LUT
Lappeenranta
University of Technology

LUT School of Energy Systems
Degree Program in Electrical Engineering

Sampsa Eloranta

DEVELOPMENT OF ADVANCED INDOOR CLIMATE MONITORING AND CONTROLLING CONCEPT IN COMMERCIAL OFFICE BUILDINGS BASED ON STAKEHOLDER'S NEEDS AND REQUIREMENTS

Master of Science Thesis

Examiners:	Professor, D.Sc. (Tech)	Jero	Ahola
	Professor, D.Sc. (Tech)	Risto	Soukka
Supervisions:	D.Sc. (Tech)	Panu	Mustakallio
	Laboratory engineer, Lic.Sc. (Tech)	Simo	Hammo

ABSTRACT

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96 pages, 31 figures, 22 tables and 13 appendices

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As we are fighting against the climate change, the values of energy efficiency and environment have raised. The purpose of this thesis was to create a ventilation concept for Halton Oy, based on the needs of different stakeholders of office buildings, while taking into consideration the current energy policy and new possibilities of technology development. In addition, the thesis strived to provide a viable proposal for the technical implementation for the concept.

Conceptualization in this thesis was conducted based on theoretical research on global energy policy drivers such as legislation and standards, general technical improvements in areas that could be utilized in building management systems and inside air controlling techniques. Office building stakeholders' needs for the concept were clarified by empirical study with surveys for each stakeholder. The outcome of one stakeholder group was completed with interviews due to the inadequate number of respondents. In addition, the state of art in ventilation system innovations were examined by benchmarking other companies' product concepts.

The concept itself was the result for the thesis. It shows 13 features in total for three different stakeholders. Secondary result was transient power measuring function for chilled beam, coded into room controller that could be used in real-time monitoring. According to measurements and simulation results, the function had 0.3-2.0% error. Despite air perspiration is always subjective, the thesis presents also ideas on how to indicate inside air quality and additionally involve office occupants to the ventilation controlling loop in order to achieve controlling set point in consensus between people inside one room.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
Teknillinen tiedekunta
Sähkötekniikka

Sampsa Eloranta

Toimistorakennusten sisäympäristön monitorointi- ja ohjauskonseptin kehittäminen sidosryhmien tarpeiden mukaan

Diplomityö

2019

96 sivua, 31 kuvaa, 22 taulukkoa ja 13 liitettä

Tarkastajat:	Professor, D.Sc. (Tech)	Jero	Ahola
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Hakusanat: Sisäilma, ilmanvaihto, rakennusten hallintajärjestelmä, reaaliaikainen monitorointi, konseptointi

Ilmastonmuutoksen seurauksena energiatehokkuuden ja ympäristöarvojen merkitykset ovat kasvaneet. Tämän diplomityön tarkoituksena oli luoda Halton Oy:lle ilmanvaihtokonsepti toimistotalojen eri sidosryhmien tarpeiden mukaan, huomioiden nykyinen energiapolitiikka sekä nykyteknologian innovaatiot. Lisäksi työ tarjoaa ehdotuksen konseptin käytännön toteutukselle.

Konseptointi perustui globaalin energiapolitiikan ohjaamaan lainsäädäntöön ja standardeihin, sekä olemassa oleviin teknisiin ratkaisuihin, joita voitaisiin hyödyntää rakennusten hallintajärjestelmissä ja sisäilman säädössä. Toimistorakennusten sidosryhmien tarpeita selvitettiin empiirisellä kyselytutkimuksella. Yhden sidosryhmän tuloksia täydennettiin haastatteluilla, vastaajien pienestä määrästä johtuen. Lisäksi nykypäivän ilmanvaihtojärjestelmiä tarkasteltiin vertailuanalyysin avulla.

Diplomityön päätuloksena saatiin ilmanvaihtokonsepti edellä mainitun tutkimuksen pohjalta. Se sisältää yhteensä 13 ominaisuutta työlle rajatulle kolmelle eri sidosryhmälle. Toissijainen tulos oli jäähdytyspalkin hetkellistä tehoa mittaava funktio huoneohjaimessa, mitä voitaisiin käyttää reaaliaikaisessa seurannassa. Funktion virheeksi saatiin 0,3-2,0 prosenttia mittaus- ja simulointituloksia vertaamalla. Huolimatta siitä, että ilmanlaadun aistiminen on aina subjektiivista, diplomityössä esitellään myös ideoita ilmaisemaan ilmanlaatua, sekä kuinka sisällyttää toimistotilassa olijat ilmanvaihdon säätöpiiriin säätöjärjestelmän asetusarvon saavuttamiseksi konsensuksessa kaikkien kesken.

PREFACE

This thesis was made as a part of Tekes programme "*Witty City*" and Halton's project "*Business models for integrated Indoor-Energy-Use in China*" where the main focus was on developing innovative solutions concerning the indoor environment quality, energy efficiency and end-user engagement for the real estate markets, especially in China. Project had also societal aim that is opening up business opportunities for the Finnish clean-tech companies in the world's largest market place.

Supervisors for the thesis from Halton were Offering Management Director Panu Mustakallio and Sales Support and Project Management Director Janne Summanen. I received also valuable instructions and professional comments from the whole research & development team in Kausala, especially from Heimo Ulmanen, Tapani Salo, Kai Patjas, Timo Toivanen and Ville Kauppi. I would also like to thank all the Halton employees whom I was working with while I was writing this thesis.

Examiners from Lappeenranta University of Technology were Professors Risto Soukka and Jero Ahola, and Laboratory Manager Simo Hammo. I would like to thank them for their high quality teaching, as well as their mind opening remarks and advices during my studies and writing this thesis.

I am also giving a thankful shout-out to my fellow students on my trail of university education, not to mention my family, friends and every other person who has supported me.

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APPENDICES

SYMBOLS AND ABBREVIATIONS

A	Water flow rate-model coefficient	
a	Beam dependent parameter for flow rate-model	
B	Water flow rate-model coefficient	
b	Beam dependent parameter for flow rate-model	
C	Water flow rate-model coefficient	
c	Beam dependent parameter for flow rate-model	
d	Beam dependent parameter for flow rate-model	
e	Euler's constant	
q	Ventilation rate	$[(l/s) * olf]$
$q_{m,w}$	Water mass flow rate	$[kg/s]$
t_a	Local air temperature	[℃]
T_u	Local air turbulence intensity	[%]
v	Local mean air velocity	$[m/s]$

AC	Air Conditioning
ADC	Analog to Digital Converter
AHU	Air Handling Unit
BLE	Bluetooth Low Energy
BMS	Building Management System
CAV	Constant Air Volume
CO2	Carbon Dioxide
DAC	Digital to Analog Converter
DC	Direct Current
DCV	Demand Controlled Ventilation
DR	Draught Rating
EPA	United States Environmental Protection Agency
ETERA	Office in Helsinki equipped with various sensors connected to internet
GPS	Global Positioning System
GUI	Graphical User Interface
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IDA	Indoor Air category according to EN 13779

IoT	Internet of Things
IR	Infrared
LCC	Life Cycle Cost
MAC	Media Access Control
MC8	Room controller in VARIO concept
MV1	Master Device for MC8 controllers for specific zone in VARIO concept
PD	Percent of Dissatisfied
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
RFID	Radio Frequency Identification
RHC	Radiant Heating and Cooling
ROI	Return On Investment
RTU	Remote Terminal Unit
TCP	Transmission Control Protocol
UI	User Interface
VARIO	Halton air conditioning concept
VAV	Variable Air Ventilation
VDC	Volts of Direct Current
WHO	World Health Organization
ZC	Control Controller (damper) in air channels

1. INTRODUCTION

As we are fighting against the climate change, what is unquestionably one of the biggest challenges faced by this generation, trying to prevent catastrophic disruption of life in our planet, the values of energy efficiency and environment have raised and are going to rise even more along the international agreements, concerning the climate change and global warming (Lins C., Williamson L., Leither S. & Teske S., 2014). The action in consequence, has influence on specifications and standards over building engineering, together with widely reduced and regulated emissions by the governments in all over the world. For example in year 2009, Finnish committee of energy efficiency published long-term suggestions to reduce energy consumption in end-usage sector by 37TWh, from year 2008 to year 2020 (Energiatehokkuustoimikunta, 2009, p. 3). The same publication set goals to reduce at least one third, yet from year 2020 to year 2050, and Finnish government accepted it in 2010 (Motiva, 2010, p. 1).

Major of this reduction potential has reputed to be in the industry sector but the European commission has published also a strategy more closely for heating and cooling what concerns the whole building stock in Europe. It states that the energy consumer control will increase with better technology for energy use controlling, metering and billing. (European commission, 2016) This obviously denotes that current Building Management Systems (BMS) and Building Automation Controls (BAC) need improvements. BMS and BAC concerning the building's Heating, Ventilation and Air-Conditioning (HVAC) systems in general, means systems that observes the inside environment conditions and AC system's status in building. That status information and knowledge is then used to keep circumstances in a desired level as steadily as possible. This is possible due to different active components in the systems, but those and the controlled variables are covered more precisely in chapters 2 and 3.

Today's most recent, advanced and energy efficient solution in HVAC systems has been the Demand Controlled Ventilation (DCV), where the ventilation, heating and cooling is provided to meet the indoor climate requirements based on various condition variable measurements from a space in a building. That is more efficient method compared to the fixed weekly schedule, what has been used conventionally earlier. Still, understanding the details of energy usage at the level of individual components, the automation, control and supervision systems are supposed to have energy consumption reducing potential in buildings by 10, 20 or even 50%. (REHVA, 2017, pp. 9,45-50) To illustrate the saving possibilities in bigger scale, the final energy usage breakdown of Europe is depicted on the left side in Figure 1.1. Right side stands for energy consumption breakdown of non-residential buildings in Europe.

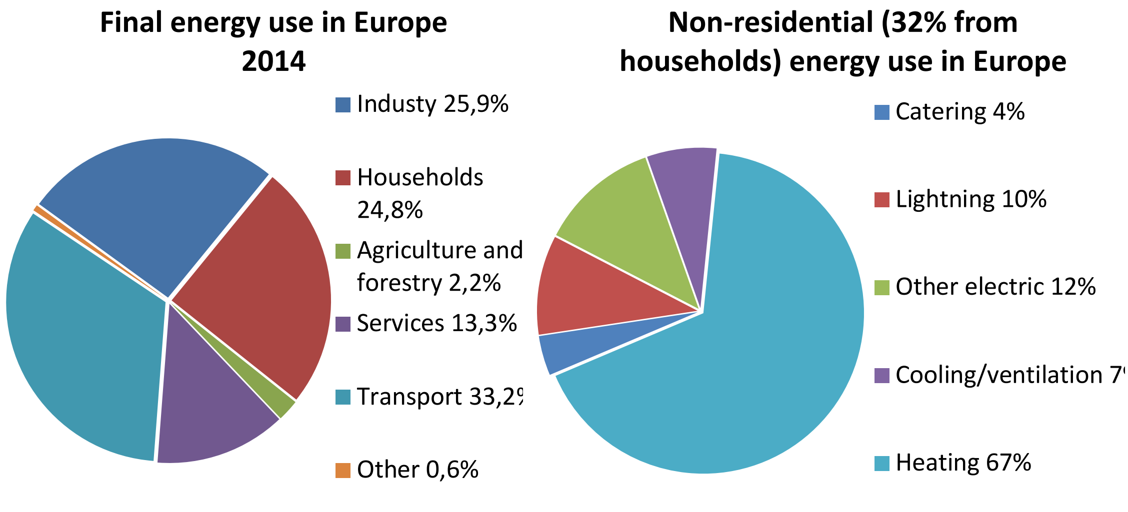


Figure 1.1 Final energy use breakdown in Europe, 2014 (European Commission, 2014)

The breakdown shows that households uses 24.8% of Europe's total energy in end usage and 32% from those households are non-residential, where the biggest, 50% saving potential is seen. This means that the best outcome in non-residential buildings will reduce the energy usage of Europe's total energy consumption by 2.9%. (European Commission, 2014) Some references believe that the same number for all European buildings could be 6% (Gaval, Valentin et al., p. 1).

At the same time, the concept of Internet of Things (IoT) is evolving and development of technical standards, networks, sensors and mobile devices have enabled the IoT on a global scale. That growing area of applications allows physical objects being able to generate all kinds of information and utilize the internet to communicate data about their condition, position, status or other attributes. In practice, this provides a relatively low cost information distribution channel, combined with PC's, mobile phones and tablets, giving an access to any information, almost on any device from anywhere. (Stackowiak R., Licht A., Mantha V. & Nagode L., 2015, pp. 20-22)

In general, among the others, those matters mentioned above, have lead us to apply the IoT enabled monitoring and control technology to the automated management of building's Heating, Ventilation and Air-Conditioning (HVAC) systems, for the sake of more efficient ventilation solutions and lower energy consumption. One application what pursues to achieve the aspiration is predictive and preventive maintenance. Being aware that HVAC system maintenance is executed periodically although the numerous system failures happens randomly, it is clear that if the retrieved data from building could be utilized to detect and inform about any failure occurrences, it could have a remarkable relevance on energy consumption in the operation phase of the ventilation system (IBM & Watson IoT, pp. 2-3). (Myrefelt, 2004, p. 3)

Other objective for IoT has been a better individual comfort indoors by integrating the occupants as a part of the control system. The Federation of the European Heating, Ventilation and Air Conditioning Associations (REHVA) has already identified some focal questions and points to consider, in order achieving the balance in energy usage and building user comfort. Solution could be found in innovative technology what combines user's behavior and HVAC system controlling. Arisen questions concerning the optimal solution of indoor climate controlling are such as:

- "How to integrate the occupants to the control system?"
- "How actively involve the occupant in the control loop as a sensor or controller?"
- "How to find the consensus in a group of people?"
- "Is it possible to provide an individual service according to the expectations of each person? Is there equipment able to meet this need of individual control?"

It is also worth noting that adding the aspect of individual occupant's comfort in advanced automation control, system does not guarantee the lowest energy use in buildings, thus the presented challenge is both, technical and human. (REHVA, 2017, pp. 78-79)

As some people might spend over 80% of their time indoors, the quality of indoor air may have an impact on human health. For that reason, there is also a growing interest to have straightforward and efficient ways for the characterization of the indoor air. (European Commission Joint Research Centre - Environment Institute, 1997, p. 3) However, the research has not established any global indicator or index for indoor indicating.

1.1 Objectives of the thesis

This thesis studies the possibilities of extending the traditional BMS and BAC systems in commercial office buildings, so that stakeholders could utilize it as much as possible. The focus is on office users with aspect of comfort so the study is connected to the questions presented in the introduction. Other stakeholders for the commercial office in this thesis are office space tenants and the building owners. It is also assumed that every stakeholder has certain requirements for the system and one of the objectives is to define a concept design that specifies those requirements as features for above mentioned stakeholders. Second objective along to global aspiration to meter energy consumers more closely, is to research the possibility of monitoring individual room device's power consumption. According to Halton's product catalogue, chilled beam was chosen as exact objective for the power monitoring. Third objective is to clarify the key points of preventive maintenance in practice. The concept in general, should outcome with a list of development objects and implementation proposal that are able to achieve approximately with 2 years of a development.

Integrating stakeholder's requirements to the concept, they are considered as features available for stakeholders. Clarifying the desired features for the concept and researching the power consumption possibilities, the research questions for this thesis are following:

1. What features do the defined stakeholders need for the concept?
2. How the arisen features can be implemented to the current BMS or additional system?
3. How to implement the transient power consumption calculation of chilled beam?
4. Is it possible to detect a fault in HVAC system by monitoring system? What characteristics in fault detection are important?

Research methods in this thesis are determined along the research questions. The most suitable methods for clearing out the stakeholder needs are benchmark and empirical survey. Benchmark's outcome gives the outline for survey and the questions are prepared based on it. Final concept is outcome of the benchmark and survey result analysis. At last, this thesis gives an implementation proposal for the concept features within the present applicable technologies.

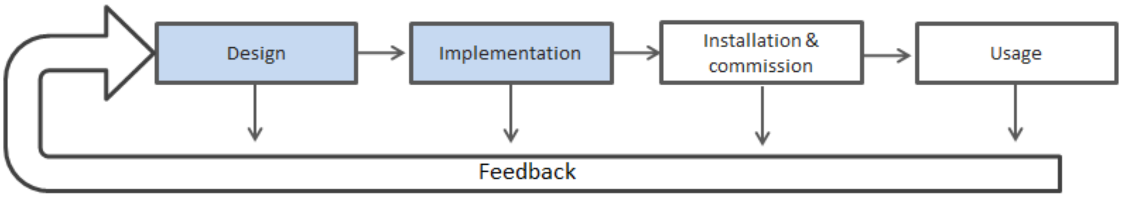


Figure 1.2 Objective phases of the whole conceptualization in this thesis.

This thesis aims to achieve the monitoring system concept design and part of the produce phase within the objectives set for this thesis. Because of the rapid development in technology and the numerous executions for the solution, from which not all can be presented, the implementation proposal is just one possible solution.

1.2 Outline of the thesis

This thesis proceeds chronologically according to Figure 1.3

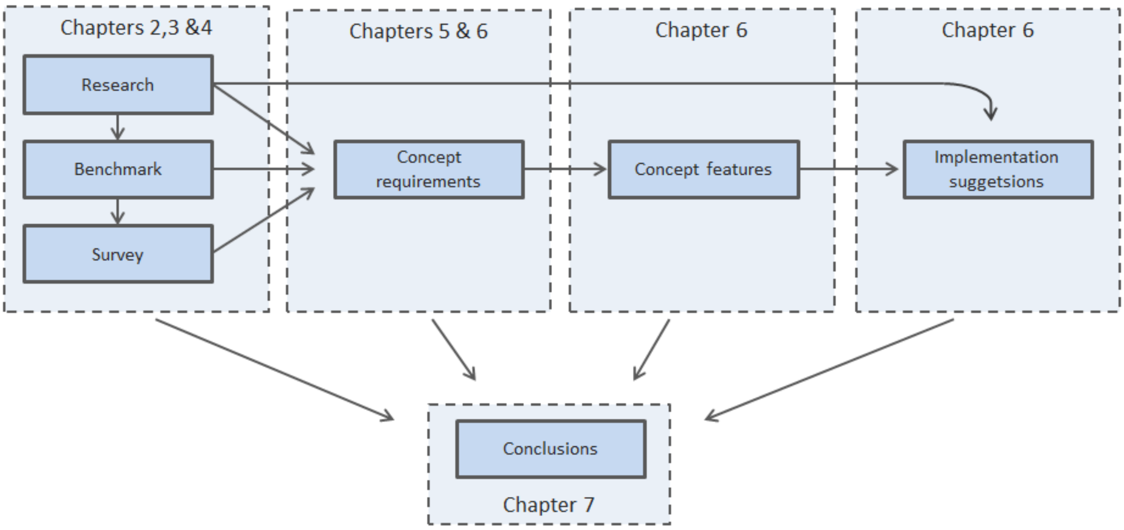


Figure 1.3 Outline of the thesis.

The objectives of this thesis are approached by research on the effective subject areas. Then a benchmark is done on similar systems on markets, followed by survey for the core stakeholders. Concept requirements are gathered from research, benchmark and survey, and are integrated to concept features. Finally, this thesis presents implementation suggestions for the determined features upon the research and available technologies. More detailed outline of this thesis chapter by chapter is following:

Chapter 2 introduces the reasons and principles for ventilation, with three basic ventilation methods that have used over the ages. Secondly, it gives some elements for evaluating the air quality and possible insanitary effects due to air pollution. Rest of the chapter concerns HVAC systems, presenting the operation based classification and commonly used components in such systems.

Chapter 3 is dedicated for theory of Building Management System (BMS), control engineering used in the building management and data-driven fault diagnosis. It offers extensive overview to BMS functions in the level of data transfer protocols and signal processing, explaining general restrictions and imprecisions in digital sensors, processors and other devices used in the BMS. The most common controller type is presented and applied to the room temperature control with chilled beam. This chapter presents also potential technologies for people counting and introduces principles and models in data-driven fault diagnosis.

Chapter 4 presents the current drivers for the concept development. Drivers are focused on core stakeholders, which are determined precisely regarding on commercial office buildings. Chapter lists also other possible stakeholders for the system and gives a view on existing general drivers, representing basis on legislation, standardization, certifications and classification over buildings, and the hierarchy of such documents.

Chapter 5 is actual development part of the concept designing phase. First, it presents the current system based on Halton demo-office located in Pasila, Finland. This gives limitations for the concept measurands and presents the Halton VARIO concept that is used in the demo office. Then, it prepares for collecting the requirements and needs from the core stakeholders by presenting the detailed use of benchmark and survey methods.
Chapter 6 presents the results from benchmark and targeted surveys for core stakeholders. After that, the new concept is combined from the results and presented as features available for the stakeholders. This chapter gives also implementation suggestions for system technical architecture, mobile application functionality, indoor air quality indicator, transient water power monitoring for chilled beam in practice and fault diagnosis methods.

Chapter 7 gives analysis for the results of this thesis. It evaluates the success of the method usage for concept determination. It also assesses the functionality of proposed concept execution given in the chapter 6.

Chapter 8 summarizes the thesis by presenting the key results of this thesis. It also gives suggestions for future work concerning the concept implementation, air quality indicator and chilled beam water power monitoring testing.

2. INDOOR AIR AND VENTILATION

When people and animals breathe inside a building, it effects on indoor air by removing the oxygen and producing the Carbon Dioxide (CO2) and humidity. There is also organic matter soled or other originates pollutants that can migrate to, or be formed inside a building over the time, thus the conditions can get uncomfortable. Along that, the poor indoor climate can be insanitary for individual occupants, causing for example irritation, headache, tiredness or other unwanted effects. Those are the major reason to intentionally remove the used and polluted inside air to outdoors and replace it with clean air, what is also known as ventilation. Along with preventing all the possible health risks, correctly enforced ventilation contributes the productivity of building occupants, by keeping the indoor climate in desired level (REHVA, 2006, pp. 19-23). (Sandberg, Esa et al. (1), 2014, pp. 11-12) This includes indoor thermal environment, the air quality and the acoustic environment. It is also instructed to do it in the most energy efficient way so that the energy consumption is the lowest possible. This can be illustrated with Figure 2.1. (CEN, 1998, p. 4).

