (European Commission, 2018). In Finland, the heating of buildings accounted for 26% of the final energy consumption in 2017 (Official Statistics of Finland, 2018). Buildings are the single biggest consumer of energy in the EU and the second biggest consumer in Finland. A great potential to save energy lies in increasing the energy efficiency of buildings as 75% of the EU building stock is considered inefficient (European Commission, 2017). In the EU the 2010 energy performance of buildings directive (EPBD, 2010) and the 2012 energy efficiency directive (EED, 2012) are the main legislation covering the improvement of energy efficiency and smart technologies in buildings. The EPBD has been updated twice, first in November 2016 when the promotion of smart technologies was added, and in 2018. The recent update included a series of measures to accelerate the building renovation towards more energy efficient systems and aims to create a clear path towards a low and zero emission building stock in the EU by 2050. This is achieved by mandating member countries to establish long-term strategies focusing on building renovation investments on the worst-performing building stock to increase their energy efficiency. The European Commission has conducted an impact assessment which states that an average rate of 3% annual renovation would be needed to cost-effectively accomplish the Union's goals for energy efficiency (Artola *et al.*, 2016). The long-term goal to 2050 is to reduce greenhouse gas emissions in the EU by 80% - 95% compared to 1990. The decarbonization of buildings targets are set in line with this target. The whole building stock of EU shall be decarbonized by 2050. The directive also requires all new buildings in the EU to be nearly zero energy buildings (nZEB) from December 31, 2020 and all new public-owned buildings from December 31, 2018. (EPBD, 2018)

In the new proposed EPBD, a smart readiness indicator is introduced for buildings, which will measure the buildings' readiness to utilize smart technologies to improve energy efficiency and indoor environment quality. The directive states that the indicator should be used to measure buildings' capacity to use ICT and electronic systems to adapt the operation of the building to the needs of the occupant and the grid and to improve its energy efficiency and overall performance. The directive has also a clause that mandates non-residential buildings with an effective rated combined heating and ventilation system output of over 290 kW to be equipped with an automation and control system by 2025 if considered technically and economically feasible. (EPBD, 2018) To fully use smart technologies in a building, an automation and control system is needed. The EU sees that buildings play a key role in developing the future energy system in Europe. By developing buildings, energy-savings are achieved, economic opportunities increase, and the quality of indoor environment is increased. Buildings can also support the use of intermittent renewable energy sources by providing demand response services. (Council of the European Union, 2018)

The addition of smart technologies and building automation and control systems in the updated directive are a good addition to the older measures. Previous directives have mainly concentrated on achieving energy efficiency through improving the envelope of the building i.e. improving the insulation in the walls and windows. These types of improvements decrease the flow of energy through the building envelope. This type of improvement does not respond to the occupants' behavior. It can for example have the side-effect of people opening windows during winter time to avoid overheating, which is the clear opposite of what is trying to be achieved. By introducing smart technologies these types of user-based mistakes can be avoided, thus improving the energy efficiency of the whole building system.

Some clear technologies that can be used in improving the energy efficiency are demand-based technologies, such as variable air volume ventilation, occupancy-based lighting and accurate heating. These technologies include sensors and actuators to be installed and managed in the proper way to work efficiently. The level of accuracy of the sensors varies with technologies used. Cheaper sensors, such as infrared occupancy sensors can be used with smart lighting as the number of people does not change the demand for lighting. For demand-based ventilation on the other hand, the number of people in the room does make a difference, so a more accurate sensor is needed. This way an adequate amount of outdoor air can be supplied to the room. The aim is both to improve the energy efficiency as well as increase the satisfaction of the users, which can be very difficult as people have varying opinions on what is a good indoor environment.

The criteria that is used for the indoor environment in buildings influences the energy consumption. The indoor environment affects health, performance and comfort of the occupants. (Al Horr *et al.*, 2016) Recent studies show that the effect of poor indoor environment on the productivity of the occupants has higher costs for the employer, the building owner and society than the energy costs of the same building (World Green Building Council, 2014). It has also been shown that great indoor environment quality increases the working and learning productivity and decreases absences in the workplace (Al Horr *et al.*, 2016).

Different criteria for indoor environmental quality have been defined in various standards and frameworks both internationally and in Finland. The basis in Finland is defined by the Ministry of Environment (2017) and by standards SFS-EN ISO 7730 (2006) and SFS-EN 15251 (2007). These are used when designing a building. In occupied buildings, the indoor environment quality should be assessed with post-occupancy surveys to ensure the that the design conditions are met.

1.1 Research Objectives

The research objective of this thesis is to study how smart HVAC-solutions can be incorporated in retrofitted buildings. The building that is studied is an educational building. The objectives of the thesis are to evaluate how ICT-technology and services can be used in buildings through case examples and to integrate different systems to co-operate including building automation, HVAC and a mobile application. The main improvements of the new system are:

1) the monitoring of the variable air volume ventilation system performance
2) the controllability of ventilation and water radiator heating system in an energy efficient manner
3) measuring the room occupancy with different technologies
4) collecting feedback from the users' perception on the indoor climate.

The improvements are evaluated with a series of measurements conducted in Aalto University campus.

1.2 Structure of thesis

The theory and basis for smart technologies and its different specifications are presented in Chapters 2, 3 and 4 and measurements and their results are discussed in Chapters 5, 6, 7 and 8.

Chapter 2 presents which standards and classification frameworks are used, and which are in development in this context. The standard SFS-EN 15232 (2017) and Smart Readiness Indicator developed by the European Commission are the focus in this thesis. Also, a method for monitoring and analyzing data from smart buildings is described.

Chapter 3 describes the different specifications for a healthy and comfortable indoor environment and how it affects user satisfaction and productivity of occupants. Comfortable indoor environment has a significant effect on the wellbeing of users as most of our time is spent indoors. Different methods to assess indoor environment are also described.

Chapter 4 describes technical systems in buildings. The variable air volume ventilation system is described in more detail as it is used in the case rooms. Also, the building automation and control system is discussed. The different methods for measuring building occupancy are described as well as the benefits of knowing how many people use the building and when. CO_2 concentration- and image-based methods are more closely studied in this thesis.

Chapter 5 describes the methodology of the measurements and the results of the seven case rooms. A total of six different measurements are included in this study to analyze occupancy, system performance and user satisfaction.

Chapter 6 presents the results of the measurements.

2 Standards and other frameworks

The building industry utilizes different standards that define the type of services, technologies and materials that should be used in a smart building. Also, different indicators are used. The most recent is the introduction of the Smart Readiness Indicator (SRI), that is part of the new EU energy performance of buildings directive (EPBD) (2018). The introduction of smart technologies to a building means more effective use of ICT, which use a lot of data. Data needs to be gathered and analyzed in a systematic way to guarantee excellent indoor climate, high performance of HVAC- system and energy efficiency for the building. For this purpose, a framework has been developed that is described in this chapter.

2.1 SFS-EN15232 Energy performance of buildings

The European standard SFS-EN 15232 (2017) "Energy performance of buildings – Impact of building automation control and building management" – has defined methods for estimation of the impact of building automation and control system (BACS) and technical building management on energy performance and energy use in buildings. The standard is part of a series of standards that aim to harmonize the assessment of the energy performance of buildings in Europe. In the standard, four different classes (A, B, C, D) were defined on the efficiency of the building automation and control for both non – residential and residential buildings. Functions that have an impact on the energy performance of the buildings are also listed which are the basis of the classes. The functions are divided in three groups based on what they are for: automatic control, building automation and technical building management. The four different classes are defined as:

- Class D: Non - energy efficient BACS, buildings classified in this class shall be retrofitted and new buildings should not be built with such systems
- Class C: standard BACS
- Class B: Advanced BACS and building management systems
- Class A: High energy performance BACS and building management systems.

For example, for supply air temperature control the classes are defined as:

- Class D: No control
- Class C: Constant set point
- Class B: Variable set point with outdoor temperature compensation
- Class A: Variable set point with load dependent compensation

The standard made possible to qualify and quantify the benefits of BACS. By creating a classification system, the standard has given value and a clear way to compare different BACSs and thus promotes the use of them. With this classification, the comparison of buildings has become easier and decision makers can more easily choose which kind of BACS suits the building.

2.2 Smart readiness indicator

Smart readiness indicator (SRI) is an indicator that is developed by the European commission to help recognize smarter building technologies and functionalities which enhance the energy efficiency, indoor environment quality and other relevant performance characteristics of the European building stock. It is part of the new EPBD (2018) amending Directive 2010/31/EU and it complements measures under the energy efficiency directive as well as EU legislation on energy efficiency of products. The SRI aims at proving the added value that smart technologies bring to the building owners, users and tenants. As this sort of indicator has not existed before, it will make it easier to understand how well smart technologies are utilized in a building.

Smart technologies in buildings are technologies that are utilized for example in increasing the energy efficiency, giving the ability to be flexible in the electricity load and increasing the comfort of the occupants of the building. A preliminary study has been conducted for support in setting up the SRI. In this study smart readiness is analyzed in three different aspects (Verbeke *et al.*, 2017):

1. Readiness to adapt in response to the needs of the occupant
2. Readiness to facilitate maintenance and efficient operation of the building in a more automated and controlled manner
3. Readiness to adapt to the demands of the energy grid

Verbeke study also states that when assessing a building's smart readiness, identifying the services is only one part of it. It is also important to set certain boundary conditions for the services to fulfill. These could be related to the indoor climate as well as comfort of the occupants. The first draft of services that the SRI could include were divided into ten domains where examples of services are mentioned in brackets:

- Heating (storage, generation, distribution and emission of heat)
- Domestic hot water (efficiency of distribution, generation, storing the energy needed)
- Cooling (thermal storage, emission control systems, generators, energy consumption)
- Mechanical ventilation (air flow rate and temperature control)
- Lighting (artificial and natural lighting control)
- Dynamic building envelope (controlling windows and blinds)
- Energy generation (local energy generation, local use, flexibility to the grid)
- Demand side management (flexibility of systems in relation to the power grid)
- Electric vehicle charging (charging, feed-in to the grid, storage)
- Monitoring and control (various sensor data)

Each group is then divided in relation of their functionality. The scale is from 0 to 3 where level 0 represents the very basic situation and level 3 a developed smart service. Example service "Storage of locally generated energy" would be divided as follows:

- Level 0: no storage
- Level 1: small scale storage for example batteries
- Level 2: storage which can supply self-consumption for a given duration
- Level 3: dynamically operated storage which can also feed back into the grid based on price signals.

The impact of the services is defined for eight different criteria:

- Energy savings on-site
- Flexibility for the energy grid and storage
- Self-generation of energy
- Comfort
- Convenience
- Health
- Maintenance and fault prediction
- Information provided to the occupant

It has not yet been decided on how exactly the final indicator value is defined, but it will most likely be on a five-step scale from A to E, where A is the highest score and E the lowest. It will most probably have differences between countries and regions as the demands for buildings differ. Comparing for example the northern cold countries with the temperate climate countries in EU, there is clearly a difference in demand for heating services. Also, the type of building affects what kind of services are relevant for example comparing residential and non-residential buildings. These factors will be taken into consideration by assessing the importance of the domains and impact criterion to be more region and building specific. (Verbeke *et al.*, 2017)

2.3 Framework for monitoring and data analysis

Installing smart technologies to buildings require the use of ICT with sensors and actuators. The use of smart technologies raises questions on how data should be gathered, processed and analyzed to achieve the full benefit of the new technologies. The whole system can be controlled by BACS, but the strategy used for the data is dictated by the desired result. For example, data could be collected continuously or just assessed monthly. As the cost of sensors have decreased, they are more readily available for different applications. As a result, it can easily lead that large amounts of data are collected without real utilization plan. This can cause challenges as the data needs to be stored, corrected from errors and analyzed. When considering how data is sampled different aspects must be taken into consideration to achieve the most effective solution, in terms of cost, time and effort. Table 1 shows the different aspects and their alternatives that need to be considered. (Bolchini *et al.*, 2017)

Table 1. Sampling strategies characteristics (Bolchini et al., 2017).

Monitoring aspect	**Available alternatives**	
Battery life	Long	Short
Amount of data	Limited	High
Sampling strategy	Change of value	Fixed period
Collected data	Events	Values
Sensing goal	Control	Assessment / analysis

The framework presented by Bolchini et al. (2017) consists of different domains that characterize the monitoring solution related to the application solution. This methodological framework helps to develop a monitoring campaign by identifying the main choices available and the alternatives for each identified application. Each dimension has many different alternatives, or values, which have an impact on the other dimensions as well. The impact can be for example so that if the objective of an application is dynamic control, then the real-time sampling strategy must be chosen as the control must be taken from the latest values to be working properly. The different domains and their alternatives are shown in Figure 1.

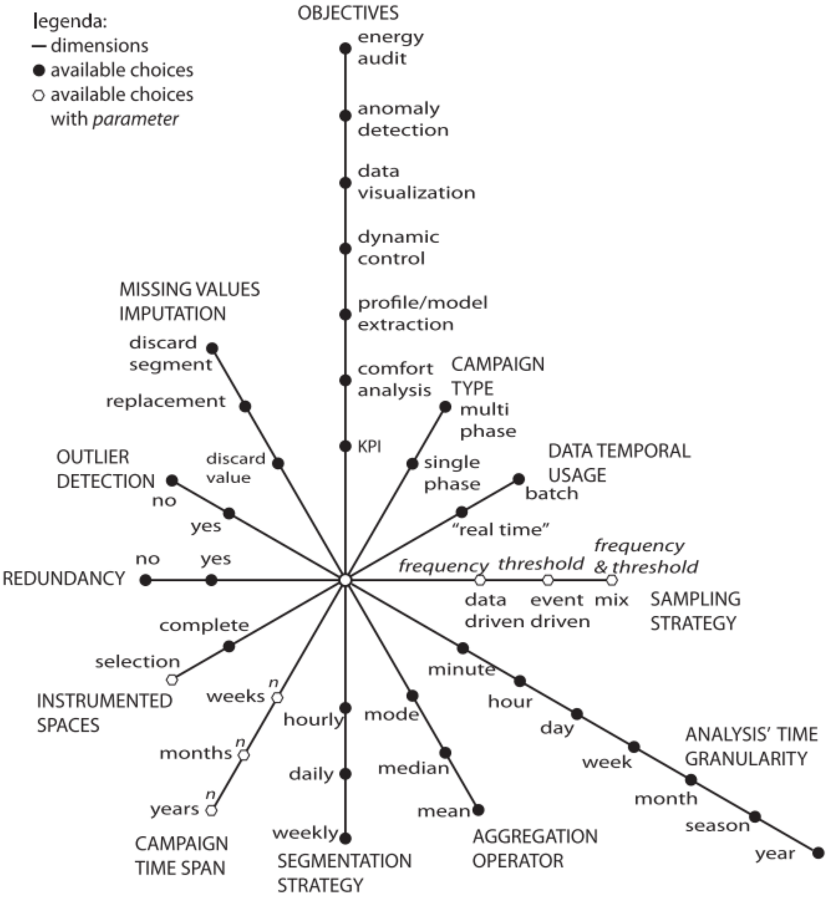


Figure 1. The monitoring campaign dimensions and alternatives within the framework (Bolchini et al., 2017).

This framework is one way to help to identify how data is collected and analyzed and can be used by consultants and building owners. The introduction of smart technologies requires a new way of thinking of building monitoring to get full benefits of the possibilities digitalization offers.

3 Indoor environment quality and user satisfaction

This chapter describes factors that influence indoor environment quality, occupants' satisfaction, productivity and well-being. Also, the methods to evaluate indoor environment quality is discussed.

3.1 Indoor environment quality

The indoor environment consists of air quality, thermal comfort, lighting and acoustics. European commission states that energy efficiency is achieved in buildings by maintaining a good IEQ with less energy use than before (European Commission, 2018). People typically spend 90% of their time indoors, which gives value to a well-designed indoor environment (Al Horr *et al.*, 2016). The IEQ has clear effects on the comfort, health and productivity on the occupants (De Giuli *et al.,* 2012). Dissatisfaction can be caused by for example suboptimal temperatures, bad indoor air quality, noise or glare. The percentage of dissatisfied people for acoustics privacy ranges from 30% to 60% and for thermal comfort and indoor quality is often over 30% (Abdul-Wahab, 2011). People's thermal satisfaction varies from person to person and is affected by multiple factors including (Li *et al.*, 2017):

- Environmental (temperature, humidity)
- Physiological (gender, heart rate, metabolism)
- Psychological (stress, beliefs, attitudes)
- Behavioral (clothing level, activity).

The IEQ has a big impact for a typical business set in an office as usually 90 % of costs are staff costs (World Green Building Council, 2014). Small improvement to workers' conditions can have a big effect on the performance of the whole work force and thus the profit of the company. For example, Seppänen and Fisk (2006) suggests that worker productivity decreases by 2% per 1°C increase in temperature in the range of 25°C - 30°C. Measuring worker productivity is difficult as there are a wide variety of different kinds of tasks an office worker could be doing, but this result gives some idea as to what the effect of a suboptimal temperature can be. A study conducted by Allen *et al.* (2016) found out that people who work in well-ventilated offices have significantly higher cognitive functioning skills than those who work in offices with typical levels of ventilation. Overall eight different factors affect occupant satisfaction and productivity in an office environment (Al Horr *et al.*, 2016):

- Indoor air quality and ventilation
- Thermal comfort
- Lighting and daylighting
- Noise and acoustics
- Office layout
- Biophilia and views
- Look and feel
- Location and amenities

3.2 Design parameters for indoor environment

To ensure that good IEQ is being designed in buildings in Europe, some standards and indicators have been introduced. The European standard SFS-EN 15251 (2007) defines parameters addressing indoor air quality, thermal environment, lighting and acoustics. The standard specifies four different categories for each parameter. The categories are described in detail in Table 2.

Table 2. Description of the categories in SFS-EN 15251.

Category	Description
I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
II	Normal level of expectation and should be used for new buildings and renovations
III	An acceptable, moderate level of expectation and may be used for existing buildings
IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year

Ventilation rates are defined separately for pollution from people and from building material emissions. Building material emissions consists of total volatile organic compounds, formaldehyde, ammonia and carcinogenic compounds. The exact levels of emissions per substance are defined in more detail in the standard SFS-EN 15251 (2007). Very low polluting materials are for example natural materials such as glass, metals and stone. The total ventilation demand is calculated by combining the two airflow demand values. The defined values are shown in Table 3.

Table 3. Recommended ventilation rates for non-residential buildings (SFS-EN 15251, 2007).

		Airflow for building emissions pollutions (l/s/m^2)		
Category	**Airflow per person (l/s/person)**	**Very low polluting building**	**Low polluting building**	**Non-low polluting building**
I	10	0.5	1	2
II	7	0.35	0.7	1.4
III	4	0.2	0.4	0.8

The maximum value for CO_2 concentration indoors above the outdoor concentration (that is 400 ppm) is also defined in the standard, shown in Table 4.

Table 4. Recommended CO_2 concentrations above outdoor concentration (SFS-EN 15251, 2007).

Category	**CO_2 concentration above outdoor concentration**
I	350
II	500
III	800
IV	< 800

In Finland the design parameters for indoor environment are set by the Ministry of Environment in Decree 1009 (2017). The parameters' latest update was introduced in 2017. It says that the indoor temperature must be designed to be comfortable during occupied time. Air movement, solar radiation, surface temperatures, temperature fluctuations and variations should not decrease the quality in anyway. The design temperature should be 21°C. The operational temperature may vary between 20°C and 25°C during heating seasons and between 20°C and 27°C outside the heating season. The indoor air should not contain harmful concentrations of pollutants or odors. The momentary concentration of CO_2 can be maximum 1450 mg/m^3 (800 ppm) more than the outdoor concentration. Also, the humidity of the room should be so that it does not harm the building or the occupants' health. To prevent condensation and risk of mold, the relative humidity should be lower than 60 %. (Decree 1009, 2017)

The indoor association of Finland has defined a more detailed classification than the Ministry of Environment for assessing the indoor air quality, called the Classification of indoor environment (Sisäilmayhdistys ry, 2017). The classification is a tool to adjust target values during design process to guarantee comfortable and healthy living environments. In the classification, three different classes (S1, S2, S3) are specified where S1 is the best and S3 corresponds to the minimum requirements of the Ministry of Environment. The minimum requirements define the parameters, so that a typical healthy person is not harmed in any way if there are no significant sources of pollutant and the ventilation works as designed. The classes are defined as:

- S1: Individual indoor climate. The air quality is very good, and temperatures can be adjusted individually. The thermal conditions are comfortable, and no overheating occurs.
- S2: Good indoor climate. The air quality is good, but the temperature cannot be adjusted individually. There is usually no draft, but during warm periods some overheating is possible.
- S3: Satisfactory indoor climate: The indoor air and thermal conditions fulfill the requirements set by the National building code.

Specific targets for indoor operative temperature, indoor air velocity and air quality are shown in Table 5 – 7. respectively.

Table 5. Classification of indoor operative temperature (Sisäilmayhdistys ry, 2017).

	S1	**S2**	**S3**
Operative temperature			
t_u[1] ≤ 0 °C	21.5	21.5	
$0 < t_u \leq 20$ °C	$21.5 + 0.15 \times t_u$	$21.5 + 0.2 \times t_u$	
$t_u > 20$ °C	24.5	24.5	
$t_u \leq 10$ °C			21
$10 < t_u \leq 20$ °C			$21+0.55 \times (t_u - 10)$
$t_u > 20$ °C			27
Allowed deviation from design value °C			
deviation upwards			
$t_u \leq 0$ °C	< 22.5	< 23	
$0 < t_u \leq 15$ °C	$22.5+0.166 \times t_u$	$23+0.2 \times t_u$	
$t_u > 15$ °C	< 25	<26	
$t_u \leq 10$ °C			<25
$t_u > 10$ °C			<27
deviation downwards			
$t_u \leq 0$ °C	> 20.5	> 20.5	>20.0
$0 < t_u \leq 20$ °C	$20.5+0.075 \times t_u$	$20.5+0.025 \times t_u$	>20.0
$t_u > 20$ °C	> 22	> 21	>20.0
Maximum value for operative temperature			
$t_u \leq 0$ °C	< 23	< 23	
$0 < t_u \leq 20$ °C	$23 + 0.2 \times t_u$	$23 + 0.2 \times t_u$	
$t_u > 15$ °C	< 27	< 27	
$t_u \leq 10$ °C			< 26
$t_u > 10$ °C			< 32
Minimum value for operative temperature	20	20	18
Stability of the conditions (% of usage)[2]			
Non-residential	90 %	90 %	
Residential	90 %	80 %	

[1] tu is the outside temperature.

[2] Stability of conditions is assessed as the moving one-hour average of the temperature.

Table 6. Classification for indoor air velocity (Sisäilmayhdistys ry, 2017).

Air velocity (m/s)	**S1**	**S2**	**S3**
$t_{air} = 21$°C	< 0.14	< 0.17	0.2 (winter)
$t_{air} = 23$°C	< 0.16	< 0.20	
$t_{air} = 25$°C	< 0.20	< 0.25	0.3 (summer)

Table 7. Classification for indoor air quality (Sisäilmayhdistys ry, 2017).

	S1	S2	S3
CO_2 concentration (ppm)	< 350	< 550	< 800
Radon concentration (Bq/m^3)	< 100	< 100	< 150
$PM_{2.5}$[1] (μ/m^3)	< 10	< 10	< 25
$PM_{2.5}$[1] inside/outside	< 0.5	< 0.7	-
Stability of the conditions[2] (% of usage)			
Non-residential	90 %	90 %	
Residential	90 %	80 %	

[1] Particulate matter with a diameter of 2.5 micrometers or less.

[2] Stability of conditions is assessed as the moving one-hour average of CO_2 concentration.

3.3 Assessment of indoor environment quality

Indoor environment quality (IEQ) assessment procedure can be separated into two different methods: classification and diagnosis. Classification means that the IEQ parameters are measured to see into which category they belong to in different standards. This way rooms and buildings can be compared more easily with one another. Diagnosis means more detailed assessment which includes for example studying the seasonal behavior and identifying system faults. Diagnosis is a more long-term assessment whereas classification is a short term. (Corgnati *et al.*, 2011)

Assessing the effects of different indoor environment factors to humans is very complex as these factors affect also each other, for example cooler air gives a feeling of fresher air in the room. A study by Fang *et al.*, (1998) also suggests that the air quality of warm air will be perceived as poor whether it is clean or polluted. If this is not being considered, it will lead to increased ventilation being a waste of energy as it would not increase the quality of perceived air.

The standards SFS-EN ISO 7730 (2006) and SFS-EN 15251 (2007) have defined guidelines for design of high-class IEQ by defining different parameters, such as mean radiant and operative temperature, air velocity and humidity for both summer and winter periods. The standard SFS-EN ISO 7730 (2006) has defined a method for assessing the share of people dissatisfied with the whole body thermal sensation in a room using predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD). The PMV is an index that predicts how occupants would rate their feeling of thermal sensation on a seven-step scale shown in Table 8.

Table 8. PMV Thermal sensation scale (SFS-EN ISO 7730, 2006).

+ 3	Hot
+ 2	Warm
+ 1	Slightly warm
0	Neutral
- 1	Slightly cool
- 2	Cool
- 3	Cold

The index considers occupants' clothing factor, metabolic rate, air temperature, mean radiant temperature, air velocity and humidity. It is based on the heat balance of the human body. (SFS-EN ISO 7730, 2006)

The PMV predicts the mean vote while the PPD gives a prediction on the percentage of dissatisfied people, i.e. people who feel too cold or too warm. The dissatisfied are people who would vote hot, warm, cool or cold on the thermal sensation scale. The PPD can be calculated for average person from the PMV, the correlation is shown in Figure 2. In a large group, there are always a share of people that are dissatisfied with the thermal environment as thermal satisfaction is a highly individual sensation and PPD index can only predict the average thermal sensation.