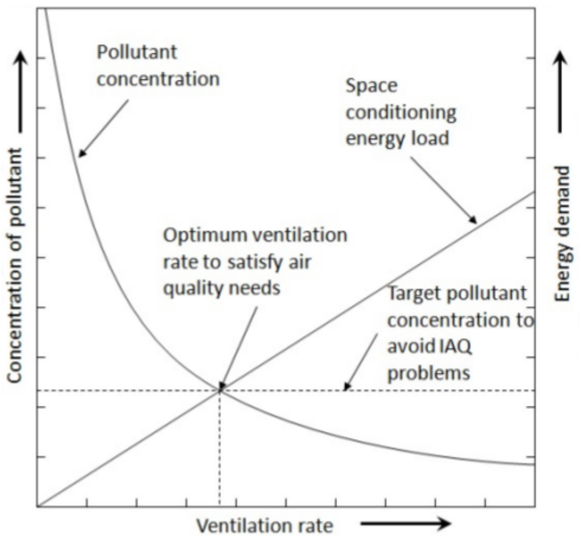


Figure 2.1 Concentration of pollutant and energy consumption as a function of ventilation rate. (International Energy Agency, 1996, p. 5)

By knowing the characteristics of each contaminant emissions, it is possible to define needed ventilation to prevent the pollutant exceeding from a pre-defined threshold. This determination should correspond to the dominant pollutant emissions. The Figure 2.1 shows the relationship between concentration of pollutant and energy consumption as a function of ventilation rate. The optimal ventilation rate is in a crossing point of energy demand and satisfied air quality according to pollutant concentration. Increasing the ventilation rate from that point lowers the pollution concentration but on the other hand, it increases the energy demand. (International Energy Agency, 1996, p. 5)

Ventilation can be carried out with natural, mechanical or mixed ventilation and the chosen option defines the outcome of its technical implementation. The natural ventilation was used majorly before 70s, since there was no other solution and even when the mechanical technology was invented, it was too expensive to utilize in most buildings at first. This method utilizes the natural forces like wind, temperature and pressure driven flows in supplying and exhausting the air. In this passive solution, the exhaust occurs because of gravity that depends on density difference between in- and outside air together with altitude difference in air channel. Air is lead outside through the exhaust ducting and supply air is lead inside through the building surface, for example from window gaps or other untight structures where it is easiest way to flow in. Benefit of natural ventilation compared to mechanical is almost non-existent energy consumption in ventilation. However, the poor controllability, operation variability according to the weather and technical evolving outdated the pure natural ventilation method so it is rarely used today. It was replaced in the mid-70s, when building engineers were focusing in development of the mechanical ventilation systems. (Sandberg, Esa et al. (1), 2014, pp. 113-115,120-121)

The mechanical ventilation utilizes pumps or fans to assist the ventilation to get higher and more constant flow rates. In order to get the pumped air spread to the every room in a building, system needs ducting to deliver it. Because pumps and fans need power for operating, it also requires electricity applied and hence consumes energy according to the provided flow rate and energy efficiency of the system. In full mechanical system both, supply and extract air is forced with mechanical devices what enables the DCV (Sandberg, Esa et al. (1), 2014, pp. 115-116,123-124) Although, the mechanical system has assessed to have several benefits compared to natural system, adding the mechanical devices and parts to the ventilation system increases the risk of system problems and interruptions (Dragan A., 2000, p. 642)

The mixed or hybrid ventilation means combination of the natural and mechanical systems. Its golden age was in the 70’s after pure natural ventilation, when extract air operation was equipped with roof exhaust fan and before the full mechanical systems had become a common solution. (Sandberg, Esa et al. (1), 2014, pp. 115-117) Regardless of the increasing energy efficiency values and the competitiveness of mixed ventilation is getting weaker along with stricter tightness demands in buildings, applying the natural ventilation as mixed ventilation is still popular in some countries. In addition, the past researches on combining these two methods have pointed out that it is possible to achieve acceptable indoor climate same time with the smaller energy consumption compared to the fully mechanical system. Still, the mixed ventilation has some disadvantages such as the requirement of two different systems designing instead of one. (Sandberg, Esa et al. (1), 2014, p. 128)

2.1 Air quality

As the objective of the ventilation and air conditioning is to maintain the air quality at acceptable or at least healthy level, it is important to be aware of the total composition and possible risks related to it.

Air in general, is composed of several constituents. Major components are Nitrogen (78.1%), Oxygen (20.9%), Argon (0.9%) and Carbon Dioxide (0.04%). However, it can also include numerous of small particles and matters, and some of them have evidenced to have harmful effects on environment and human health. Some of those substances are safe for human health but irritate and decrease the individual comfort, whereas some of them irritates only very sensitive group of people (EPA, 2016). In addition, other variables such as relative humidity and temperature of the air are taken into account classifying the buildings rate according to its inside environment (CEN, 1998). Thus, defining the air quality is depending on various characteristics, which can differ even individually, what makes the air quality slightly subjective notion.

2.1.1 Pollutants

Air pollution is one major effective factor on people's health. Along some references, it is also world's deadliest environmental problem that kills approximately 7 million people a year. (Copenhagen Consensus Center, 2015) Pollutants are described as any present substance that adversely alters environment by its concentration, damaging the growth rate of species or restraining with the food chains, is toxic or affects the health, comfort or property. There is a list for several individual pollutants in ambient and indoor air quality guidelines by WHO, but those are sometimes grouped according to the health significance, origin or other attribute. Hence, they can be handled as mixture of solid and liquid particles, both organic and inorganic contaminants in the air. For example, the most affecting group of pollution is Particulate Matter (PM) where the major components are sulfate, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water. (WHO, 2016)

The guidelines for health affecting pollutants by WHO include 35 pollutants, selected based on special environmental and health significance of the European Region. Selected pollutants are listed in the Appendices I. WHO has published guidelines also for indoor pollutants. In both publications, suggestion values are expressed with mean concentration and averaging exposure time. Pollutant concentration in the air is expressed as grams per liter like in the Appendices II but other commonly used unit is Particles Per Million (PPM). (WHO, 2000) (WHO, 2014) Because there are normally several compounds in the air, the concentration can be reported also as Total Volatile Organic Compounds (TVOC) in practice (Sandberg, Esa et al. (1), 2014).

Pollution concentrations in ambient air have local differences. It is changing continuously according to its sources such as energy generation, transportation, industry, population locus, as well as the prevailing weather conditions. Today, it is possible to monitor the global present and past ambient air quality effectively, from measurement stations around the world, through internet service providers. World Environmental Protection Agencies (EPA) has web page (www.aqicn.org) where it is even possible to preview the short-term forecast for the specific pollutants. Analysis of the past data has identified an increasing trend in long-term evolution of air pollution (Pei H. & Shiliang W., 2016, p. 2).

2.1.2 Health effects and air quality classification

Breathing is essential function for human beings and it is vital to have continuous supply of air, approximately 10-20 cubical meters per day. If the air we breathe contains pollutions, it affects our health insanitary according to the concentration of each pollutant component and its health effects. (WHO, 2000, p. 1)

As already mentioned PM is one and the most effecting pollution. PM is divided in two groups due to the particulate diameter (PM10 and PM2.5) and smaller particles are generally more dangerous for humans. Exposures to PM in relatively high concentration or long time have noticed to increase cancer incidence, especially cancer of the lung and urinary bladder. It is also causing cardiovascular and respiratory diseases. Figure 2.2 shows the affecting area of the PM in function of its diameter.

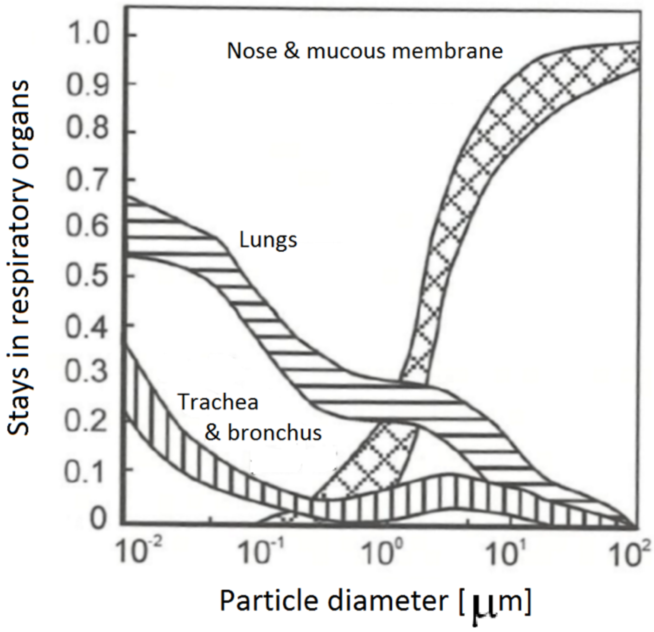


Figure 2.2 Area of influence in function of PM diameter.
(Sandberg, Esa et al. (1), 2014, p. 60)

As we can see, the smaller the diameter is the further particles penetrate to human respiratory organs. This shows that smaller particles are more dangerous. (Sandberg, Esa et al. (1), 2014, pp. 59-60) Other pollutants causing diseases provably are ozone, nitrogen dioxide and sulfur dioxide (WHO, 2016). The health effects of those pollutants are in the Table 2.1.

Table 2.1 Health effects of ozone, nitrogen dioxide and sulfur dioxide. (WHO, 2016)

Pollutant	**Health effect and diseases**
Ozone	Breathing problems, asthma, lung function reducing, lung diseases
Nitrogen dioxide	Symptoms of bronchitis, reduced lung function
Sulfur dioxide	Respiratory system and lung function reducing, eye irritation, couching, mucus secretion, aggravation of asthma and chronic bronchitis

More health risks of each pollutant are evaluated in the Air Quality Guidelines for Europe publication by WHO.

Regardless that air quality is at least partly subjective notion, U.S. Environmental Protection Agency (EPA) uses air quality index for outdoors. It is based on the health effect of each pollutant. Outdoor Air Quality Index (AQI) is a number between 0 and 500, so that higher value represents greater concentration of pollution in the air. Index tells how clean or unhealthy the current air is according to specific pollutant with seven levels. (EPA, 2016) The level description and breakpoint boundaries for each pollutant, affective to EPA AQI, due to the concentration are shown in the Table 2.2

Table 2.2 The EPA IAQI level descriptions and boundaries. (U.S EPA, 2016, p. 12)

These Breakpoints...							...equal this AQI	...and this category
O_3 (ppm) 8-hour	O_3 (ppm) 1-hour	$PM_{2.5}$ (µg/m^3) 24-hour	PM_{10} (µg/m^3) 24-hour	CO (ppm) 8-hour	SO_2 (ppb) 1-hour	NO_2 (ppb) 1-hour	AQI	
0.000 - 0.054	-	0.0 – 12.0	0 - 54	0.0 - 4.4	0 - 35	0 - 53	0 - 50	Good
0.055 - 0.070	-	12.1 – 35.4	55 - 154	4.5 - 9.4	36 - 75	54 - 100	51 - 100	Moderate
0.071 - 0.085	0.125 - 0.164	35.5 – 55.4	155 - 254	9.5 - 12.4	76 - 185	101 - 360	101 - 150	Unhealthy for Sensitive Groups
0.086 - 0.105	0.165 - 0.204	(55.5 - 150.4)	255 - 354	12.5 - 15.4	(186 - 304)	361 - 649	151 - 200	Unhealthy
0.106 - 0.200	0.205 - 0.404	(150.5 - (250.4)	355 - 424	15.5 - 30.4	(305 - 604)[4]	650 - 1249	201 - 300	Very unhealthy
([2])	0.405 - 0.504	(250.5 - (350.4)	425 - 504	30.5 - 40.4	(605 - 804)	1250 - 1649	301 - 400	Hazardous
([2])	0.505 - 0.604	(350.5 - 500.4)	505 - 604	40.5 - 50.4	(805 - 1004)	1650 - 2049	401 - 500	Hazardous

The outdoor AQI for single pollutant with concentration n, can be calculated with equation

$$AQI(n) = \left(\frac{I_{hi}-I_{lo}}{BP_{hi}-BP_{lo}}\right)(C - BP_{lo}) + I_{lo}, \qquad (1)$$

where C is pollutant concentration, BP_{lo} concentration breakpoint for lower level, BP_{hi} concentration breakpoint for upper level, I_{lo} the index breakpoint corresponding to BP_{lo} and I_{hi} the index breakpoint corresponding to BP_{hi}. The equation (1) converts the pollutant concentrations to linearly transient index variable that has various slopes according to the seven index levels. (U.S EPA, 2016, p. 11)

Regarding of indoor air quality, there is no globally established indicator or index. However, some repositories can be used as assistance when designing to achieve specific level of indoor climate such as WHO guidelines presented above and Indoor Air (IDA) classification according to standard EN 13779. EN 13779 has four IDA categories that can be classified either by rate of outdoor air per person, air flow rate per floor area, CO2 level in room or concentration levels of specific pollutants. IDA categories in EN 13779 are presented in the Table 2.3. (CEN, EN 13779, 2007, p. 28)

Table 2.3 IDA classification. (CEN, EN 13779, 2007, p. 86)

Category	Description	Outdoor air rate/ person [*(l/s)/person*]	Air flowrate/ floor area [$(l/s)/m^2$]	CO2 level [*ppm*]
IDA 1	High quality	> 15	-	400
IDA 2	Medium quality	10 - 15	> 0,7	400 - 600
IDA 3	Moderate quality	6 - 10	0,35 – 0,7	600 - 1000
IDA 4	Low quality	< 6	< 0,35	1000 -

Air flowrate per floor area method in Table 2.3 is not sufficient to classify the IDA 1 category.

2.2 Heating, ventilation and air-conditioning systems

Like already mentioned the ventilation system has to take care of every indoor climate characteristic. Hence, the system must be able to process the supplied air what makes it more complex. Rudimentary processing task of the system is to control the supplied air temperature to provide the inside air temperature within the limits of thermal comfort zone or set point values overt the time. Normal case is to heat the supply air in winters and cool it summers as the inside air strives to variate according to outside temperature due to insulation of the building envelope. (Ahmad M., Riffat S. & Ismail M., 2016, p. 4) This all is of course depending on the building's geographical location but the basic idea is presented in the Figure 2.3

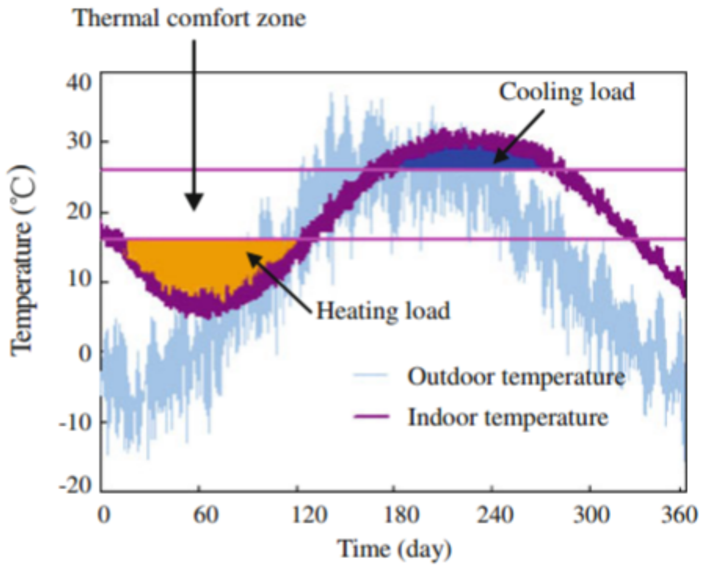


Figure 2.3 Basic ideology on heating and cooling. (Ahmad M., Riffat S. & Ismail M., 2016, p. 4)

When adding thermal and air quality controlling to the basic ventilation system, it is called an Air Conditioning (AC) or Heating, Ventilation and Air Conditioning (HVAC) system.

2.2.1 HVAC system classification

There are several HVAC systems differing from each other, based on its technical implementation and heat transfer method used in cooling or heating. Therefore, HVAC systems can be divided into Constant Air Ventilation (CAV) and Variable Air Ventilation (VAV), and depending on used room device operation, those can be specified more precisely to all-air, air-water, all-water and distributed systems. The principles of all systems operation and dimensioning philosophy are presented briefly below and the classification according to room devices is made in Table 2.4

All-air systems

All-air systems in general utilize same air channels for ventilation, cooling and heating the controlled space so the material in heat transfer is air. The supply and extract airflow rate are dimensioned due to the loads of the pollution, thermal and humidity conditions so that the production and income are in balance with the outcome of all these three variables. Cooling demand in summertime is normally the determining characteristic in dimensioning. In order to change all the room air over the time, the air must be distributed to everywhere in the space volume. This means taking also the internal airflows into account and sometimes dynamic dimensioning is needed. All-air system is always either a CAV or VAV, and depending on building location and seasonal outside temperatures, room can be provided with radiators. (Sandberg, Esa et al. (1), 2014, pp. 130-136)

Air-water system

Air-water systems are very similar to the all-air systems but along with supply air temperature from AHU and radiators, thermal conditions can be adjusted with heat exchanger in room device. Heat exchanger has water piping for cool or/and warm water so that the room supply air temperature is controlled with inlet water valves. This enables the temperature control in room level. Dimensioning of airflow is determined due to ventilation need and room devices are designed majorly according to cooling demand in summer time. In these systems, the supply air is dried to prevent the condensing in room devices but usually the applied space has relatively small humidity loads. The heating load is usually relatively big for example due to IT instruments in offices or people in meeting rooms. Thus, the air-water system's room devices like fan coils, perimeter induction units, radiant panels and chilled beams must be able to cool the space with comparatively high power. (Sandberg, Esa et al. (1), 2014, pp. 130,137-148)

All-water systems

In all-water systems, the heat transfer is done only with water and ventilation is taken care with separate system where the supply air is not thermally managed. Therefore, the condensing is usually allowed in the room devices and there must be water pools in the devices. Room temperature is kept in level with controlling the devices inlet water temperature. These systems uses either fan coils, normally in renovation buildings, or fan radiators in spaces where the cooling requirement is relatively high, like in IT-rooms, engine rooms and electricity distribution rooms. (Sandberg, Esa et al. (1), 2014, pp. 130,148) In all-water systems, water as a heat transfer medium has much higher thermal capacity than air and in that case, it has slightly lower pumping energy consumption compared to other systems (R. & K, p. 167).

Distributed systems

Distributed systems are used because there are some spaces that do not want to be connected to the main AHU, or the space has retrofitted or designed heat pumps that are based on user demands. The idea of distribution is that one system covers and controls only one specific space. Common objects for these systems are renovation buildings, separate office rooms, schools and spaces, where are temporary heat loads so that it needs additional heating. These systems have enforced with different room level cooling devices and heat pumps. (Sandberg, Esa et al. (1), 2014, pp. 149-151)

CAV

CAV means that system is operating with only one airflow rate constantly. Usually the system is dimensioned due to summertime maximum cooling requirements. Temperature control is executed with changing the supply air and radiant panel's supply water temperature. More flexibility for the system is achieved when choosing the room devices with maximal operating range. (Sandberg, Esa et al. (1), 2014, pp. 131-132)

VAV

VAV means that system operates with different flow rates in specific situations. In practice, system feeds equivalent temperature of supply air to all room devices so that it is always below the room temperature. In wintertime, system utilizes outside cold temperature if possible and in summer, the air is processed with air cooler device. The system enables more accurate climate controlling in room or zone level but it has technical requirements because it is operating according to room demand. Demand is sensed with different sensor and devices that are covered in the chapter 3. (Sandberg, Esa et al. (1), 2014, pp. 133-136)

The systems presented above are classified in Table 2.4 and every room device in the table is explained in the next chapter.