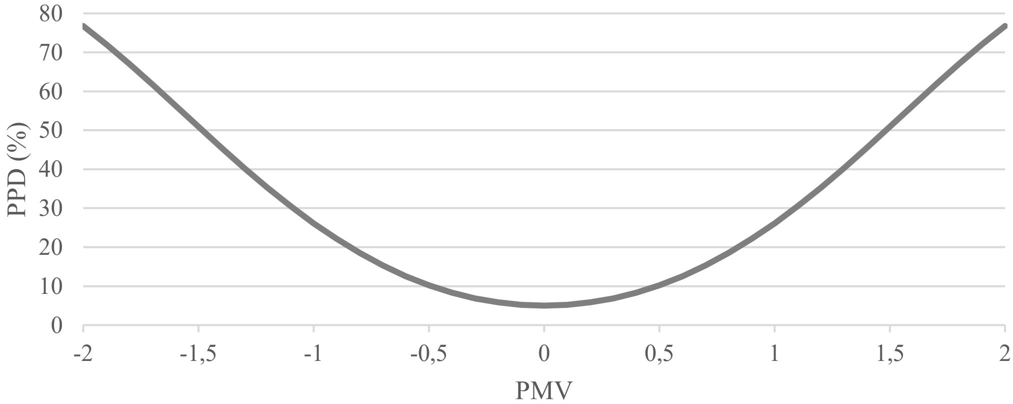


Figure 2. PPD as a function of PMV (SFS-EN ISO 7730, 2006).

The PMV and PPD expresses the thermal discomfort for the whole body. Thermal discomfort can also be caused in a specific part of the body. This is known as local discomfort which can be caused by draught, high vertical temperature differences between head and feet, warm and cool floors and radiant asymmetry. (Corgnati *et al.*, 2011)

Draught is the unwanted local cooling of the body due to air movement. It can be caused by for example open windows or high ventilation rates. The percentage of people predicted to be bothered by draught can be calculated knowing the local air temperature, local mean air velocity and local turbulence intensity. Vertical air temperature difference between head and ankles causes also discomfort in people. The percentage of people dissatisfied can be calculated as a function of the vertical air temperature difference, shown in Figure 3. (Corgnati *et al.*, 2011)

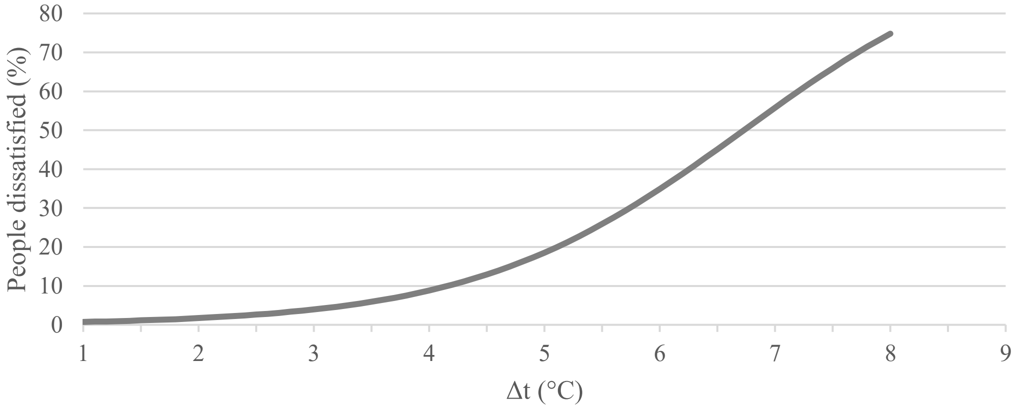


Figure 3. Percentage dissatisfied caused by vertical air temperature difference.

The temperature of the floor can also be the cause for discomfort. The percentage dissatisfied from too cold or too warm floors can be calculated as a function of the floor temperature, shown in Figure 4.

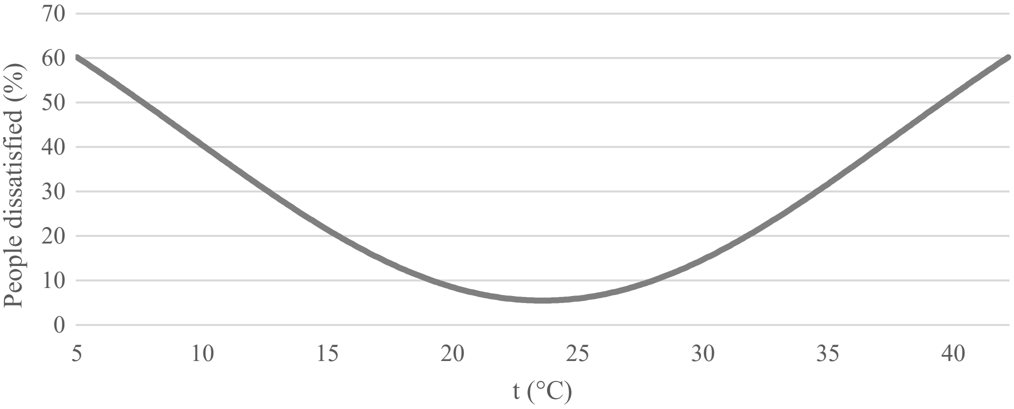


Figure 4. Percentage dissatisfied caused by the floor temperature.

Radiant temperature asymmetry can also cause dissatisfaction in users. It can be due to, for example warm/cold windows, or warm/cold ceiling. This is especially important to be considered when designing radiant systems. The percentage dissatisfied can be calculated for each of the four different cases as a function of the radiant temperature asymmetry, shown in Figure 5. (Corgnati *et al.*, 2011)

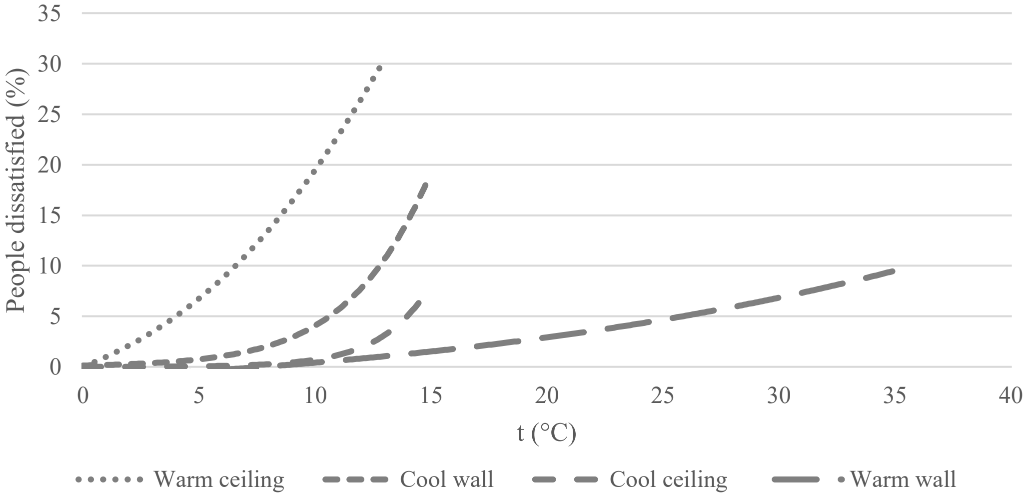


Figure 5. Percentage dissatisfied caused by radiant temperature asymmetry.

How a building is designed and how it works can differ from one another. Differences from the design and what can occur are the result from the assumptions of the designers on for example internal heat loads and operation hours and how the systems are maintained. Post occupancy evaluation means gathering data on the actual well-being of the occupants and operation of the building systems after occupation to find out if the building is performing as it should. (Leaman and Bordass, 2001)

The evaluation can be conducted in many ways such as using questionnaires, sensor data and audits or combination of those methods. A web based standardized survey has been developed by the Center of Built Environment at University of California Berkley, which focuses on occupant satisfaction and comfort related to IEQ issues. The survey is constructed so that it has a set of core questions which are about the indoor air quality, thermal comfort, lighting and acoustics. If the occupant evaluates some area poorly, new questions are asked to get to the root of the problem. (Zagreus *et al.*, 2004) This way only relevant questions are asked, and problems are found.

If any problems are identified from the questionnaire, closer measurements can be conducted. SFS-EN ISO 7726 (2001) has defined relevant parameters to be measured for air velocity, air temperature, mean radiant temperature and relative humidity. Four heights where air velocity and temperature measurements should be performed are recommended by the Standard. The heights are defined for a sitting and a standing person shown in Figure 6.

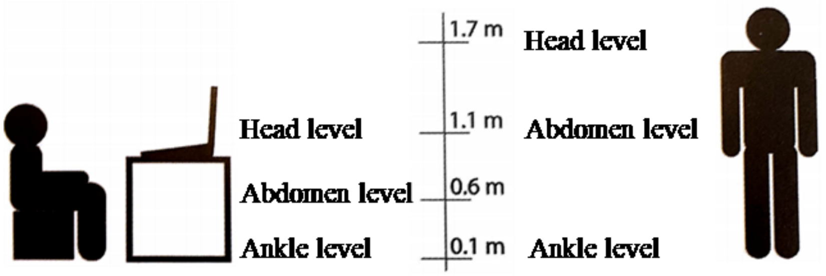


Figure 6. Recommended measurement heights for sitting and standing persons (Müller et al., 2013).

To further investigate the thermal comfort of humans, a thermal manikin can be used. A thermal manikin is a typical human sized manikin, which can be used to measure the skin temperature on different parts of it. This way some real data can be measured on the thermal conditions. The manikin is useful especially for non-uniform thermal conditions, as it shows how it affects human body in different parts. (Foda, 2012)

4 Building systems

Building technical systems include HVAC- systems, room specific devices and building automation and control systems. The challenge in building smart buildings is to get all these systems to work together. A building needs to be provided with adequate heating, cooling and clean outdoor air. There is a wide array of options to achieve this. In Chapter 4 we look at a variable air volume ventilation system as the basis of operation for non-residential buildings, such as offices or educational buildings, as it the most energy efficient to control ventilation (Okochi and Yao, 2016). This chapter also presents how building occupancy is defined and measured and how it affects the performance of ventilation.

4.1 Variable air volume ventilation

Variable air volume (VAV) ventilation systems are defined as ventilation systems which vary the supply and exhaust air flow to meet the heating or cooling load and the ventilation requirements of the space (Okochi and Yao, 2016). Indicators used in assessing the air volume demand are usually CO_2 concentration of the indoor air and room air temperature. If one of these crosses a set-point level, the airflow is adjusted to meet the demand. (California Energy Commission, 2003) Ventilation can also be adjusted with time-based ruling, for example that the ventilation has occupancy mode on during the office hours and off during night time. These types of systems do not vary the flow as frequently as for example occupancy-based systems, but they can still be considered to be one type of VAV system.

The VAV system includes central air handling unit (AHU), ductwork and room units. The central air handling unit includes filtration, heat recovery, heating and cooling operations. During the winter time, AHU's can utilize cold outdoor air for free cooling of the supply air. In the summer time, the supply air is cooled with chiller or district cooling. In summer with the VAV system, the supply air temperature could be constant (e.g. 16 °C) or the temperature could be varied as a function of the outdoor air or the exhaust air temperature. Ductwork and room units include the required dampers to control supply air flow rate. (Sandberg *et al.*, 2014) Figure 7 shows the schematic diagram of a VAV system, including the separate room and heating system with water radiators.

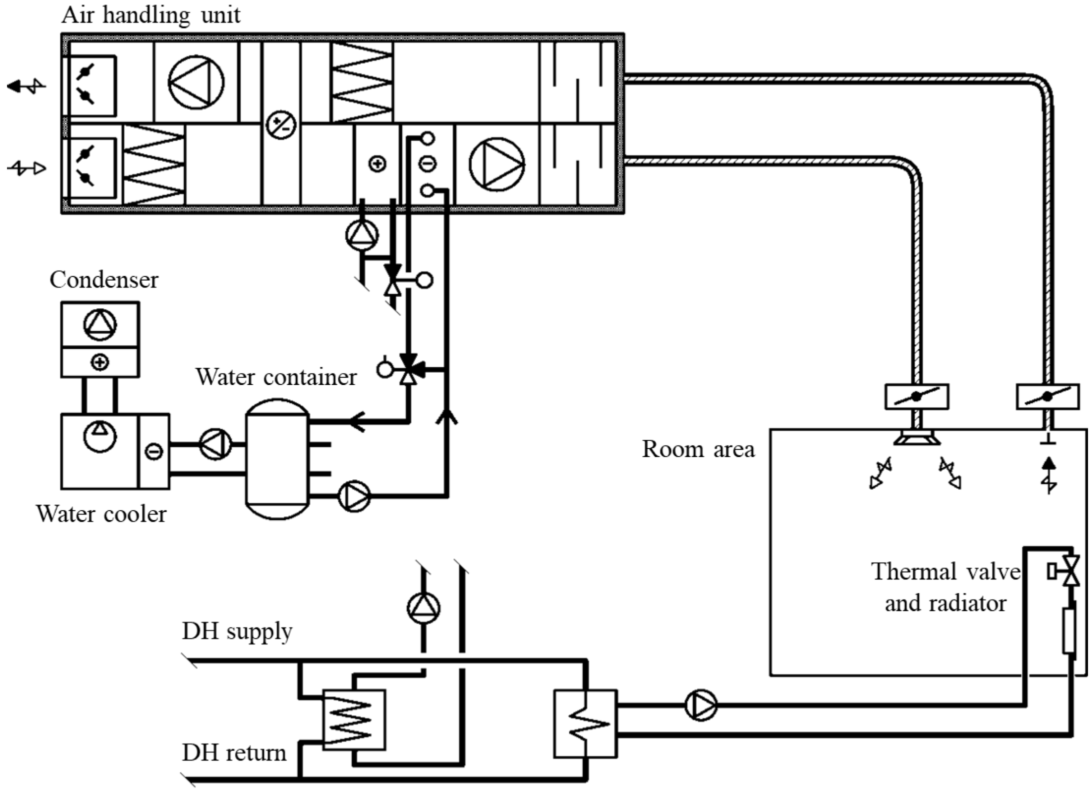


Figure 7. Schematic diagram of a VAV system (Seppänen et al., 2004).

As the VAV system works based on demand, the performance of the system's sensors is important. Without proper performance, the system either uses too much energy or the indoor climate quality is poor. (Liu *et al.*, 2014) The basic working method of the VAV system in the test building is through mechanical dampers which open and close based on either the heating or cooling demand or CO_2 concentration in the room. When there is a need for cooling in the room, one of the dampers opens wider to let more airflow through. This causes a pressure drop which informs the supply fan to increase its speed. The exhaust air flow rate is adjusted accordingly to keep the ventilation in balance. (Yao *et al.*, 2007)

The VAV system can be used as zonal, meaning many rooms, or room specific. When designed zonally, the air flow rate is adjusted by the area with the largest need for air flow rate of the combined rooms or by the zone average. If designed as room specific, the air flow rate is regulated independently according to each rooms' demand. VAV ventilation provides the highest benefit in buildings which have a varying cooling demand or occupancy. Good applications are schools and commercial buildings which have large variations in demand. (Sandberg *et al.*, 2014)

The VAV system has an intertwined structure in a way that when one component has a malfunction the whole system will try to compensate it. This leads to inefficient working of the whole system as multiple parameters change. This can make the fault diagnosis difficult as the root cause can be difficult to find. (Liang *et al.*, 2017) VAV air conditioning system may have faults on different system levels, including actuators, measurement devices, sensors and controllers. The reason for faults are mostly due to improper system design, operation or maintenance of the system. There are two types of faults: abrupt faults and faults that are developed over time. Abrupt faults are for example faults in actuators of dampers.

Faults that develop over time may include for example the degradation of sensors in the system, causing the VAV system to work inefficiently. Faults are usually diagnosed by comparing set point values to measured values. If any deviation is found, a system diagnosis is conducted, and the cause and location of the fault is searched. The most common faults that can occur in a VAV system include fouling of water in heating/cooling coils, stuck air dampers, zone temperature sensor offset, fan stuck at full/intermediate speed and fails to respond to control signal. Also, the throw pattern of cold supply air can be a challenge as the air flow rate varies with standard diffusers. If the throw pattern is not optimal, it can cause a feeling of draft which can be felt as unpleasant. (Okochi and Yao, 2016) VAV system have a lot of components meaning they are more complicated to design, install, use and maintain than traditional constant air volume (CAV) ventilation systems. Potential faults can occur during each phase. CAV-terminal units maintain a constant supply of air velocity and these systems require a constant static pressure in the ductwork. CAV-systems are not considered in this study as they are not an optimal solution for rooms which have a high variation in heating and cooling loads. (Seppänen *et al.*, 2004)

If the VAV system is not working properly, an unwanted pressure difference is formed over the envelope of the building. This happens because of unbalanced supply and exhaust air flows, either the supply or the exhaust air flow dampers have not adjusted as it should. Large overpressures in the building can cause a flow of internal moisture to the building structures causing long-term damages. Underpressure can cause a flow of impurities such as microbes, radon or odors from sewage to the indoor air (Kiviste and Vinha, 2017). When a room is underpressured, air comes into the room from where there is least resistance. This can then be through building structures, sewers or window frame cracks. The problem is worse in areas with polluted outdoor air as it then infiltrates the indoor air. The Decree 1009 (2017) on indoor climate states that the supply and exhaust air flows of a building must be designed so that they do not cause significant under- or overpressure which can cause polluted air to come in or damage the building structures.

4.2 Room systems

The heating and cooling of a room can be controlled by numerous different technologies and solutions. Heating can be done for example with floor heating, a fan coil unit or water radiators. Cooling can be done for example with chilled beams, radiant ceiling panels or ventilation. (Sandberg *et al.*, 2014) In this chapter, VAV system's room specific devices with water radiators are shown (Figure 8), as this type of system is very common in Finland. The cooling of the room is controlled by the ventilation as it supplies the room with cooler air than the indoor air temperature. The cooling power is controlled by adjusting the flow rates of supply and exhaust air. The heating of the room is controlled with water radiators. Radiators are traditionally equipped with manually adjustable thermostats which traditionally are used to control the room from overheating. The room can also be equipped with a control panel for the occupants to adjust the ventilation rate.

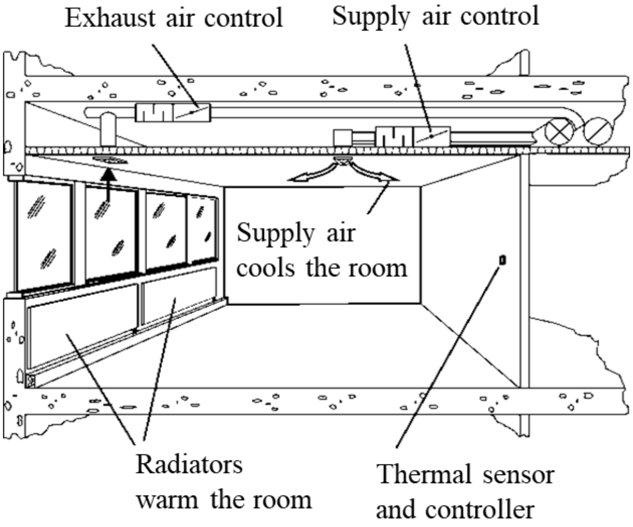


Figure 8. Room units of a VAV system (Seppänen et al., 2004).

Radiators can also be equipped with smart thermostats, which can adapt their performance according to usage context. Smart thermostats are controlled for example with machine learning algorithms which configure the demand responded heating to achieve a comfortable indoor temperature taking into consideration e.g. the outside temperature, weather conditions and forecast, room occupancy, indoor activity, hourly-based pricing of district heating and the heating latency of the room. Heating latency means the thermal mass of the room i.e. how long does it take for the room to heat up or cool down. An example between different latencies can be seen in example between a perimeter area room and a room located in the center of the building. The perimeter area room needs typically more time to heat up than the center room as it has more walls that are next to outdoor air. The smart thermostat takes this into account and operates the heating in accordance. Room occupancy can be predicted by the smart thermostat, which in turn enables savings as the thermostat can start to lower heating earlier, but still keep the room air temperature at a comfortable level. (Nacer *et al.*, 2017) Also, individual preferences can be adjusted more easily than with standard thermostats (Salama, 2014).

Smart thermostats can also be installed to adjust the temperature from different systems such as air conditioning units. These types of thermostats are more common than the previously described smart thermostats for radiators, especially in the United States. The smart thermostat market is growing worldwide, and the largest manufacturers are Nest, Honeywell and Ecobee. A market for service providers and aggregators have also emerged where companies such as Weatherbug and EnergyHub aggregate smart thermostats in the residential sector and provide demand response programs for utilities. (Rotondo *et al.*, 2016) The type of heating and cooling technologies influences the choice on how it can operate on the demand response market, for example if a building is operated on electrical heating/cooling it can operate on the electricity market (Nordpool, 2017), whereas district heating buildings do not have a specific market setup at this time. Several studies have been conducted on the possibilities of such a market and some utilities have calculated an hourly based pricing for their district heating (Kärkkäinen *et al.*, 2003) (Syri *et al.*, 2015).

4.3 Building automation and control system

Building automation and control system (BACS) is the basis of operation of a modern building. It is a digital, intelligent network of electronic devices that are designed to monitor and control the functionalities of a building, meaning the mechanical, electronical, lighting and solar shading systems. The BACSs improve occupant comfort, security, safety and efficient operation of building systems, saving energy and operational costs. IEQ standards are used to define how well a BACS works and what the targets are. (Litiu *et al.*, 2017) A generic system model of BACS is shown in Figure 9, where three functional levels are shown: management, automation and control and field.

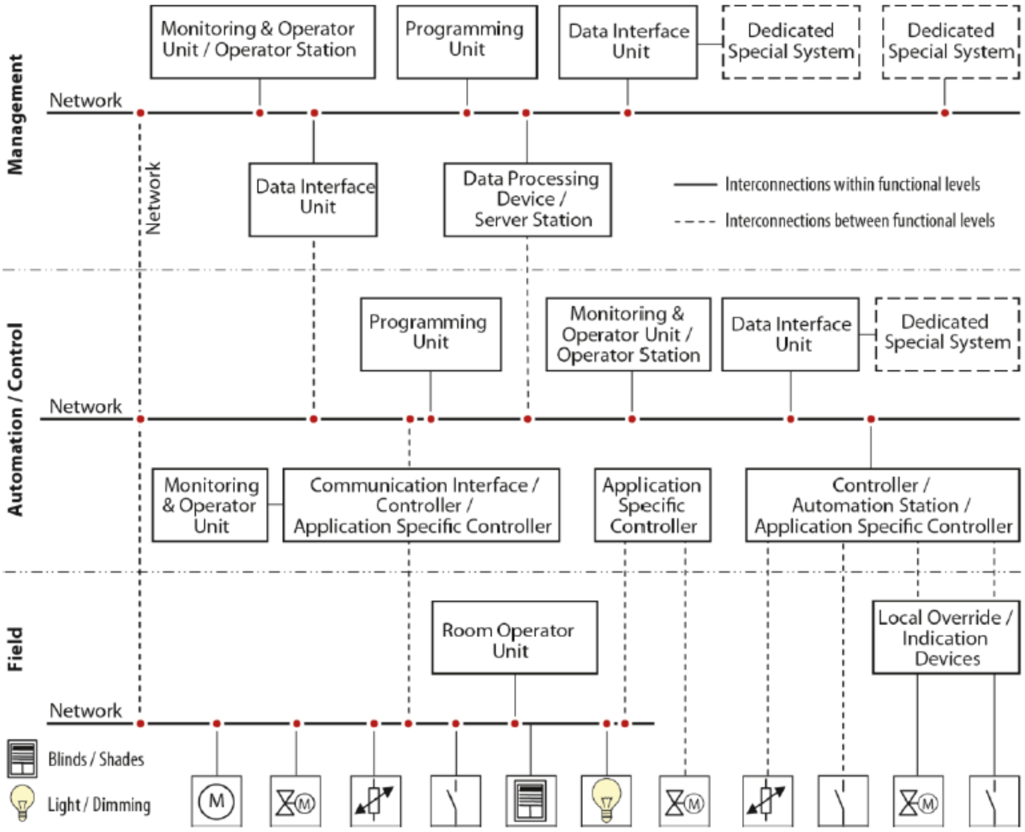


Figure 9. A generic architecture model for the BAC network and its different levels (SFS-EN ISO 16484-2, 2005).

A more simplified version of the same model is shown in Figure 10, showing more closely how different protocols and technologies are used and connected.

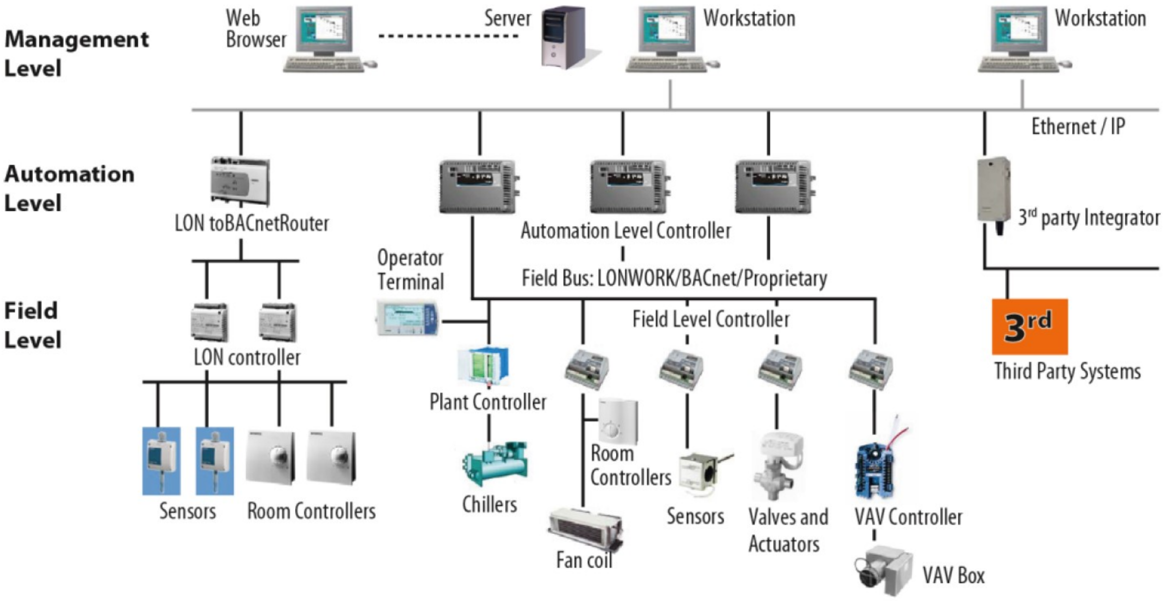


Figure 10. Simplified model of the BAC network and its different levels (Litiu et al., 2017).

The management level includes the management software of the whole system. The operations of the level can include devices that connect the BACS to a web-based management software that can then be used to monitor and control the system remotely. The automation level includes the actual controllers for the field level devices. The automation level connects the management level with the field level. The field level devices are the actuators and sensors which react to the commands from the upper levels. Field level devices such as sensors also gather information for the upper levels, where it is used and analyzed. (Salo, 2017)

A wide range of different building automation technologies are used, but the main protocols used today are BACnet (SFS-EN ISO 16484-5, 2017), LonWorks (SFS-EN 14908-1, 2014) and Modbus (Modbus, 2012). These are interoperable standard network protocols which are widely used. The protocols are used for different purposes. BACnet is a network protocol developed by ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) that is used for multiple devices to communicate across building automation systems by system users and building system manufacturers. LonWorks is a communication network protocol developed by Echelon Corporation for networking devices through power lines, fiber optics and other media. Modbus is a network protocol developed by Modicon Inc. for connections between devices through a central controlled system. It works best with industrial automation systems, but its simplicity allows it to be used in building automation. The main difference between Modbus, BACnet and LonWorks is that Modbus needs its information to be transported through a central control. (SETRA, 2016)

4.4 Building occupancy

Building occupancy means how many people are in the building and at what time. It includes the patterns of when and where people move in the building. This sort of information is important in determining the heating and cooling loads of a room. (Yang and Becerik-Gerber, 2016) Knowing the number of occupants in the room is also valuable information to the building owners. They can use that information for example to develop the spaces to be more suitable for the users and thus increasing the value of the building. The presence of occupants in a room releases both sensible and latent heat which originates from people's individual metabolism rates. Occupants' behavior has also an effect on the overall building energy performance through their actions such as, opening of windows or blinds and using electrical equipment. (Yang *et al*, 2016) Studies show that there is a great potential in energy savings based on occupancy control compared to conventional temperature set-point scheduling. The estimated cost savings vary from 18 % to even 50 % (Jiang *et al.*, 2016; Petersen *et al.*, 2016; Yang and Becerik-Gerber, 2016) The variation in the estimates are based on different modelling techniques as well as different sites used in the models (residential/commercial). A study conducted in Britain found out that in a typical office, 30% - 40% of desks are empty during working hours (Bedford *et al.*, 2013). This unused space consumes energy year-round as the supply air flow is heated in the winter and cooled in the summer, also fans use energy to blow the air. The unused space could be better optimized in terms of area and energy consumption if the peak building occupancy rates are known. For example, unused desks could be rented via new sharing economy websites that focus on this sort of business or office area could be decreased saving in rent and energy costs. (Dooley and Stjelja, 2017)

Assessing the amount of people in a room can be done by different types of occupancy sensors for example using image-based methods, CO_2 sensors, passive infrared detection systems (PIR), radio frequency identification (RFID) tags and Wi-Fi-based methods. All have their own pros and cons for usage. (Jiang *et al.*, 2016) By using image-based methods an accurate estimation of people can be made. The downside is that the systems are usually expensive and there is an issue with privacy. CO_2 sensors are non-intrusive and widely used in the industry. The issues arise from the accuracy of estimation and the latency in sensing a change. If the ventilation is only controlled by the CO_2 concentration, the latency in sensing can cause uncomfortable indoor air. PIR sensors are good when wanting to know the room occupancy. The detection is binary in nature, detecting that either the room is occupied or not. The PIR sensors cannot estimate the number of people in the room, so for optimized use of ventilation this technology is not suitable on its own. PIR sensors are usually used for controlling lighting, where it suits very well. RFID tags work so that each person carries one with them and as they move through the building sensors know where they are. This presents some privacy issues as people do not want them to be followed. For ventilation purposes the RFID tags are not perfect either as there might be occupants in the building not carrying a tag, which will cause errors to the HVAC system. (Jiang *et al.*, 2016) Some new development has also been done on non-intrusive occupancy sensing by utilizing Wi-Fi-enabled mobile devices. This technique has same downside as the RFID tag, that it does not consider people who are not carrying their mobile devices or have turned off the Wi-Fi-mode on the device. Also, some people might carry multiple devices with Wi-Fi-mode such as a mobile phone and a tablet, which then gives false information on the occupancy to the system. (Zou *et al.*, 2017)

4.4.1 CO_2 sensors

Carbon dioxide sensing is a well-known and widely used method to assess the correct amount of ventilation and to characterize the indoor air quality. CO_2 is generated mainly by persons in the room. Moderate to high CO_2 concentration (2000 – 5000 ppm) within a building can cause multiple symptoms to humans such as headaches, dizziness and significantly lower cognitive functions (Satish *et al.*, 2012)(Allen *et al.*, 2016). A high concentration of CO_2 can also indicate high concentrations of other impurities in the air and is thus widely used as a basis for characterizing the quality of indoor air (Hengitysliitto, 2017).

CO_2 sensors are utilized worldwide and are commercially available. (Gruber *et al*, 2014) For assessing the number of people, the sensors work well in a closed room where breathing is the only source of CO_2. The basis behind assessing the amount of people comes from knowing the average CO_2 generation rate of a person. These can be derived from the fields of human metabolism and exercise physiology. The metabolism rate is derived from the occupants' body size and composition, age, sex, diet and level of physical activity. (Persily and de Jonge, 2017) If there are open windows or doors, the CO_2 levels are affected by the incoming air from outside the room, which is very difficult to model precisely, leading to errors. (Ito and Nishi, 2012) Previous experiments using CO_2 sensors show an error of 10 % - 30 % in counting the number of people (Tachikawa *et al.*, 2008) (Ito and Nishi, 2012). Possible reason for the error is caused by the assumptions regarding metabolic rates for average humans as well as open windows and/or doors in the rooms.

The decree on indoor climate by the Ministry of Environment (2017) of Finland states that the maximum concentration of CO_2 in indoor air can be 800 ppm higher than the outdoor concentration to be deemed satisfactory. CO_2 sensors are important in keeping the concentration optimal. A room's CO_2 concentration is a sum of many factors: the amount of people in the room, the duration of their stay, the metabolism rate of each person, the volume of the space and the amount of supply and exhaust air flows. A person's CO_2 generation rate correlates with his/her metabolism rate. For a sitting person the metabolism rate corresponds to 105 W, meaning a CO_2 generation rate of 15.4 dm^3/h. (FINVAC ry, 2017)

CO_2 concentration balance state can be calculated with equation 1. To include the CO_2 released in the space equation 2 can be used. (FINVAC ry, 2017)

$$\Delta C_{CO2} = \frac{2}{n}\ , where\ n = \frac{q_{iv}}{V} \tag{1}$$

$$\Delta C_{CO2} = 1000\ \times \frac{q_{CO2}}{3.6 \times q_{iv}} \tag{2}$$

where,

ΔC_{CO2}	the concentration of CO_2 over the outside air concentration (ppm)
n	air exchange coefficient (1/h)
q_{iv}	the amount of outside air coming into the space (dm^3/s)
V	volume of the room (m^2)
q_{CO2}	the amount of CO_2 released in the space (dm^3/h).

As the metabolism rate correlates with the generation rate of CO_2, some typical values are shown in Table 9.

Table 9. The production of CO_2 correlating with the metabolism rate (FINVAC ry, 2017).

Activity	**Level of physical activity (met[1])**	**Metabolism rate = total heat output (W)**	**CO_2 generation rate (dm^3/h)**
Sleeping	0.8	85	12.4
Sitting calmly	1.0	105	15.4
Office work, Standing	1.2	135	18.5
Teaching	1.4		21.6
Moving calmly	1.6	165	24.7
Shop work	1.8	189	21.6
Walking (3.2 km/h)	2.0	210	30.9
Walking (5.0 km/h)	3.0	315	46.2
Walking (6.5 km/h)	4.0	410	61.6
Brisk walking (8.0 km/h), Badminton	6.0	630	92.4
Squash, Basketball	7.0	735	107.8

[1] Met is the unit for human metabolism. 1 met equal 58 W/m^2,skin. Average human 1 met equals 105 W, which releases from the body as dry convection and radiation and as wet heat as bound in vapor.

A closer evaluation on the different levels of physical activity is studied by Persily and Jonge (2017), which study the effect of sex, age and mean body mass to the physical activity. The results are shown in Table 10.

Table 10. CO_2 generation rates at 273 K and 101 kPa for ranges of ages and level of physical activity (Persily and de Jonge, 2017).

		CO_2 generation rate (dm^3/h)						
		Level of physical activity (met)						
Age (years)	**Mean body mass (kg)**	**1.0**	**1.2**	**1.4**	**1.6**	**2.0**	**3.0**	**4.0**
Males								
<1	8	3.24	3.96	4.68	5.04	6.48	9.72	12.96
1 to <3	12.8	5.4	6.48	7.56	8.64	10.8	15.84	21.24
3 to <6	18.8	6.84	8.28	9.36	10.8	13.68	20.52	27
6 to <11	31.9	9	10.8	12.6	14.4	18	27	36
11 to <16	57.6	12.24	14.76	17.28	19.44	24.48	36.72	48.96
16 to <21	77.3	13.32	16.2	19.08	21.6	27	40.68	54
21 to <30	84.9	14.04	17.28	20.16	23.04	28.8	43.2	57.6
30 to <40	87	13.32	16.56	19.08	21.96	27.36	41.04	54.72
40 to <50	90.5	13.68	16.56	19.44	22.32	27.72	41.76	55.8
50 to <60	89.5	13.68	16.56	19.44	22.32	27.72	41.76	55.44
60 to <70	89.5	11.88	14.4	16.56	19.08	23.76	35.64	47.88
70 to <80	83.9	11.16	13.68	16.2	18.36	23.04	34.2	45.72
≥80	76.1	10.8	12.96	15.12	17.28	21.6	32.4	43.2
Females								
<1	7.7	2.88	3.6	4.32	5.04	6.12	9	12.24
1 to <3	12.3	5.04	6.12	7.2	7.92	10.08	15.12	20.16
3 to <6	18.3	6.12	7.56	8.64	10.08	12.6	18.72	25.2
6 to <11	31.7	8.28	9.72	11.52	13.32	16.56	24.84	33.12
11 to <16	55.9	10.44	12.6	14.76	16.92	20.88	31.68	42.12
16 to <21	65.9	10.44	12.96	15.12	16.92	21.24	32.04	42.84
21 to <30	71.9	11.16	13.68	15.84	18	22.68	33.84	45.36
30 to <40	74.8	10.44	12.6	14.76	16.92	21.24	31.68	42.48
40 to <50	77.1	10.44	12.96	15.12	17.28	21.6	32.4	42.84
50 to <60	77.5	10.8	12.96	15.12	17.28	21.6	32.4	43.2
60 to <70	76.8	9.72	11.88	13.68	15.84	19.8	29.52	39.6
70 to <80	70.8	9.36	11.52	13.32	15.12	19.08	28.44	38.16
≥80	64.1	9	10.8	12.6	14.4	18	27	36.36

Persily and Jonge's values are more detailed compared to FINVAC's. The average value of male and female's aged 16 to 60 years defined by Persily and Jonge's are close to FINVAC's values, although FINVAC's are slightly higher. A reason for the difference is the different assumption on the temperature. Persily and Jonge have calculated the metabolism rate for 273 K and FINVAC for room temperature. The number of people can then be calculated by modifying equation 2 to be in form of:

$$n = 3.6 \times \frac{q_{iv} \times \Delta C_{CO2}}{1000 \times q_{CO2}} \qquad (3)$$

where,

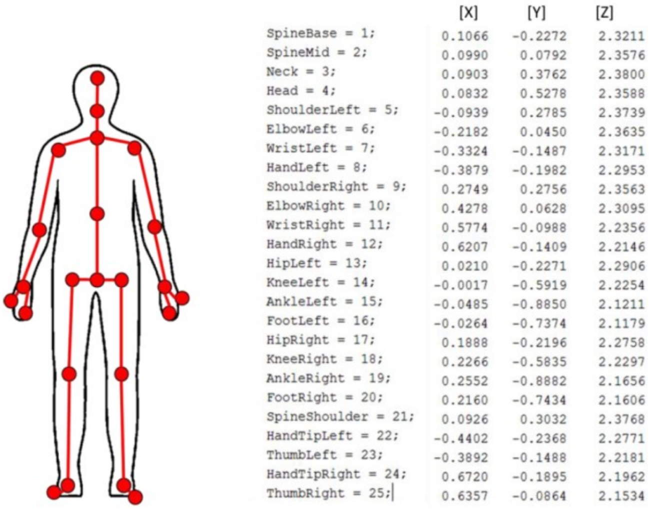
n	the number of people
q_{iv}	the amount of outside air coming into the space (dm^3/s)
ΔC_{CO2}	the concentration of CO_2 over the outside air concentration (ppm)
q_{CO2}	the amount of CO_2 released in the space (dm^3/h).

A value for q_{CO2} is chosen from Table 9 or Table 10 which suits best the situation.

4.4.2 Image-based methods

Image-based methods have a high accuracy in assessing the number of people in a room. Studies using depth frame data from a Kinect sensor detecting and tracking people have had precisions of circa 99 % (Zhang *et al.*, 2012; Petersen *et al.*, 2016). The use of image based methods can raise questions on privacy from the occupants and also, they are usually more expensive than for example CO_2 sensors (Petersen *et al.*, 2016). Privacy concerns can be eased by placing the sensor on top of the door facing downwards where the identification of people is difficult. This is also an ideal place for a motion detection sensor to use for occupant counting. The sensor counts people coming in and out, resulting in the number of occupants in the room. This type of counting has been used in studies by for example Dooley and Stjelja (2017).

Two different image sensors are used in this study: Microsoft Xbox One Kinect (Microsoft, 2017) and AXIS M3045-WV(AXIS Communications, 2018). The Kinect has a sufficient capability to identify occupants' movements in any lighting conditions. It works as a depth camera, projecting a grid of dots in the infrared spectrum and analyses the distance from each projected dot. The effective range of the Kinect camera is a 45° radius of circa five meters. (Dziedzic *et al*, 2017) The sensor is programmed to record only infrared data, from which identification of people is impossible. This eases the privacy concerns of occupants. The Kinect camera tracks 25 joint points of a bound skeleton, shown in Figure 11 and can detect up to six persons at a time. Each dot has a value in three dimensions in relation to the sensor's local [0,0,0] point. This way the camera shows the exact position of each dot in its range. The camera streams a one-layer picture, with each pixel having the value ranging from 0 to 5120. This number represents the distance of observed point from the device in millimeters. The Kinect camera works well for tracking the movement of people and for example Dziedzic *et al.* (2018) have used it to study occupant migration in a residential building and measuring the dynamic clothing factor. (Dziedzic *et al.,* 2017)



	[X]	[Y]	[Z]
SpineBase = 1;	0.1066	-0.2272	2.3211
SpineMid = 2;	0.0990	0.0792	2.3576
Neck = 3;	0.0903	0.3762	2.3800
Head = 4;	0.0832	0.5278	2.3588
ShoulderLeft = 5;	-0.0939	0.2785	2.3739
ElbowLeft = 6;	-0.2182	0.0450	2.3635
WristLeft = 7;	-0.3324	-0.1487	2.3171
HandLeft = 8;	-0.3879	-0.1982	2.2953
ShoulderRight = 9;	0.2749	0.2756	2.3563
ElbowRight = 10;	0.4278	0.0628	2.3095
WristRight = 11;	0.5774	-0.0988	2.2356
HandRight = 12;	0.6207	-0.1409	2.2146
HipLeft = 13;	0.0210	-0.2271	2.2906
KneeLeft = 14;	-0.0017	-0.5919	2.2254
AnkleLeft = 15;	-0.0485	-0.8850	2.1211
FootLeft = 16;	-0.0264	-0.7374	2.1179
HipRight = 17;	0.1888	-0.2196	2.2758
KneeRight = 18;	0.2266	-0.5835	2.2297
AnkleRight = 19;	0.2552	-0.8882	2.1656
FootRight = 20;	0.2160	-0.7434	2.1606
SpineShoulder = 21;	0.0926	0.3032	2.3768
HandTipLeft = 22;	-0.4402	-0.2368	2.2771
ThumbLeft = 23;	-0.3892	-0.1488	2.2181
HandTipRight = 24;	0.6720	-0.1895	2.1962
ThumbRight = 25;	0.6357	-0.0864	2.1534

Figure 11. Skeleton model of the Kinect camera, positions as meters from the sensor's local point (Dziedzic et al., 2017).

The AXIS M3045-WV network camera is a fixed mini dome surveillance camera. It offers a live streaming option and is designed to be used in stores, hotels, schools and offices. The sensor can be used for different applications such as direction detection and facial recognition. In this thesis, the AXIS direction detection application was used for detecting if people enter or depart the room. The sensor has a wireless network interface and can also be connected over Ethernet. The live stream can be accessed through the internet. The sensor can be easily mounted on walls or ceiling. (AXIS Communications, 2018) Dooley and Stjelja, (2017) used this sensor in their research and found out that is very accurate in detecting people. The typical error occurs when a large amount of people goes past the sensor at the same time for example when going to lunch. The sensor does not then detect each person.

4.5 Ethical issues and security of smart technologies

The increasing use of smart devices in buildings open new possibilities for hacking and cyber-attacks. Internet-of-Things (IoT) devices' security issues are not always the main concern of their developers, as they can have tight schedules to get the devices to the market. Also, all the devices cannot be patched or upgraded to fix arising security issues. Some devices have inherent problems as they are driven by microcontrollers that do not have the power or capabilities for a proper security stack. (Li and Da Xu, 2018) Min and Varadharajan (2015) developed a malware that can attack a smart home and overtake the system without requiring to compromise of an individual smart home device, i.e. a traditional attack. This way they could access all the devices in the network. With this information they could for example know if the building is occupied or not.

Cascone *et al.* (2017) studied the ethical issues arising from the increased usage of smart technologies and especially building occupancy data in an office. The main concerns that people have relate to their privacy and data security. For example, managers could monitor the behavior of the workers or unauthorized people could get the occupancy data and use it for their own gain for example to help them steal equipment from the buildings. When installing new sensors and IoT-devices the security of the software is very important. The security of IoT-devices can be considered challenging at the present moment due to their varied technologies and used protocols. (Sicari *et al.*, 2015)

5 Methodology

In this chapter the measurement setup and the case rooms are presented. The measurements were conducted in Aalto University's Undergraduate center located in the Otaniemi campus in seven different rooms. The rooms differ in size, but they were equipped with the same technical systems and measurement setup. The methodology in studying the performance of the room systems is to measure the output of the different system components as well as the satisfaction of the users.

5.1 Case building

The case building is in Aalto University's campus in Otaniemi and it is called the Undergraduate center, shown in Figure 12. It is the main building for all the studies for the undergraduate students in technology and business. The building was designed by architect Alvar Aalto. It was built in 1964 and retrofitted in the autumn of 2015. (Aalto University, 2018a) The building has five floors and is divided into four different wings. The case rooms are all located in the U-wing of the building, where mainly business studies are held, shown in Figure 13. (Aalto University, 2017) The U-wing includes group working spaces, lecture halls and a cafeteria.

Figure 12. The Undergraduate center from outside.

Figure 13. U-wing of the Otakaari 1 building. Case rooms marked with a red square in the figure (Aalto University, 2017).

5.2 Case rooms

The seven rooms, named U101, U103, U105, U106, U107, U108 and U109d, are used as group working spaces and meeting rooms for the students and faculty. They are equipped with tables, chairs, sofas and TV's that can be used for studying and meetings (Figure 14). The rooms are reserved through a mobile application called Aalto space, but can also be used without reservation (ACRE, 2016). The seven rooms differ in size as well as the amount of people they are designed for. Figure 15 shows the specifications in more detail.

Figure 14. Room U107 (ACRE, 2016).

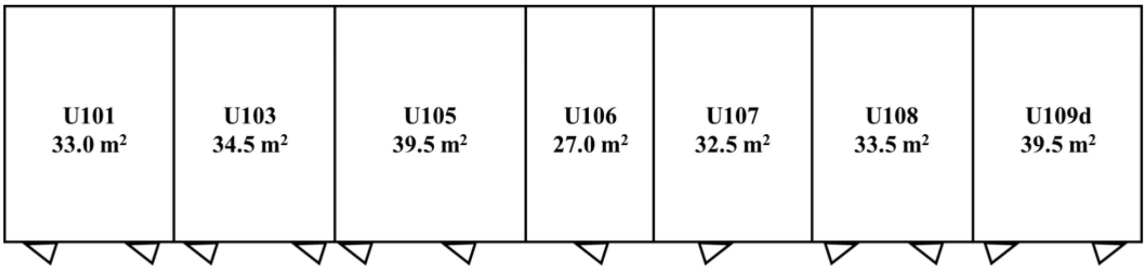


Figure 15. Schematic figure of case rooms with floor areas.

5.2.1 HVAC System

The HVAC system in Otakaari 1 building consists of centrally regulated inlet water temperature for water radiators and zonal ventilation. The demand of ventilation varies significantly in different parts of the building as the building includes multiple different types of spaces such as lecture halls, group working rooms and large corridors. There is a total of 21 different AHU's in the U-wing.

Ventilation

The seven case rooms are all in the same ventilation zone, controlled by one AHU (U305, model GOLD 14 RX by Swegon (2018)). The zone also includes eight other rooms and hallway areas. The ventilation system is a VAV system which varies the supply and exhaust air volume by temperature and CO_2 concentration individually in each room. The rooms are equipped with two pairs of supply and exhaust terminals, example shown in Figure 16. The ventilation concept is presented in more detail in Appendix 1. The terminals are controlled by on/off principle, either the dampers are fully opened or fully closed. The VAV system in the rooms can be considered simple, as the dampers have only two positions open or closed. The dampers are controlled by three parameters: identifying if the room is occupied or not, temperature and CO_2 concentration levels in the rooms. The room occupancy influences the thresholds that are used for both. If either of the temperature or the CO_2 concentration crosses a set threshold, the second damper pair is opened, increasing the air flow to the maximum value. The rooms are also equipped with control panels for users to increase the ventilation. In practice, it is a button on the wall where the ventilation can be increased for one to five hours opening the second pair of dampers, if they are not already opened.

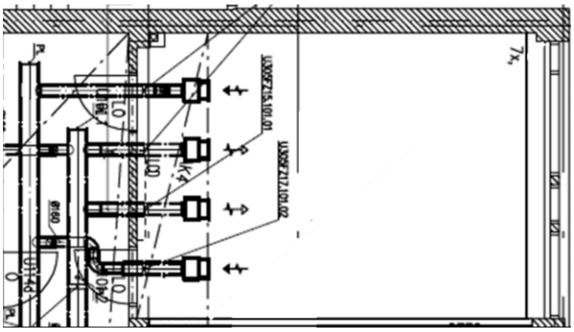


Figure 16. Room units for room U101.

Temperature of the supply air is varied with a control program, the valve (FV04) of heating coil, the speed of rotation of the heat recovery disc (SC02) and the valve (FV05) of cooling coil so that the supply air set point temperature is achieved at temperature sensor TE10. The supply air temperature varies with the outside air temperature so that the maximum supply air temperature is 19° C when the outside air temperature is -10° C. The minimum is 16° C when outside air temperature is +10° C or higher, which is shown in Figure 17.

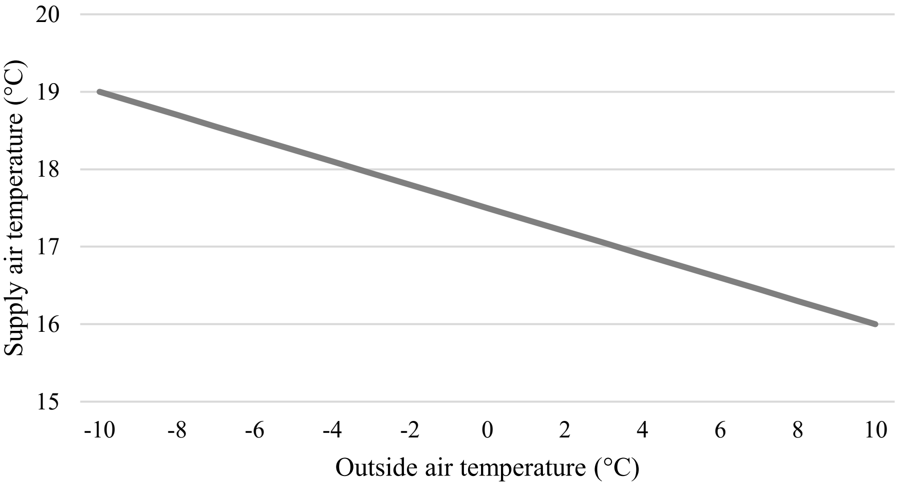


Figure 17. Relationship between supply air temperature and outside air temperature.