Table 2.4 Classification of HVAC systems. (Sandberg, Esa et al. (1), 2014, p. 129)

All-air	**Air-water**	**All-water**	**Distributed**
CAV VAV: -zone or room level controlling	Fan coils Perimeter induction Chilled beams Radiant panels	Fan coils Fan radiators	Room level cooling devices Heat pumps

2.2.2 HVAC system components

To get more comprehensive understanding on the HVAC system, the main components are illustrated and explained with the Figure 2.4. The figure stands for a building and the components have been positioned in the place where they normally are in the practice. However, solutions can vary depending on designer's decisions. Arrows in Figure 2.4 shows the airflow direction. It is worth noting that air can move through the walls so there is no necessary need for providing a ducting and air supply room device in every room. (Sandberg, Esa et al. (1), 2014, p. 22)

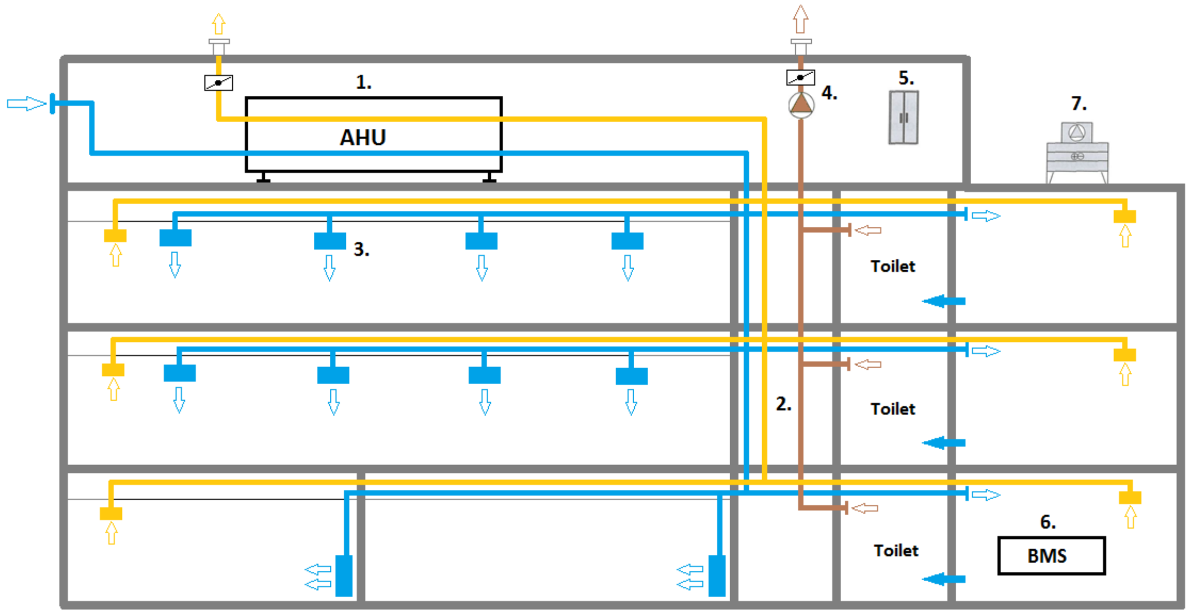


Figure 2.4 Common parts of ventilation or air-condition system situated in the building: 1. Air handling unit, 2. Channeling network, 3. Room devices, 4. Separate fans, 5. Electric system, 6. Building automation system, 7. Cooling system, 8. Heating system (does not show in the figure). (Sandberg, Esa et al. (1), 2014, p. 22)

Ducts and duct devices

Conveying the air between AHU and room devices occurs in sheet metal ducts or air channels. Material of the ducting in residential buildings is usually zinc coated or stainless steel because they need to be fireproof in case of a fire. Vertical channelings are usually located in fireproof chases and isolated so that the air does not get too warm before blowing to the rooms. Channels are usually circle or rectangle shaped, but because of demanding requirements in tightness and clearness, the use of circle shaped channels has become preferable lately. In circle channels, the suggested diameter is from 63 to1000mm, as measures for rectangular shaped are from 200 to 2000mm in width and from 100 to 1200 mm in height. Required thickness of the channel depends on the size of the ducting but defined minimum in standards is 0,5mm. Assuring the perceived air quality in the whole building and making the ventilation process more effective by preventing the leaks and pressure losses, ducting needs to be clean and duct connections tight. Those features are tested and verified in the end of the construction phase and the requirements are set in building classifications. For example in Finland, it is building classification D2. There are also other considerations for ducting like its attachment, cleansable, fire-safety, insulation, acoustics and airflow stability. (Sandberg, Esa et al. (1), 2014, pp. 213-216)

Providing the system with extensive controllability for airflow and meeting the demands in several standards, there are different devices assembled into the ducting:

Shutoff and control valves control the airflow in ducting. Shutoff valve have two positions: open and closed, what is normally determined according to AHU's operating status; Position is open when AHU is working and otherwise it is closed. There is also control valves, which have more positions than shutoff valves. Actuator in control valve could be stepless so it has infinite number of positions in theory. Both shutoff and control valves can be either an insulated or uninsulated, and they have integrated unit what measures its position. Control valves are usually connected to the airflow or/and pressure meter so that the control loop of the whole system gets the needed feedback. Ducting can be equipped also with separate measurement units. (Sandberg, Esa et al. (1), 2014, pp. 216-220)

Fire shutoff valves closes in case of fire to prevent the spread of smoke and fire. It goes off due to thermal fuse and spring, which activates when the temperature is over a specific limit for a certain time. Other option is to use motorized actuator that is controlled according to temperature and smoke detector. (Sandberg, Esa et al. (1), 2014, p. 217)

Ducting needs to be easily cleaned after installation so it is required to install cleaning hatches to different places, which are defined in standard EN 12097. The air ducting characteristics and devices determines the place and size of the hatches. There can be also silencers in the ducting and the principles are the same as in AHU, which are covered later. (Sandberg, Esa et al. (1), 2014, p. 221)

In the controlling of the AHU and duct valves, it is critical to understand the pressure performance in the ducting to get the feedback from the right position. The total pressure in ducting is constant according to Bernoulli's law. It means that the static pressure and dynamic pressure, subtracted by occurred pressure losses is always at same level. The air is distributed normally from the main channel with T-junctions where the dynamic pressure is transformed to static pressure. In order to supply the air to the farthest room device from AHU, it needs dynamic pressure in that point of the ducting. Hence, the feedback is needed from the point where the dynamic pressure is at the lowest and the optimal energy consumption is achieved when the valve controlling that junction is fully open. (Sandberg, Esa et al. (2), 2014, pp. 98-99)

The pressure performance in ducting is depicted in the Figure 2.5

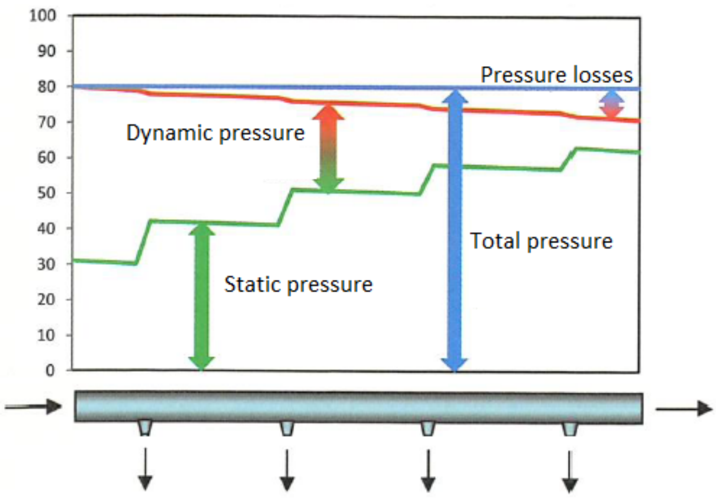


Figure 2.5 Pressure performance in the ducting. (Sandberg, Esa et al. (2), 2014, p. 99)

The basics for the control engineering concerning the duct valves controlling are covered in the chapter 3.

Room devices

Room devices are positioned in the room according to the design calculations. Purpose of room devices is applying the air to the room as even and smooth as possible and keeping the room temperature almost the same in every point of the space. There can be also different ventilation grates and valves for extract air. Common room devices are covered extensively in the chapter 2.1.2.1. (Sandberg, Esa et al. (1), 2014, p. 24)

Additional exhaust fan

Some of the spaces in the building cannot be connected to the AHU for hygienic reasons. Meeting room, kitchen and toilet exhaust air can usually be reason so they need own exhaust ducting and separate fan to remove the air. (Sandberg, Esa et al. (1), 2014, pp. 24,195)

Electricity distribution board

Air-conditioning needs electricity system in order to work. Distribution board is usually located in the machine room and there can be several boards due to big scale of system. Distribution board includes control switches, contactors, thermal relays and control logics that are connected to the air-conditioning machines and building automation system with wirings. (Sandberg, Esa et al. (1), 2014, pp. 287,310-311)

Cooling and heating system

Temperature control is done with circulating either cool or warm water through water piping and heat exchangers of the system. The source of cooling in buildings is conventionally executed with water-cooling units, where cooling process is provided with hermetic piston compressors, half-hermetic piston or screw compressors and turbo compressors. The cooling power range according to different water-cooling unit can vary from five to 5000kW. Warm water is produced with district heating and cool water get from chiller. In addition, the district cooling or individual cooling and heating wells have become more common these days. The AHU's heat exchanger and room devices are connected with separate circuits. (Sandberg, Esa et al. (1), 2014, p. 250)

Air Handling Unit

One essential and probably the biggest component is Air Handling Unit (AHU) that is usually located in separate machine room above the controlled spaces. It is the safest position in most cases and the extract and intake air are easier to put in practice. There is only one machine room in the Figure 2.4, but if the building is bigger, additional machine room and AHU might be required. More detailed picture of AHU to clarify its function, is shown in the Figure 2.6

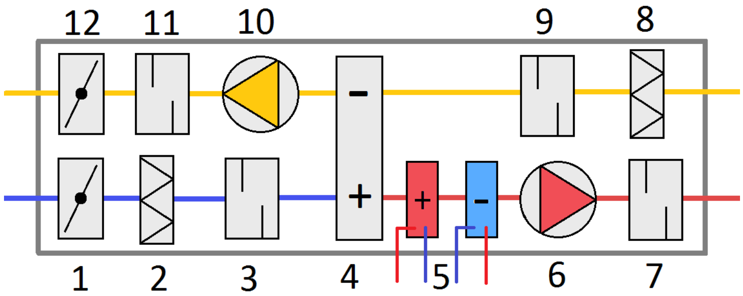


Figure 2.6 The air-handling unit: 1. Gate valve. 2. Filter. 3. Silencer. 4. Heat recovery unit. 5. Heat exchangers. 6. Intake fan. 7. Silencer. 8. Filter. 9. Silencer. 10. Extract fan. 11. Silencer. 12. Gate valve.

There are plenty of divergent operational AHU designs but the principle is the very same. Biggest differences between separate AHUs are in heat recovery unit and heat exchanger. In general, the whole unit operates to blow the supply air inside a building by producing the pressure and flow rate into the ducting. Provided supply air needs to fulfill the required characteristics so the AHU must have possibility to process the inlet air. Second task is to soak up the polluted air outside from indoor spaces. AHU in commercial office buildings is normally a cabinet-type box which outer casing and partly the separating walls are thermally insulated. (Sandberg, Esa et al. (1), 2014, p. 157) The components inside the casing are presented in order of airflow circulating direction and the numbers are seen in the Figure 2.6:

When supply air is led from outside to the AHU, there is gate valves (1 &12) that opens when the handling unit is activated. The valves must be tight and insulated so that there is minimum heat loss when AHU is not operating. The location of the gate valves is determined so that exhausts air does not get into the inlet gate valve. Extract air is also led out so that it does not get near windows which can be opened. (Sandberg, Esa et al. (1), 2014, p. 116)

Air filters (2 & 8) remove unwanted pollutions and particles from supply air and they are classified depending on its structure and roughness. According to its efficiency, it removes 25 to 95% from 3-10 micron particles and contaminants from the air. This is important because of the health effects presented earlier. Filtering on air intake side is sometimes in two sections: first preliminary purification filter and secondly, the main filter. As the filter collects the dust and other particles, it needs to be cleaned or changed periodically so that it keeps AHU performance at desired level. However, the covered filtering area should be relatively big, keeping the pressure loss in tolerable level in case the filter gathers dust. (Sandberg, Esa et al. (1), 2014, p. 158)

After filtering, the air is driven forward to the silencer (3), which prevents the noise coming out from the supply and extract air fans. In silencer, mechanical sound energy is directed to the sound absorbing laminas, which moves along the air molecule movement, induced by sound waves. As the lamina moves, the sound energy is transformed to heat energy because of friction between the lamina and silencer housing. The width of the lamina has effect to the dampening frequency so that the wider lamina dampeners the lower frequencies. Wider lamina adds also the unwanted pressure loss. Normally the noise spectrum from the fan is focused on low frequencies, so the noise-silencing solutions are balancing between dampening amplitude and pressure loss. In addition, walls and ceiling of the AHU's machine room are usually provided with sound dampening elements to prevent the out coming noise. (Sandberg, 2014, ss. 158-159)

Heat recovery system (4) is heat exchanger shared by intake and extract channels. Its function is to preheat the intake air with extract air, hence improve the energy efficiency of the heating or cooling process. There are several designs for heat recovery units on the market like cross flow, counter flow and rotating heat exchangers but the principle in those are very same: In heating situation, the removed warm inside air heats the cold supply air from outside and in cooling situation removed air cools down the warmer supply air. Heat recovery system has two important parameters: pressure drop and heat transfer efficiency. The first parameter declares the energy consumed while driving the air through the component. Heat transfer parameter indicates the amount of heat regained from the exhausted air. (Sandberg, Esa et al. (1), 2014, pp. 178-179)

After that comes cooler and heater (5) what are used to control the supply air temperature according to system demands. Those are normally heat exchangers connected to heating and cooling sources. The heat exchanger consist numerous aluminum laminas that have holes for circulating water piping in the heat exchanger. Circulated water as a heat transfer fluid, warms or cools the laminas temperature that effects to the air temperature also as it flows through. Normally water temperatures in heating situation is 60°C and 40°C (inlet and outlet) and in cooling situation 7°C and 12°C. The district heating, geothermal wells or other sources are used for heating as the district cooling or different refrigerating machines are used for cooling. (Sandberg, Esa et al. (1), 2014, pp. 170-172)

Intake fan (6), exhaust fan (10) and just as the separate extract fan in the Figure 2.4, produces the pressure or vacuum, transferring the air between inside and outside air through the channelings. Fan is a component producing work to the air with impeller rotated by electrical motor. It is designed so that the dynamical pressure is striven to transfer into the static pressure in impeller outer edge, minimizing the pressure losses and noise. The desired airflow is achieved by changing the rotation speed with belt pulley diameter in about 6% steps or frequency converter for stepless control, like usually in VAV system. Possible motor types in fan are squirrel cage motor, commutator motor or permanent magnet motor. (Sandberg, Esa et al. (1), 2014, pp. 174-175)

2.2.2.1 Room devices

As already said, used room devices specifies the system partially according to Table 2.4. The operation principles of appearing room devices are covered in this chapter. Chilled beam is presented more precisely compared to others, because it is used in waterpower consumption monitoring in chapter six. Power calculation method is presented for Halton's VARIO (R6O/B-3000-B-2800) active chilled beam.

Fan coil

Fan coil is usually to the ceiling or window seat installed room device that is able to heat and cool spaces. Room device has either a shared heat transformer, or alternatively two, for both heating and cooling circuits where used medium is water. Water is circulated according to room temperature and heating and cooling effect can be boosted with higher airflow rate. Airflow rates are designed according to room occupant's need and the unit's cooling requirement are based on the heat loads. Cooling water is normally around +15 to 16°C so that any condensing will not happen in the device. Unit has also a filter for recycled inside air and sometimes, to be on the safe side, it is provided with condense pool and ducting. (Sandberg, Esa et al. (1), 2014, pp. 137-139)

Perimeter induction unit

Perimeter induction system is similar to the window seat installed fan coil system. The difference is in the supply air ducting and room device, where instead of fan there is supply air duct and nozzles in the duct. Changing the nozzle direction and size has an effect to the airflow circulation inside a room. Supply air is brought to the nozzles with such high pressure that the jet induces the needed cooling like ejector. The air comes through the heating element, where it is either cooled or heated, so the temperature is controlled with inlet water of the element. This means that the air needs to be supplied in order to heat a space even if it's not occupied and ventilation is not necessary required. Perimeter induction system cannot be installed to the building where humidity loads are relatively big for the sake of condense risk. (Sandberg, Esa et al. (1), 2014, pp. 140-142)

Chilled beams

Chilled beam is "*A cooled element or cooling coil situated in, above or under a ceiling which cools convectively using natural or induced air flows. The cooling medium is usually water*". Chilled beams have rapidly spread all over the Europe, used for indoor climate cooling and heating in hotels, hospitals, retail shops, bank halls and open plans offices. It provides desirable thermal comfort, energy conservation and use of space. The advantages of chilled beam are low noise generation, low room velocities, flexibility, high energy efficiency, low maintenance costs and long free cooling periods. (REHVA, 2004, pp. v-1) Chilled beams can be divided into two groups according to the operation method:

In **passive chilled beam,** primary air is supplied with separate diffusers, and cooling or heating operation is based on natural convection with a minor part by radiation. One passive chilled beam can be used only for one operation, either a cooling or heating. Therefore, it needs at least two beams if both operations are required, using passive chilled beams. (REHVA, 2004, p. 1) Passive chilled beam is depicted in the
Figure 2.7

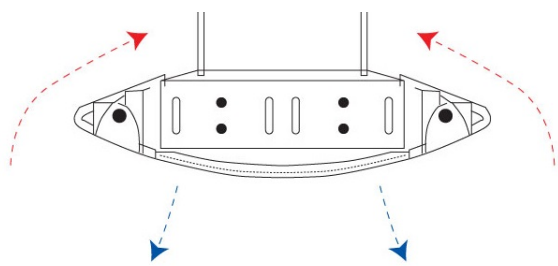


Figure 2.7 Cross-section picture of passive chilled beam. (Dwyer, 2007)

Arrows in the Figure 2.7 and Figure 2.8 represents the airflow so that the red arrow is warmer that blue arrow. In both figures, the beam is operating in cooling mode.

Active chilled beam is connected to the ventilation supply air and the water circulation. The primary air is supplied through the chilled beam into controlled room inducing the room air recirculate through the heat exchanger. Room temperature is controlled with the water flow rate in heat exchanger. In order to decrease the temperature in room, cycled water to the heat exchanger is cold, typically 14-18°C. Whereas warm, typically 30-45°C water is cycled to increase the room temperature. (REHVA, 2004, p. 1) Product picture of active chilled beam and cross-section picture is depicted in Figure 2.8

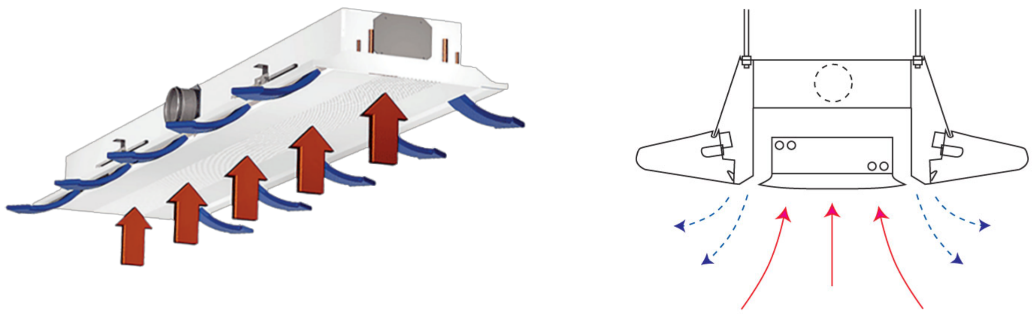


Figure 2.8 Left: Product picture of active chilled beam; the primary air supply induces room air through the heat exchanger (Halton Oy, 2015). Right: Cross-section picture of active chilled beam (Dwyer, 2007).

Radiant panel

Radiant panel is either to the ceiling, floor or building structure installed cooling or heating panel. System separates the cooling or heating from ventilation tasks so using radiation panels, independent ventilation system is required. The heating or cooling is provided majorly by radiation but convection can be increased with separate ventilation system by supplying the air along the radiant panel. Radiation panels utilize surrounding aluminum or other metal surfaces to cool or heat the room conditions with internal medium, which is normally water. Along the surface, there is copper piping circulating what induces the heat transmission to the panel. Panel is normally isolated from the top so that the cooling or heating effect is directed completely to a controlled space. (Sandberg, Esa et al. (1), 2014, pp. 146-148)

3. BUILDING MANAGEMENT SYSTEM

In order to have properly and efficiently working HVAC system, it is necessary to be aware of the conditions in ventilated spaces and control the system accordingly. BMS executes that task and its performance and energy efficiency is at its best when controlling of every variable is performed concentrated. BMS has overarching role of heating, cooling, air-conditioning, lightning, domestic hot water and auxiliary energy, aiming to improve the indoor climate and reduce the total energy consumption of the building. Executing its task optimally, it needs to collect data from HVAC system, energy consumption, environment conditions and every other object's status connected to the communication network, and send signals to the actuators to keep the building systems in designed level. Advanced system may have thousands of data points in non-residential building, while residential and some of the non-residential buildings still have traditionally single room thermostat controlling the boiler and pump on/off. State-of-the-art in BMS is microprocessor-based controllers that can be programmed to increase the artificial intelligence in the building's systems. (REHVA, 2017, pp. 1-3) In modern buildings, the whole system is automatic, data is collected and controlled in room-level, and system management is done from the control center situated in the building itself or separate control center over the internet. Properly working BMS requires several equipment and instrumentation installed in the building and connected to the management center, making data transfer possible. In addition, some parts of the system is connected together.

The management and monitoring processes of BMS consists of 3 levels: Field level, Automation level and Management level.

Field level includes sensors for data collection, actuators to control the indoor environment conditions, and field level controllers to send/receive data from actuators and management level devices. Achieving the monitoring and control possibility in the room level requires measurements almost for every monitored or controlled variable in the building, in every room. However, some variables can be calculated from other variable measurements so the used sensors should be designed cost-effectively according to need. (Sandberg, Esa et al. (1), 2014, pp. 293-295)

Automation level consist the controllers that transfer the data between management center and field level. This level is required in buildings where the number of data points in the field level is bigger than number of management devices input/output ports. Thus, the need of automation level is depending also on used hardware in management device what specifies the number of capable number of connected sensors and actuators. (Sandberg, Esa et al. (1), 2014, pp. 294-296)

Management level is the center where every actuator and sensor is connected. Management and automation center is normally situated somewhere in the controlled building. Having the central or concerted control of all energy related components assures the highest efficiency of the system (REHVA, 2017, p. 8). Management level can be provided with different third party systems and access to the internet.

The levels and the architecture of BMS are depicted in the Figure 3.1

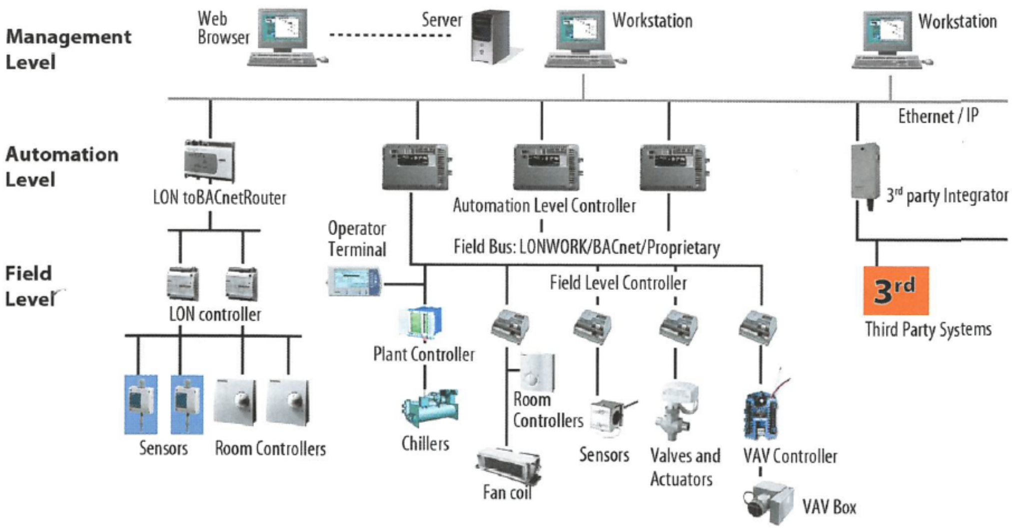


Figure 3.1 Example of BMS architecture in a building. (REHVA, 2017, p. 5)

Working BMS requires that the used devices shown in the Figure 3.1 are compatible with each other's. Next subchapters discuss the compatibility and other effective factors in the hardware level, and present the most common controller type, in general, used in the field of automation.