The airflow is adjusted with a control program which varies the speed of the supply air fan (TF01) so that the static pressure in the supply air duct (PE10) maintains in the set point value. The controller also controls the speed of the exhaust air fan (PF01), so that the static pressure in the exhaust duct (PE19) stays in the set point value. The optimizer (GW01) follows the position of the dampers in the constant pressure regulators in both the supply and exhaust ducts and keeps the pressure in the ducts as low as possible by keeping the damper positions open.

Heating

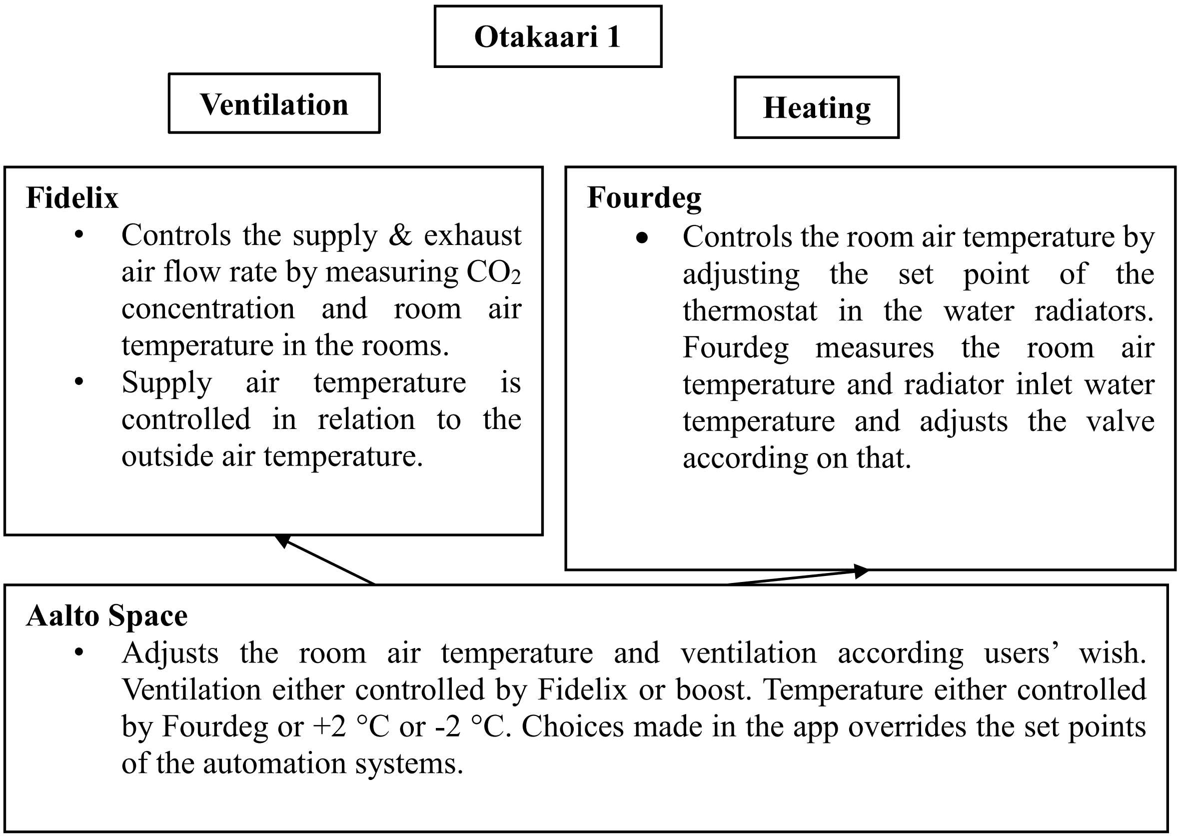
The room air temperature is controlled by both the ventilation and the centrally controlled water radiator system. The radiators heat the rooms and the ventilation is used for cooling. The radiators are equipped with smart IoT thermostats, operated by a Finnish company called Fourdeg. The thermostats control the water flow, and thus the heating power, to achieve a comfortable room air temperature in an energy efficient way. The thermostat takes into consideration the outdoor temperature, weather forecast, indoor heat loads, the heating latency of the thermal mass and an hourly based pricing of district heating. The thermostat is connected to a cloud server which has machine learning algorithms, enabling the thermostat to learn what the specific heat demand is in each room at a given time. For example in an office setting, the thermostat reduces the heating power during night time to save energy and increases the heating power in the morning to provide comfortable room air temperature as people arrive to the workspace. (Fourdeg, 2018)

During this study, Otakaari 1 is also conducting a centralized demand response scheme in heating. This means that the radiator's inlet water temperature is adjusted with demand and price signals from the district heat provider. The demand response is part of a separate research project called Reino, which studies the effects of centralized demand response to the indoor environment and its cost savings in Otakaari 1.

In Finland, the district heating price is divided into three parts: connection charge, power charge and energy charge. The connection charge is a one-time payment which accounts for the connection installation between the customer and the district heating network. The power charge is based on max flow requirement of the facility at peak load condition and it is meant to cover fixed-costs of the network operation. Energy charge is paid according to the energy used. The studied demand response scheme includes an hourly based pricing for the district heating, enabling saving opportunities for the customer by utilizing cheaper energy. This presents new opportunities for utilities and heat customers. Utilities are studying this as a future business model for some of their district heating networks. If this is implemented and used at a large enough scale, it can save money for the heat customers and decrease the use of peak heat plants for the utilities saving them money as well. (Sarvaranta *et al.*, 2012)

Control Scheme

The indoor climate is controlled by two different systems: Fidelix automation system and Fourdeg, shown in Figure 18. Fidelix controls the supply and exhaust air flow rate from the room air temperature and CO_2 concentration. Fourdeg smart thermostats control the heating power of the water radiators based on the room air temperature and users demand. During the Aalto Space reservation period, Fourdeg thermostats control according to the user demand. When the spaces are not reserved, Fourdeg's own algorithm controls the heating power.



Fidelix

- Controls the supply & exhaust air flow rate by measuring CO_2 concentration and room air temperature in the rooms.
- Supply air temperature is controlled in relation to the outside air temperature.

Fourdeg

- Controls the room air temperature by adjusting the set point of the thermostat in the water radiators. Fourdeg measures the room air temperature and radiator inlet water temperature and adjusts the valve according on that.

Aalto Space

- Adjusts the room air temperature and ventilation according users' wish. Ventilation either controlled by Fidelix or boost. Temperature either controlled by Fourdeg or +2 °C or -2 °C. Choices made in the app overrides the set points of the automation systems.

Figure 18. Control scheme of the case rooms in Otakaari 1.

Aalto Space – mobile application

In the Aalto University campus, rooms can be reserved by a mobile application called Aalto Space, which has been developed by Aalto Campus and Real Estate (ACRE). Aalto Space works in both Android and iOS devices, which can be used to find and reserve group work facilities and meeting rooms within the campus. The app includes a map which can be used to navigate in the Otaniemi campus. It also includes an emergency messaging feature that allows the communications department of Aalto University to send notifications in case of emergency on campus. Within this project, the integration of building control systems with IoT sensors and room booking system was carried out with open standards Open Messaging Interface (O-MI) and Open Data Format (O-DF). The open messaging standards were developed in Aalto University (Buda *et al.*, 2017).

The integration enables the modification of the room air temperature and ventilation. The user is asked how they would like to modify the indoor climate parameters when they have reserved the room, shown in Figure 19. The choices made by occupants override all the automation system settings. The user is given three options for temperature and two for ventilation. The temperature choices are: Cooler, Auto and Warmer. Cooler means -2 °C and warmer +2 °C. Auto-option means that the HVAC system keeps the room air temperature at 21 °C. For the ventilation the options are: Auto and Boost. Auto is the normal ventilation controlled by Fidelix and boost means that maximum air flow rate is used. In the rooms, it means opening the second supply and exhaust damper pair. The dampers may already be opened by the automation system due to the demand from the room, so the choice made by the occupants might not have any effect. This can happen for example when the room is fully occupied.

The app sends a request if the user select any non-default setting. This request goes to the Aalto Smartcampus server from which it transferred to either the building automation control system or the smart thermostats. These then carry out the request according to the user's wish.

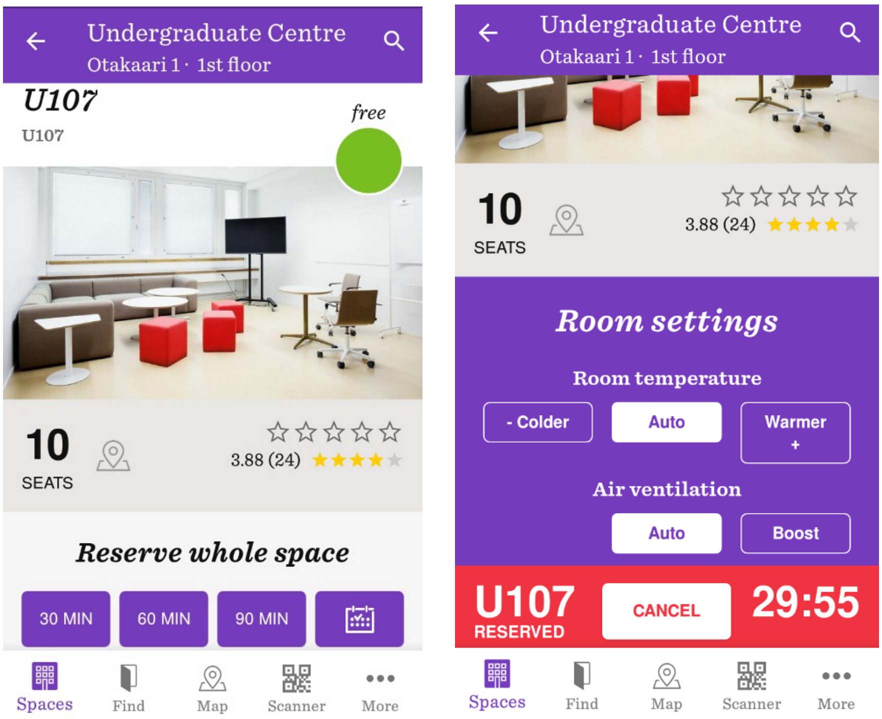


Figure 19. Aalto Space application reservation and room settings -views (ACRE, 2016).

5.3 Measurements

A total set of seventeen different variables are measured in the test rooms. The detailed description of the measurement arrangement is shown in Figure 20. The focus is to enhance the user satisfaction in the rooms. Satisfaction is measured by two methods: 1) conducting a questionnaire in paper format in the rooms, which the occupants fill in themselves and 2) by asking the users on their thermal comfort and opinion about the ventilation through Aalto space – app after their reservation period. The ventilation and heating system performance is measured in the rooms by measuring the pressure difference over the building envelope, the room air temperature and indoor CO_2 concentration. Also, the number of people is measured through image-based methods and calculated from the CO_2 concentration. These measurements show how well the HVAC system performs with different occupancy ratio.

The whole system is evaluated based on three different tests by changing the set point for the boosted ventilation:

1. Only temperature control
    i. Damper are controlled by setting the set point indoor temperature to 21°C, CO_2 concentration to 800 ppm and the smart thermostats to 21°C. This test was conducted in all case rooms.
2. Only CO_2 concentration control
    i. Damper are controlled by increasing the set point indoor temperature to 26.5°C, CO_2 concentration to 1200 ppm and smart thermostats to 20°C. This test was conducted in room U101 for a period of six days.
3. By temperature and CO_2 concentration control
    i. Damper are controlled by setting the set point indoor temperature to 22.5°C, CO_2 concentration to 800 ppm and smart thermostats to 20°C. This test was conducted in all case rooms.

The performance of the ventilation system is measured by gathering data on the positions of the dampers, on the pressure levels in the supply and exhaust ducts and on the pressure difference over the building envelope. Also, the supply air temperature and the supply and exhaust air flow rates are measured from the air handling unit. The centralized demand response scheme influences the inlet radiator water temperature.

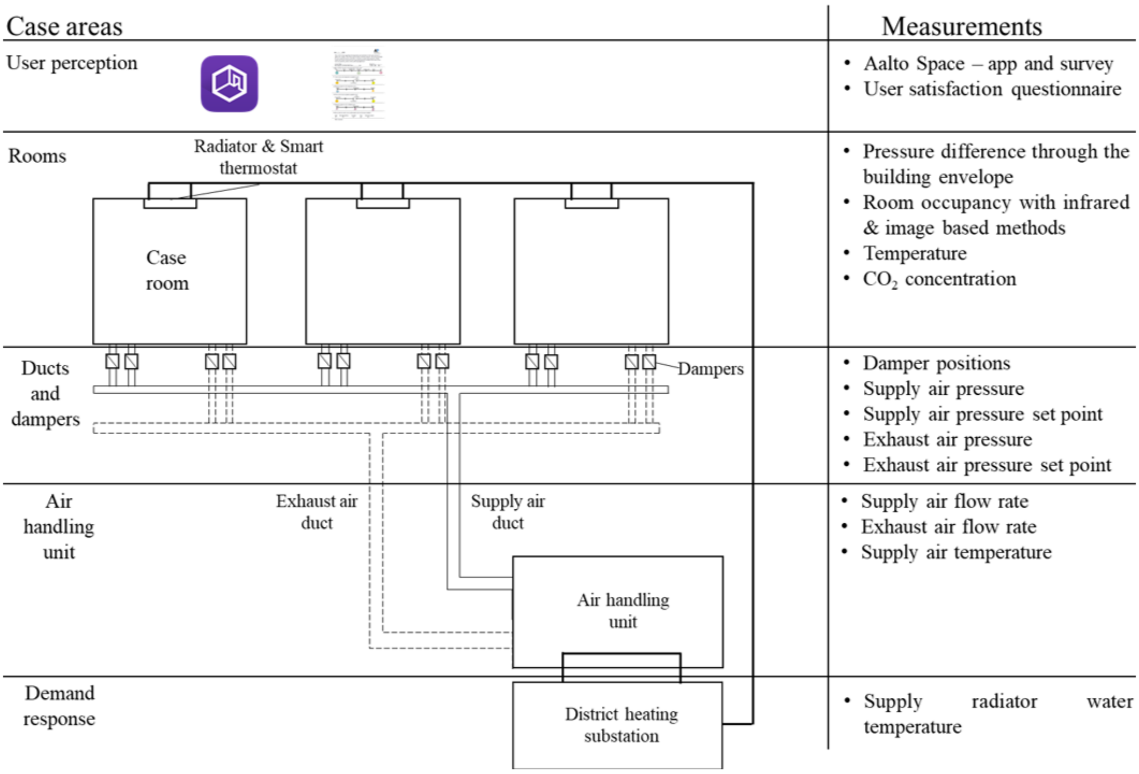


Figure 20. Measurement arrangement scheme in test rooms.

The data of the measurement points of these sub-systems is collected in different ways, shown in Table 11 and Figure 21. Data of the ventilation system is collected through the

Fidelix automation system. This data is transferred to the Aalto SmartCampus server, where it is downloaded from (Aalto University, 2018b). The Aalto Space – application provides data on usage and user satisfaction through a survey. This data is collected by the application and transferred to the Aalto SmartCampus servers. A separate post-occupancy evaluation of user satisfaction is set up in paper format in the rooms. Pressure difference over the building envelope is measured by separate sensors, which transfer data wirelessly by Sigfox IoT radio network to Integral's servers from which it is read. Fourdeg smart thermostats interact with their own cloud servers. The thermostats send data on the position of their valves, the set point temperature and the actual temperature. From Fourdeg's own servers, the data is then sent to the Aalto SmartCampus servers.

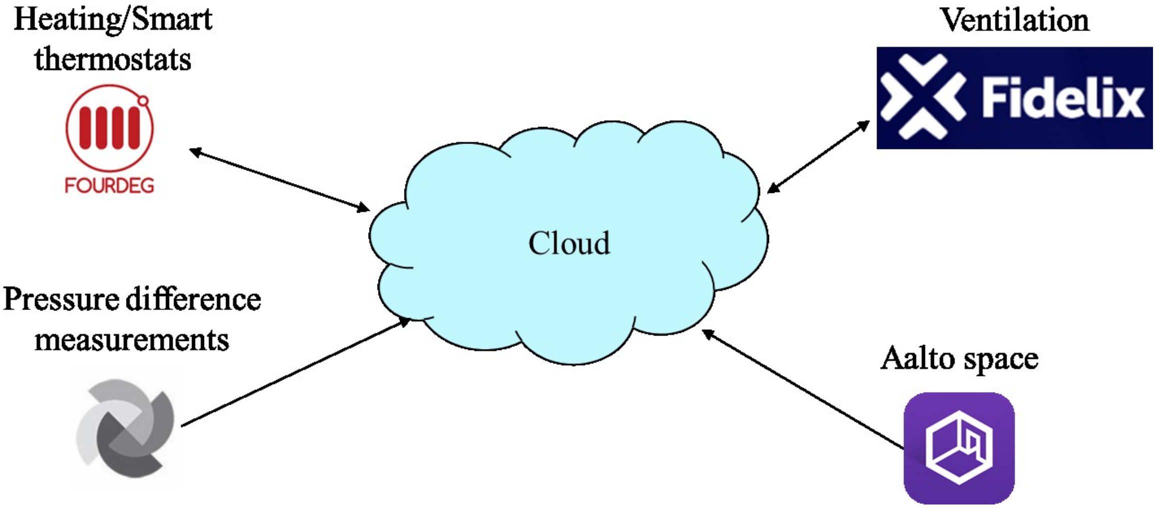


Figure 21. Data transfer model.

Table 11. Data collection method for each measurement.

Case area	Measurements	Data collection
User perception	Aalto Space - app and survey	Aalto Smart Campus server
	User satisfaction questionnaire	Paper format
Rooms	Pressure difference over the building envelope	Data wirelessly by Sigfox IoT radio network to Integral's servers where it can be accessed
	Room occupancy with infrared & image-based methods	Image based data through Kinect camera to a laptop, Infrared data through Fidelix to Aalto IT servers. AXIS sensor data to the AXIS servers.
	Temperature	Through Fidelix automation system to Aalto Smart Campus server
	CO_2 concentration	
Air handling unit	Damper positions	Through Fidelix automation system to Aalto Smart Campus server
	Supply air pressure	
	Supply air pressure set point	
	Exhaust air pressure	
	Exhaust air pressure set point	
	Supply air flow rate	
	Exhaust air flow rate	
	Supply air temperature	
Demand response	Inlet water temperature for water radiator	Through Fidelix automation system to Aalto Smart Campus server

The sensors used for temperature measurements are Produal TEHR NTC10-P. The accuracy of the sensor is ±0.2 °C at 25°C (Produal, 2018b). For the CO_2 concentration measurements Produal HDHv3_12d0 is used. The accuracy of the sensor is ±40 ppm + 3% of the reading (Produal, 2018a).

5.3.1 Air flow

The supply and exhaust air flow rates were measured in each of the seven rooms in both normal and boosted ventilation modes. The air flow rates are also used in CO_2 concentration-based building occupancy calculations. During the measurements, the ventilation mode was changed by pressing the boosting ventilation button in the rooms. The measurements were conducted with a manometer, vane anemometer and an airflow horn, shown in Figure 22 and Table 12.

The supply air flow rate was measured by first measuring the pressure difference in the supply duct with manometer Swema 3000 (Swema AB, no date) through the pitot static tubes. The air flow rate can be calculated when the pressure difference is known with equation 4.

$$q_{supply} = 3.6k\sqrt{\Delta p} \qquad (4)$$

where,

k	is a constant defined by the manufacturer which connects the pressure difference with air flow rate. This constant varies with duct length and with different VAV-terminals. In this case the value of k is 30.8.
Δp	pressure difference (Pa)

The exhaust air velocity was measured with a Wallac AM-1200 airflow horn which was placed firmly on top of the exhaust terminal. The Testo 435 vane anemometer (Sensorcell, 2016) was then placed perpendicularly above the horn thus measuring the air velocity. The correlation between air velocity and air flow rate was given by the air flow horn manufacturer and is shown in equation 5.

$$q_{exhaust} = 100v \qquad (5)$$

where,

v	is the air velocity (m/s)

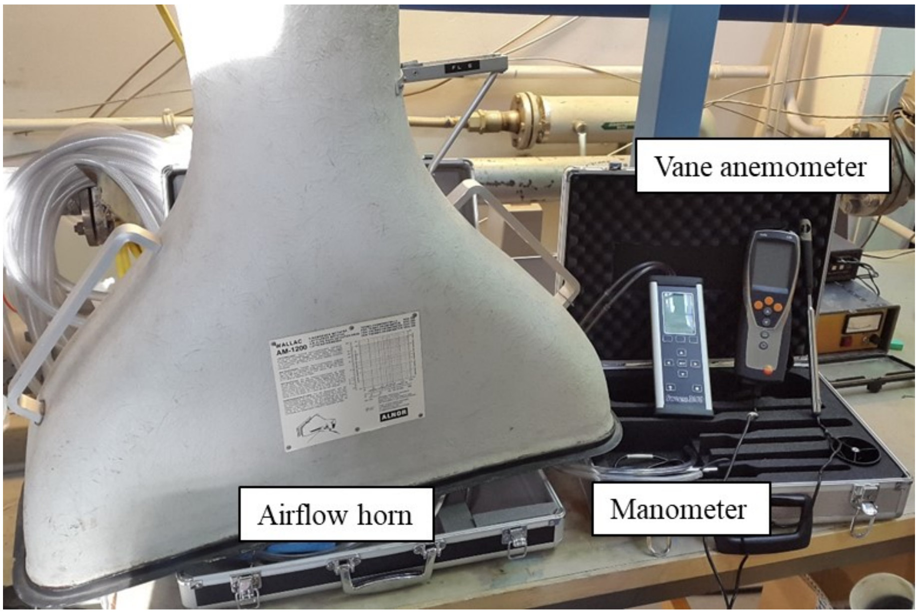


Figure 22. Measurement devices used in the air flow measurements. From left to right Wallac AM1200 airflow horn, Swema 3000 manometer and Testo 435 vane anemometer.

Table 12. Technical specifications of Testo 435 and Swema 3000 sensors (Sensorcell, 2016)(Swema AB, no date).

Parameter	**Testo 435**	**Swema 3000**
Measuring range	0.6 to 40 m/s	-300 to 1500 Pa
Operating temperature	0 to 60 °C	0 to 50 °C
Uncertainty	± (0.2 m/s + 1.5% of mv)	±0.3 read value, minimum ±0.3 Pa
Resolution	0.1 m/s	0 to 2 decimals
Vane diameter	16 mm	-
Telescopic handle length	890 mm	-
Max load	-	± 50 000 Pa
Temperature dependent	-	0.2 Pa/°C

5.3.2 Pressure difference

The objective of this measurement is to analyze the performance of the VAV-ventilation system. Pressures over the building envelope form in rooms due to unbalanced ventilation. As the VAV-ventilation system varies the supply and exhaust air flow rates according to demand, there is a higher probability that the flows are not balanced and pressures forms. Some changes in the air flows can also happen if the neighboring rooms control the flows, as the rooms are connected to the same ducts. With this measurement, it is possible to analyze the pressure difference over the envelope of the building in each of the seven rooms. The measurement was carried out with a sensor model SDP816-125PA by Sensirion, shown in Figure 23. Detailed specifications of the sensors are shown in Table 13.

Table 13. Technical specifications of the pressure difference sensor SDP816-125Pa (Sensirion, 2017).

Parameter	**SDP816-125Pa**
Measurement range (linear configuration)	- 12.5 to + 125 Pa (-0.05 to 0.5 in. H_2O)
Zero-point accuracy	0.08 Pa
Span accuracy	3 % of reading
Zero-point repeatability	0.04 Pa
Span repeatability	0.5 % of reading
Span shift due to temperature variation	< 0.5 % of reading per 10°C
Offset stability	< 0.05 Pa/year
Temperature and pressure compensation	Mass flow compensated differential pressure
Response time	< 5 ms
Internal digital resolution	16 bit
Calibrated for	Air, N_2
Media compatibility	Air, N_2, O_2, non-condensing
Calibrated temperature range	-20 °C to +85 °C

The sensor measures the differential pressure by a thermal sensor element using flow-through technology. The sensors are delivered by Integral as a part of their service concept, which collects and provides the data from the sensors through their IoT – service. Integral collects the data from the sensor to their own servers in which the data is processed and then sent to the client. The sensors collect data every 30 minutes using radio network as their transport medium. (Integral, 2017)

The pressure difference is measured by placing the sensor inside the room and attaching a pipe that goes outdoors. The effect of wind is minimized to the outdoor pipe with placing a cube of extruded polystyrene on top of it (Figure 23). By doing this, the dynamic pressure caused by the wind is minimized and only the static pressure is measured.

Figure 23. On the left the pressure sensor and on the right outdoor pipe of the pressure sensor with extruded polystyrene placed on top.

The measurements were done over a period of two months. By doing a long term continuous measurement, an adequate data set was acquired to assess the performance of the VAV-ventilation system.

5.3.3 Building occupancy

Building occupancy is measured in three different measurements with CO_2, image-based methods and by physically observing the actual number of occupants. The image-sensor was specifically installed for this experiment. The CO_2 sensors were already installed earlier. The measurements were conducted at the same time. The occupants were counted every 30 minutes. The measurements were conducted over a one-week period (19.-23.3.2018) between 9 and 15 every day.

CO_2 concentration-based method

CO_2 sensors measure continuously the concentration in the rooms. By knowing the concentration, the number of occupants can be calculated. The method is based on the metabolism rate of humans derived from the occupants' body size and composition, age, sex, diet and level of physical activity. Comparing these two measurements, it is possible to assess the accuracy of the CO_2 method. The number of people is estimated using equation 3 shown in Chapter 4.4.1. The value for CO_2 generation rate is chose from Table 9. The chosen value is for office work, standing equaling to 18.5 dm^3/h.

Image based method

Three different image-based measurements were conducted. Two with the Kinect sensor and one with the AXIS M3045-WV sensor. The first Kinect measurement was in room U107, because it has only one door making it easier to count the number of people coming in and going out. The camera was placed on a table facing the door perpendicular. The sensor records the movement of people in 3D-coordinates. The stream of data from the sensor is analyzed in Matlab software with the extension Image Acquisition Toolbox. Matlab is also used for calculating the number of people in the room at any given time by summing the arrivals and departures. The movement of occupants was counted by creating a gate in the coordinates from which if the movement is from left-to-right it is counted as an arrival and if from right-to-left as a departure, shown in Figure 24. To be counted as either one, the sensor must trigger the person before entering the gate. The coordinates were chosen to optimize the sensor to be as accurate as possible. The software was set to save a file for every 15 minutes which has the time, date and number of arrivals and departures.

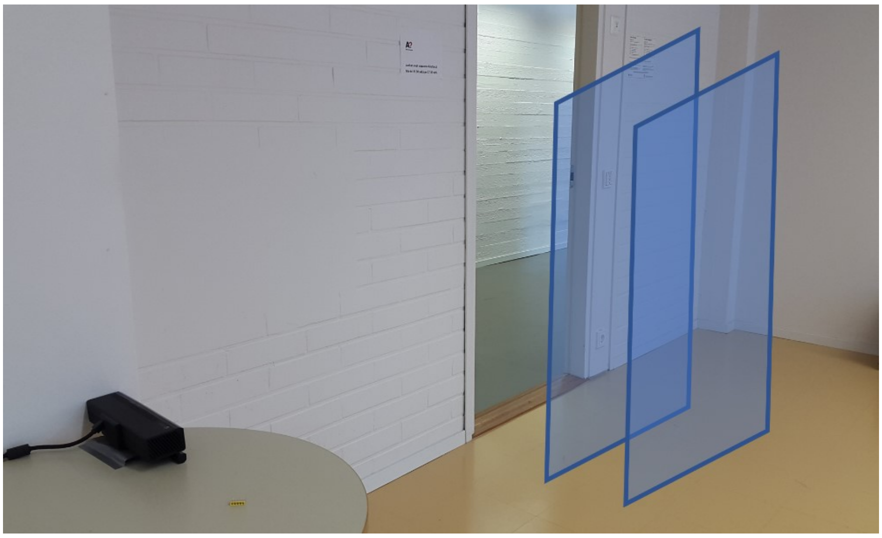


Figure 24. Kinect camera in U107 and the gate that was used to calculate the arrivals and departures.

The second Kinect measurement was conducted in one office room of the HVAC-department in Sähkömiehentie 4. The sensor was installed on eye level perpendicularly facing four desks, shown in Figure 25. The number of people was recorded every minute and compared with the actual number of people that were manually counted. This measurement was done to see if the sensor works better at measuring the number of people in the room at a given rather than measuring the arrivals and departures.

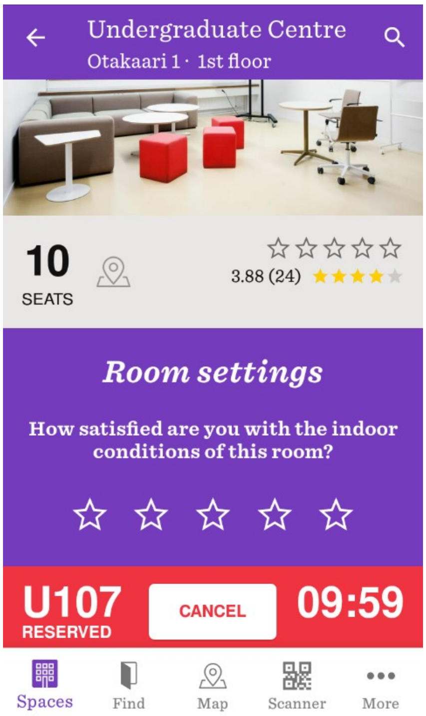
Figure 25. Kinect camera in HVAC-department office.

The third measurement was conducted with the AXIS M3045-WV sensor in an office room in the HVAC department in Sähkömiehentie 4. The sensor was placed above the door facing downwards, shown in Figure 26. The AXIS direction detection application was installed to detect the direction of movement under the sensor. The measurement was done with a group of six people walking past the sensor in varying speeds and groups. First each assistant walked past the sensor one by one. After this varying groups were tested, either two, three or four at a time. The data was recorded by the sensor and was gathered from the AXIS servers.

Figure 26. Measurement setup for the AXIS M3045-WV sensor.

5.3.4 User indoor environment modification and satisfaction

The case rooms are reserved through the Aalto Space – application. At the end of the reservation period, the user is asked "How satisfied are you with the indoor conditions of this room?", shown in Figure 27. If the user rates it one or two stars, an additional question is asked about why they rated so low. This way problems can be assessed more clearly. The application also collects data on which options of indoor climate condition are chosen and when. This way information on the user's preferences can be compared with the known indoor temperature and ventilation mode at that same time.



How satisfied are you with the indoor conditions of this room?

☆ ☆ ☆ ☆ ☆

Figure 27. Aalto Space - User satisfaction questionnaire (ACRE, 2016).

Occupants are also asked to fill in a paper survey on their opinion of the indoor environment. The questionnaire is shown in Appendix II. The questionnaire contains six different questions:

1. How would you rate the current temperature in this room?
2. Is the current room temperature acceptable to you?
3. Would you prefer the room temperature to be?
4. Is the current room air quality acceptable to you?
5. Would you prefer the room ventilation to be?
6. Do you notice any other sources of discomfort in the room thermal condition?

The questionnaire is written both in English and Finnish to be able to increase the response rate.

6 Results

6.1 Air flow

The measurements were done separately for the supply and exhaust air flows in each room with both normal and boosted ventilation modes. Table 14 shows the total flows and balance of the supply and exhaust airflow rates. Table 15 shows the immediate effect of turning on the boost mode in the supply air flow in room U105 as the other measurements were done separately for normal and boosted modes.

Table 14. Supply and exhaust air flow balance of the rooms.

Room	**Mode**	**Supply air flow**		**Exhaust air flow**		**Difference (l/s)**[1]	**Supply and exhaust ratio**
		(l/s)	**(l/s,m^2)**	**(l/s)**	**(l/s,m^2)**		
101	Normal	74	2.2	75	2.3	-1	98 %
	Boosted	146	4.4	139	4.2	7	105 %
103	Normal	79	2.3	75	2.2	4	105 %
	Boosted	158	4.6	142	4.1	17	112 %
105	Normal	77	1.9	81	2.0	-4	95 %
	Boosted	151	3.8	153	3.9	-2	99 %
106	Normal	52	1.9	81	3.0	-28	65 %
	Boosted	107	4.0	142	5.2	-34	76 %
107	Normal	75	2.3	83	2.6	-9	90 %
	Boosted	144	4.4	167	5.1	-23	86 %
108	Normal	76	2.3	86	2.6	-10	88 %
	Boosted	160	4.8	139	4.1	21	115 %
109	Normal	81	2.1	136	3.4	-55	60 %
	Boosted	175	4.4	206	5.2	-30	85 %

[1]Difference between supply and exhaust air flows.

Table 14 show that rooms U101, U103 and U105 are quite well balanced in both modes as the supply and exhaust air flow ratio is between 95 % and 112 %. Rooms U107 and U108 are moderately balanced with ratios between 86 % and 115 % and rooms U106 and U109 are not balanced properly as the ratio is between 60 % and 85 %.

Table 15. Supply air flow with normal and boosted modes.

Room	**Mode**	**Duct**	**Air flow (l/s)**
105	Normal	Supply 1	0
		Supply 2	77
	Boosted	Supply 1	77
		Supply 2	74

Table 15 shows that the immediate effect of turning the boosted mode on is a decrease of 3 l/s in the supply duct 2. This change can be the cause of the pressure difference that happens in the supply duct because of the new damper opening. The change is small, which indicate that the system works well.

6.2 Room system performance

Three different control strategies where used when running the ventilation system:
1) Temperature
2) CO_2 concentration and
3) Temperature and CO_2 concentration driven control.

Temperature controlled ventilation was measured between 5.-10.3., seen in Figure 28. The ventilation set point temperature was set to 21°C and smart thermostats were set to 21°C. The results show that the temperature is stable and fluctuates only 1°C around 22°C. The CO_2 concentration has peaks that go up to 1100 ppm during the days. The concentration does not increase further as the dampers are opened and the ventilation is increased. 10.3. onwards was the weekend, so the concentration stays at circa 400 ppm.

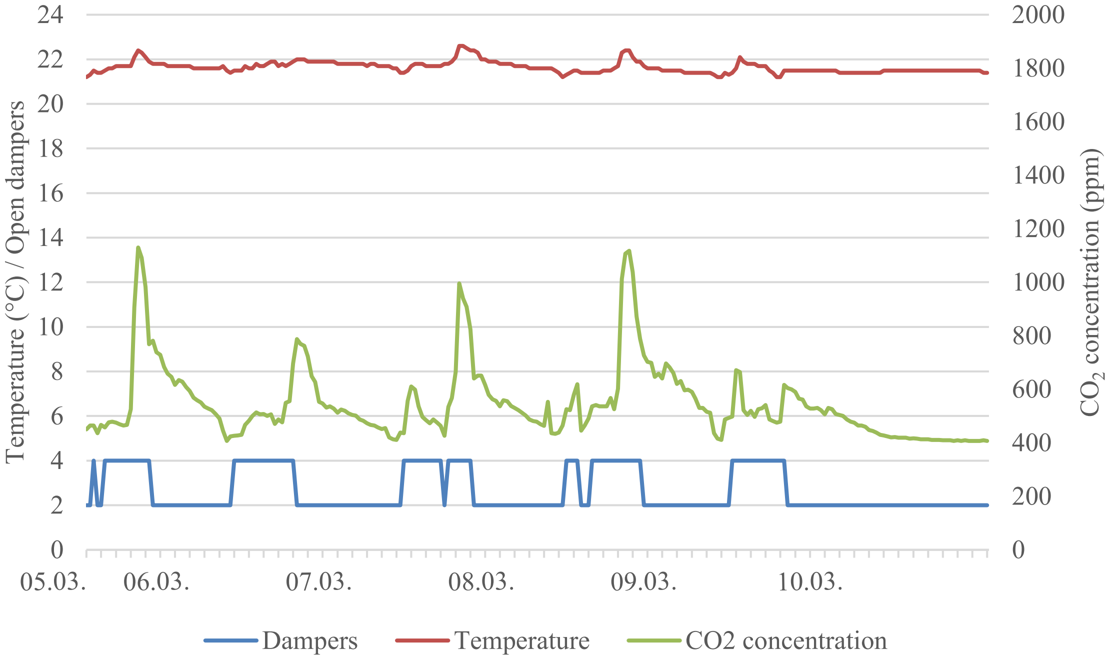


Figure 28. Temperature control of ventilation in room U101 5.-10.3.2018.

CO_2 based control was measured between 16.-21.3., seen in Figure 29. The set point temperature was set to 26.5°C, the set point CO_2 concentration to 1200 ppm and smart thermostats to 20°C. Room occupancy measurements were conducted in 19.-23.3.2018. The results show that the temperature remains stable and fluctuates by 1°C around 22°C. The CO_2 concentration remains stable during the weekend (16.-18.3.) as there is no occupation during that time. Each weekday the concentration has clear spikes. The concentration has time to increase even to 1900 ppm before the dampers open and it starts to decrease back to a more suitable level between 500 – 800 ppm. The concentration increases quickly but starts to decrease immediately when the dampers are opened. The effect of occupants is seen as the concentration starts to increase when more people occupy the room.

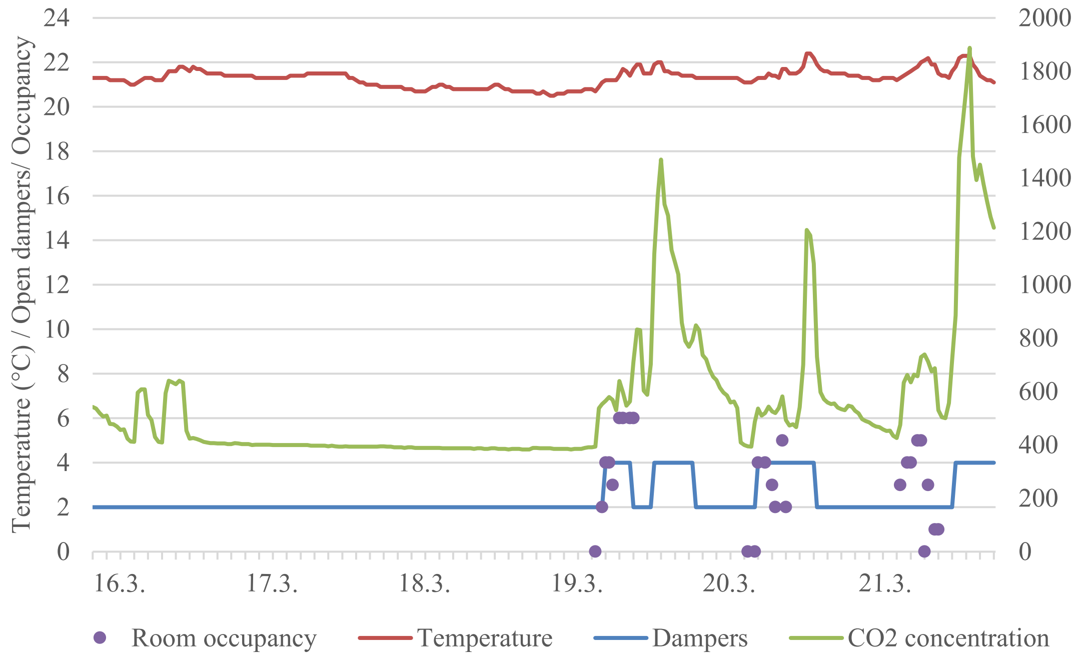


Figure 29. CO₂ concentration control of ventilation in room U101 16.-21.3.2018.

Temperature and CO₂ based control was measured between 26.-31.3., seen in Figure 30. The set point temperature was set to 22.5°C, CO₂ concentration to 800 ppm and smart thermostats to 20°C. The results show that the temperature remain stable and fluctuate by 1°C around 22°C. CO₂ concentration does have peaks, but they are lower than in only CO₂ based control reaching 1500 ppm.

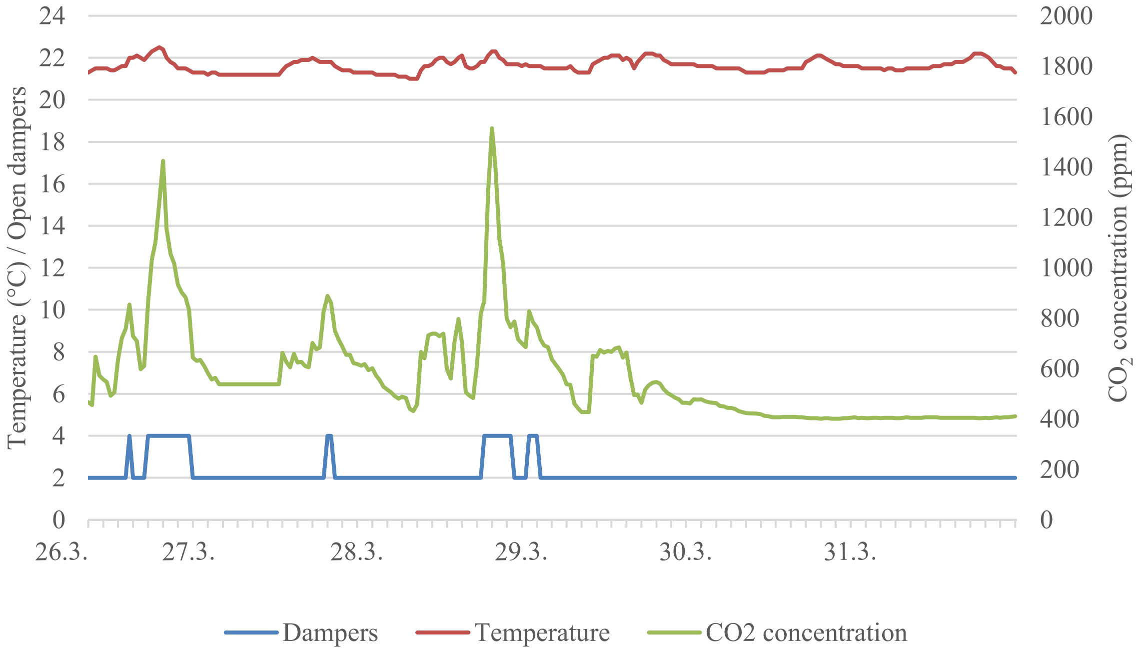


Figure 30. Temperature and CO₂ concentration control of ventilation in room U101 26.-31.3.2018.

The overall results are that the room air temperature stays stable during all the control periods. During the measurements, the outdoor temperature was mainly lower than 0°C and there was no cooling needed. In these rooms, the heating is controlled well as it has more power. The cooling is only done by the ventilation system and the cooling power is small compared with the heating power. If these tests were to be conducted during summertime the indoor temperature would likely be higher.

The rooms have varying supply and exhaust air flow rates which are not all balanced, seen in Table 14. The effect of the air flows and room occupancy on the indoor conditions was studied. Room occupancy measurements were conducted between 19.-23.3. Room U103 has a balanced ventilation (Figure 31) and room U109 has an unbalanced ventilation (Figure 32). The effect of people can be clearly seen in the increasing concentration of CO_2 in the rooms. Also, the room air temperature has an increase when there are big peaks in CO_2 concentration. As the dampers open, the concentration decreases to less than 600 ppm. Large spikes in concentration can be seen in room both rooms. The maximum for room U103 is 1600 ppm and for U109 1800 ppm. The temperature fluctuates more in room U103 than in U109 but remains on a good level.

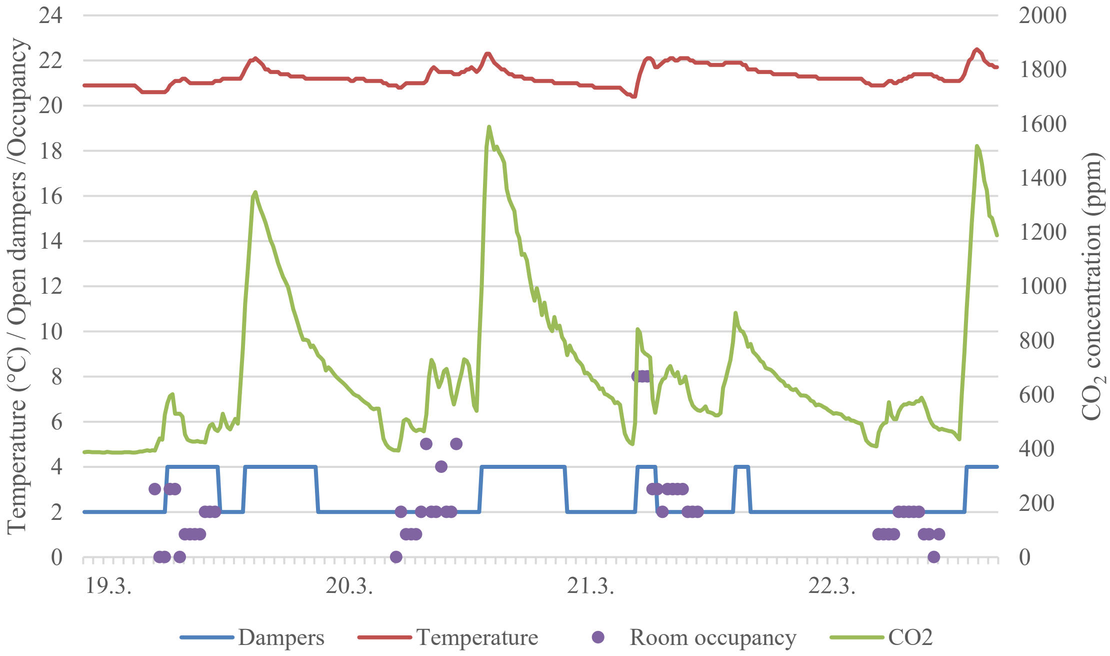


Figure 31. Room air temperature, damper openings, occupants and CO_2 concentration in balanced ventilation room U103.

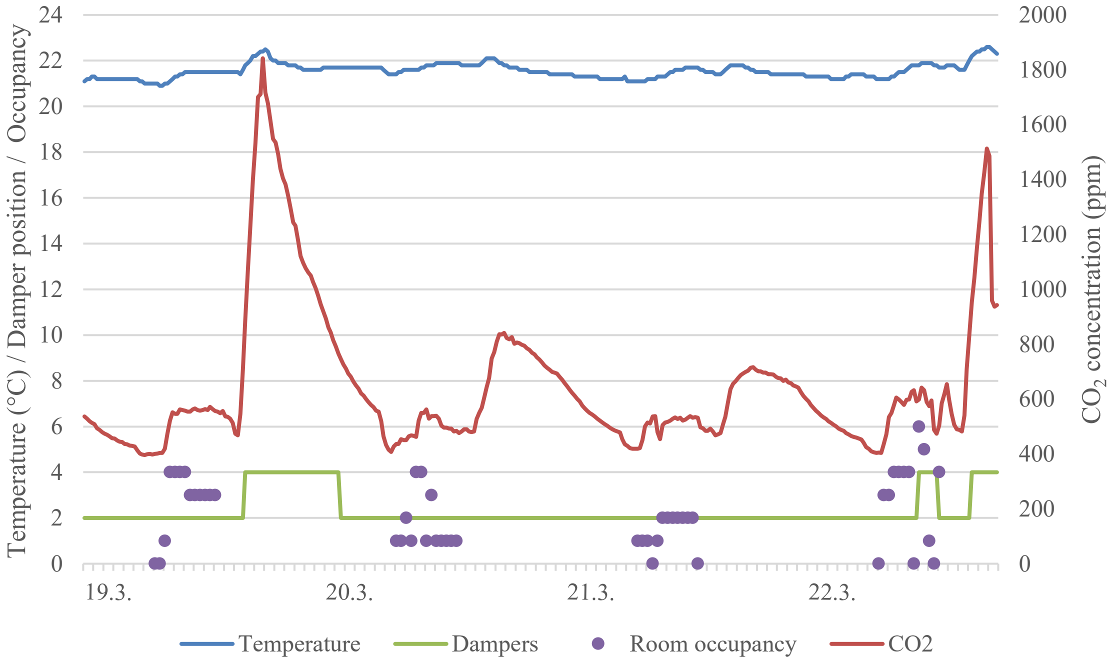


Figure 32. Room air temperature, damper openings, occupants and CO₂ concentration in unbalanced ventilation room U109.

6.3 Pressure difference

Pressure difference measurements were conducted over a period of two months (February and March). The results show that the rooms are all underpressured, which mean that there is no risk that condensation could happen in the building envelopes in these rooms. There is a clear variation in pressures between day and nighttime. During the day, the pressures vary between -2 Pa and -10 Pa. During the night, the pressures vary between -10 Pa and -15 Pa, respectively. During the night, the air handling unit is not running, but there are other general exhaust fans that are still working that cause significant pressure difference over the envelope. For the period 19.-24.03.2018, the opening of doors and windows was also observed by going through the rooms every 30 minutes. This and the pressures of the room U101 is presented in Figure 33 and for U109 in Figure 34.

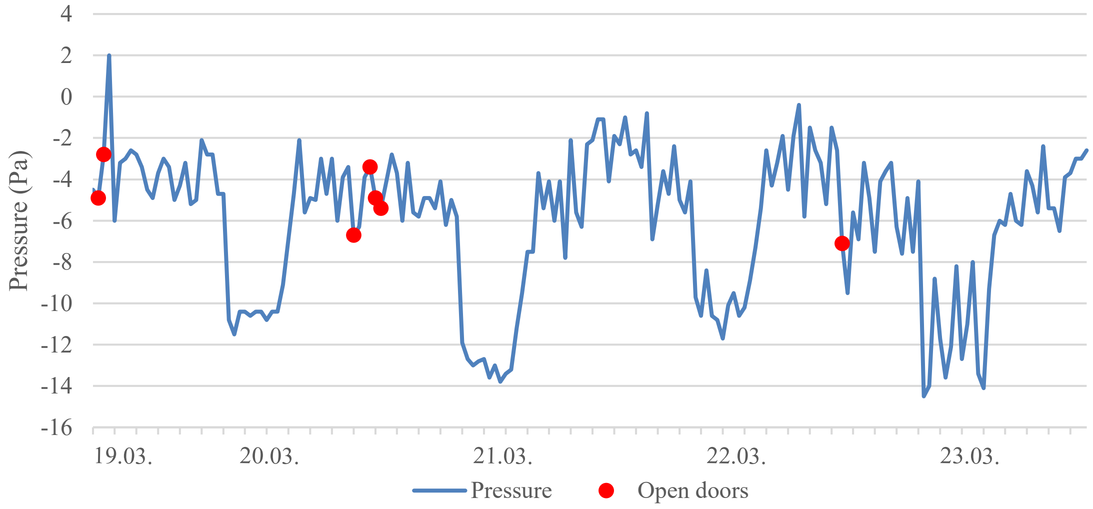


Figure 33. Pressure difference of the balanced ventilation room U101 19.-24.03.2018.