3.1 Data collecting and processing

The data collecting and processing in general is either digital or analog. The main difference in those is that the analog signal has continuous and infinite values while the digital method has series of discrete and finite quantities to represent the real signal. As the signal processing today is majorly done digitally and most of the measured signals are analog, the analog signals have to be converted to digital signals with Analog to Digital Converter (ADC). This means that the continuous analog signal is sampled within a constant time-interval and every interval presents a single measurement of amplitude. That is also known as discretization. The Nyquist theorem states that signal can be reconstructed from its samples if the sample-rate frequency is twice as high as the highest frequency of the signal being discretized. Analog signal is almost exceptionally filtered with low-pass filter before the ADC to prevent the aliasing of the sampled signal. Aliasing means that any analog frequencies above the Nyquist frequency, appears to be something else in the digital signal than it really is. (Proakis J. G. & Manolakis D. G, 1996)

Every sample of infinite analogic value is approximated to finite amplitude along to available amount of bits. This process is called quantization and it produces quantization error what is depending on resolution of the process. (Proakis J. G. & Manolakis D. G, 1996) The ADC process and its error are explained with simple sinusoidal analog signal in Figure 3.2.

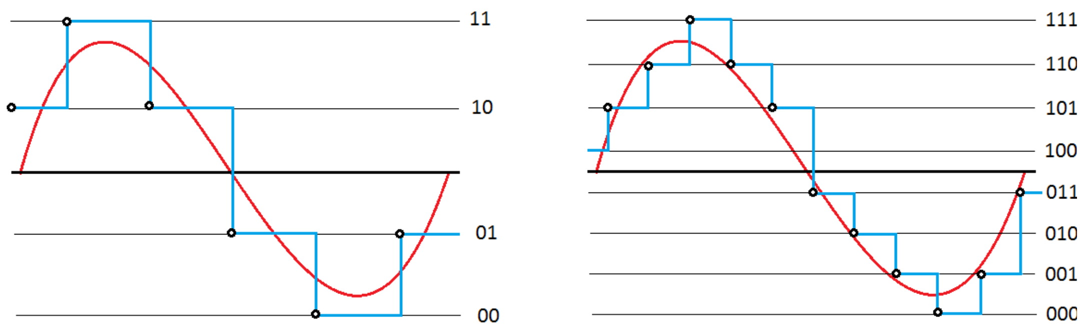


Figure 3.2 ADC with 2 bits on the left and ADC with 3 bits on the right.

Left side of the Figure 3.2 shows two bits ADC and the right side same conversion with three bits. The red line is analog signal, blue line represents the digital signal from the conversion and the dots are sampling points. As we can see, the number of quantization levels with two bits is four, as it is also the number of possible bit combinations. This means that every possible bit combinations, which in two-bit case are 00, 01, 10 and 11, represents one finite value of the analog signal. Thus, the amplitude of digital signal does not always meet the analogical signal at the sampling point. The difference between analog and digital signal in that point is called quantization error. The error can increase or decrease according to the progress of the analogical signal before the next sampling point, which is also seen from the Figure 3.2. ADC with three bits in the right side of the Figure 3.2 shows that the number of quantization levels is eight and therefore produces smaller quantization error over the time. Thus, it is clear that bigger number of used bit quantity leads to a bigger quantization error. In addition, the bigger sampling rate leads to a smaller error over the time. (Proakis J. G. & Manolakis D. G, 1996)

This denotes that measurements include error in ADC. For example, the temperature measurement with 8 bits means that measuring range is divided in 256 parts. The quantization accuracy is then 0,4% what causes the quantization error of 0,6°C for 0-150°C measuring range. (Sandberg, Esa et al. (1), 2014, p. 297) The target level of the BMS accuracy hence sets requirements for system hardware. However, today's price level of sufficient hardware for BMS is relatively low and measured phenomenon are relatively slow and rough so the effect of those requirements in BMS is minor.

Since the signals from the field level are digital or analogic, the automation center needs input and output (I/O) ports, both digital and analogical. Those are embedded in I/O-modules. I/O ports are used to give information from the field level to the BMS and send control signals to the actuators and devices in the field level. (Sandberg, Esa et al. (1), 2014, p. 296)

Digital hardware input's value is either a zero or one according to some contact terminal position (open or closed) and the indication type is hardware dependent. Meaning that closed input terminal can be one or zero, depending on the input type of the hardware. These types of inputs are normally utilized in applications to tell if some process or object, for example pump, is on or off. The information is provided with voltage that is usually under 30VDC. (Sandberg, Esa et al. (1), 2014, p. 296)

Analog input indicates usually some measurement information. In building engineering systems, the normal information message is 4-20mA Direct Current (DC) with under 30VDC. In order to get the correct information from current measurement, actual value needs to be processed with operations such as scaling, filtering and linearization. (Sandberg, Esa et al. (1), 2014, p. 296)

Outputs are also either analog or digital. Digital outputs control pumps and blowers with contactor so that when the low voltage control-circuit is active, the power-circuit delivers the voltage for the actuator. The control-circuit voltage level is normally 24VDC and the controlling is executed by way of supplementary relay. Analog outputs control directly mechanisms as control valves or frequency controllers. Those are normally 0-10VDC signals constructed with Digital to Analog Converter (DAC) from software calculations. (Sandberg, Esa et al. (1), 2014, p. 297)

3.2 Communication network

Enabling the data collecting from the field level to the management center, the system needs communication network for transferring the signals between devices. Physical network between BMS center and all the system parts is executed with twisted pair cable or data bus. Harmonious data communication method through data bus requires also a data transfer protocol. Protocols can be considered as instructions or guidelines for data transfer of the whole system. (REHVA, 2017, p. 5) Since the data flow is predefined bit-length (Normally 8, 16 or 32) of "packages", sent one bit (serial communication) or for example 8 bits (parallel communication) at the time sequentially, the transfer protocol tells the BMS devices relative to data transfer, what kind of information in each bit is meaning. This can be also method to tell devices connected to the bus, what messages are for them. Protocol requirements and specifications are covered in standard EN ISO 16484, that includes 5 documents concerning Building and Automation Control Systems projects and requirements for the hardware to perform BACS tasks and overall functionality. Well-implemented BMS can be switched to communicate with different protocols.

Majority of HVAC systems in Europe has put in practice using BACnet, LonWorks and Modbus.

Modbus is master/slave communication protocol published in 1979 and used widely due to its reliability and simplicity. It includes Remote Terminal Unit (RTU), Transmission Control Protocol (TCP) and ASCII transmission modes, and supports the most serial data-communication transmission like RS-232, RS-422, RS-485 and Ethernet based equipment. Master/slave refers to a method where Master Device requests some information from Slave Device that produces the response to the requested information. The method depiction is in Figure 3.3

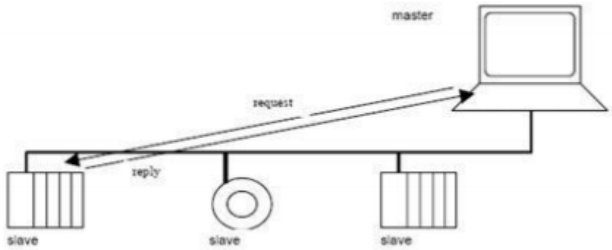


Figure 3.3 Modbus communication depiction. (National Instruments, 2009)

This is possible because each device has unique Internet Protocol (IP) addresses. These addresses are limited due to 8-bit address numbers so that the maximum number of slave devices in one Master Device is 255 what is comparatively small number. (Modbus organization, 2017) The most concerning feature of Modbus is that it does not support any authentication nor encryption, meaning it is more vulnerable to cyber-attacks. There are already references of attacks to the Modbus based systems (Jakaboczki G. & Adamiko E., 2015).

LonWorks was created in 1988 by Echelon Corporation. The vision was to create method that allows inexpensive devices communicate effortlessly. The standard was optimized for control networks. The protocol has been used already in lightning control, energy management systems, HVAC systems, security systems and home automation systems. LonWorks consists of seven layers what defines the transmission from raw bit transfer to application level communication and it supports any topology combination of star, loop and bus wiring. The example architecture of LonWorks is depicted in Figure 3.4.

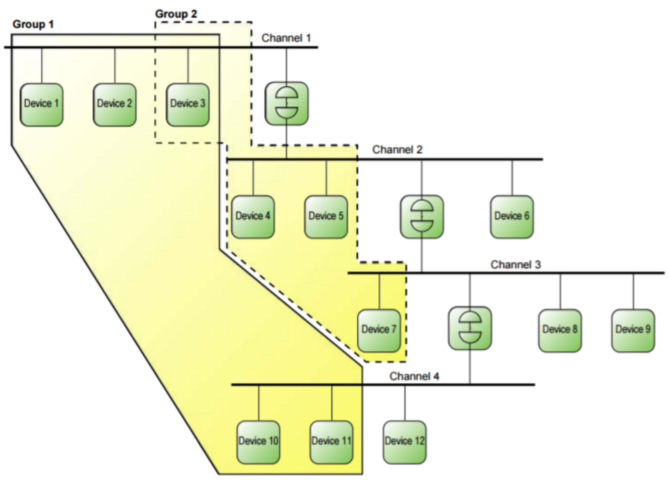


Figure 3.4 Example architecture of LonWorks. (Echelon Corporation, 2017, p. 54)

Devices in LonWorks are connected to a channel where the devices can be compiled into a logical collection of devices. The collection is called a subnet and the maximum number of devices is 127. Two or more, up to 255 channels, can be connected together with a repeater or router. Thus, the maximum number of devices in a single domain is 32 385 (127 devices on subnet * 255 subnets). Furthermore, devices can be grouped over the subnets and channels. That is efficient way to use network for messages addressed to multiple devices. Unique devices can also be shared with two groups. (Echelon Corporation, 2017, pp. 52-53)

BACnet is in year 1995 published protocol by ANSI/ASHRAE and since 2003 it has gained status of international standard (ISO 16484-5 and ISO 16484-6). BACnet was designed especially for building automation controlling. It is object oriented protocol, meaning that physical inputs and outputs are considered as objects that has different properties. Difference to a conventional variable method is that where variables normally has only some value, the object could have additionally the unit of the value, information of used equipment to get the value or other useful details as properties of the object. There are 123 pre specified properties by the protocol and three of them are mandatory for every object: identifier, object-name and object-type. The information between devices is handled through services what is similar to a function in conventional serial languages like C. Protocol defines that every object must support at least the “Read-property” –service and the data transmission happens transaction based, one property at the time. Today BACnet have two versions: Ethernet version using TCP and MS/TP version what is used through RS-485. (ASHRAE) (RTA automation, 2017)

3.3 Control engineering

Control engineering in general, strives to have stabilizing effect on operation and get the most effective outcome from the system. The functionality in most cases is based on the measurements and processing the measurement values in controlling with microcontroller. That method is called closed loop controlling and it is said that there is feedback in the system. (Johnson M. A. & Moradi M. H., 2005) The principle of the feedback is depicted in the Figure 3.5.

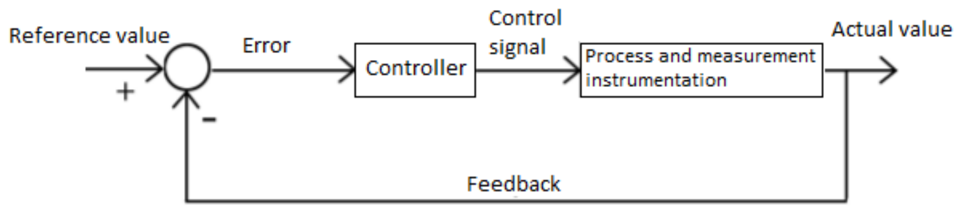


Figure 3.5 Control systems block diagram. (Johnson M. A. & Moradi M. H., 2005)

The measured output is called actual value and it is being compared to the reference value what is the value that was wanted for the system output. In basic situation, the system is controlled according to error of these two values what is delivered to the actual controller. The controller then forwards a control signal to the process actuators according to the error and the controlling parameters of the controller. (Johnson M. A. & Moradi M. H., 2005)

The controller in the Figure 3.5 includes parameter that can be used to have effect of the controller's operation. Regarding to the structure of the controller it can include P,I or D parameters, or combinations of those, so that the possible controllers are for example P-, PI-, PD- and PID- controllers. In addition, the controller might have inside loops, when it is called cascade controller. The mostly used controller in industry processes is PID-controller because of the simplicity. PID-controller calculates the error from the actual and reference values and the one ambition is to minimize the delay in the controlling process. The controller is suitable for example to control a flow valves or systems like heating devices and motor control voltages. (Savolainen J. & Virtanen R., 1998)

The selection of the controller structure is dependent of the controlled process and the requirements set for it. If goal is to get zero steady-state error in the process, the PI-controller is usually suitable for that. Adding the D-parameter to the controller improves the operation significantly and it might be necessary in the control of higher degree processes. (Visioli A., 2006)

PID-parameters are amplifying factors of the controlling error. The factors can be also smaller than one, when it blankets the signal. The error value from the feedback is delivered in the basic PID cases into the three different blocks, where it is being processed according to the function of the block. Then the outputs from those three blocks are summed to get the control signal. (Savolainen J. & Virtanen R., 1998) Thus, the Figure 3.5 can be presented differently with Figure 3.6

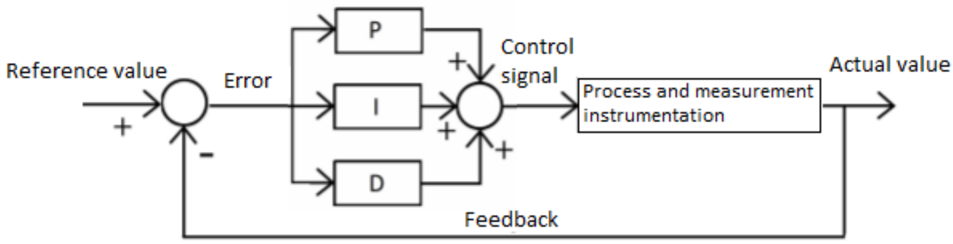


Figure 3.6 The controller with PID parameters. (Savolainen J. & Virtanen R., 1998)

The PID-parameters together forms the controller which discrete transfer function is presented with the following equation

$$\frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s, \tag{2}$$

where $U(s)$ is the output of the controller, $E(s)$ error as the input for the controller, K_p proportion factor, K_i integration factor and K_d derivation factor. s tells that the transfer function is in Laplace domain instead of time domain. (Johnson M. A. & Moradi M. H., 2005)

K_p forms the Proportional (P) part of the controller. It induces the offset to the system and leaves a permanent difference between the reference and the actual value. Amplification and the offset are inversely proportional so that the bigger the K_p value is the smaller offset it produces. On the other hand, proportion cannot be increased exceedingly because it might make the controlled process oscillate or even unstable. (Johnson M. A. & Moradi M. H., 2005)

K_i forms the Integration (I) part of the controller. The I-parameter includes also the integrative term $\frac{1}{s}$, what means that the parameter observes the error over the time. Integration part strives to correct the steady-state error by integrating the area between the reference and output of the process continuously. By increasing the K_i it increases the velocity of the system. (Johnson M. A. & Moradi M. H., 2005)

K_d forms the Derivative (D) part of the controller. The D-parameter includes also the derivative term s, what means that it has effect on the reaction or rising velocity of the system. Derivation part constrains the time rate of change of the system and increasing of the K_d it makes the system more stable. (Johnson M. A. & Moradi M. H., 2005)

Applying the PID controller in Figure 3.6 to the room temperature controlling situation is depicted in the Figure 3.7

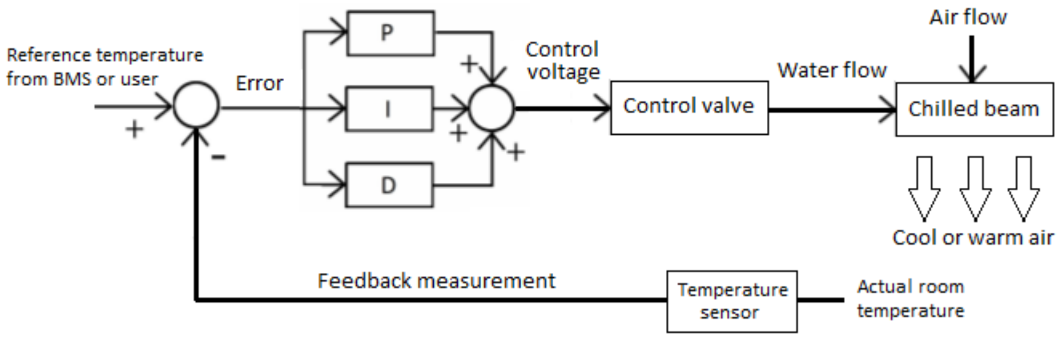


Figure 3.7 Room temperature controlling with PID controller.

The control signal in room temperature control is controlling the control valve of the chilled beam what occurs water flow according to the error between reference temperature and actual room temperature, and controller parameters. The water flow heats or cools the supply air by heat transformer and it effects to the room temperature. The air flow can be also controlled with PID controller but it would have different block diagram.

3.3.1 Feedback of people count in derivative control

Conventional PID control is sometimes inadequate to maintain the performance due to changing conditions. Such situation can be encountered if several people enter one room and CO2 and temperature level drops in consequence. Example situation according to CO2 concentration, from school classroom is showed in the Figure 3.8.

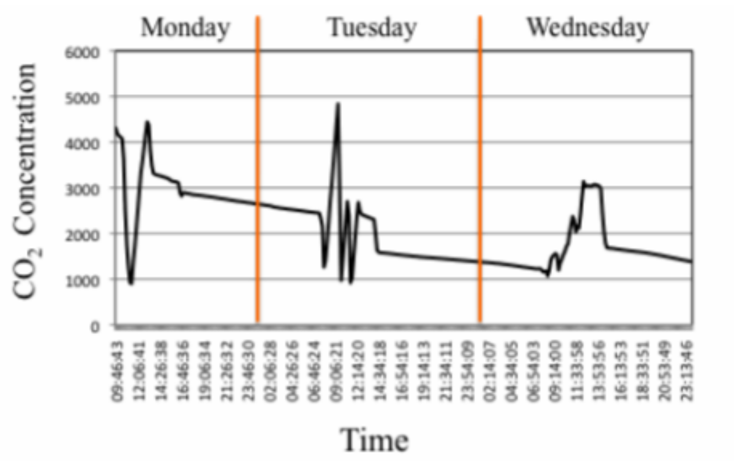


Figure 3.8 CO2 concentration from classroom over time.
(Sabrowski A. & Silva P., 2010)

Measurements shows that the CO2 concentration starts to rise as soon as students enters the room. The situation could be moderated or prevented by having a feedback from people count in a room and boosting the ventilation according to the feedback. Previous research also points out that energy consumption can be reduced by 51% with infrared (IR) occupancy sensor-based CDV compared to CAV ventilation (Mynsen;Berntsen;Nafstad;& Schild, 2005). Precise room level solution for people count feedback would also gain additional value for the office monitoring system because it enables for example the accurate office utilization-rate information, building usage habits learning, utilizing in emergency and evacuation situations, and it also gives knowledge of people activity according to CO2 production. An accurate video-based solution already exists but those are excessively costly regarding the room level solution. According to PR Newswire Association LLC's research, the global market forecast for accurate people counting solution for indoors is supposed to be 23.13 billion by year 2021 (PR Newswire Association LLC, 2016) and there is even an In-Location Alliance with 25 member companies that focuses creating the accurate indoor positioning technologies (In-Location Alliance, 2017). Thus, the effective valid solution for the problem might arise in the near future. This chapter presents principles of the current potential technologies, which could work alone or combined as a solution for people counting or tracking. Key factors in sensing solutions estimating should be accuracy, ease of deployment, communication protocol, granularity, cost and availability (Ahmad M. W et al., 2016).

Radio-frequency identification (RFID) is generic notion for technology that uses radio waves – normally from 125 kHz to 900 MHz – in automatic identification of people or objects. The way of identification may vary but the most common is to link a serial number to object or person and store it on a microchip that has antenna attached to it. The composition is called RFID transponder or tag that has maximum storing capability of 2kB. Thus, it is possible to store also other needed information on the chip and transmit it electronically through magnetic fields. It requires reader to receive the electronic signal and transforms it into digital information that can be utilized on applications. (RFID Journal LLC., 2017) RFID tags are used already as access control tags to log in and out in many companies, so it would be easy to integrate the information of people's normal position in a building. As person logs in at work, the data about person's presence and probabilistic location is to be known. With this method the costs would be negligible as the office workers already has tags and even buying those costs approximately 0,5€ per passive tag which read range is typically less than 6 meters (RFID Journal LLC., 2017).

Bluetooth Low Energy (BLE) beacons as RFID utilizes also radio technology but the difference is that BLE is normally integrated in some devices for example smart phones. Since every BLE-enabled device has unique Media Access Control (MAC) address it is possible to identify every BLE devices around the required BLE scanner that searches continuously for discoverable devices. It is obvious that in order to track wide areas it requires several BLE scanners. Range of the BLE scanning is 1-100 meters according to the device. Other weakness with BLE positioning is that not everyone has BLE enabled device and some might have several of them. The count of people in that case is not reliable.

Global Positioning System (GPS) is space satellite based system owned by USA government. The GPS tracking unit position is calculated from time-difference of the signals from satellites takes until they reach the tracking unit. Rise in the number of satellites have gained the global GPS accuracy of 2 meters. The problem with GPS is its bad accuracy inside a building. Still, the time-of-flight method could be applied inside a building locally with accuracy of 30 centimeters and those systems are available on the present markets (Eliko, 2017).

Infrared (IR) **sensors or beams** can be installed on doorways to count the number of people passing. Principle of the sensor is to have two IR transmitters and receivers. As person walks across the IR beam, it breaks and the sensor sends information that someone has gone through the doorway. Beam needs to be complete again to accept a new change in the count. Time difference in those two beam breakings tells if the count needs to be increased or decreased. This way the number of people in the building can be find out if the sensor is installed on every entrance. Room level count is provided when sensor is installed on every doorway in the building but the cost of the solution is significantly higher. Due to its operational principle, it has relatively big probability to miss the count at some point. Installation height of the sensor has effect on the accuracy but even so, it will not give 100% reliability. Other way to utilize IR sensors is to install it to the ceiling or HVAC components. When sensor is pointed down, it can be used to inform if there is people under it.