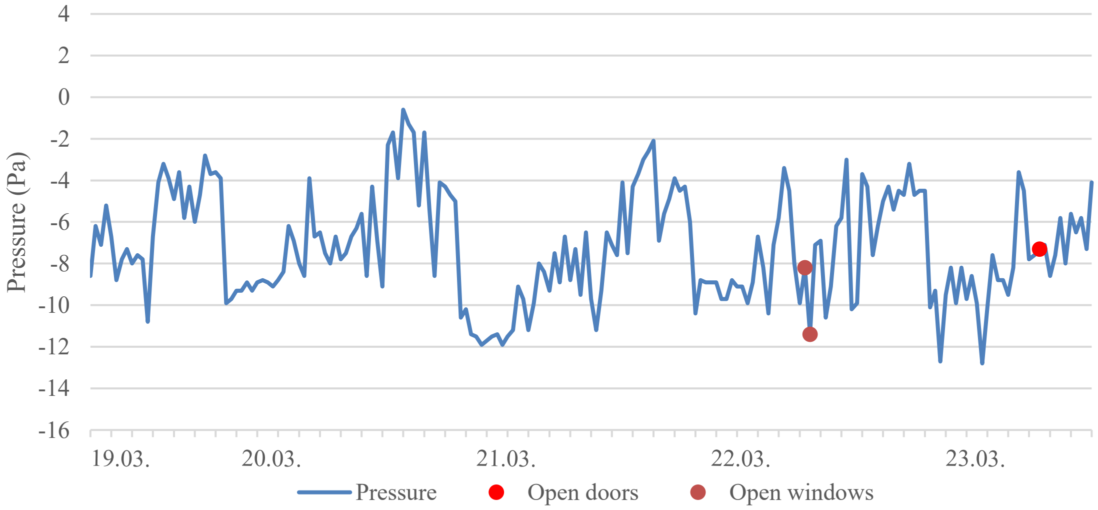


Figure 34. Pressure difference of the unbalanced ventilation room U109 19.-24.03.2018.

Room U101 has a balanced ventilation and U109 has a larger exhaust air flow rate than the supply air flow rate (Table 14). In room U101, there is a clear variation between night and day times. During the night time when the ventilation is turned off, the pressure decreases to less than -10 Pa. During the day time, the pressure is around -4 Pa. In room U109, the variation is smaller, as even the day time, pressures stay at the level of -10 Pa. This is the result of the larger exhaust air flow rate compared with the supply air flow rate in the room. The daytime pressure variations are quite small.

As the rooms are connected via the same supply and exhaust ducts, the airflows of adjacent rooms could impact one another. The measurements indicate that this is not the case, as the pressures stay within the same level through the measure period. Also, the opening of doors and/or windows seem not to have a large effect on the pressure in the rooms. This indicates that the pressures in the hallways and rooms are on a same level.

6.4 Building occupancy

The building occupancy measurements in the case rooms were conducted over a one-week period during 19.-23.3.2018. The CO_2 concentration- and image-based methods were compared with the actual room occupancy data that was acquired by observing and counting the people in the rooms every 30 minutes.

6.4.1 CO_2 concentration – based method

The results of the calculations are presented in Figure 35. The graph shows the difference between the calculated occupancy and the actual room occupancy for the seven rooms.

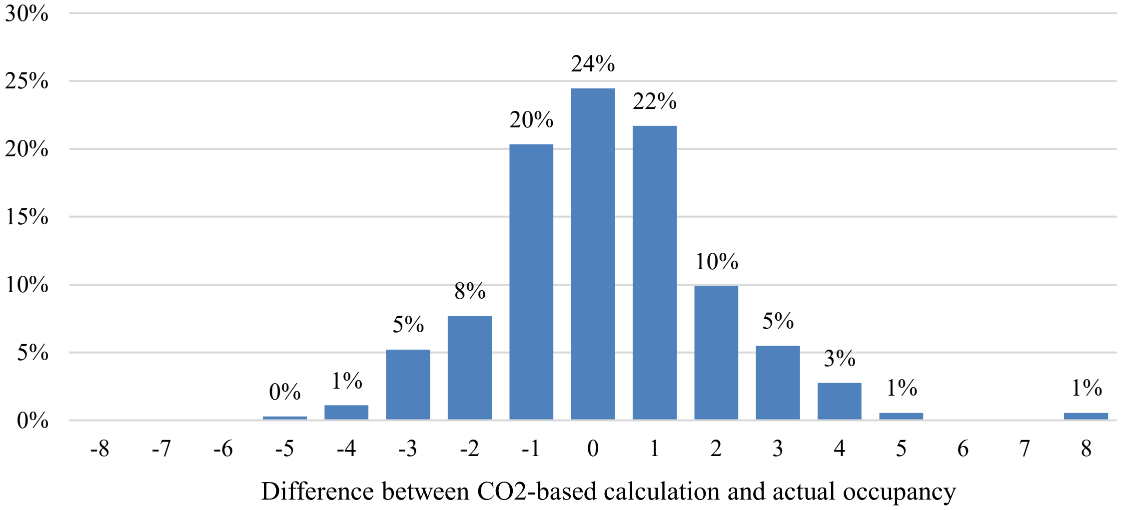


Figure 35. CO_2 concentration-based number of occupants compared with the actual amount.

It was noted that 24 % of the half-hours the calculation was correct and 42% of half-hours there was only a difference of one person. This method proved to be quite accurate in estimating the occupancy of the rooms as 66% of the half-hours fall between a variation of 1 person.

CO_2 concentration can also be used to identify the occupancy of the rooms. The result was that 89% of the half-hours the CO_2 concentration – based calculation proved to be correct and 11 % incorrect, shown in Figure 36. The error is due to the time delay of the change in CO_2 concentration. This will happen for example when the room was unoccupied for an hour in the middle of the day before and after occupation. The concentration did not decrease to an unoccupied level and thus resulted in a "occupied" status. Also, when the room is unoccupied, it takes a moment for the concentration to increase.

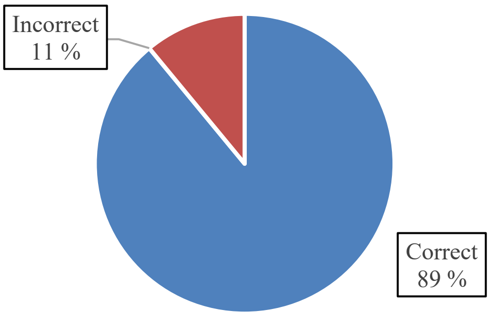


Figure 36. CO_2 concentration-based room occupancy compared with actual occupancy.

6.4.2 Image-based method

The Kinect image sensor was tested in two different ways. The first method was to count the number of people arriving and departing from the room. The second method was to point the Kinect sensor to the room and counting the people in the room. The AXIS sensor was used in one measurement.

The first measurements took place over five days. Figure 37 shows the results of the two measured days.

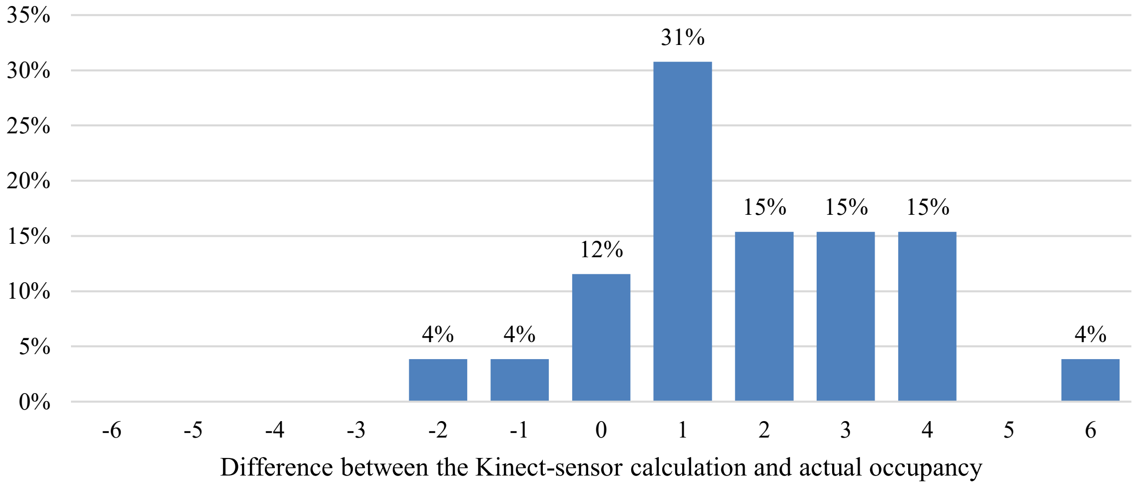


Figure 37. Number of occupants compared with the actual amount of the occupants with the sideways facing Kinect sensor.

When the sensor was used to count the occupants passing the door, the results are not accurate. There were many occasions where the sensor could not detect the movement of people through the doorway. The differences are not very big, as there were not so many moving persons through doorway at a given time. Inherently the system is flawed, as it kept the same number of occupants in the room without detecting movement. So, it just happened to be correct many times as new people came into the room and previous people left.

The problem is caused by the trigger rate of the sensor. The sensor does not identify people well in the cases of very fast movement. In slow movement cases, it records the movement very well.

The second measurement was conducted on 13.4.2018 with changing the number of people in the room every minute. A total of 20 changes were made. The results, shown in Figure 38, demonstrate that the sensor could not detect all the people in the room and underestimates the number of persons most of the time. It had trouble at detecting the people sitting far away from the Kinect system and behind other people. The accuracy of within one person was 75% which is relatively good.

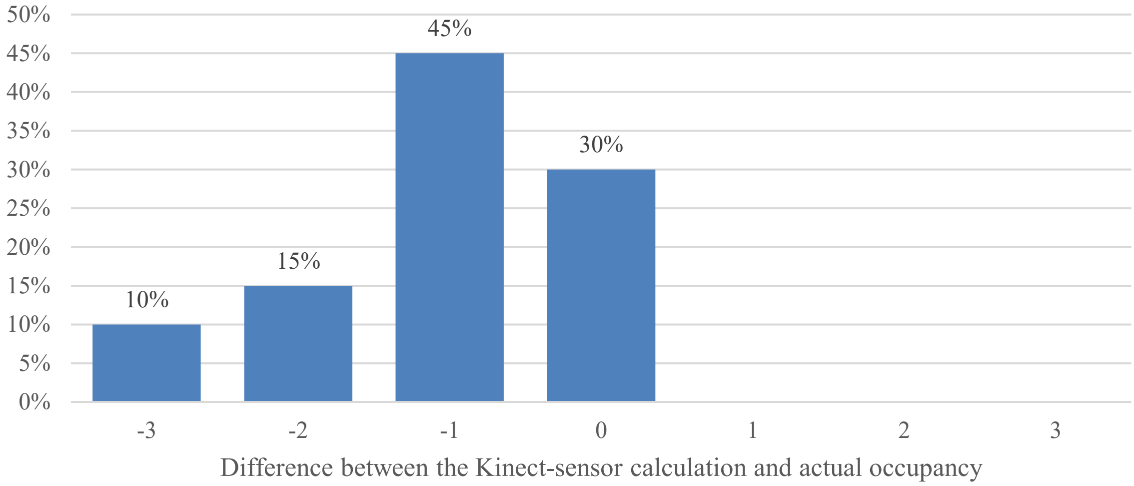
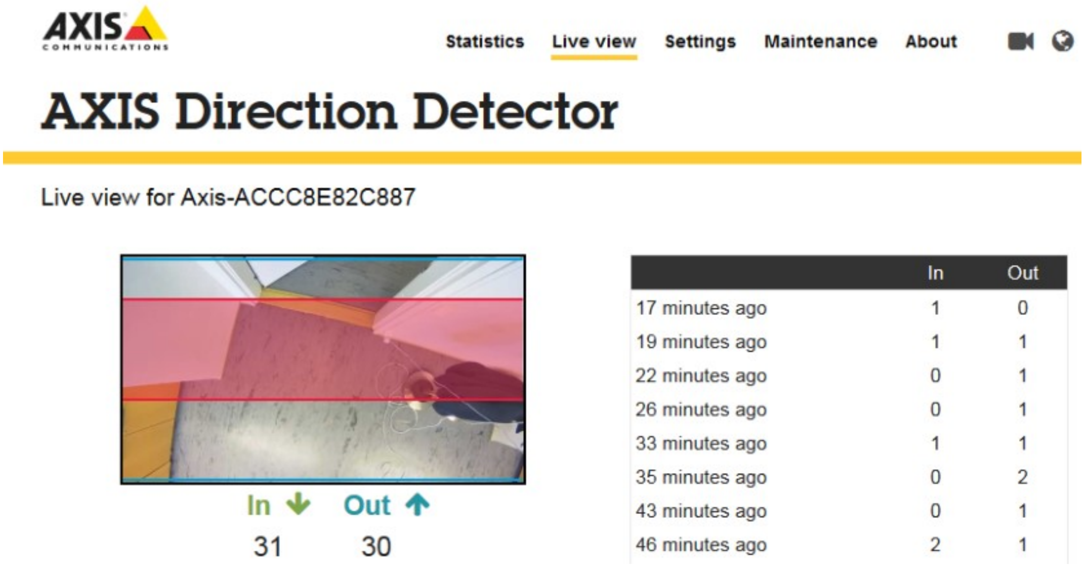


Figure 38. Number of occupants compared with actual amount with the room facing Kinect sensor.

By using the Kinect sensor to identify the persons in the rooms by using it as a depth camera which projects infrared dots on a skeleton model, the placement of the sensor is important. It needs to have sufficient view of the space to see clearly the human shapes. It also works better if it is installed on the eye-level of humans. Tests were made to place it on the ceiling or high level on a shelf, but then the human shape is obscure, and the system is not able to identify persons. This then causes errors in calculations. Study conducted by Zhang *et al.* (2012) utilize the Kinect sensors as only a depth camera which is placed on top of a doorway achieving better accuracy in results than in this study. The basic logic behind this is that if a difference in depth is measured, then it can be identified to be a person walking past the sensor. The data that the sensor outputs needs to be analyzed to work efficiently through various software and algorithms and it was not in the scope of this study.

The third measurement was conducted with AXIS-3045-WV. The measurement was conducted by varying the amount of people in the room. A total of 31 arrivals and 30 departures was identified with 3 errors. The accuracy of the sensor is thus 95%, which is very good. A view from the livestream is shown in Figure 39. The errors happened when a group of four people moved fast through doorway. The sensor did not detect one person of the group of four persons, and this occurred a couple of times. The accuracy can be improved by installing the sensor higher as in the test setup the sensor was installed only at level of 210 cm from the floor.



AXIS Direction Detector

Live view for Axis-ACCC8E82C887

In ↓ Out ↑
31 30

	In	Out
17 minutes ago	1	0
19 minutes ago	1	1
22 minutes ago	0	1
26 minutes ago	0	1
33 minutes ago	1	1
35 minutes ago	0	2
43 minutes ago	0	1
46 minutes ago	2	1

Figure 39. View from the live stream of the AXIS sensor.

6.5 User satisfaction

User satisfaction was analyzed with a survey where six questions are asked of indoor climate quality during March. A total of 29 answers was acquired. The answers indicated that the occupants are quite satisfied on the indoor climate in the rooms. Most of the answers indicated that the occupants prefer only a slight change or no change at all in temperature or ventilation.

The temperature in the room is mostly rated as “Neutral” or “Slightly cool”, shown in Figure 40. Only a minor share of the responses would rate the room either “Cold” or “Hot”. The room air temperature was around 21°C during the assessment period and the temperature did not include any peak values. During the measurements, there was a typical outdoor temperature for winter period as it was less than 0°C. The rooms are oriented to north and the solar radiation does not heat up the rooms.

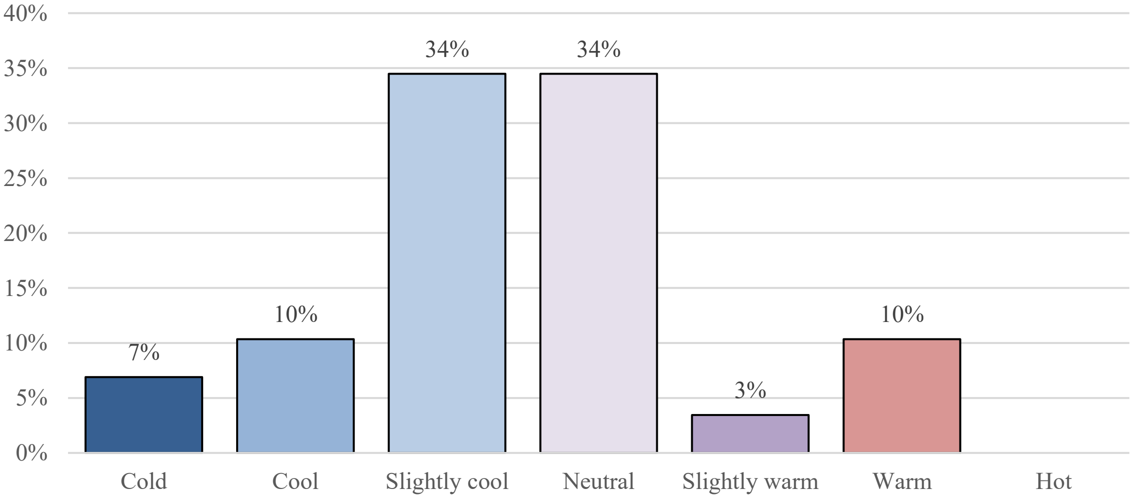


Figure 40. Answers for the question "How would you rate the current temperature in the room?".

The occupants' perception on the room air temperature and air quality is shown in Figure 41. Temperature is deemed acceptable by 69% of respondents and the air quality by 79% of the respondents. These acceptance levels are quite common as same type of results were found by Kosonen *et al.*, (2008).

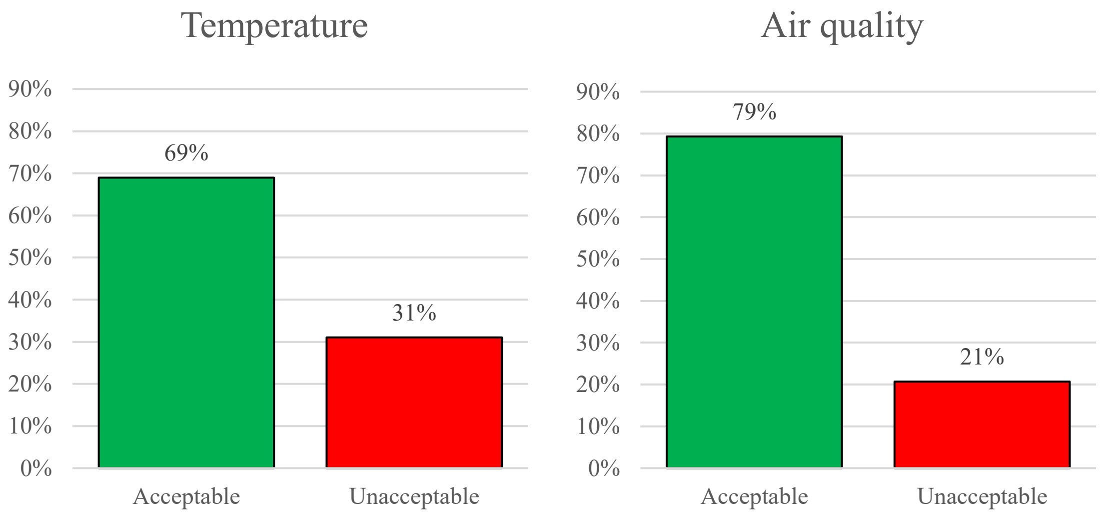


Figure 41. Answers for "Is the current room temperature/air quality acceptable to you?".

Half of the occupants responded that they do not need any change in the indoor temperature (Figure 42). A slightly warmer or warmer temperature was preferred by 44% of the respondents and only 3% of occupants wanted cooler temperature.

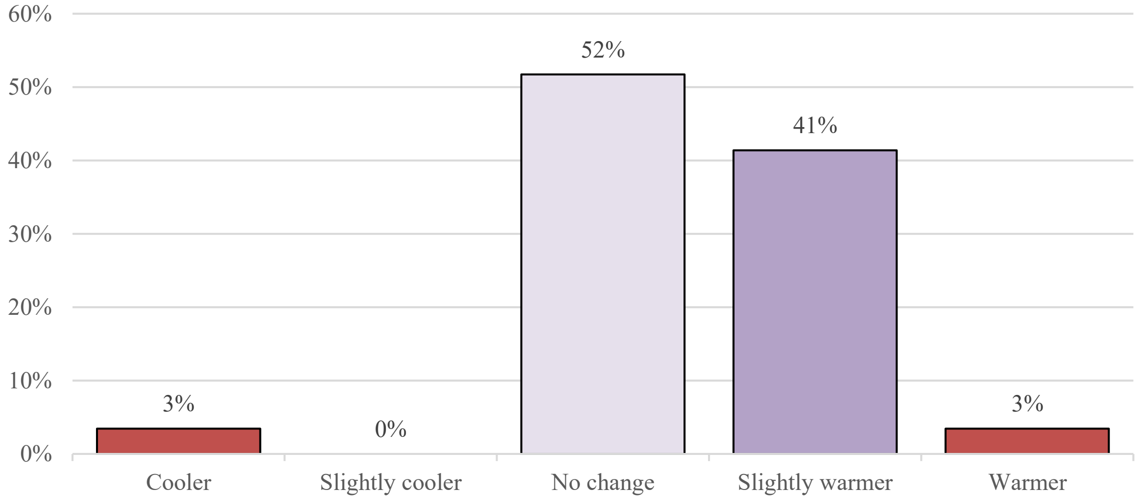


Figure 42.Answer for the question "Would you prefer the room temperature to be ...?".

Over half of the occupants (55%) answered that they preferred the level of ventilation as it is now in the room, 38% preferred slightly more and 7% much more, shown in Figure 43.

As most respondents preferred no change and some slightly more, the ventilation can be deemed good in the rooms.

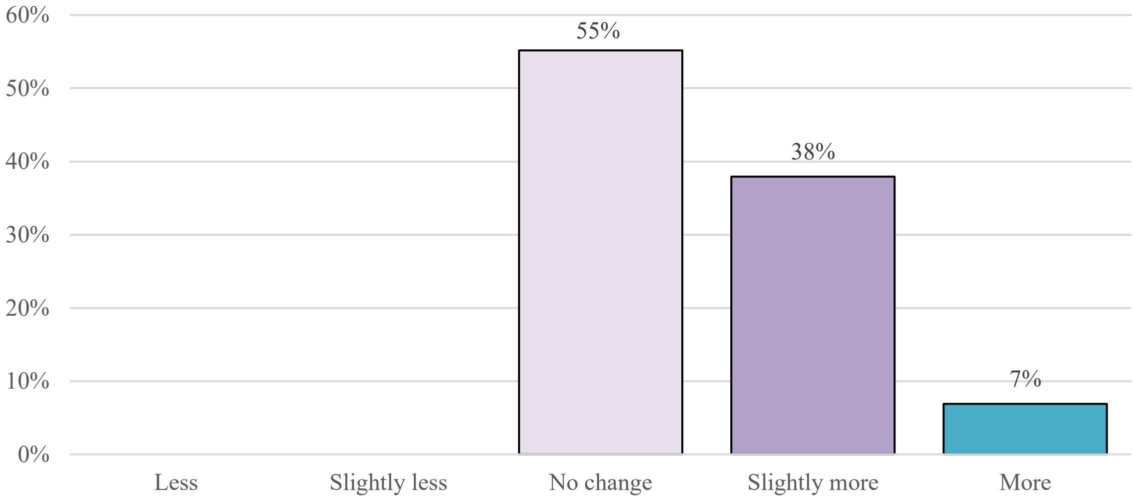


Figure 43. Answers for "Would you prefer the room ventilation to be …?".

Nearly half of the respondents (42%) did not feel any other sources of discomfort (Figure 44). The most common sources of discomfort were stuffy air, cold draft and glare. Some comments noted that the lights made a buzzing noise, which can be fixed by repairing the lights. Glare was commented to come from too strong sunshine. This can be easily fixed by closing the curtains in the room. The perception on the air quality could be improved by increasing the ventilation. In practice, the occupants need to be made more aware of their possibilities in modifying their personal ventilation in the rooms, with the Aalto space application.

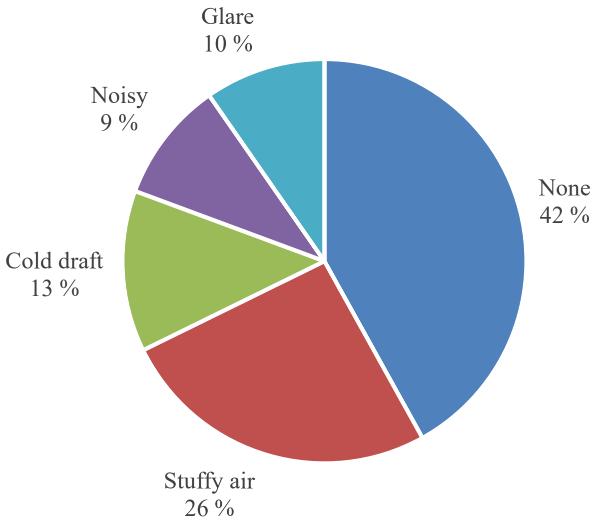


Figure 44. Answers for "Do you notice any other sources of discomfort?".

User feedback was collected through the Aalto Space – mobile application as well. The questionnaire was introduced 10 minutes before the reservation period ends by asking “How satisfied are you with the indoor conditions of this room?”. The results of the 33 answers received are shown in Figure 45. These results were received over a period of two weeks in April.