Camera based counters are installed to every doorway just like the IR based sensors but the principle is very different. Video from the camera is transferred to microcontroller what recognizes every person in the frame. The recognition is based on digital signal processing what is normally done in graphical user interface driven in PC. This kind of solution works even in wide doorways where is multiple people passing simultaneously but just like IR sensors, to get the room level solution the camera units should be installed on every door. This method is probably the most accurate as some retail companies guarantees over 99% of accuracy. On the other hand, it is the most expensive. According to offers of two companies, the unit price is approximately from 1500-5000 euros. (SenSource Inc. & Ariki)

The people counting solution might be found from **CO2 concentration level**. One case study was approximating the people count in a meeting room from CO2 level in space and supply air, supply air flow rate and CO2 generation per person. The equation gives people count according to present variable values with approximately 1,5-hour delay. (Elsevier B.V, 2015) The new idea is to find different levels of rising velocity according to people stepping inside to a room when it is not occupied before. If room is occupied the model or algorithm observes the increasing or decreasing velocities in the room CO2 level. This way it is capable to keep count during the day and even if there is error of one or two at the end of the day.

3.4 Data-driven fault diagnostics

Problems due to degraded equipment, sensor failures, improper installation, poor maintenance and incorrectly implemented controls in HVAC systems can lead to inefficient operation, increased energy costs, user discomfort, reduced reliability and shorter equipment lifetime. Fault diagnostics could be used to indicate such problems and hence has focal role in guaranteeing the best conditions with minimum operation costs in HVAC systems. (Beghi A., Brignoli R., Cecchinato L., Menegazzo G. & Rampazzo M., 2015, p. 966) Fault diagnosis tools can be used in different levels of understanding the faults. Diagnosis tools could for example indicate, detect, analyze and predict the faults according to the Figure 3.9.

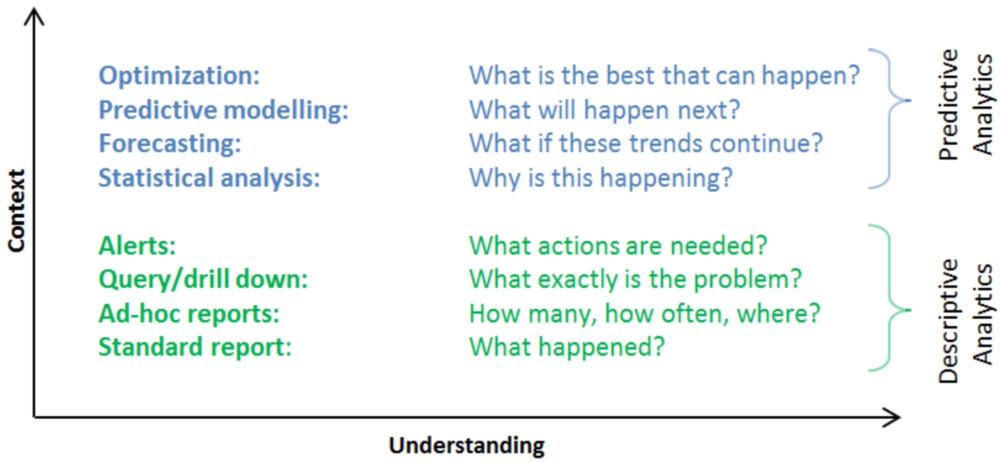


Figure 3.9 Context and understanding in HVAC fault diagnostic. (Sinha S., Taparia S. & Biswas S., 2013)

The most simplified form of the diagnosis tools is to tell that something is wrong in some system. As the understanding increases on the monitored process and its components, it is possible to increase the coverage of the fault diagnosis tools to tell what is wrong and why, give forecasts or even optimization suggestions for users. This means that the diagnosis tools can be set to give both, descriptive and predictive analytics on the faults.

Regarding the monitoring concept of the HVAC systems, automatic data-driven fault diagnosis is relatively reasonable and easy to apply since the major of the data is collected anyway for the operation and controlling. In addition, the desired fault diagnosis tool should support major of the identified properties for the fundamental and practical fault diagnostic systems by VTT:

"*A practical fault detection and isolation system has more or less the following properties. Such system*

- *Needs only a few input data submitted by the user.*
- *Needs only domain knowledge for initiation or updating.*
- *Adapts easily to new faults.*
- *Does not disturb normal operation of the process.*
- *Causes no human assistance during detection or isolation.*
- *Causes no additional energy/fuel consumption.*
- *Requires only a short training period/a few training data.*
- *Applies to many kinds of HVAC processes; generic over processes.*
- *Applies to many kinds of faults; generic over faults.*
- *Supports both fault detection and isolation.*
- *Needs only an uncomplicated process model.*
- *Is easy to configure to new applications.*

- *Is easy to embed and integrated in a building energy management system.*
- *Requires only a minimum or moderate amount of work/costs for development and implementation.*
- *Requires no additional instrumentation."*

(Pakanen J., Hyvärinen J., Kuismin J. & Ahonen M., 1996, p. 10)

In recent years, fault diagnostics have appeared to markets with several number of methods and it is required to evaluate them to select the most apposite for the regarding application. In general, methods for fault diagnostics can be divided into three categories: quantitative model-based, qualitative model-based and process history-based. Quantitative methods mean that fault detection occurs along to detailed or simplified physical models, whereas qualitative utilizes rule-based systems and models based on qualitative physics. Process history-based methods include those models based solely on historical data available from the process. (Behgi A., Cecchinato L., Corso L., Rampazzo M. & Simmini F., 2013, p. 1165)

One well operating method of the fault detection in practice according to Pakanen J. et al. (1996) is to define performance index and intent to classify the performance of the process due to its output. This can be applied to any or all of the monitored signals of the process. The more common but also more rarely achieved objective is to have actual process and process model in parallel and observe the residual from the outputs. In this method, the residual is able to evaluate the size and indicate the type of the detected fault. These both methods block diagrams are depicted in the Figure 3.10.

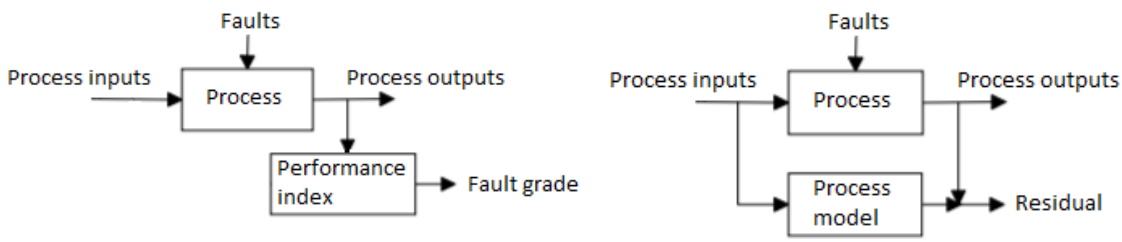


Figure 3.10 Fault diagnostics diagrams. Left: Performance monitoring and classification of process output as an independent operation, Right: Parallel operation of a performance classifier and model-based fault detection. (Pakanen J., Hyvärinen J., Kuismin J. & Ahonen M., 1996, pp. 18-19)

These models can be used to detect faults in level of the whole HVAC process or more preferably, like Pakanen J. et al mentions, directly to some components in the HVAC system. This way it is necessary to be aware of the possible faults or at least those of them that needs to be identified with the diagnosis system. (Pakanen J., Hyvärinen J., Kuismin J. & Ahonen M., 1996, p. 12). Typical faults of the HVAC components are presented in the Table 3.1

Table 3.1 Identified typical faults in HVAC system.
(Pakanen J., Hyvärinen J., Kuismin J. & Ahonen M., 1996, p. 13)

Component	**Faults**
Heat exchanger	Leakage, blockage, dirtiness
Valve	Stuck or binding, failure open or close, leakage
Controller	Drift, bias, hunting, faulty electronics, faulty computer program
Actuator	Shaft seizure or binding, failure open or close, bent or disconnected linkage
Sensor	Bias, drift, poor location
Pipes	Clogging leakage, faulty insulation

If the available data and fault detection models from those components in the Table 3.1 or specific part of the HVAC system, could indicate somehow about their condition, it helps for example planning the maintenance schedules, observing the health of equipment, estimating the remaining service life of equipment, refining product specifications and finding any improvement areas (Metwally I. A., 2011, p. 40).

4. DRIVERS FOR DEVELOPMENT OF ADVANCED CONCEPT

As already mentioned in the thesis objectives, the concept development is based on stakeholders' requirements. Thus, those requirements are considered as drivers for the development. Particularly the requirements from determined core stakeholders are weighted in this study but there are also other possible stakeholders and even global drivers for the system. This chapter gives wide overview on those drives by means of theory and strives to identify any interests for the concept, already recognized in the literature.

4.1 Stakeholders

Definition of stakeholder in this thesis is applied from Freeman's Stakeholder Theory, introduced first in 1984. Stakeholders are defined as any group, individual or union, which have or could have something to gain or lose from the development process and the outcome. Later on, the stakeholders were divided into primary and secondary stakeholders according to Clarkson's suggestion in 1995. (Han Q., 2010, p. 87) The division concerning the possible stakeholders for the concept development is presented in the Table 4.1.

Table 4.1 Possible stakeholders divided into primary and secondary stakeholders.

Division	Stakeholder
Primary	- Property owners - Office space tenants - Office users
Secondary	- Maintenance - System assemblers - Scientific research - Governments

Apart from the stakeholders presented in the Table 4.1 the other drivers are discussed later.

4.1.1 Property owners

Property owner in high-level commercial building is usually company, government, county council or city. The building itself can be considered as an investment that is usually striven to bring income to the investor. That is again depending directly on rental income from tenants as customers and indirectly from space user's and space tenant's satisfaction. Therefore, it is notably important for the property owner to fill major or at least the critical parts of the tenant's and space user's requirements yet, with optimal expenses. It is also important to be able to prove that the property fills the other stakeholder's requirements. The possible benefits from the developed concept for property owners are: (REHVA, 2017, p. 13)

- Higher building value
- Low LCC and higher return of investment
- Higher rental value and tenant retention
- Real-time certification that property fills some specific level of requirements

4.1.2 Space tenants

Space tenants in offices are usually companies, cities, government or other parties that rents facility for their workers. It is obvious that tenants pursue to have high quality office for their workers with minimal total occupancy costs. For some companies the location and style might also have significant importance. In addition, it is proven that poor indoor air quality has effects on office workers productivity and absence regarding to the adverse health effects (REHVA, 2006, pp. 29-34). Thus, the good air quality is both space tenants and office workers benefit. The possible benefits from developed concept for space tenants are: (REHVA, 2017, p. 13)

- Guaranteed high indoor air quality
- Minimal total occupancy costs
- Employee satisfaction and productivity

4.1.3 Office users

Office users are employees that are working in the office. Office users are the most direct stakeholder group connected to the building and scientific references shows that building characteristics has several straight effects to office users. For example, working performance has pointed out to have relationship between ventilation rate, perceived air quality and temperature. Lightning and acoustics could also have an impact on the office user's performance. The possible benefits from developed concept for office users are: (REHVA, 2017, p. 13)

- More effective information distribution channel for HVAC-related complaints
- Better comfort and safer working environment

4.1.4 Secondary stakeholders

Secondary stakeholders are presented in the Table 4.1. These stakeholders are not weighted in this development but they can still benefit from the outcome. Those are also taken into account in conclusions of this thesis and should be taken also, if the concept gets further development. Possible benefits for secondary stakeholders are specified in the Table 4.2.

Table 4.2 Possible benefits for secondary stakeholders. (REHVA, 2017, pp. 13-14)

Stakeholder	Benefits
Maintenance	Remote supervision, information of total run time and condition of all equipment, failure predictions
System assemblers	Automation features for example in commissioning, system simplify installation
Scientific research	Plenty of utilizable data from the field level
Governments	Exact information on energy end-usage, support of standards

4.2 Other drivers

Emerging conditions of climate change and evolving in the field of IoT as well as in building engineering has come out with many other drivers for developing the monitoring concept. These drivers cannot be considered as stakeholder based requirements but are in the obligating and advantaging role more or less. For example, different recommendations or minimum criteria for ventilation are specified in EU-regulations and standards. Such documents are typically shared goals and instructions that every country should aspire but decision-making is country-independent. In Finland, there is additional D2 specification and instructions for indoor environment and ventilation, whereas building's energy efficiency criteria are defined in D3 specification. Some regulations and standards have still become an obligation. (Sandberg, Esa et al. (1), 2014, pp. 28-30)

Since there are various information sources for building criteria, they need to have specific priority hierarchy. The hierarchy of the information sources in Finland is depicted in the Table 4.3.

Table 4.3 Hierarchy of information sources in Finland.
(Sandberg, Esa et al. (1), 2014, p. 28)

Criteria order	Information source	Documents
1	Statutes (always valid)	Law, specifications, department decisions, general safety precepts
2	Statutes (valid only if referred to)	Department instructions
3	Manners (valid only if referred to)	Standards, Building information foundation
4	Helpful information sources	Heating, Plumbing, Air-Conditioning (HPAC) files, manuals and textbooks

Number 1 is the highest criteria in the hierarchy. First, there are statutes that are always valid and obeyed, second there are statutes that are valid only when referred to. Third, comes good habits/ways lined in standards and last one are other information sources that do not have obligated position. (Sandberg, Esa et al. (1), 2014, p. 28) There can be also some juridical restrictive documents for the concept development such as patents but those are not covered in this thesis.

4.2.1 Legislation

Legislation is enacted and has differences in country level. For example, in Finland, there is a code of building regulations. It regulates general prerequisites, minimum technical requirements, building's regulation relation procedure and government oversight. Today's technical requirements involve structure strength and stability, fire-safeness, healthiness, impartiality, noise abatement, sound conditions and energy efficiency of the building. This code of regulations concerns comprehensively only new buildings. It can be applied also to reconstruction and renovation buildings in required quality and scale. Applying the building regulations are partly intended to be flexible, but only within the building's features and special characteristics concerning limits. Regulations are continuously updated and the next improvements will take effect in year 2018. More specific and always updated limits and requirements in the regulation can be found from the web pages of Ministry of the Environment. (Ympäristöministeriö, 2016)

4.2.2 Standards

Standards are specifications for products, services and systems, used world widely to ensure the quality, safety and efficiency. Standards are also perceived as good general manners that are obligatory only if referred to. There are several existing associations or organizations that publish standards, such as International Organization for Standardization (ISO), International Electrotechnical Commission (IEC) and Association for Automation and Measuring Systems – Automotive technology (ASAM). The most referenced and used of those is independent, non-governmental and international ISO that has 163 national members. It has published 2163 standards and related documents related almost on every industry. (International Organization for Standardization, 2017)

Standards regarding of the HVAC systems and BMS are at least ISO EN 7730, EN 15251, CR 1752 and ISO 50001. The subject of those are presented in the

Table 4.4 Standards regarding the HVAC systems and BMS.

Standard	**Subject**
ISO EN 7730	Determination of thermal environment and comfort using PMV and PPD indices and local thermal criteria
ISO EN 15251	Parameters for design and assessment of energy performance in buildings indoor air quality, thermal environment, lightning and acoustics
ISO 50001	Requirements for energy management systems with guidance
CR 1752	Design criteria for the indoor ventilation in buildings

There are also national standardization organizations like SFS in Finland. It has for example classification for HVAC system filters in standard SFS-EN13779.

Indoor climate requirements for this thesis are applied from ISO EN 7730, which defines precise values and ranges for every different environment aspects including thermal, air quality and acoustic environments. These aspects are valued separately and certain space can be qualified among the three categories, A, B and C. Still, within the standard, the indoor environment is considered as a whole. Generally, ventilation system is designed to work under specific internal and meteorological conditions and therefore the desired indoor environment will only be provided when the made assumptions are valid. (CEN, ISO EN 7730, 2005, p. 17) Defined criteria for operative temperature and maximum air velocities in standard ISO EN 7730 are showed in Appendices III.

The criteria in the standard are based on Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices predict the percentage of occupants feeling too warm or too cold as a whole body. Dissatisfaction can also be expressed due to different types of local thermal discomfort such as draught, abnormally high vertical temperature difference, too warm or cold floor temperature and high radiant temperature asymmetry. This includes the cases when dissatisfaction is caused in one particular part of the body. (CEN, ISO EN 7730, 2005, pp. 4-5)

PWM is following the 7-point scale, which express the thermal sensation mean among the large group of people. It is depending in six parameters: the occupants' physical activity (metabolic rate), thermal resistance of occupants clothing, air temperature, mean radiant temperature, air velocity and partial water vapour pressure. (CEN, ISO EN 7730, 2005, p. 2)The scale for PWM is depicted in Table 4.5

Table 4.5 PWM index according to temperature above and beneath the predicted average. (CEN, ISO EN 7730, 2005, p. 2)

Temperature [°C]	+3	+2	+1	0	-1	-2	-3
PWM index	Hot	Warm	Slightly warm	Neutral	Slightly cold	Cool	Cold

PPD can be presented as a function of PWM by equation

$$PPD = 100 - 95e^{(-0{,}03353PWM^4 - 0{,}2179PWM^2)} \tag{3}$$

and it is depicted in Figure 4.1

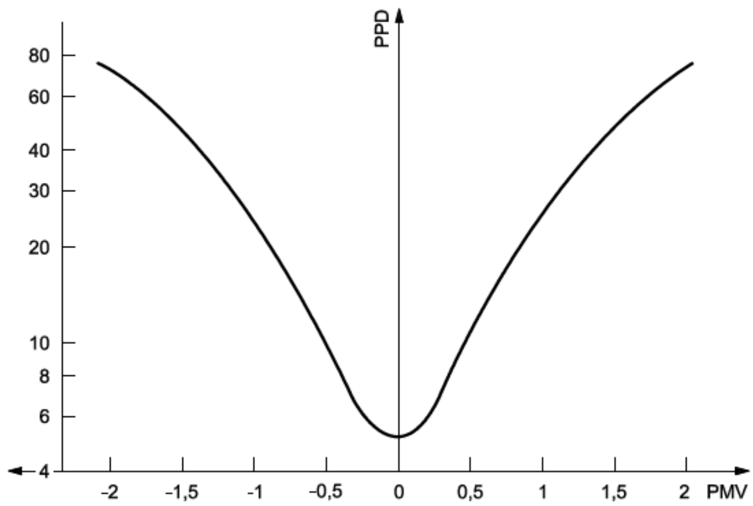


Figure 4.1 Predicted percentage of dissatisfied as a function of predicted mean vote. (CEN, ISO EN 7730, 2005, p. 5)

4.2.3 Classification

Buildings, inside conditions and building's characteristics can be classified to describe building's performance. Different classifications are used in the standards, code of building regulations and independent Associations around the world. Peculiar to the classifications is to have several levels for the classification, level description and some numerical limits for the levels. This thesis presents the indoor climate classification by Indoor-climate Association in Finland. Buildings can be classified also according to different certifications what are discussed after the indoor climate classification.

4.2.3.1 Indoor climate classification by Indoor-climate Association

The classification method by Indoor-climate association is used widely as guideline for designing and constructing buildings in Finland. It is aiming for healthier and more comfortable indoor climate in new construction but it can be applied also in reconstruction sites. Classification is divided into three categories: S1 is excellent, S2 is good and S3 acceptable category. (Säteri J., 2008, p. 2) Descriptions for the categories are following:

In category S1, the indoor climate quality is excellent and there are no noticeable odours in the building spaces. Thermal conditions are comfortable and there is no draught or overheating appeared. Users can control thermal and lightning conditions individually. In

addition, spaces have good sound conditions according to the purpose of use. (Säteri J., 2008, p. 2)
S2 category has good indoor climate quality and there are no noticeable odours in the building spaces. Spaces and structures contacted to the indoor climate have no damages that have decreasing effect on indoor climate or sources of contaminants. Thermal conditions are good and there is normally no draught. Overheating is allowed in warm summer days. Like in the S1 category, spaces have good sound conditions according to the purpose of use. (Säteri J., 2008, p. 2)

S3 category fulfills the minimum requirements for indoor climate quality, thermal, lightning and sound conditions set in code of building regulations. (Säteri J., 2008, p. 2)

Numerical limits for classification are set only for temperature and CO2 levels. Temperature is represented along with 24-hour mean and transient maximum values. Limits for the categories are showed in the Table 4.6.

Table 4.6 Numerical limits for indoor climate classification. (Säteri J., 2008, p. 3)

Category	**S1**	**S2**	**S3**
Temperature 24-hour mean [°C]	20-23	20-23	18-25
Transient max temperature [°C]	26	27	30
Max CO2 [ppm]	750	900	1200

4.2.3.2 Certifications

It has frequently become more common that buildings require proof of energy efficiency. In year 2010 established Energy Performance of Building Directive states that every European country must have their own energy performance certificate. Certificate must provide information about energy performance rating and recommendations for cost-effective improvements and it must be included in all media where building is put for sale or rent. This ensures that potential tenants or buyers are aware of the energy consumption and resulting carbon footprint of the regarding property. (European Commmission, 2010) In addition, as the energy consumption and energy cost will be playing a bigger role in the future property rentals, the requirement for certificate is encouraging the owners and occupiers to reduce their energy consumption (REHVA, 2017, p. 58).

There are also non-profit organizations, which has own certification methods for buildings. For example, Building Research Establishment (BRE) organization has worldwide certification – Building Research Establishment Environmental Assessment Method (BREEAM) (European Green Office, 2011) . Second widely used certification is Leadership in Energy and Environmental Design (LEED) established by U.S. Green Building Council (USGBC). These are voluntary but give positive environmental image to the community. They are used to rate the level of green building with several sections such as sustainability, water efficiency, indoor environment quality, innovation in design and regional priority. The effective sections in certification are rated individually and summed together, which forms the final grade for the building. The level of certification is determined according to final grade.

Some of the sections are required to fill in order to have any certification level. For example, in LEED, there is necessary to have permanent and continuous measurement device within specific accuracy that provides feedback on ventilation system performance that ensures the minimum outdoor airflow rates in any operating conditions. More specific requirements for the monitoring varies depending on the ventilation type and system implementation. For example, in mechanical VAV system there needs to be direct supply airflow measurement device measuring the minimum outdoor intake flow with ±15 percentage accuracy of the design minimum supply flowrate. Air flowrate must have alarm that indicates if it varies 15% or more from the supply air set point. There must also be CO2 sensor between one and two meters above the floor that has accuracy of no less than 75ppm or five percentage of the reading. If these are not fulfilled, the building will not get the LEED certification.

Comparison of the basic properties of LEED and BREEAM is presented in the Table 4.7.

Table 4.7 Basic properties of the LEED and BREEAM.