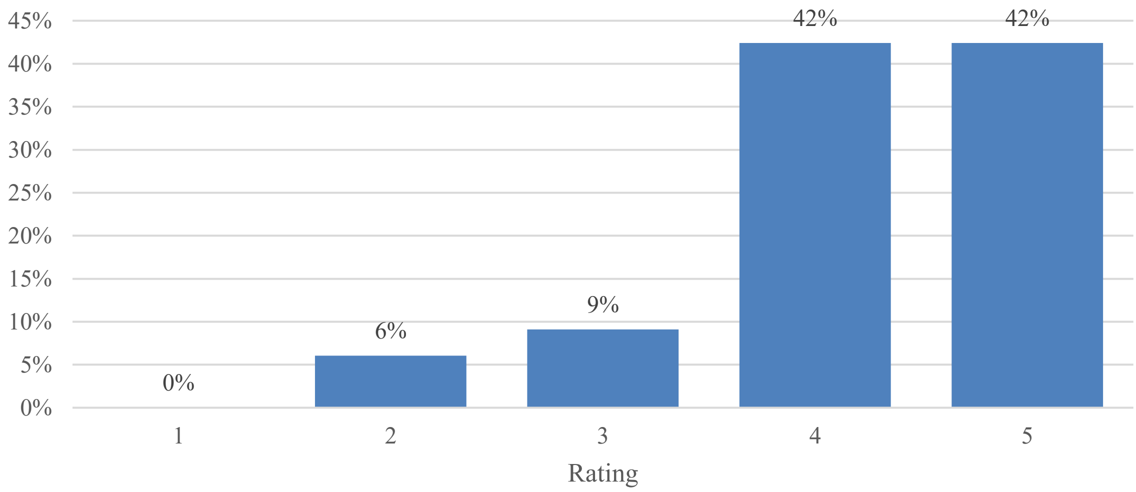


Figure 45. Users' perception on indoor climate collected with the Aalto Space - app.

The results of Aalto Space –app indicate a similar level of satisfaction on indoor conditions as in the previous paper questionnaire. Major share of the answers is either 4 or 5 on a 5-step scale, meaning a high level of satisfaction on the indoor climate conditions. The possibility of adjusting the ventilation and temperature in the rooms was introduced in late April. The preliminary results indicate that this feature has been welcomed and students have started actively to use it. As the features were introduced at this stage of the year, the heating season is over, and the water radiator heating is not needed. The modification of temperature is thus nonexistent. During the next autumn and winter, this feature can be studied in more detail.

7 Discussion

The Smart Readiness Indicator introduced in the new EPDB is used to assess the smartness of buildings and at the same time raise awareness of how smart technologies can be utilized in buildings. In the spirit of this indicator, the smartness of the case rooms has been improved with technological additions. The rooms were equipped with smart thermostats which improve the thermal comfort of occupants while working in demand response, saving energy costs for the building owners. The pressure over the building envelope of the rooms were measured with sensors, which indicate how well the ventilation system is in balance and prevents associated building damages from forming. User controllability and satisfaction monitoring was done with Aalto Space mobile application which is easy to use and specific to the Otaniemi campus. All the improvements work towards a better service offering for the occupants, which would be shown in the SRI rating for this building. This in turn can increase the value of the building for the building owners.

The measurements took place during winter and spring, which is still heating season in Espoo. This enabled the room air temperature to be modified by varying the heating power of the water radiators. The room air temperature was quite stable during the measurement periods as the water radiators equipped with the smart thermostats worked as planned. The results would probably be different in the summer time when the solar radiation will heat up the rooms. The ventilation system would probably not have sufficient capacity to cool down the rooms to a comfortable level. The satisfaction and acceptance of the occupants would then also be different. This is a hypothesis that would need more research to be confirmed.

The studied VAV-ventilation system worked well after the set points were adjusted. These results proofed that the conducted retrofitting can be recommended to be installed also in the future. The ventilation system works based on data gathered by different sensors in the system, which is also used in analyzing the indoor climate conditions. These sensors can have inaccuracies, which can hinder the performance of the system. VAV systems can also have problems with for example choosing the optimal set points for the system, the damper motors and with different controllers. As VAV-systems can be more complicated than many other ventilation systems, these types of malfunctions can deter their installations as they are more difficult to repair. VAV-systems can be an energy efficient ventilation solution, but if the disadvantage is that it is not always reached, then a more robust and simpler solution is chosen. The monitoring conducted in this study is one way to improve the performance of the system. During the measurements, the VAV-system was assumed to have a malfunction. After analyzing data on the system performance, the chosen set points were noted to be the cause of the suboptimal performance of the system.

When assessing the physical measurements, the accuracy of measurement devices must be considered. The same must be done with answers from user satisfaction questionnaires. These are based on the psychological factors of humans: people might exaggerate their answers to ensure that something will be happen about the thermal conditions. Also, the low rate response rate does not represent the everyone's opinion on the indoor conditions. Typically, an answer rate of 50% of all users is deemed good in post-occupancy evaluations.

The building occupancy is important information for the building owners as well as the functioning of the HVAC system. Acquiring accurate data of the room occupancy can be challenging as the cost can be high, privacy concerns may rise from the occupants, and the installation can prove to be difficult. New technologies can provide a solution. For example, a simple motion detection sensor with a wireless connection could be suitable solution for office spaces. This could be the future of HVAC control rather than relying on temperature and CO_2 concentration. With image-based methods, the indoor parameters can be controlled better than with the traditional measurements of room air temperature and CO_2 as the system can react faster and prevent overheating or stuffy air. For example, the peaks in CO_2 concentration seen in this study could be prevented with accurate image-based control. This technology has the potential to replace at least the major portion of the use of CO_2 sensors in buildings, as they provide also the information on the space utilization rate. This information opens possibilities for a wider use for real estate business rather than only knowing the CO_2 concentration in rooms as use that for ventilation control.

Space utilization rate can also be improved by the introduction of controllability to users through the Aalto Space mobile application. With this service, occupants can modify the indoor climate to fit their needs rather than for the HVAC system providing each user with the same conditions. With tailored solutions, the user satisfaction is likely to enhance in an energy efficient manner. The building owners are interested of the space utilization rate as it is their core business. The owners want to increase their occupancy ratio as higher as possible. Saving costs on energy is a positive thing, but that should happen demand-based. In this way the Aalto Space application is a good service as it can be used for room reservation, modifying the indoor climate as well as collecting user feedback on the rooms.

The addition of new smart technologies that integrate different systems cause a need for a new type of design thinking. Traditionally buildings are designed by each design discipline by themselves, meaning the HVAC-, building automation- and electric systems, with a lack of planning on how to integrate these systems. This has been a method that works as there really has not been a need for a complete integration of different systems within the building. In our case, the ventilation and heating system was integrated with building automation system, space reservations and user modifications through the mobile application. This retrofitted integration was done within this project successfully thanks to a great cooperation with the different companies involved. As these types of services become more common, they should be considered in the design phase of the building. Retrofitting the building automation system, HVAC-system, electricity and other services can be difficult and time consuming as all of these operate with different software and communication protocols. If these are already integrated from the beginning, savings in time and costs can be significant.

Identifying the demand for integration of different systems can prove to be a business opportunity for companies not previously associated with building technologies. IT-companies could be suited for providing this service as they have the knowledge of how information is transferred through different systems and integrated to work with one another. By providing a cloud service with relevant API's for building owners and external service providers, the IT-companies could widen their business and provide value for the building industry. API's enable the introduction of new digital services to be installed and used in the building context. The case example of Aalto Space in this study was only able to be introduced as there were working API's installed between the mobile application, the integration server and the building automation system. With a wider application of this principle, the industry could have new companies come in and provide new types of services enhancing the user satisfaction, develop the energy efficiency and extend the technical lifetime of the building.

8 Conclusions

The objectives of this thesis were to study how smart HVAC-solutions can be incorporated in retrofitted buildings and how they perform. The indoor climate quality and controllability of indoor parameters by users have not been in focus in previous legislation considering buildings. Also, ensuring the performance of technical building systems throughout the lifetime of the building is difficult. The topic was studied by incorporating new technologies to seven rooms in the Undergraduate center in Aalto University's Otaniemi campus, retrofitted in 2015. These seven rooms are used by students and faculty as meeting rooms and can be reserved through the Aalto Space – mobile application. The rooms include variable air volume ventilation and centrally controlled water radiators equipped with smart thermostats in room spaces. The main improvements to the case rooms were: the monitoring and controllability of the variable air volume ventilation- and water radiator heating-system, occupancy measurements and collecting perception of the user satisfaction.

The monitoring and controllability of the HVAC system was improved and proved to work well. The supply and exhaust air flow rates were measured in each room and proved to have differences in their balance. Some rooms were balanced properly, while most of the rooms were unbalanced. The unbalanced rooms had a greater exhaust air flow than supply. This could be seen in the CO_2 concentrations and pressure differences over the building envelope as they did not increase as much as in the well-balanced rooms.

Three different control strategies of VAV ventilation system were tested. These included controlling based only on temperature, only on CO_2 concentration and with a combination of the two. The choosing of the right set points is important for the indoor climate quality. If the ventilation is controlled with only one parameter, it can have unwanted side-effects. For example, if only temperature is used the ventilation is not energy-efficient as in our study all the dampers were opened most of the time, causing unnecessary supply and exhaust air flows. This causes unwanted energy usage and increases costs. However, if only the CO_2 concentration is used, then the indoor air temperature can increase to unwanted levels if the rooms have heat loads and only a few people in it. This way the CO_2 concentration does not increase enough to cross the set point value to initiate higher ventilation air flows. Also, with only CO_2 concentration control the indoor CO_2 concentration can increase to high levels before the system has time to decrease to an acceptable level. This was seen happening in this study. A combination of the two parameters can provide the best result. Although, the most important factor is choosing the optimal set points for both parameters. New digital solutions can provide information on what these could be. If the indoor air is analyzed to see how temperature and CO_2 concentration behaves in different situations, the optimal set points can be chosen with ease.

The pressure differences over the building envelope in the rooms were measured for two months. The rooms are clearly underpressured and only a few times some overpressure was measured. The underpressure in the rooms is good for the building structures as it does not damage them in any way. If an overpressure was formed then mold could form in the structures, damaging the building and the indoor air quality. There is a clear difference between night and day pressures. During the night, the air handling unit is not running, but there are other general exhaust fans that are still working that cause significant pressure difference over the envelope. Also, the opening of doors and/or windows seem not to have a large effect on the pressure in the rooms. This indicates that the pressures in the hallways and rooms are on a same level. The variations in ventilation in neighboring rooms was deemed not to cause any effects on the rooms.

Room occupancy measurements were done with three methods: CO_2 concentration-, image- and physical-based observation and counting. The physical counting was done to accurately compare the first two methods. The information on the amount of people in the rooms could be used for modifying the heating, cooling and ventilation powers to better accumulate to each situation. With fast and reliable occupancy measurements the system could vary the parameters to prevent for example overheating or stuffy air. CO_2 concentration-based method results were quite accurate. The error with this method is due to the time delay of change in CO_2 concentration. Image-based methods were measured in three different settings: two with Kinect sensor and one with AXIS-M3045-WV. The Kinect sensor proved not to work with the tried settings. The sensor did not identify occupants quickly enough to count them and had trouble identifying people sitting behind others. The AXIS-M3045-WV was very accurate and proved that it can be used in the future. This sensor has a different design compared with the Kinect so that it does not need to identify a human shape, but rather detects motion. The Kinect has more developed functions for example for identifying how humans move in the room, which could be studied further and used for more personalized ventilation solutions or analyzing how a room is used.

Post-occupancy evaluation on indoor climate was analyzed with two methods: 1) with a paper survey 2) Aalto space -application. The paper survey had six questions in total on the indoor thermal comfort and ventilation and the Aalto Space application a simple five-star rating with detailed questions for those who answered two stars or less. 29 answers were acquired from the paper surveys and 33 from the Aalto space application. Both surveys' results depict that the user satisfaction in the rooms is on a good level, with only a few complaints.

9 References

Aalto University (2017) *Otaniemi Campus*. Available at: http://biz.aalto.fi/en/campus/otaniemi/ (Accessed: 21 February 2018).

Aalto University (2018a) *Architecture*. Available at: http://www.aalto.fi/en/about/campus/architecture/ (Accessed: 11 April 2018).

Aalto University (2018b) *Smartcampus*. Available at: https://smartcampus.org.aalto.fi/.

Abdul-Wahab, S. A. (2011) *Sick Building Syndrome in Public Buildings and Workplaces*. Springer. doi: 10.1007/978-3-642-17919-8.

ACRE (2016) *Aalto Space -mobiilisovellus (Aalto Space - application) [in Finnish]*. Available at: https://aaltocre.fi/aaltospace/ (Accessed: 27 November 2017).

Allen, J. G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J. and Spengler, J. D. (2016) 'Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments.', *Environmental health perspectives*. National Institute of Environmental Health Science, 124(6), pp. 805–12. doi: 10.1289/ehp.1510037.

Artola, I., Rademaekers, K., Williams, R. and Yearwood, J. (2016) 'Boosting Building Renovation: What potential and value for Europe? Study for the ITRE Committee', *Directorate General for Internal Policies. Policy Department A: Economic and Scientific Policy*, PE 587.326, pp. 1–72. Available at: http://www.europarl.europa.eu/RegData/etudes/STUD/2016/587326/IPOL_STU(2016)587326_EN.pdf (Accessed: 28 March 2018).

AXIS Communications (2018) *AXIS M3045-WV Network Camera*. Available at: https://www.axis.com/en-ae/products/axis-m3045-wv (Accessed: 7 May 2018).

Bedford, M., Harris, R., King, A. and Hawkeswood, A. (2013) 'Occupier density study 2013'. British Council for Offices, p. 36. Available at: https://www.architectsjournal.co.uk/Journals/2013/09/10/c/y/n/BCO-Occupier-Density-Study---Final-report-2013.pdf (Accessed: 23 March 2018).

Bolchini, C., Geronazzo, A. and Quintarelli, E. (2017) 'Smart buildings: A monitoring and data analysis methodological framework', *Building and Environment*. Pergamon, 121, pp. 93–105. doi: 10.1016/J.BUILDENV.2017.05.014.

Buda, A., Kinnunen, T., Dave, B. and Främling, K. (2017) 'Developing a Campus Wide Building Information System Based on Open Standards', in *LC3 2017: Volume I - Proceedings of the Joint Conference on Computing in Construction (JC3)*. Heraklion, Greece, pp. 733–740. doi: 10.24928/JC3-2017/0338.

California Energy Commission (2003) 'Advanced Variable Air Volume System Design Guide', p. 228. Available at: https://newbuildings.org/sites/default/files/A-11_LG_VAV_Guide_3.6.2.pdf (Accessed: 30 November 2017).

Cascone, Y., Ferrara, M., Giovannini, L. and Serale, G. (2017) 'Ethical issues of monitoring sensor networks for energy efficiency in smart buildings: a case study', *Energy Procedia*. Elsevier, 134, pp. 337–345. doi: 10.1016/J.EGYPRO.2017.09.540.

Corgnati, S., da Silva, M., Ansaldi, R., Asadi, E., Costa, J., Filippi, M., Kaczmarczyk, J., Melikov, A., Olesen, B., Popiolek, Z. and Wargocki, P. (2011) *Indoor Climate Quality Assessment - Evaluation of Indoor Thermal and Indoor Air Quality (REHVA Guidebooks; No. 14)*. REHVA. Available at: http://www.rehva.eu/publications-and-resources/eshop/eshop-detail.html?tt_products%5Bcat%5D=3&tt_products%5Bproduct%5D=42&cHash=5c1c113220f19bfc1457907f756cbf26.

Council of the European Union (2018) 'Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 2012/31/EU on the energy performance of buildings - Analysis of the final compromise text with a view to agreement'. Brussels: EUR-Lex, p. 39. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=consil:ST_5562_2018_INIT.

Decree 1009 (2017) *Ympäristöministeriön asetus uuden rakennuksen sisäilmastosta ja ilmanvaihdosta 1009/2017 (Decree of the Ministry of the Environment on indoor climate and ventilation of a new building 1009/2017) [in Finnish]*. Helsinki: Ministry of Justice. Available at: http://www.ym.fi/download/noname/%7BAAD7DB92-F571-4766-A3F1-BFF63383191B%7D/133875.

Dooley, K. and Stjelja, D. (2017) 'Are patterns of use the key to resource efficiency in existing buildings?', *The REHVA European HVAC Journal*, 55(1), pp. 14–21. Available at: http://www.rehva.eu/publications-and-resources/rehva-journal/2018/012018/are-patterns-of-use-the-key-to-resource-efficiency-in-existing-buildings.html (Accessed: 23 March 2018).

Dziedzic, J. W., Yan, D. and Novakovic, V. (2018) 'Measurement of Dynamic Clothing Factor (D-CLO)', in *4 th International Conference On Building Energy, Environment*. Melbourne, pp. 208–213. Available at: http://www.cobee2018.net/assets/pdf/p/072.pdf (Accessed: 16 March 2018).

Dziedzic, J., Yan, D. and Novakovic, V. (2017) 'Occupant migration monitoring in residential buildings with the use of a depth registration camera', *Procedia Engineering*. Elsevier, 205, pp. 1193–1200. doi: 10.1016/J.PROENG.2017.10.352.

EED (2012) 'Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC Text with EEA relevance', *Official Journal of the European Union*, L315, pp. 1–57. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32012L0027.

EPBD (2010) 'Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings', *Official Journal of the European Union*, L 153, pp. 13–35. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2010.153.01.0013.01.ENG&toc=OJ:L:2010:153:TOC.

EPBD (2018) 'Proposal for a directive of the European Parliament and of the Council amending directive 2010/31/EU on the energy performance of buildings (COM(2016/0765) – C8-0499 – 2016/0381(COD))'. Available at: http://www.europarl.europa.eu/RegData/commissions/itre/inag/2018/01-31/ITRE_AG%282018%29616909_EN.pdf.

European Commission (2017) *Commission welcomes agreement on energy performance of buildings - European Commission*. Available at: https://ec.europa.eu/energy/en/news/commission-welcomes-agreement-energy-performance-buildings (Accessed: 10 January 2018).

European Commission (2018) *Buildings - European Commission*. Available at: https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings (Accessed: 10 January 2018).

Fang, L., Clausen, G. and Fanger, A. P. O. (1998) 'Impact of Temperature and Humidity on the Perception of Indoor Air Quality', *Indoor Air*, 8, pp. 80–90. doi: 10.1111/j.1600-0668.1998.t01-2-00003.x.

FINVAC ry (2017) 'Opas ilmanvaihdon mitoitukseen muissa kuin asuinrakennuksissa (A guide for dimensioning ventilation in non-residential buildings) [in Finnish]', p. 24.

Foda, E. (2012) 'Evaluating Local and Overall Thermal Comfort in Buildings Using Thermal Manikins'. Helsinki: School of Engineering, p. 187.

Fourdeg (2018) *Use Your Energy Better - Heat Smart*. Available at: https://fourdeg.com/ (Accessed: 28 February 2018).

De Giuli, V., Da Pos, O. and De Carli, M. (2012) 'Indoor environmental quality and pupil perception in Italian primary schools', *Building and Environment*. Pergamon, 56, pp. 335–345. doi: 10.1016/J.BUILDENV.2012.03.024.

Gruber, M., Trüschel, A. and Dalenbäck, J.-O. (2014) 'CO2 sensors for occupancy estimations: Potential in building automation applications', *Energy and Buildings*. Elsevier, 84, pp. 548–556. doi: 10.1016/J.ENBUILD.2014.09.002.

Hengitysliitto (2017) *Hiilidioksidi | Hengitysliitto (Carbon dioxide |The Alliance for breathing) [in Finnish]*. Available at: https://www.hengitysliitto.fi/fi/sisailma/sisailma-asiat-sisailmaongelmat/kaasumaiset-epapuhtaudet/hiilidioksidi (Accessed: 8 December 2017).

Al Horr, Y., Arif, M., Kaushik, A., Mazroei, A., Katafygiotou, M. and Elsarrag, E. (2016) 'Occupant productivity and office indoor environment quality: A review of the literature', *Building and Environment*. Pergamon, 105, pp. 369–389. doi: 10.1016/J.BUILDENV.2016.06.001.

Integral (2017) 'Liite 1. Integral IoT-palvelukuvaus (Appendix 1. The IoT-service description of Integral) [in Finnish]', p. 7. Available at: https://www.integral.fi/palvelut/iot-palvelut/.

Ito, S. and Nishi, H. (2012) 'Estimation of the number of people under controlled ventilation using a CO2 concentration sensor', *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, pp. 4834–4839. doi: 10.1109/IECON.2012.6388997.

Jiang, C., Masood, M. K., Soh, Y. C. and Li, H. (2016) 'Indoor occupancy estimation from carbon dioxide concentration'. Available at: http://arxiv.org/abs/1607.05962 (Accessed: 21 November 2017).

Kärkkäinen, S., Sipilä, K., Pirvola, L., Esterinen, J., Eriksson, E., Soikkeli, S., Nuutinen, M., Aarnio, H., Schmitt, F. and Eisgruber, C. (2003) *Demand side management of the district heating systems*. Espoo: VTT Research notes 2247. Available at: http://www.vtt.fi/inf/pdf/tiedotteet/2004/T2247.pdf (Accessed: 6 March 2018).

Kiviste, M. and Vinha, J. (2017) ‘Air pressure difference measurements in Finnish municipal service buildings’, *Energy Procedia*. Elsevier, 132, pp. 879–884. doi: 10.1016/J.EGYPRO.2017.09.690.

Kosonen, R., Kajaala, M. and Takki, T. (2008) ‘Perceived IEQ conditions: Why the actual percentage of dissatisfied persons is higher than standards indicate?’, *Indoor Air 2008, 17-22 August 2008, Copenhagen, Denmark, Paper ID: 861*. Available at: https://www.isiaq.org/docs/papers/861.pdf (Accessed: 17 April 2018).

Leaman, A. and Bordass, B. (2001) ‘Assessing building performance in use 4: the Probe occupant surveys and their implications’, *Building Research & Information*, 29(2), pp. 129–143.

Li, D., Menassa, C. C. and Kamat, V. R. (2017) ‘Personalized human comfort in indoor building environments under diverse conditioning modes’, *Building and Environment*. Pergamon, 126, pp. 304–317. doi: 10.1016/J.BUILDENV.2017.10.004.

Li, S. and Da Xu, L. (2018) *Securing the Internet of Things*. First. Syngress. doi: B978-0-12-804458-2.00010-X.

Liang, Y., Meng, Q. and Chang, S. (2017) ‘Fault diagnosis and energy consumption analysis for variable air volume air conditioning system: a case study’, *Procedia Engineering*. Elsevier, 205, pp. 834–841. doi: 10.1016/J.PROENG.2017.10.021.

Litiu, A., Brook, B., Corgnati, S., D’Oca, S., Fabi, V., Keel, M., Kranz, H., Kurnitski, J., Schönenberger, P. and Ullmann, R. (2017) *Introduction to Building Automation, Controls and Techincal Building Management (REHVA Guidebooks; No. 22)*. REHVA. Available at: http://www.rehva.eu/publications-and-resources/eshop/eshop-detail.html?tt_products%5Bcat%5D=3&tt_products%5BbackPID%5D=1560&tt_products%5Bproduct%5D=60&cHash=b560c1a63f41a133ef962dfc44f4efd0.

Liu, R., Wen, J. and Waring, M. S. (2014) ‘Improving airflow measurement accuracy in VAV terminal units using flow conditioners’, *Building and Environment*. Pergamon, 71, pp. 81–94. doi: 10.1016/J.BUILDENV.2013.09.015.

Microsoft (2017) *Kinect for Xbox One | Xbox*. Available at: https://www.xbox.com/en-US/xbox-one/accessories/kinect (Accessed: 22 November 2017).

Min, B. and Varadharajan, V. (2015) ‘Design and Evaluation of Feature Distributed Malware Attacks against the Internet of Things (IoT)’, in *2015 20th International Conference on Engineering of Complex Computer Systems (ICECCS)*. IEEE, pp. 80–89. doi: 10.1109/ICECCS.2015.19.

Modbus (2012) *Application Protocol Specification V1.1b3*. Available at: http://www.modbus.org (Accessed: 8 January 2018).

Müller, D., Kandzia, C., Kosonen, R., Melikov, A. K. and Nielsen, P. V. (2013) *Mixing Ventilation - Guidebook on mixing air distribution design (REHVA Guidebooks; No. 19)*. Belgium: REHVA. Available at: http://www.rehva.eu/publications-and-resources/eshop/eshop-detail.html?tt_products%5Bcat%5D=3&tt_products%5BbackPID%5D=1560&tt_products%5Bproduct%5D=49&cHash=16f886811b4c2afeb9d55a22f50ab1e2.

Nacer, A., Marhic, B. and Delahoche, L. (2017) ‘Smart Home, Smart HEMS, Smart heating: An overview of the latest products and trends’, in *2017 6th International Conference on Systems and Control (ICSC)*. IEEE, pp. 90–95. doi: 10.1109/ICoSC.2017.7958713.

Nordpool (2017) *The power market*. Available at: https://www.nordpoolgroup.com/the-power-market/ (Accessed: 28 February 2018).

Official Statistics of Finland (2018) ‘Energy supply and consumption’. Helsinki. Available at: http://www.tilastokeskus.fi/til/ehk/index_en.html (Accessed: 28 March 2018).

Okochi, G. S. and Yao, Y. (2016) ‘A review of recent developments and technological advancements of variable-air-volume (VAV) air-conditioning systems’, *Renewable and Sustainable Energy Reviews*. Pergamon, 59, pp. 784–817. doi: 10.1016/J.RSER.2015.12.328.

Persily, A. and de Jonge, L. (2017) ‘Carbon dioxide generation rates for building occupants’, *Indoor Air*, 27(5), pp. 868–879. doi: 10.1111/ina.12383.

Petersen, S., Heidmann Pedersen, T., Nielsen, K. U. and Knudsen, M. D. (2016) ‘Establishing an image-based ground truth for validation of sensor data-based room occupancy detection’, *Energy and Buildings*. Elsevier, 130, pp. 787–793. doi: 10.1016/J.ENBUILD.2016.09.009.

Produal (2018a) *HDH*. Available at: http://www.produal.com/shop/web_concentration_transmitters/sku-1135040 (Accessed: 14 May 2018).

Produal (2018b) *TEHR NTC 10-P*. Available at: http://www.produal.com/shop/web_ntc_10_sensors/sku-1175230 (Accessed: 14 May 2018).