Feature	**LEED**	**BREEAM**
Certification levels	4	5
Effective sections	12	11
Maximum points	110 points	100%
Points needed for certification	40 points	30%

5. DEVELOPMENT OF ADVANCED MONITORING CONCEPT

This chapter focuses on the concept development in practice. First, the current situation is explained and available characteristics presented with prototype office. Then this chapter gives details for empirical studies, explaining the benchmarked companies and features, and presenting the question definition for the surveys.

5.1 Prototype office for the system

Halton has indoor climate monitoring prototype what has been built in co-operation with Etera. It is situated in Pasila, Helsinki and equipped with several sensors. The measurements are logged to the internet database, which is physically operating in Cloud, U.S. The system can be controlled through a web browser where users needs to be logged in, in order to have view or control of the system. The advanced monitoring concept is executed with one of the Halton's air conditioning solution, VARIO, which principle functionality is also presented in this chapter.

5.1.1 Available characteristics

There are several points that need to take into account when applying the developed concept in practice; the practical implementation brings limitations for the available characteristics because of the cost-effectiveness, competitiveness and numerous other attributes faced, when designing the advanced concept. The relation of all the effective factors is not discussed but the technical limitations are presented in the following sub-chapters along with prototype office as a reference.

5.1.1.1 Current measurands and features

Measurands of the system includes every measured variable value that system uses for the operation and system controlling. The measurement values are scaled so that they are easy to express with units that are commonly used in European area. Most of the measured numbers are integers, multiplied by 10 if compared to the correct value. Hence, using the numbers in the software gives accuracy of one decimal when dividing it by 10. All the measurands with the measurement locations, sensors with accuracy if provided and units are listed in

Table 5.1. The measurands from outdoors are no in the system yet, but inasmuch as the ease of installation, cheapness and possibility to invocation for example in preventing overheating, those are added to the table (Taylor J. et al., 2014).

Table 5.1 All measurands in the system according to its physical location.

Location	Measurand	Error	Unit
Chilled Beam	Beam inlet water temperature	±0,2	°C
	Beam outlet water temperature	±0,2	°C
	Boost enable status	-	-
	Cooling valve	-	%
	Heating valve	-	%
	Static chamber pressure	±3	Pa
Room	Room occupancy	-	-
	Space temperature	±0,2	°C
	Space CO2 level	±30	ppm
	Relative humidity	±2	%
	VOC level	-	ppm
	Occupy status	-	-
	Condense	-	-
Ducting	Supply damper position		%
	Actual supply air flow rate		l/s
	Supply duct air temperature	±0,2	°C
	Supply duct pressure	±10 [%]	Pa
	Extract damper position	-	%
	Actual extract air flow rate	-	l/s
	Extract duct air temperature	±0,2	°C
	Extract duct pressure	±10 [%]	Pa
AHU	HVAC mode status	-	-
	On/Off damper	-	%
Outdoors globally	Outside weather: - Temperature - Humidity - Wind speed and direction - Rain - Pollution	-	-

Features in the current system are following:

- Overview of the system (only for maintenance)
- Change the data collecting time interval (only for maintenance)
- Set limits for e-mail alarms and the alarm description regarding of every measurement variable (only for maintenance)
- View of the space temperature [$°C$], carbon dioxide [ppm], VOC [ppm] and humidity [$\%$] measurements
- Scheduling a meeting room and viewing the schedule
- Control the space temperature $\pm 3°C$ in $1°C$ steps
- Boost activation and de-activation
- Request a data report from history

5.1.2 VARIO concept

VARIO is Halton's solution for air-conditioning in high-level commercial offices. High level in this context refers to the indoor climate management that fills the highest requirements set in the standards ISO EN 7730, EN 15251 and CR 1752. VARIO can be executed with air-water or all-air room devices and it is reputed to provide flexibility and satisfaction for both, building owners and users by its features. For building owners, the system LCC are reduced, compared to conventional solutions, because of lower operation costs due to smaller energy consumption in use. In addition, the designing of the whole system is considerably simple because of constant duct size. For office user, the system is able to maintain desired indoor climate conditions for specific rooms so that every room can have their own temperature for example. (Halton Oy, 2014)

Basic idea of the VARIO's technical structure is to have one or few vertical ducting channels connected to the room devices and AHU with branches. This is called fork structure and its outline is depicted in Figure 5.1

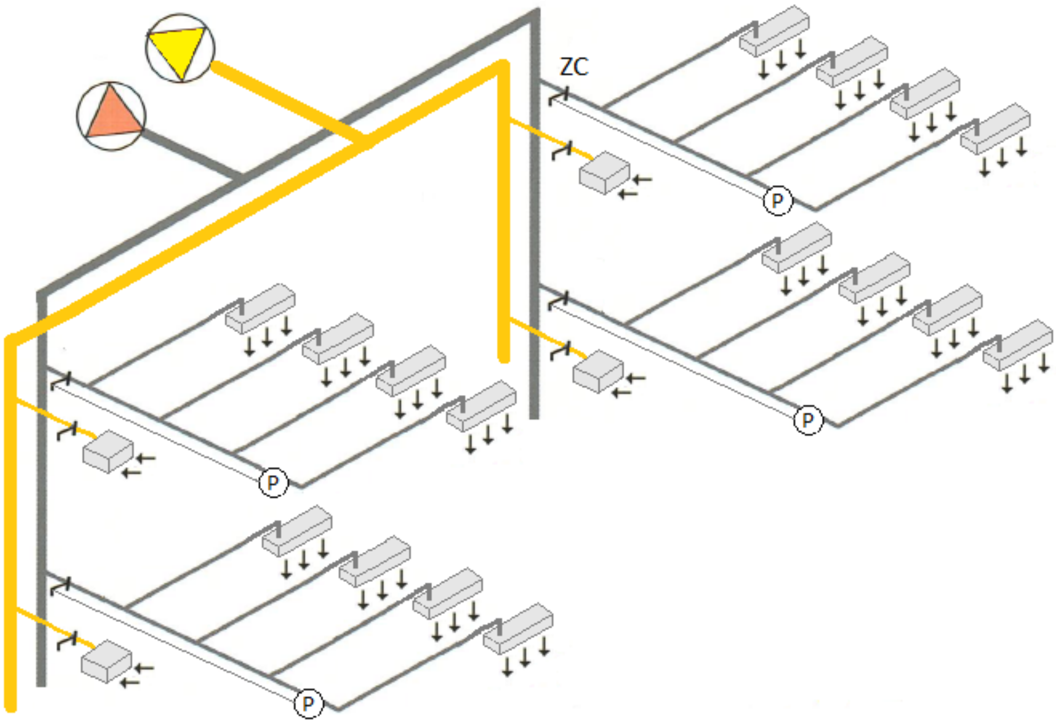


Figure 5.1 Fork structure for VARIO. (Sandberg, Esa et al. (2), 2014)

The branch of the floor is always controlled with controlling damper, what is called Zone Controller (ZC), and the exhaust air is removed either with one centralized outlet device from floor or in a distributed manner from every room. This type of structure is commonly used in Europe but there is also another option what is called circle structure. Circle structure means that ducting forms a circle shape in floor level. Building can be provided with one, two or more vertical channels. Circle structure is depicted in Figure 5.2.

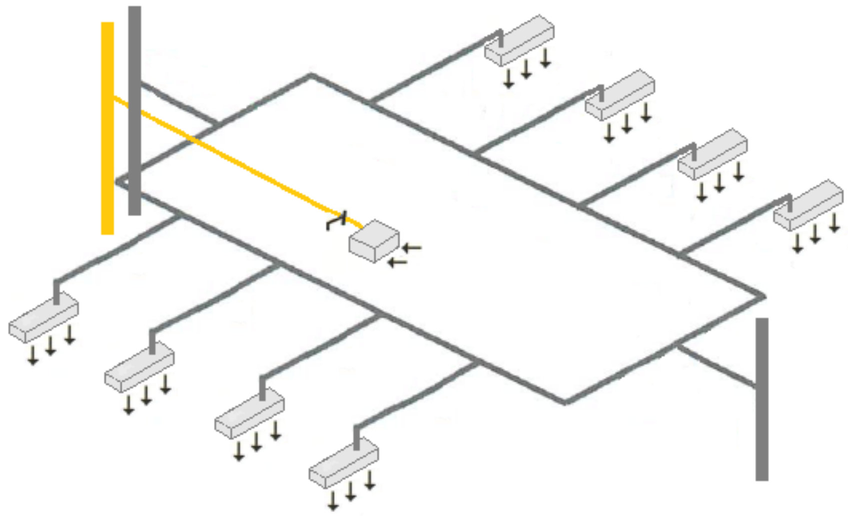


Figure 5.2 Circle structure for VARIO. (Sandberg, Esa et al. (2), 2014)

The indoor climate controlling ideology in VARIO concept is to have a Room Controller (RC) in every chilled beam or at least in every room and perform areal controlling according to the conditions in a specific room or space. Thus, the system has feedback of controllable variables by direct measurement or calculated from derivative variables and some constant information of the system. In order to control the conditions automatically in room level, the feedbacks for the controlling is measured and calculated also in room level.

Enabling the concentrated control of the building, every sensor of the VARIO concept is connected to the main controller directly or through some other hardware like router or repeater.

The hardware of the controlling in general are depicted in the Figure 5.3. Specific hardware is determined according to the used protocols in the BMS.

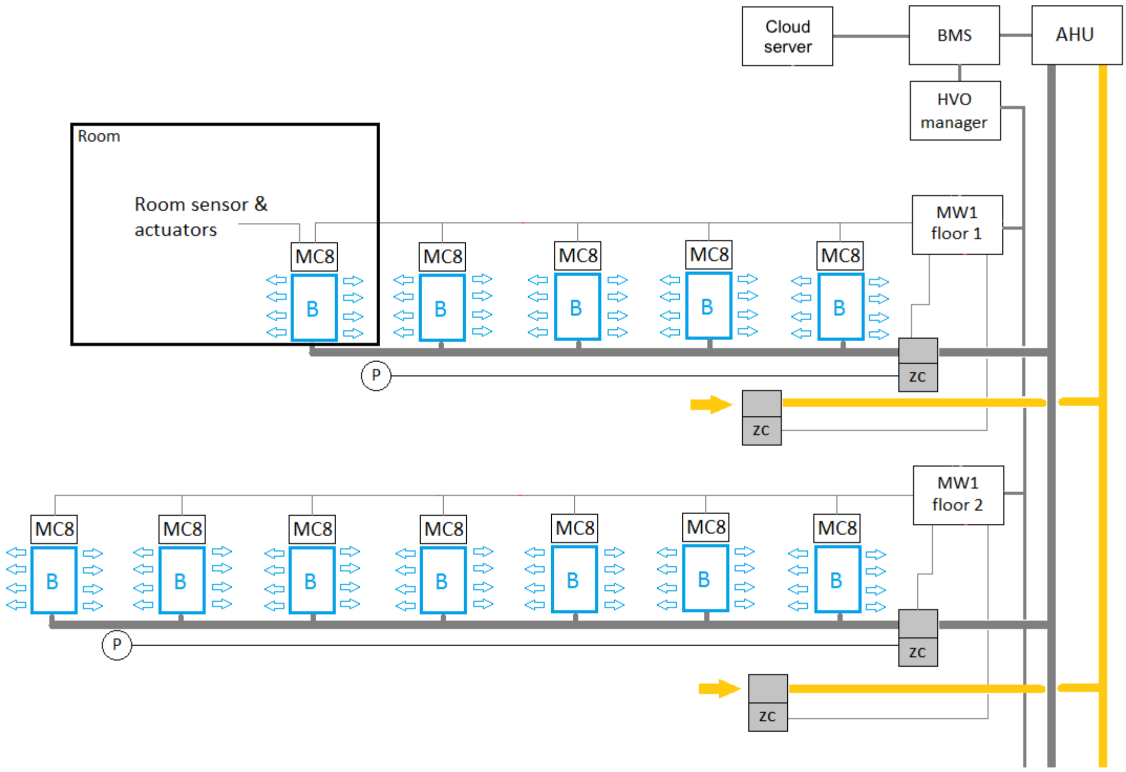


Figure 5.3 Hardware and sensors connection in the system structure.

Beams and channel dampers are controlled with several hardware. In room level or in every beam there is Room Controller (RC) MC8, in floor level there is repeater or router (MW1) for the main controller (HVO manager) that is connected to the BMS of the building. Room sensors and actuators in Figure 5.3 includes temperature, occupancy and condense sensors, wall control panel, window switch, window blinds and beam control valves.

When the current system is controlled through the cloud server, it is noticed to have approximately 3-10 seconds delay.

5.2 Advanced monitoring concept features recognition

As already mentioned, the recognition of the features for the advanced system is done with empirical studies on the field. First, this chapter gives the practice for benchmark by presenting the benchmarked companies and characteristics of their products. Then it produces the question for the surveys according to interest variables, which are also defined in this chapter.

5.2.1 Benchmarking

The first idea and outline for the concept design is sketched with research on other optional commercial indoor monitoring and control systems, available on markets by various suppliers. This method produces the knowledge on used and the most general features, basic level on the markets and used marketing assets in such systems. It is worth noting that benchmark gives only general review on the system, meaning that it is hard to make any exact decisions for example from the cutting-edge technology or features on the field, according to the results. Still, the outcome gives possibility for analysis on the current situation and principles of the systems that are available on the markets. The observed features of every benchmarked company's monitoring and control system are represented and explained in the Appendices IV.

Research was made benchmarking the top-competitors of Halton and relatively big HVAC system suppliers globally. Introduction of this thesis already mentioned the energy reduction potential in buildings, which has led to arise of many pure hardware and software supplier companies that focuses on building management. The most visible software production companies in the market according to HVAC system monitoring were involved to the benchmark. The total number of benchmarked companies is twelve and their products, advertisement concepts, strong operation areas and special top-technologies are presented below shortly. The mentioned characteristics of each company are the ones that the company itself seems to give value and importance according to their web pages.

Nonetheless, they all have own or collaboration outcome monitoring system available on the markets.

Lindinvent

This Swedish located competitor sells air diffusers, dampers, controllers, climate sensors and creates low life cycle cost ventilation solutions for offices, meeting rooms, schools and laboratories. The service for investigating the priors to renovating of existing systems, design and suggestions for old and new projects, control measurements and adjustments of air speed and pressure, and different supplements for existing projects are offered also. The company advertises to have “smart” ventilation solutions and increase the efficiency of HVAC system by demand based controlling due to building occupancy. That feature is relying on occupancy detectors integrated to every diffuser. (Lindinvent, 2017)

Fläkt woods

Fläkt woods is located in Finland and its products are fans and air blowers, air-handling units, control systems, room devices and air ducting supplements. The market segments of the company are residential buildings, non-residential buildings, special buildings, ship engineering and industry like tunnels and metros. The company advertises to be one of the market leaders and support the sustainable development by manufacturing and testing the products along to the international quality standards (ISO 9001, ISO 14001 and AH-SAS 18001). In addition, the sales organization can be consulted in order achieving the different levels of certifications like LEED, BREEAM, DGNB and HQE. Fläkt Woods has E3 concept that combines environment, economy and expertise. This concept is reputed to endorse inter alia optimal and comfort indoor climate, fire safety, environment, decreased life cycle costs and bringing additional value to the building projects. (Fläkt Woods, 2017)

Swegon

Swegon is Sweden located competitor that products are air-handling units, air diffusers, chilled beams, water chillers, fans, silencers and different controlling products. Swegon has HVAC solutions for hotel, office, retail and hospital segments but also for residential buildings. Swegon aspires to deliver intelligent products and solutions that creates good indoor climate and contribute energy savings. The vision is to be leading supplier in HVAC systems. The Swegon solutions are advertised to focus on better health & comfort, savings in installation & operation and reduced environmental impact. The most advanced systems of Swegon are executed wirelessly and the benefits are advertised to support and contribute the project's system specification, planning, installation, commissioning and operation. (Swegon, 2017)

EasyIO

EasyIO is Netherland located company that has no actual air-conditioning products. Still, they are offering comfort, savings and better buildings with their products that are controlling devices and software for the building energy management. EasyIO advertises to have easy, cost saving and environmental friendly solutions on HVAC controlling. The products are said to support multiple protocols such as Sox, BACnet, Modbus, EnOcean and Web API. It can also operate with any kind of HVAC system. The idea of the products is to first monitor the energy consumption and then analyze, optimize and control the system to save energy. EasyIO has also wireless solution, which is reputed to decrease the installation time and costs of the system. (EasyIO) (EasyIO, 2017)

Schneider

Schneider is France based multidimensional company that has numerous segments and fields on several industries as well as multiple service concepts for their products and other consulting utilities. Company focuses on automation solutions and does not have any actual air-conditioning products. Instead, it has many solutions on facilities management categorized due to the purpose of use. Schneider advertises to reduce systems downtime and maintenance costs, increase asset utilization and deliver maximum economic return on assets. The solution is outcome of collecting, visualizing, analyzing and reporting data the way that customers really need. (Schneider Electric, 2017)

Lynxspring

Lynxspring is United States located software and hardware supplier company delivering innovative IoT solutions for commercial, healthcare, educational and retail building segments. The company focuses on energy consumption reduction and aims for better performance in buildings. Company advertises to provide economical, technological, operational value for building as well as increased ROI. These values are generated with cybersafe and real-time remote access and control of all facility operating systems, better overall performance and energy management, increased occupation comfort, preventative maintenance, remote diagnostics, reduced downtime and providing knowledge of individual consumption patterns and trends. (Lynxspring, 2017)

Tridium

Tridium is United States located software and hardware company with several other hardware and HVAC company partners, providing IoT and automation solutions for commercial buildings, healthcare, government, industrials and smart cities. Software is advertised to be safe, easily customized and integrated, faster and more powerful for real-time data analytics. Tridium has also controllers with capability to communicate wirelessly with sensors. Wi-Fi can be also used as an access point for mobile phones. (Tridium, 2017)

KMC Controls

KMC Controls is manufacturing controllers, sensors and smart devices for building automation and energy management. This United States located company is providing solutions for achieving higher energy efficiency and indoor environmental quality. It also advertises to increase the occupant comfort and productivity. KMC Controls have partnership with Intel to secure the IoT-based communications of the products. In addition, KMC Controls mentions to have ISO 9001 certifications, meaning that the products are tested and validated during development and production. They give also 5 years limited warranty for all hardware manufactured by KMC Controls. (KMC Controls, 2017)

Trox

Trox is Germany located competitor manufacturing air-diffusers, several air-water room devices, silencers, control-, fire- and smoke-valves, air-handling units and fans. The field of expertise covers retail, office, healthcare, laboratory, hotel and educational buildings. Trox advertises to provide ecological and economical sustainability with simultaneously high comfort and low investment costs. Trox has also technical services offering reliability and efficiency for the delivered systems. (Trox, 2017)

Building Robotics

Building Robotics is United States based company with roots of advanced computing providing unconventional software solutions. The company has platform that can be applied in smart buildings offering comfort for individuals. The solution relies on smart phone or browser application where people can control various variables from indoor climate such as lightning, temperature and windows. Individual comfort comes from user personal preferences, ability to report about the discomfort, machine learning algorithms and the combination of those. (Building Robotics, 2017)

Dencohappel

Dencohappel is subsidiary of Fläkt woods manufacturing air-handling units, fan coil units, control devices, water chillers, filters and fan radiators. The Germany located company says to fulfil the requirements of all international standards in areas such as hospitals, cleanroom applications, data centers, factory buildings, offices and hotels. Dencohappel has also technical support service in those areas. Dencohappel's solutions are reputed to comprise efficiency, environmental friendliness, technical excellence, low operating costs and providing health and wellbeing. (Dencohappel, 2017)

Trane

Trane is United States based company manufacturing water chillers, air-handling units, fans and control devices with wide expertise areas, including educational, retail, healthcare, government, data center, commercial real estate and hospital buildings. Trane advertises to have innovative solutions with energy-efficiency, comfort, reliability, high quality and sustainability. (Trane, 2017)

5.2.2 Stakeholder based requirements with survey

In order to get knowledge and information on required features for the concept, relatively good method for researching those is to make a survey for the stakeholders. The scope for the survey in this thesis is to define the requirements for the concept, divided for the stakeholders.

Survey presumes that the information needs must be determined in terms of interest variables with their characteristics and objective quality of the results (Davino, C. & Fabbris, L., 2013, p. 5). Since the three core stakeholders might have different requirements for the concept like already noticed in the chapter 4.1, the highest information quality is gained when defining the interest variables and combining the surveys separately for each target group. The idea of gathering data, is not only find out about purpose of the product use or their workflow but also ask about stakeholders beliefs and attitudes (Nielsen L., 2013, p. 5). Interest variables for surveys was defined according to the benchmark results in Appendices VI, the questions presented in the introduction and possible benefits for different stakeholders, presented in the chapter 4.1.

Shared interest variables for every stakeholder was

- General gratification to the convention of current HVAC system
- Desire for air quality indicator
- Desire to give and receive feedback

Other interest variables for the core stakeholders are presented in the Table 5.2

Table 5.2 Interest variables for questions according to stakeholders.

Stakeholder	Interest variables
Property owner	1. Need for better energy monitoring and controlling 2. Willingness to give information and authority to monitor and control the space conditions for space tenants and office users 3. Method of payment in practice
Space tenant	1. Need for better energy monitoring and controlling 2. Willingness to give office users authority to control space condi-tions
Office user	1. Desire for individual preference based temperature controlling 2. Willingness to use smart phones or web browser as a part of control loop

The final survey questions according to the interest variables are presented in appendices V-VII. In addition, every answerer was able to give free feedback for the survey and present any extra desires for the concept.

6. SURVEY AND BENCHMARK RESULTS, THE ANALYSIS AND DEVELOPMENT

This chapter presents the results of empirical studies and hence produces knowledge for desired concept results. The concept features for advanced indoor monitoring system are combined from the requirements and needs along those results. This chapter offers also proposal for whole concept execution and presents implementation method for the chilled beam waterpower monitoring.

6.1 Results of benchmark

Benchmark results are presented in Appendices VIII. Features in the table are sort so that most general used feature is on top and the most features having company or system supplier is on left. Listed features was not decided in a specific way or for some clear reason, merely those formed according to the features and things the companies was marketing most noticeable at the time.

The results were used defining the interest variables, presented in the chapter 5.2.2, and questions for survey in Appendices V, Appendices VI & Appendices VII.

6.2 Results of survey

Survey was executed in Finland and it was sent approximately for 600 persons in total. Reaching for property owner responses, the survey was sent for customer relations managers, property managers, real estate managers and construction managers in office rental companies such as Etera, Senaatti kiinteistöt, Sponda, Ilmarinen, Regus, Sanska and Renor. It got 14 respondents, which had 236 customers in total, so one response in property owner group covers 17 customer relations on average.

Property owner respondents were requested to forward the survey for their customers when reaching for space tenants and office users. In addition, office rental companies' country leaders, as well as space tenants and office users was contacted directly what gained 45 responses for office user and only one for space tenants.

Because of small number of space tenant respondents, three office space tenants was interviewed to get more extensive view for space tenant requirements. Survey questions in

Appendices VI were used as a base for the interview. Two of the interviewees had approximately 1300 employees in total and the last interviewee had four employees to consider different size space tenant's requirements. (Tamper T., 2017)

6.2.1 Question results

Detailed property owners' and office users' responses are presented in Appendices IX and

Appendices **X**. The stakeholder needs for the system was determined so that if 50% or over of the respondents reacted affirmatively on the question, the interest variables relative to the question was accepted as requirement for the monitoring concept. Requirements for the space tenants were determined directly on the problematics and apparent needs based on the interview topics. The arisen requirements are listed in the Figure 6.1. There is also other requirements listed, which covers the global scale needs, presented earlier in this thesis and some features arisen in benchmark.

Figure 6.1 Stakeholder requirement results.

The R in the Figure 6.1 represents a requirement that was accepted for the advanced monitoring concept. So according to the figure there is 22 requirements in total: 9 for office users, 6 for property owners, 4 for space tenants and rest of them are general requirements.

6.2.2 Feedback from respondents

Surveys had optional questions for feedback and expectations for the system. The received feedback and development topics are presented in the Table 6.1.

Table 6.1 Feedback and development topics arisen in surveys.

Stakeholder	**Feedback**
Property owners	- Perceiving the air conditioning quality is individual experience - The companies have changed to multi-space offices, which mean that there are rooms with different climate conditions and office users can decide where to work
Space tenants	- Is it possible to combine the utilization rate and working time accounting of the office workers? - The temperature controlling according to office workers' preferences would be good if it really works. The problem is that it could be used incorrectly - If tenant would pay the rent according to energy usage, it would pay more attention to the use of air-conditioning. Thus, it would be used more effectively and probably achieve longer life-time
Office users	- The easiness of application use is on priority and the user interface should be simple - Ordering some aromas like lavender or lemon to the work post could have calming and focusing effect - Fresh air is more important that temperature

Table 6.1 can be used in future development of the concept.

6.3 Desired new concept features

The final features for desired concept was collected straight from the stakeholder's requirements what can be seen in Figure 6.1 and were arranged in a new way in order to reduce repetition. This way the monitoring system supports every stakeholder in the best possible way. Difference between those figures is that the notion requirement (R) is now changed to feature (F) as it describes now a feature for one or some of the stakeholders. Features for the advanced concept are presented in the Figure 6.2.

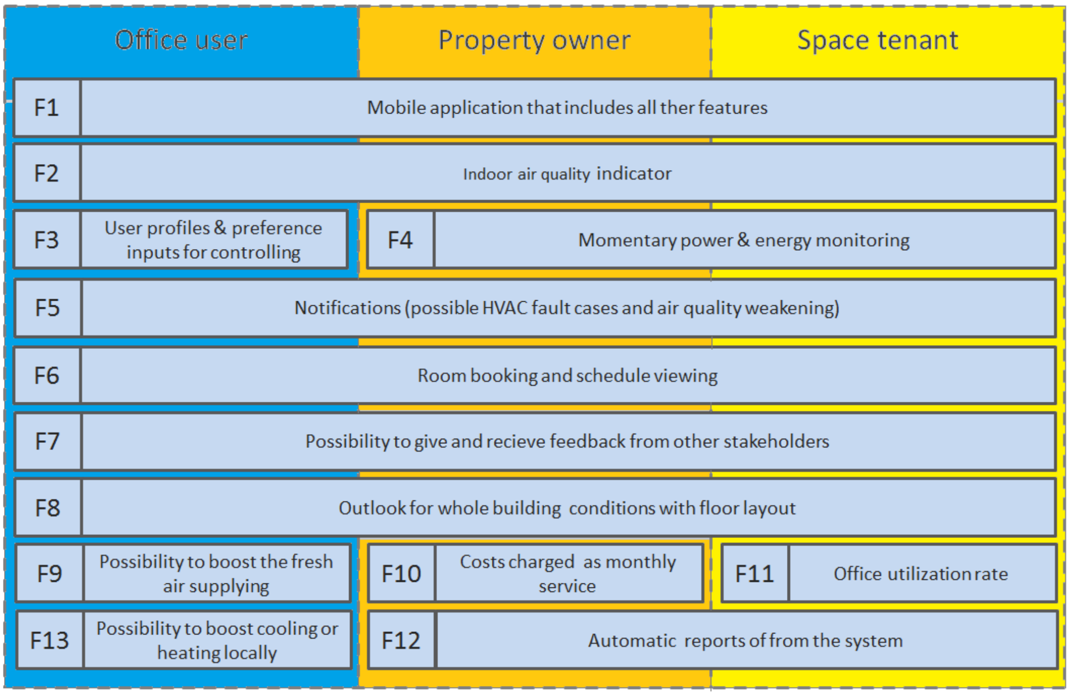


Figure 6.2 All system requirements and integration to features for stakeholders.

As already mentioned, F in the Figure 6.2 represents a feature for stakeholder. Those are numbered from 1 to 12 and appears in different sizes horizontally. The figure shows, which features are for which stakeholders so that all the features crossing the stakeholder's area (blue = office user, orange = property owner, yellow = space tenant), belongs for the regarding stakeholder. For example, F1 is for every stakeholder, F3 only for office user and F4 for property owners and space tenants.

6.4 Analysis of concept execution

Desires for the advanced concept bring changes to the concept implementation compared to the current situation. Rest of the chapter six covers implementation suggestions for the determined concept features presented in the Figure 6.2., presenting technical architecture for the concept, mobile application, indoor air quality indicator, transient waterpower consumption function in practice and suggestions for the fault detection feature.

6.4.1 Suggested technical architecture

In order to fulfill all features for desired system in a functional way, the architecture of the old system, presented in the Figure 5.3, needs modification. 3-10 second latency in data communication is speculated to originate from BMS and decrease the user experience. Thus, the delay could be prevented and user experience increased by skipping BMS when communicating between room controller, cloud server and user. The information can be updated to the BMS through the local server with that delay it has without any major disadvantages. Thus, the suggested technical architecture for the concept is presented in Figure 6.3.

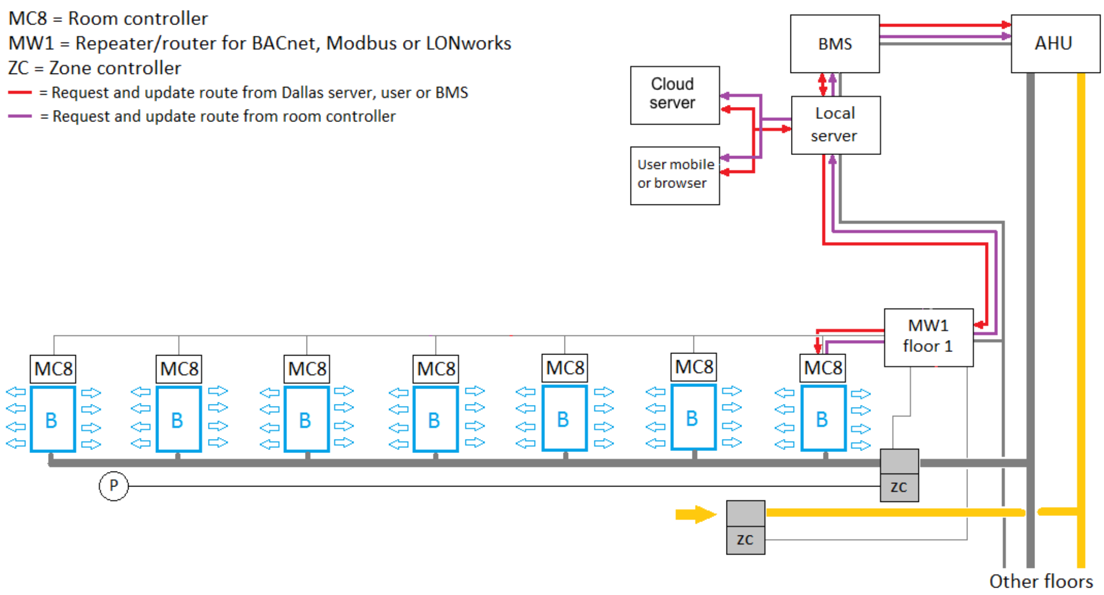


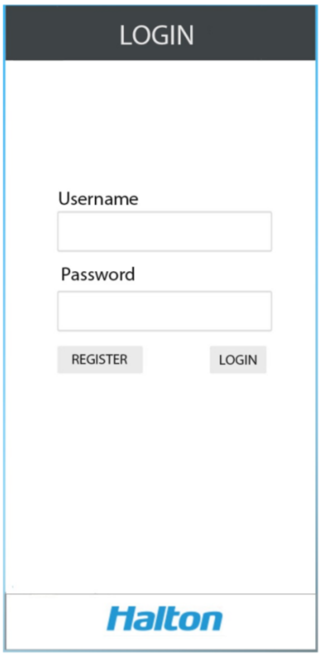
Figure 6.3 Advanced concept architecture with possible communication routes.

It is almost identical with Figure 5.3 but HVO manager is changed to a server located in the building. The communication between mobile application and room controller should be prioritized so that the delay is minimized. Thus, the situations that user gives several control requests for the system before it reacts to the first requests could be prevented. Hardware of the system should have solution for every three protocols presented in the chapter 3.2. Hence the system could be offered to the major of the buildings in Europe.

Completely other option would be using wireless room controllers like three benchmarked competitors. That would decrease the installation time and costs because the system would not have physical network wires or cables.

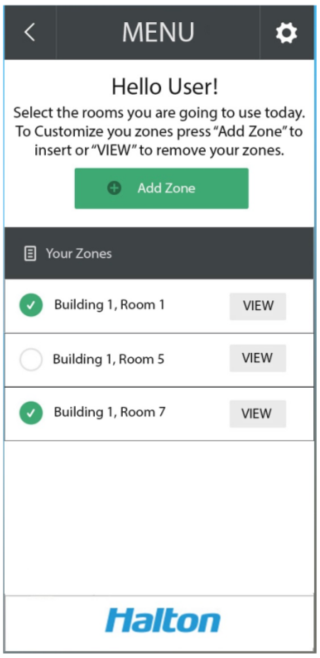
6.4.2 Mobile application

Survey indicated that majority of the respondents would use mobile application. Hence, the advanced monitoring and controlling concept features are integrated to a mobile application what users can practically use on their working office in daily basis. Suggestions for the application principles, based on the concept features in Figure 6.2, are presented below:



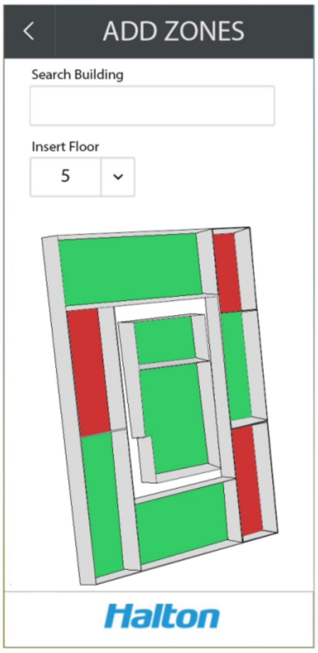
Login window

This is the login window view for every user and it opens when application is ran. Users will get register code from building's system management according to the role in the building. Register code will give the user profile with privileges of office user, space tenant or building owner, which has different features and rights in the application. After that, they can log in using the username and password.



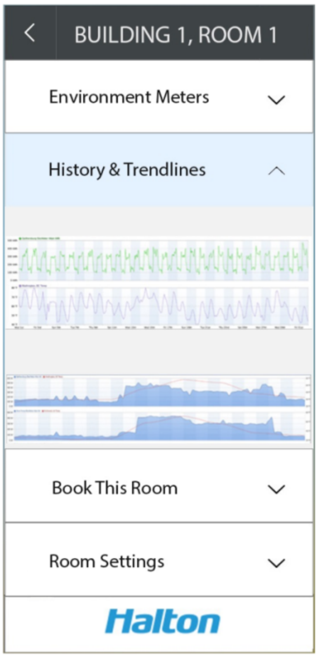
Menu

This is the menu or home view in the application. It shows instructions for the user. "Add zone"-button will take the user to the "Add zones"-view, presented in the next page. Menu is also showing "Your zones" that user has already assigned with "Add zone" request. Every zone assigned has "VIEW"-button what takes user to the "Room monitoring"-view, also presented in the next page. Zones have also option to check them with green check mark. This means that the user is using that room and users temperature preference is taken into account, calculating the reference room temperature shown in the Figure 3.7.



Adding zones

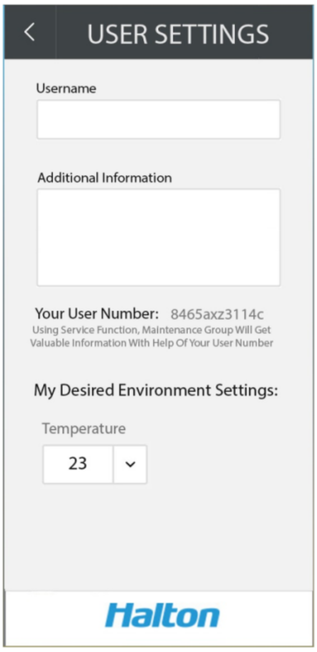
This is the view for adding zones. Users can search building with name and select the floor what will bring the floor layout to the window. Red zones indicate zones that you already have in "Your zones" and it cannot be selected. Pressing the green zone will add it to "Your zones".



Zone monitoring

By pressing the "VIEW" button in the menu will display this zone monitoring view. There user has dropdown bars for following features:

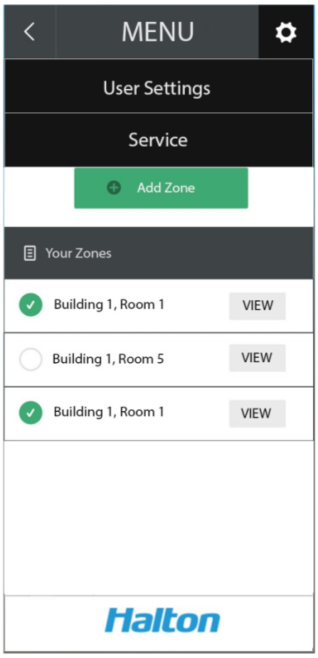
- Environment Meters shows the indoor air quality indicator presented in the next chapter. There is also option for displaying the determined individual measurements in real time.
- History & Trendlines shows history data of the indoor climate.
- Book This Room gives ability to view calendar of the room if it is a meeting room. There the user can reserve it for desired time if it is free.
- Room Settings shows the reference values for controlling. Settings can also be changed if the user has privileges for it.



User settings

This is the user settings view where user can change the profile settings. In the settings, user can change the username and add additional information such as employer company, own working post, working hours or other useful information. Settings view also shows the user number that building's management can use for identifying user more precisely if user sends service request or feedback.

User can add the temperature preference to the profile. It is used when calculating the reference temperature for a room. Every user's, that has selected the specific room in the menu view, temperature preference is included to calculating the weighted average for example based on PPD presented in Figure 4.1.



Menu dropdown for settings

This shows the dropdown bar if settings button is pressed in the menu view. There user has buttons for User Setting and service where user can send requests or feedback to other determined stakeholders.

The features, stakeholder's application view and privileges in practice will probably be project-specific since the survey results showed that there are differences in stakeholder's preferences. Thus, it is important that the software can be customized according to the customer's penchants.

6.4.3 Indoor air quality indicator

One obvious requirement from office occupants according to the survey was Indoor Air Quality (IAQ). The indicator for the IAQ is designed not only for experts in the field of environmental engineering or HVAC systems. It is designed also for the uneducated and regular persons, and hence it is essential to envision also their needs and requirements from the indicator (Nielsen L., 2013). Therefore, the developed IAQ indicator should be simple and easily usable, like arisen in the surveys free feedback section. Thus, instead of presenting the air quality according to every individual pollutant concentration, the partial IAQI should be gathered under one air quality indicator.

The EPA outdoor AQI is applied to calculate individual effective factor index of FIAQI according to Equation 1. EPA outdoor AQI is adapted to indicate the air quality with four levels which are Excellent, Good, Fair and Poor. The effective factors of FIAQI are temperature, VOC level, CO2 level and relative humidity and they were chosen according to the

Table 5.1. Boundaries for index levels are for one-hour average of measurements applied from standard EN 7730 and IDA classification. Relative Humidity (RH) and temperature is evaluated due to the difference between actual room value and desired value. Desired value for temperature is the reference value for room temperature showed in the Figure 3.7 and 50% for relative humidity. The boundaries and category descriptions are presented in the Table 6.2.

Table 6.2 Boundaries for quality meter's concentration levels according to standard EN 7730.

Description		Excellent		Good		Fair		Poor	
Index Values	Ilo	0		51		101		251	
	Ihi	50		100		250		500	
Concentration		BPlo	BPhi	BPlo	BPhi	BPlo	BPhi	BPlo	BPhi
Co2 [ppm]	1hr	0	400	401	600	601	1000	1001	2000
ΔRH [%]	1hr	0,00	5,00	5,01	10,00	10,01	15,00	15,01	30,00
ΔT [°C]	1hr	0,00	1,00	1,01	1,50	1,51	2,00	2,01	5,00
VOC [ppm]	1hr	0	400	401	600	601	1000	1001	2000

Once the individual AQI of the effective factors are calculated, the FIAQI can be determined with three methods: average, weighted average or determine every situation separately. Example for the decision table is presented in the Table 6.3.

Table 6.3 Decision table for the FIAQI.

T,RH	VOC, CO2: EE	EG	EF	EP	GE	GG	GF	GP	FE	FG	FF	FP	PE	PG	PF	PP
EE	E	E	G	G	E	F	G	G	G	G	G	F	F	F	F	P
EG	E	E	G	G	E	F	G	G	G	G	F	F	P	F	F	P
EF	G	G	G	G	G	G	G	F	F	G	F	P	P	F	P	P
EP	G	G	G	F	F	G	F	G	G	G	F	P	F	F	P	P
GE	E	E	G	G	G	G	F	G	F	F	F	F	P	F	P	P
GG	E	E	G	G	G	G	G	F	F	P	P	F	F	F	P	P
GF	G	G	F	F	G	G	G	G	F	P	P	F	F	P	P	P
GP	G	G	G	G	F	F	G	F	F	F	F	F	P	P	P	P
FE	G	G	G	F	G	G	F	P	F	F	P	P	F	F	P	P
FG	G	G	F	F	G	F	P	P	F	F	P	P	F	P	P	P
FF	F	G	F	F	F	F	F	F	P	P	P	P	P	P	P	P
FP	F	F	F	F	P	P	F	F	P	F	F	P	F	P	P	P
PE	F	F	F	P	P	P	F	P	P	F	P	F	P	P	P	P
PG	F	P	F	F	P	F	F	P	P	P	P	P	P	P	P	P
PF	F	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P
PP	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P	P

The decision table shows every possible combination of every level for the four effective factors. The scale in the table has two letters that shows the individual effective factor's index so that in the vertical axis first letter is for temperature and second for relative humidity. In horizontal axis, first letter is for VOC and second for CO2.

The FIAQI can be indicated for the user with meter depicted in the Figure 6.4

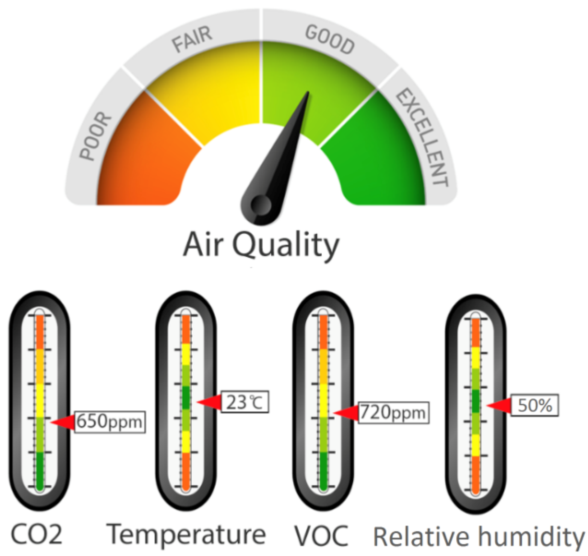


Figure 6.4 Proposal for graphical FIAQI meter.

Table 6.4 presents two example situations for using the IAQI. The weights used in the weighted average are RH=0.25, T=0.15, VOC=0.25 & CO2=0.35. Table shows that using different method in the air quality determination produces different result for the total air quality.

Table 6.4 Two example situations for using IAQI.

	Situation			
Measurements	CO2= 660 ppm, ΔT=1.2°C, VOC=470ppm, ΔRH=11%		CO2= 840 ppm, ΔT=2,1°C, VOC=520ppm, ΔRH=16%	
Index values	CO2= 123.4, ΔT=70, VOC=68.2, ΔRH=130.8		CO2= 190.4, ΔT=258.4, VOC=71,2, ΔRH=267.6	
Method	Index value	Total air quality	Index value	Total air quality
Average	98,1	Good	196,9	Fair
Weighted average	103,4	Fair	190,1	Fair
Decision table (CO2,ΔT,VOC,ΔRH)	FGGF	Good	FPFP	Poor

The used method of determining the IAQ in practice could be country-, building- or project-specific according to customer desires. One option is also to give users authority to choose the method and weight their own indicator in their user profile on mobile application. Hence, the indicator would give information according to individual preference.

6.4.4 Transient power and energy consumption monitoring software documentation and testing

The new concept needs energy monitoring for property owners and space tenants. As the space in building can be divided for several space tenants, the most efficient, accurate and profitable monitoring is achieved when monitoring is executed in the level of individual device. Hence, even the layout change due to possible renovation does not have influence on space tenant's energy monitoring because the beams can be regrouped easily for the customers. This feature could also use as base for the space tenant's energy charging according to the consumption if desired. The feature for power monitoring was implemented to the demo office presented in the chapter 5.1. The function for the calculation concerning the implementation is running in the room controller and the result is then sent to the cloud server over Modbus and internet networks. The experiment for the calculation in practice is also showed in the end of this chapter.

Function block

Function block for the momentary power calculation is showed in Figure 6.5. The function block is a screenshot from Beremiz what is the program for controller programming. The function is programmed with VHDL language and the program compiled the function block automatically according to the code.

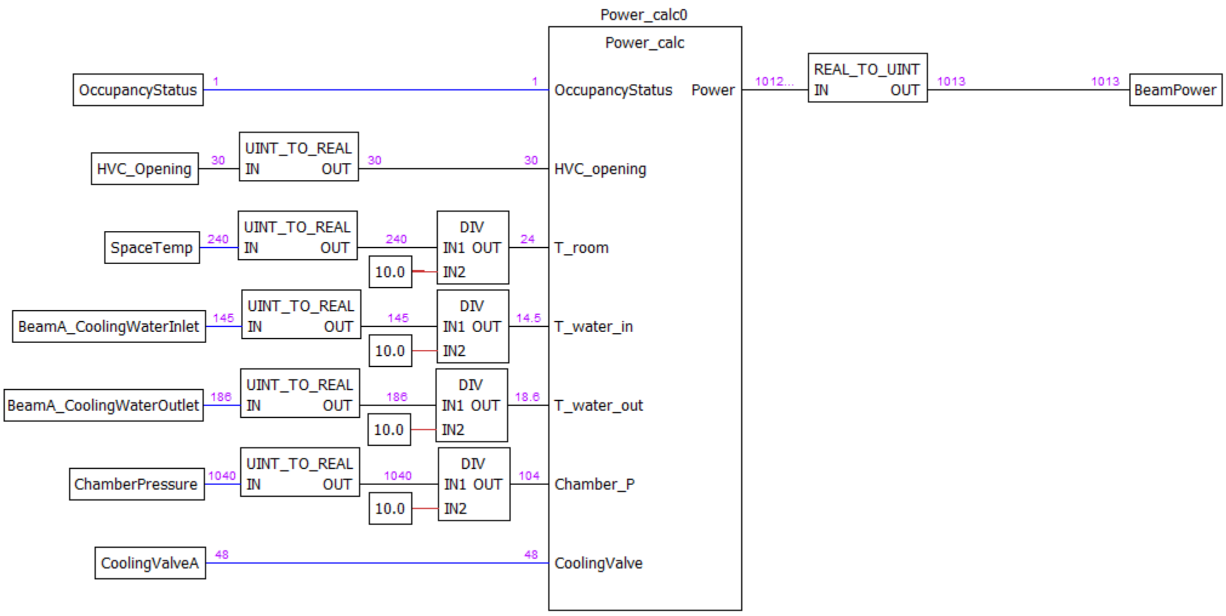


Figure 6.5 Function block for momentary power.

Function is executed so that it gives results differing from zero only if cooling valve position is 5% or over and chamber pressure is 10 pascals or over. Thus, it gives results only when the beam is using power. When OccupancyStatus have a value 3, the beam is in the boost mode and function uses the boost values in **Error! Reference source not found.** for the calculation. The input measurement datatypes from the room are Uint so it needs datatype conversion to Real in order to perform any mathematical operations. OccupancyStatus and CoolingValveA are only used as comparison in the function block code so there’s no need to do conversion for those. The converted values are also scaled with 10 as a multiplier, so to get the real value those are divided by 10 in the function block. The function block result is converted. Function block also contains beam dependent constants which are defined in power measurements done in designing phase. Those are not shown in this thesis but has been added to function block as inner parameters.

As the Figure 6.5 shows, the function block takes seven input parameters what are explained in the Table 6.5.

Table 6.5 Inputs for power function.

Input	Name in function	Datatype
Status of the beam (3=boost, others referred as min or normal)	OccupancyStatus	Uint
HVC list position in beam	HVC_opening	Real
Temperature of the room	T_room	Real
Inlet water temperature of the beam	T_water_in	Real
Outlet water temperature of the beam	T_water_out	Real
Chamber pressure	Chamber_P	Real
Cooling valve position (0-100%)	CoolingValve	Uint

Modbus Holding register allocations

In order to monitor or change the variable over the internet, it needs to be moved master device that forwards it to the Cloud server. Data communication in the demo office is done along Modbus protocol. Hence, every transferred variable needs own Modbus holding registers. At this point, there are only one variable that needs to be monitored and one variable that can be changed. Those variables need Modbus holding registers and those was allocated according to Table 6.6.

Table 6.6 Allocations to Modbus register.

Modbus holding register variable	Location	Variable for the register
MB_HR_100	%MW5.0.0.99	HVC_Opening
MB_HR_101	%MW5.0.0.100	BeamPower

Simulation test

The function calculation was tested by simulating it in Beremiz. Two random cooling situations were calculated in the simulation. First was in the normal mode and second in the boost mode. The results were compared to the Halton’s designing tool with same inputs and the comparisons are shown in the Appendices XI and Appendices **XII** but also in the Table 6.7.

Table 6.7 Comparison of the simulation and HIT design results.

Working mode	HIT result	Function result	Difference in units	Difference in percentage
Normal	1034W	1013W	21	2,03%
Boost	1379W	1383W	4	0,29%

Table 6.7 shows that simulation with Beremiz and the HIT design tool with same situation has difference. Normal mode occurred higher difference by 2,0 percentages and boost mode only 0,3 percentages. At least the part of the error occurs because of the one-decimal roundings in the Beremiz software.

Testing the function in practice

Resulting power in the practical test for the calculation function is depicted in the Figure 6.6.

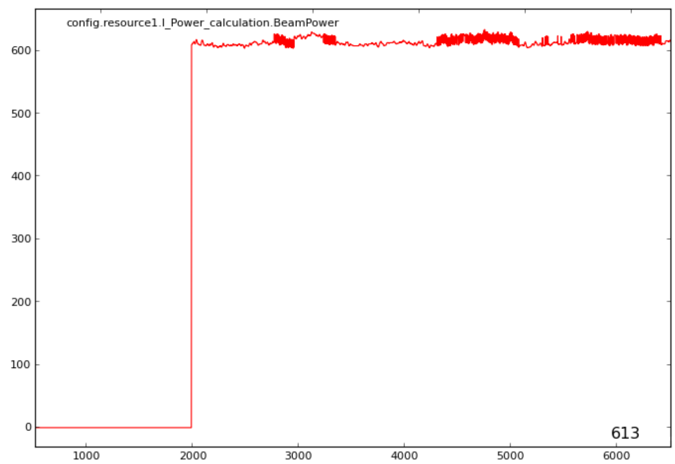


Figure 6.6 Test in the Etera demo office 23.3.2017.

The test was made in the early spring and although it was sunny, the beam was not automatically in the cooling mode. Thus, the cooling water valve was forced fully open at the point of two thousand seconds (x=2000) what can be seen from the figure. The cooling water started to flow and function started the calculation according to measurements. The red line is the power as a function of time and consumed power was 613W at this situation. Other measurements and corresponding HIT value for the power comparison, in the regarding situation are presented in the Table 6.8.

Table 6.8 Test conditions and comparison to the HIT results.

Variable	Value
Room temperature [°C]	21,4
Water inlet temperature [°C]	15,5
Water outlet temperature [°C]	17,1
Chamber pressure [Pa]	64
HIT result for situation [W]	641
Difference between HIT & calculation function [%]	4,37

Table shows that the difference between HIT design result and actual power calculation is 4,4 percentages. It is double compared to the difference between simulation and HIT results presented earlier. The reason for the total error can be sum of quantization error, rounding error and inaccuracy of the sensors. Only the temperature sensors used in the demo office (TEPK NTC10) gives ±0,2°C at 25°C, which causes ±50W mistake in worst-case scenario. This covers already the difference between HIT and calculation results.

6.4.5 Fault diagnosis features

Desired advanced monitoring concept requires notifications from fault cases. This means that the system needs to be able to detect faults and give some information from those to the users.

Current system can only be set to give alarm by email if some measurement variable crosses determined limit. Thus, it is considered to cover only the "standard report" part in the Figure 3.9. However, Figure 3.10 presents two well working methods, already used in HVAC systems, how the current fault diagnosis feature can be expanded to upper context levels in the Figure 3.9. The methods are based on the process of the components and typical faults presented in Table 3.1. Therefore, it is possible to divide the fault diagnosis into more specific, informative and causal reports. By knowing the HVAC process, it can be set to give also predictive analysis along the failed component. For example, if the process-based model notices that cooling valve in the chilled beam is stuck and fails to open, the fault report for the user could be following:

"*Cooling valve of the chilled beam number x is not working. In consequence, chilled beam is not able to provide cool air, the temperature might rise and conditions can get uncomfortable in room x. Please, check the valve.*"

Same models can be applied to a bigger process. Thus, one method for fault detection is to utilize the equations for water power calculation presented in chapter 6.4.4. Residual in the model in that case would indicate difference in efficiency of the chilled beam over the time. Possible reasons for that can be simply old age of the device or it's dirtiness.

7. CONCLUSION

This thesis shows that there exist several expectations and desires for the advanced indoor climate monitoring concept in different levels; Some of them are global and stakeholder-based requirements, but application can be also used to indicate that building meets specific parts of some certification. Certifications, as the legislation, are normally used in country-level and hence the concept is considered to have also some local requirements as well.

The presented concept according to this thesis is combined along the research on stakeholder-based requirements in Finland. The sampling size in the surveys was relatively small so the used 50% limit for requirement acceptance as a feature for the new concept might be insufficient. Still, the concept outcome can serve office building related stakeholders well in Finland but because of culture differences and local requirements, the optimal outcome can vary in other countries because of different certifications and classifications. Those requirements can be still achieved by modification of some limit values in the features, according to different certifications or other country specific desires.

Suggestion for the concept implementation given in this thesis, does not fulfill all the features and requirements according to the research, but major of them are covered relatively well. Mobile application today, is not only, but apparently one of the easiest and the most effective way to involve the occupants as a part of the building's temperature controlling loop. Also the IAQI in this thesis does not have any established method or guidelines for weighting the factors, but it gives comprehensively user-friendly method for IAQ monitoring. Among these matters, the specific methods for the temperature set point determination and other details for the system might come from the buying customer, project-specifically.

Even if there where accurate limits for the four effective factors used in developed IAQI, it would not be absolutely inclusive because of characteristics in measurands used in the air quality determination; VOC sensor in the system measures the total amount of volatile organic compounds in air and hence it can give same reading to the different combination of the pollution compounds. As the chapter 2.1 shows that different compounds have different health effects, VOC sensor lacks the accuracy in air quality determination, from the point of health risk evaluating. However, it is directional and using it, could already prevent sickness, decrease costs in health care and increase productivity and comfort of the office users. It is also method within the limitations presented in the chapter 5.1.1 and improving it would require more sensors to the systems.

8. SUMMARY

This thesis studied the possibilities to develop the indoor climate monitoring and controlling system in office buildings, based on the stakeholder's requirements and needs. Effective areas concerning HVAC systems, air quality and building management was researched. The current system was also presented with measurands and technical limitations along the demo office in Helsinki, Finland.

Then the development started by benchmarking the top competitors and systems available on the market. After that, targeted surveys was combined according to benchmark results and sent for the defined core stakeholders in Finland. Questions were sent for about 600 people in total. Building owners and office users got 59 respondents in total but space tenants only one. Thus, the space tenant's requirements were clarified by interviewing 3 space tenants more comprehensively. Space tenant companies were different size and had employees from 4 to 1300 to have wider view of the matter.

8.1 Key results of the work

The results from research, benchmark, surveys and interviews were used together to combine the new concept for indoor monitoring system, which was presented by means of features that are available for the core stakeholders. System implementation was suggested to execute by mobile application because nearly everyone got a smartphone, and hence also the monitoring device within reach all the time. It is also relatively easy way to involve occupants in the controlling loop for room temperature what strives to find the consensus for the temperature set point determination in a group of people, working in the same room.

Fault diagnosis in the concept was proposed to execute along with data-driven and history-based model on components and chilled beam waterpower consumption. The method could indicate the fault location and size by observing the residual from the model and actual process. It would also indicate if the efficiency of chilled beam decreases for some reason.

Practical indoor air quality indicator was developed for the occupants and it appeared as straightforward as expected to. However, the lack of sensors results that it is insufficient to evaluate all the health effects from the measured air accurately. The indicator presents the air quality within four levels and it can be modified to indicate if the building achieves some parts of building certifications of indoor air classification.

Water power consumption monitoring of the chilled beam was implemented to the demo office located in Pasila. Calculation function was coded based on the power measurements of the beam and it was running in the room controller. It was first simulated and then tested in practice after the simulation. Both results were compared to the chilled beam designing tool result with the same conditions according to simulation and test. It showed that difference in simulation was 2,03% in normal mode and 0,29% in boost mode. Practical test had difference of 4,37%. The error in power units was between 4 and 28 watts.

8.2 Suggestions for future work

There should be more precise research on the possible certifications and classifications. Then the whole concept should be implemented in practice with pre-defined profiles for every certification and classification levels. Thus, the concept would be versatile and used for different purposes. Implementation should be done according to Figure 1.2 so that the finest improvements to the concept is done due to the feedback received from the customers.

Life cycle cost assessment should be provided with system that has sensors what are able to measure the individual air pollution concentrations. That would give information if it would be reasonable to improve the air quality indicator with more inclusive sensors.

Accuracy of the power calculation should be tested also with real power measurement devices installed into the beam. Hence, it would give more comprehensive estimate from accuracy of the used power calculation function. Also the calculation should be implemented to indicate the energy consumption what is power integrity over tim

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Appendices I: List of WHO pollutants in the guidelines (WHO, 2000)

Organic air pollutants	Inorganic air pollutants	Indoor air pollutants
Acrylonitrile	Arsenic	Environmental tobacco smoke
Benzene	Asbestos	Man-made vitreous fibers
Butadiene	Cadmium	Radon
Carbon disulfide	Chromium	
Carbon monoxide	Fluoride	**Classical air pollutants**
1,2-Dichloroethane	Hydrogen sulfide	Nitrogen dioxide
Dichloromethane	Lead	Particulate matter
Formaldehyde	Manganese	Sulfur dioxide
Polycyclic aromatic hydrocarbons	Mercury	Ozone and other photochemical oxidants
Polychlorinated biphenyls	Nickel	
Polychlorinated dibenzodioxins and dibenzofurans	Platinum	
Styrene	Vanadium	
Tetrachloroethylene		
Toluene		
Trichloroethylene		
Vinyl chloride		

Appendices II: WHO guidelines for indoor pollutants. (WHO, 2014)

Pollutant	Mean concentration over the averaging time						Unit risk
	15 min	**30 min**	**1 hour**	**8 hours**	**24 hours**	**1 year**	
PM2.5 (µg/m3)	-	-	-	-	24	10	-
PM10 (µg/m3)	-	-	-	-	50	20	-
Benzene (leukemia risk per 1µg/m3)	-	-	-	-	-	-	$6 * 10^{-6}$
Carbon Monoxide (mg/m3)	100	-	35	10	7	-	-
Formaldehyde (mg/m3)	-	0.1	-	-	-	-	-
Naphthalene (mg/m3)	-	-		-	-	0.01	-
Nitrogen dioxide (µg/m3)	-	-	-	-	-	40	-
Polycyclic-aromatic Hydrocarbons (lung cancer risk per 1ng/3)	-	-	-	-	-	-	$8.7 * 10^{-6}$

Appendices III: Standard EN ISO 7730 requirements collected to the table.

Type of building	Activity [W/m^2]	Category	Operative temperature [C°]		Max mean air velocity [m/s]	
			Summer	Winter	Summer	Winter
Single office Landscaped office Conference room Auditorium Restaurant Classroom	70	A	24,5±1,0	22,0±1,0	0,12	0,10
		B	24,5±1,5	22,0±2,0	0,19	0,16
		C	24,5±2,5	22,0±3,0	0,24	0,21
Kindergarten	81	A	23,5±1,0	20,0±1,0	0,11	0,10
		B	23,5±2,0	22,0±2,5	0,18	0,15
		C	23,5±2,5	22,0±3,5	0,23	0,19
Department store	93	A	23,5±1,0	19,0±1,5	0,16	0,13
		B	23,5±2,0	19,0±3,0	0,20	0,15
		C	23,5±3,0	19,0±4,0	0,23	0,18

Appendices IV: The benchmarked features and the definitions on the table.

Feature	Feature definition
Remote control	Capability to control the system remotely
Protocols	Supported protocols (BACnet, Modbus, LonWorks)
History viewing	Possibility to view the history data from the system
Room level control	Capability to control the system on a room level
Graphical indicators	Values are presented with graphical indicators
Mobile app	There is a mobile application for the monitoring system
Web browser app	There is a web browser application for the monitoring system
Alarming options	Capability to set alarms on the variables
Automatic reports	Capability to give automatic reports from HVAC operation
Scheduling & viewing	Capability to schedule and view the schedule for HVAC system
Various user levels	Usage occurs in specific level (Admin, owner, tenant, occupant…)
Component viewing	System is able to show the components in graphical structure
Security	Company advertises the security of the system
Fault detection	System is able to help with fault detection
Floor layout view	Building can be viewed by its layout
Table & filter mode	Variable values can be sorted, filtered and viewed in table
Optimization	Capability to optimize the supply air temperature and pressure
Support service	Company has support service for their products and systems
PC software	There is a PC software application for the monitoring system
Real-time energy mon.	Possibility to monitor the systems energy consumption in real-time
Fire safety functions	System has some kind of fire safety function
Weather information	Showing the weather information in GUI
Individual control	Individuals have ability to affect to the system operation
Settings saving option	Settings of the system can be saved to a profile and load easily
GUI customizing	GUI can be customized based on customer needs
Component identification	System identifies automatically the new installed components
Room level energy mon.	Energy consumption can be monitored on room level
Wireless controllers	Company has wireless controllers available

Appendices V: Survey questions for property owners

1. How many office square meters is in the property that you are managing?
2. How many space tenants is there?
3. Are you satisfied in your HVAC system operation?
4. Would you like to have remote control and monitoring option for indoor climate on your property?
5. Are you ready to give space tenants and occupants rights for managing the rented space indoor conditions?
6. Are you ready to give indoor condition information to space tenants and occupants?
7. Mark the following features that you would like to have in your office:
   - Individual room device energy consumption monitoring in real-time
   - Space tenant energy charging due to exact energy consumption
   - Real-time information of indoor climate stability and response capability in change situations
   - Automatic fault detection and location
   - Booking and schedule viewing of meeting rooms
8. Would you prefer to pay the costs from the system as a one-time payment or monthly as a service?

Appendices VI: Survey question for space tenants

1. How many office workers is in your rented office?
2. Do you know the utilization rate of your office?
3. Are you satisfied in your HVAC system operation?
4. Mark the following features that you would like to know of your HVAC system:
   - Individual room device energy consumption monitoring in real-time
   - Space tenant energy charging due to exact energy consumption
   - Real-time information of indoor climate stability and response capability in change situations
   - Automatic fault detection and location
   - Booking and schedule viewing of meeting rooms
5. Are you ready to give space tenants and occupants rights for managing the rented space indoor conditions?
6. Are you ready to give indoor condition information to space tenants and occupants?
7. Would you prefer to pay the costs from the system as a one-time payment or monthly as a service?
8. Would you consider it useful if you knew the exact energy consumption of your rented space?
9. Would you like to have opportunity to remote control the temperature of your rented space?

10 Do you expect anything else from possible application?

Appendices VII: Survey questions for office users

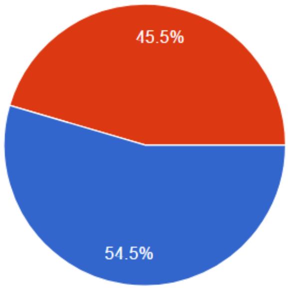
1. Have you ever felt uncomfortable in office due to bad air quality or temperature?
2. Would you like to get remote readable air quality- and thermometer to your office?
3. Do you think that individual preferences should be taken into account in office temperature control?
4. Would you use (mobile or browser) application, where every occupant in your office sets the own temperature preference and location, and the office temperature is controlled automatically based on the occupants information?
5. Mark the following features that you would like to have in your office:
   - Lightning control
   - Notifications of possible air-conditioning fault cases
   - Notifications of air quality weakening
   - Suggestions for clothing in warm or cool days
   - Booking and schedule viewing of meeting rooms
   - Possibility to have local influence on office climate by boosting the cooling or heating
   - Possibility to boost the fresh air supplying
   - Possibility to give feedback for the space tenant, maintenance or property owner
6. Do you expect anything else from the application?

Appendices VIII: Benchmark results.

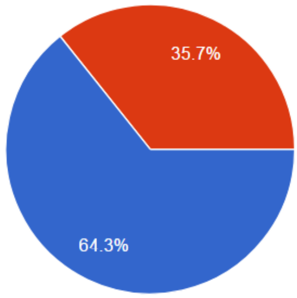
	Lindinvent	Fläktwoods	Swegon	EasyIO	Schneider	Lynxspring	Tridium	KMC	Trox	Comfy	Dencohappel	Trane	Count
Remote control	X	X	X	X	X	X	X	X	X	X	X	X	12
Protocols	X	XX	XX	XXX	XXXX	XXX	XXX	X	XXX	X			10
History viewing	X	X	X	X	X	X	X	X			X		9
Room level control	X	X	X	X	X		X	X	X	X			9
Graphical indicators	X	X	X	X	X	X	X	X	X				9
Web browser app	X	X	X	X		X	X	X	X				8
Alarming options	X	X	X	X	X	X			X				7
Automatic reports	X				X	X	X				X	X	7
Scheduling & viewing	X		X	X			X	X		X		X	6
Mobile app	X			X	X		X	X		X			6
Various user levels	X		X		X		X	X	X				6
Component viewing	X	X	X	X		X							5
Security			X		X	X	X	X					5
Fault detection	X	X								X		X	4
Floor layout view	X	X		X		X							4
Table & filter mode	X			X	X		X						4
Optimization	X	X	X										3
Wireless controllers			X	X			X						3
PC software					X				X				3
Support service					X						X	X	3
Real-time energy mon.		X				X							2
Fire safety functions	X	X											2
Weather information	X			X									2
Individual control										X			1
Settings saving option	X												1
GUI customizing						X							1
Component identification		X											1
Room level energy mon													0

Appendices IX: Property owner questions and answers. (Red = no, blue = yes).