Rotondo, J., Johnson, R., Gonzalez, N., Waranowski, A., Badger, C., Lange, N., Goldman, E. and Foster, R. (2016) ‘Overview of Existing and Future Residential Use Cases for Connected Thermostats’, p. 41. Available at: https://energy.gov/sites/prod/files/2016/12/f34/Overview of Existing Future Residential Use Cases for CT_2016-12-16.pdf (Accessed: 1 March 2018).

Salama, M. (2014) ‘Älykäs lämmönsäädin (Smart heat controller) [in Finnish] Master’s thesis. Aalto University. Department of Electrical Engineering and Automatioin.’ Espoo, p. 63.

Salo, E. (2017) ‘Talotekniikan avoimet tiedonsiirtorajapinnat (The open data communication interfaces for building technology) [in Finnish] Master’s thesis. Aalto University. Department of Electrical Engineering and Automation’. Espoo, p. 67.

Sandberg, E., Heinonen, J., Holmberg, R., Hyvärinen, K., Hänninen, R., Jokinen, L. and Kauppila, K. (2014) *Sisäilmasto ja ilmastointijärjestelmät - Ilmastointitekniikka osa 1 (Indoor climate and air conditioning systems - Air conditoning technologies part 1) [In Finnish]*. Talotekniikka-Julkaisut Oy.

Sarvaranta, A., Jääskeläinen, J., Puolakka, J. and Kouri, P. (2012) ‘Kaukolämmön hinnoittelun nykytila ja tulevaisuuden mahdollisuudet - Loppuraportti (Current pricing of district heating and the future possibilities - Report)’. Espoo: ÅF-Consult, p. 47. Available at: http://docplayer.fi/1155236-Kaukolammon-hinnoittelun-nykytila-ja-tulevaisuuden-mahdollisuudet.html.

Satish, U., Mendell, M. J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S. and Fisk, W. (Bill) J. (2012) ‘Is CO2 an Indoor Pollutant? Direct Effects of Low-to-Moderate CO2 Concentrations on Human Decision-Making Performance’, *Environmental Health Perspectives*. doi: 10.1289/ehp.1104789.

Sensirion (2017) ‘Preliminary Datasheet SDP8xx-Analog’. Available at: https://www.sensirion.com/fileadmin/user_upload/customers/sensirion/Dokumente/8_Differential_Pressure/Sensirion_Differential_Pressure_Sensors_SDP8xx_Analog_Datasheet_0v4.pdf (Accessed: 29 November 2017).

Sensorcell (2016) ‘Multi-function measuring instrument’. Available at: https://www.sensorcell.fi/WebRoot/vilkasfi02/Shops/2016080104/57CD/C0B7/8AF8/A63C/06E2/0A28/1010/C88F/testo-435-esite.pdf (Accessed: 21 December 2017).

Seppanen, O. and Fisk, W. (2006) ‘Some Quantitative Relations between Indoor Environmental Quality and Work Performance or Health’, *HVAC&R Research*, 12(4), pp. 957–973. doi: 10.1080/10789669.2006.10391446.

Seppänen, O., Hausen, A., Hyvärinen, K., Heikkilä, P., Kaappola, E. and Kosonen, R. (2004) *Ilmastoinnin suunnittelu (Designing Ventilation) [in Finnish]*. Suomen LVI-liitto.

SETRA (2016) *What is the difference between BACnet, Modbus and LonWorks?* Available at: https://www.setra.com/blog/what-is-the-difference-between-bacnet-modbus-and-lonworks (Accessed: 8 January 2018).

SFS-EN 14908-1 (2014) ‘Open Data Communication in Building Automation, Controls and Building Management. Control Network Protocol. Part 1: Protocol Stack. Second edition’. Helsinki: Suomen Standardisoimisliitto, p. 416.

SFS-EN 15232 (2017) ‘Energy Performance of Buildings. Energy performance of buildings. Part 1: Impact of Building Automation, Controls and Building Management. Modules M10-4,5,6,7,8,9,10’. Helsinki: Suomen Standardisoimisliitto, p. 109.

SFS-EN 15251 (2007) ‘Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics’. Helsinki: Suomen Standardisoimisliitto, p. 83.

SFS-EN ISO 16484-2 (2005) ‘Building automation and control systems (BACS). Part 2: Hardware’. Helsinki: Suomen Standardisoimisliitto, p. 66.

SFS-EN ISO 16484-5 (2017) ‘Building automation and control systems (BACS) - Part 5 Data communication protocol. Sixth edition’. International Organization for Standardization, p. 1340.

SFS-EN ISO 7726 (2001) ‘Ergonomics of the thermal environment. Instruments for measuring physical quantities’. Helsinki: Suomen Standardisoimisliitto, p. 59.

SFS-EN ISO 7730 (2006) ‘Ergonomics of the thermal environment. Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Third edition’. Helsinki: Suomen Standardisoimisliitto, p. 64.

Sicari, S., Rizzardi, A., Grieco, L. A. and Coen-Porisini, A. (2015) ‘Security, privacy and trust in Internet of Things: The road ahead’, *Computer Networks*. Elsevier, 76, pp. 146–164. doi: 10.1016/J.COMNET.2014.11.008.

Sisäilmayhdistys ry (2017) ‘Sisäilmastoluokitus 2017. Sisäympäristön tavoitearvot, suunnitteluohjeet ja tuotevaatimukset (The Classification of Indoor Environment 2017. The parameters, design instructions and product demands for indoor environment) [in Finnish]’, p. 51.

Swegon (2018) *Swegon - GOLD RX version F*. Available at: https://www.swegon.com/en/Products/Air-Handling-Units/ONE-PIECE-AIR-HANDLING-UNIT-GOLD/GOLD-RX-version-F/ (Accessed: 4 April 2018).

Swema AB (no date) *Manual for Swema 3000*. Available at: http://www.swema.com/Prod_docs/Swema 3000 manual 5.31_eng.pdf (Accessed: 21 December 2017).

Syri, S., Makela, H., Rinne, S. and Wirgentius, N. (2015) 'Open district heating for Espoo city with marginal cost based pricing', in *2015 12th International Conference on the European Energy Market (EEM)*. IEEE, pp. 1–5. doi: 10.1109/EEM.2015.7216654.

Tachikawa, T., Oda, A., Handa, T., Ichimura, J., Watanabe, Y. and Nishi, H. (2008) 'Cooperative Distributed Demand Control by Environmental Sensor Network - Estimating the Number of People by CO2 Concentration -', *The IEEE International Conference on Industrial Informatics (INDIN 2008)*, pp. 336–341. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=4618119 (Accessed: 21 November 2017).

Verbeke, S., Ma, Y., Bogaert, S., Bettgenhäuser, K., Waide, P. and Uslar, M. (2017) *Support for setting up a Smart Readiness Indicator for buildings and related impact assessment - Interim report*. Available at: https://smartreadinessindicator.eu/sites/smartreadinessindicator.eu/files/sri_for_buildings_interim_report_20171212.pdf (Accessed: 27 November 2017).

World Green Building Council (2014) 'Health, Wellbeing and Productivity in Offices'.

Yang, J., Santamouris, M. and Lee, S. E. (2016) 'Review of occupancy sensing systems and occupancy modeling methodologies for the application in institutional buildings', *Energy and Buildings*. Elsevier, 121, pp. 344–349. doi: 10.1016/J.ENBUILD.2015.12.019.

Yang, Z. and Becerik-Gerber, B. (2016) 'How Does Building Occupancy Influence Energy Efficiency of HVAC Systems?', *Energy Procedia*. Elsevier, 88, pp. 775–780. doi: 10.1016/J.EGYPRO.2016.06.111.

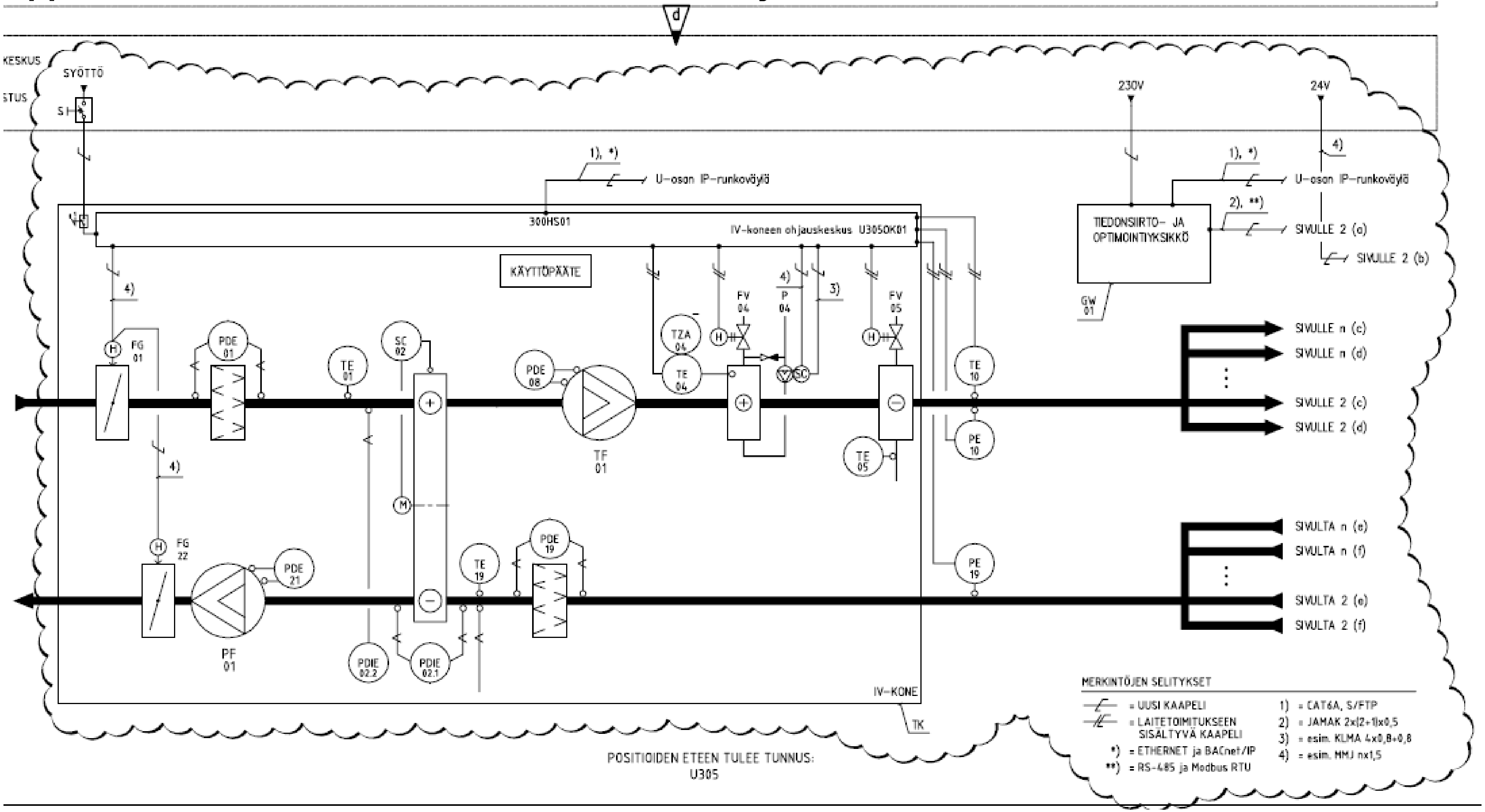
Yao, Y., Lian, Z., Liu, W., Hou, Z. and Wu, M. (2007) 'Evaluation program for the energy-saving of variable-air-volume systems', *Energy and Buildings*. Elsevier, 39(5), pp. 558–568. doi: 10.1016/J.ENBUILD.2006.09.010.

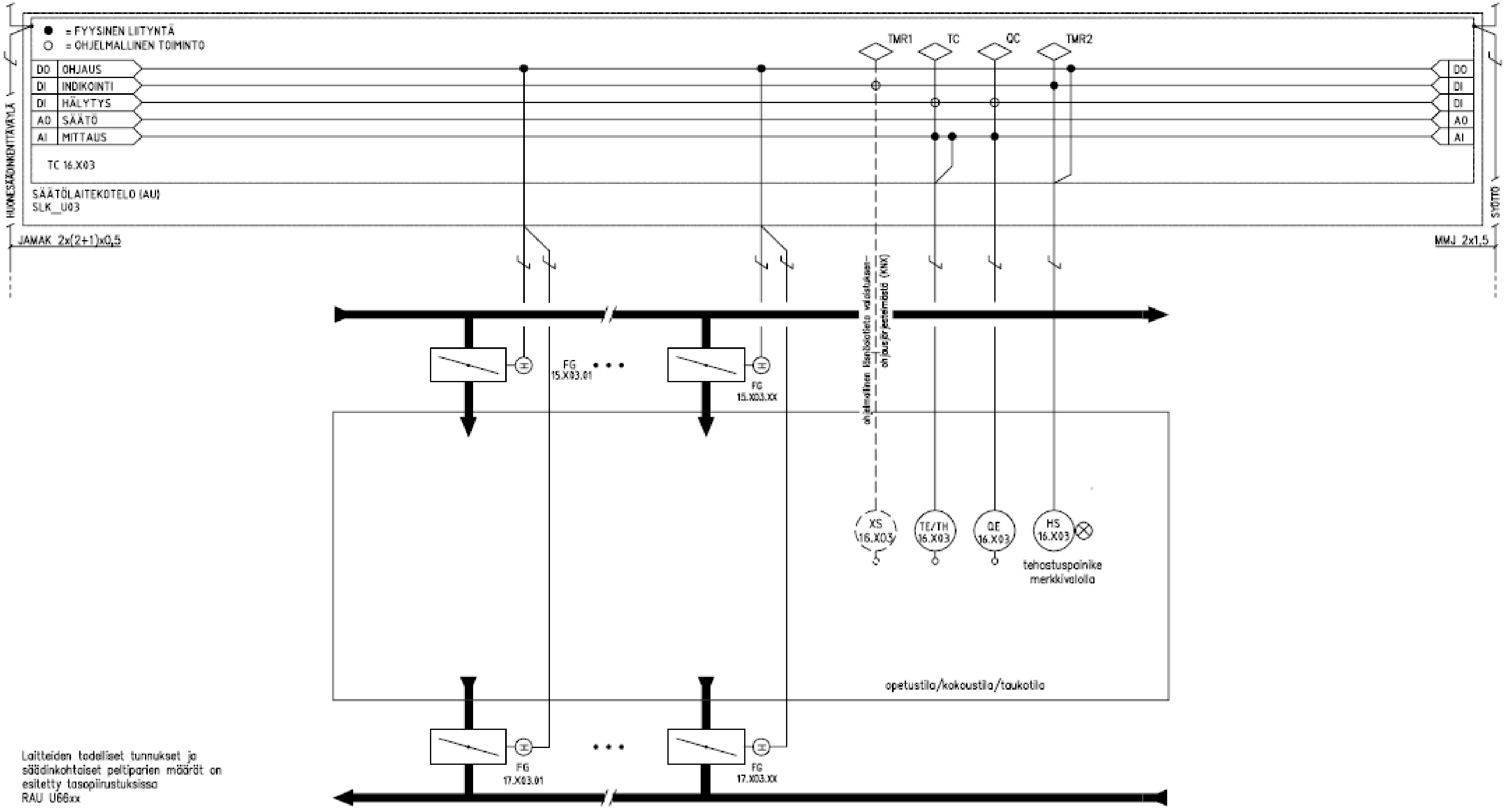
Zagreus, L., Huizenga, C., Arens, E. and Lehrer, D. (2004) 'Listening to the occupants: a Web-based indoor environmental quality survey', *Indoor Air*. Blackwell Publishing, 14(s8), pp. 65–74. doi: 10.1111/j.1600-0668.2004.00301.x.

Zhang, X., Yan, J., Feng, S., Lei, Z., Yi, D. and Li, S. Z. (2012) 'Water Filling: Unsupervised People Counting via Vertical Kinect Sensor', in *2012 IEEE Ninth International Conference on Advanced Video and Signal-Based Surveillance*. IEEE, pp. 215–220. doi: 10.1109/AVSS.2012.82.

Zou, H., Jiang, H., Yang, J., Xie, L. and Spanos, C. (2017) 'Non-intrusive occupancy sensing in commercial buildings', *Energy and Buildings*. Elsevier, 154, pp. 633–643. doi: 10.1016/J.ENBUILD.2017.08.045.

Appendix I Control scheme of the HVAC system in the rooms





Laitteiden todelliset tunnukset ja
säädinkohtaiset peltiparien määrät on
esitetty tasopiirustuksissa
RAU U66xx

MERKINTÖJEN SELITYKSET
= UUSI KAAPELI
= LAITETOIM. SISÄLTYVÄ KAAPELI

POSITIOIDEN ETEEN TULEE TUNNUS:
U 3XX

Periaatekaavio 3

KENTTÄLAITEKAAPELOINTI (MAKS. 24V):
- NOMAK nx2x0,5+0,5

Appendix II

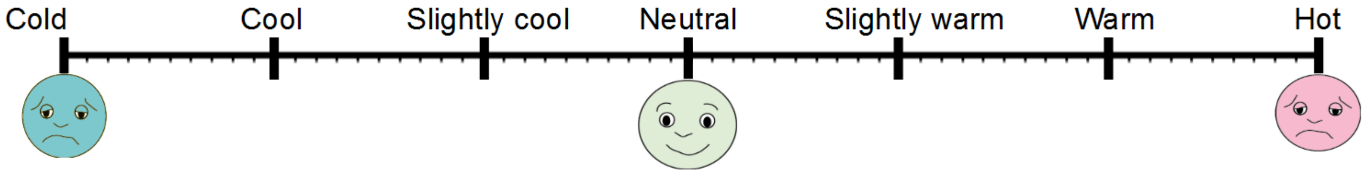
Date:___/_____/2018

Aalto University
School of Engineering

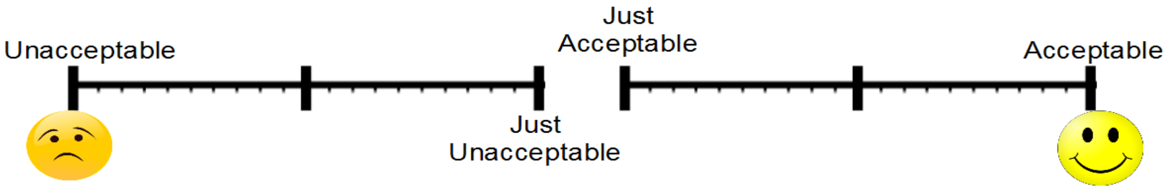
This a short survey regarding the temperature and ventilation in this room and how it affects your comfort. The survey is part of Aalto University research. We would be grateful for your cooperation if you could take 2-3 minutes to answer these questions. Please answer this survey at the end of your reservation period by ticking on the scales. If you have any questions, please contact jukka.kopra@aalto.fi

Current Time: __________________
How long have you been in this room:___________ mins
Room No.:______________
Gender: Ⓜ Ⓕ

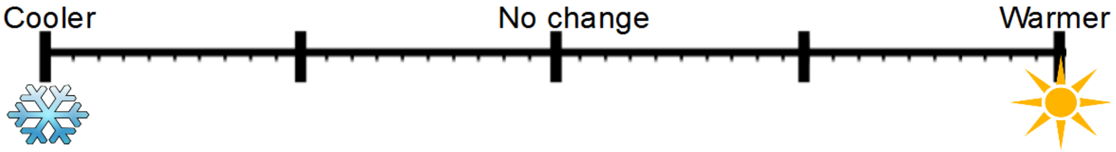
(1) ***How would you rate the current temperature in this room?***



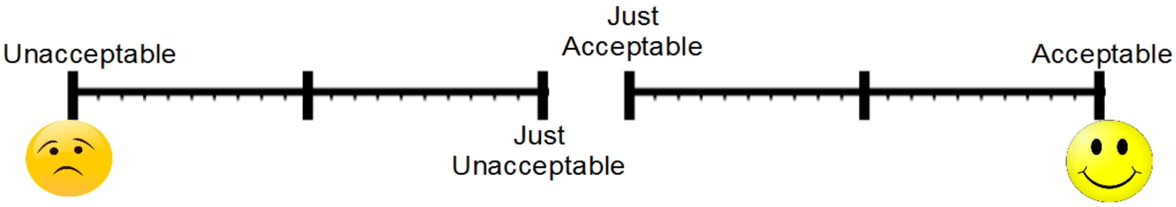
(2) ***Is the current room temperature acceptable to you?***



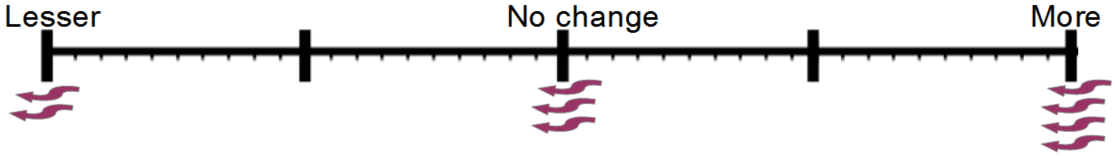
(3) ***Would you prefer the room temperature to be:***



(4) ***Is the current room air quality acceptable to you?***



(5) ***Would you prefer the room ventilation to be:***



(6) ***Do you notice any other sources of discomfort in the room thermal condition?***

None ○ Bad smell/stuffy air ○ Cold draft ○ Noisy ○ Glare from window ○

Other comments:

Päivämäärä:___/_____/2018

Aalto University
School of Engineering

Tämä on lyhyt kysely koskien tämän huoneen lämpötilaa sekä ilmanvaihtoa ja niiden vaikutusta tyytyväisyyteesi. Tutkimuksesta vastaa Aalto yliopisto. Olisimme kiitollisia, jos voisitte käyttää 2-3 minuuttia kyselyn vastaamiseen. Olkaa hyvä ja vastatkaa kyselyyn varauksenne loppupuolella raksittamalla mielipiteenne viivoille. Jos tutkimuksesta herää kysymyksiä, olkaa hyvä ja ottakaa yhteyttä jukka.kopra@aalto.fi

Kellonaika: __________________
Huone nro.:______________
Oleskeluaika huoneessa:___________ min
Sukupuoli: Ⓜ Ⓕ

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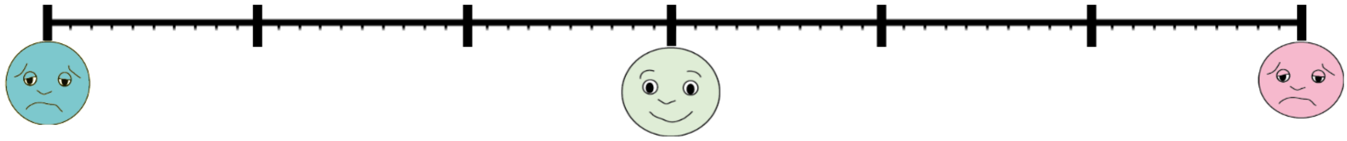
(1) ***Miten arvioisitte huoneen lämpötilan?***

Kylmä Viileä Hieman viileä Neutraali Hieman lämmin Lämmin Kuuma



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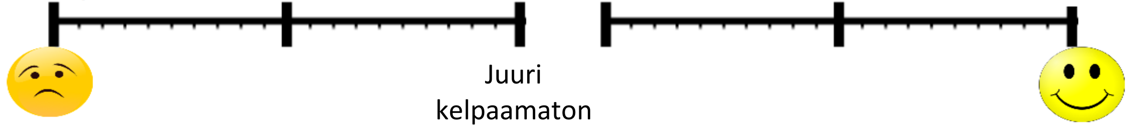
(2) ***Onko nykyinen lämpötila teille hyväksyttävä?***

Kelpaamaton Juuri hyväksyttävää Hyväksyttävää

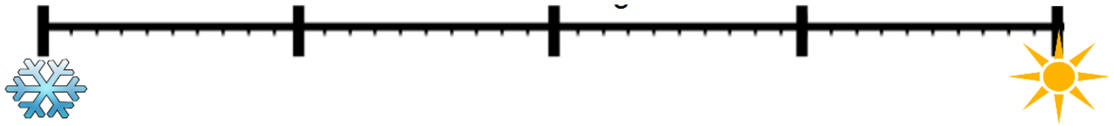


Juuri kelpaamaton

---

(3) ***Haluaisitteko lämpötilan olevan mieluummin jotain muuta?:***

Viileämpää Ei muutosta Lämpimämpää



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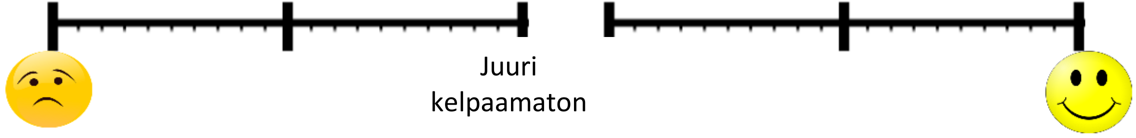
(4) ***Onko huoneen nykyinen ilmanlaatu teille hyväksyttävä?***

Kelpaamaton Juuri hyväksyttävää Hyväksyttävää



Juuri kelpaamaton

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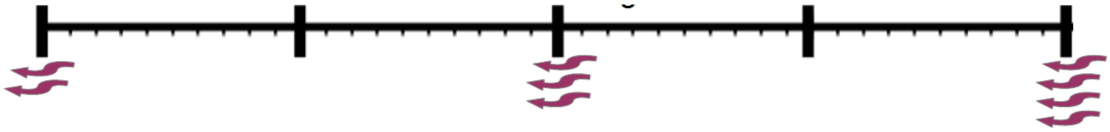
(5) ***Haluaisitteko huoneen ilmanvaihdon olevan jotain muuta?:***

Vähemmän Ei muutosta Enemmän



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(6) ***Huomaatteko jotain muuta joka olisi teille epämieluisa?***

Ei mitään ○ Tunkkainen ilma ○ Vedon tunne ○ Äänekästä ○ Häikäisevä valo ○

Muita kommentteja: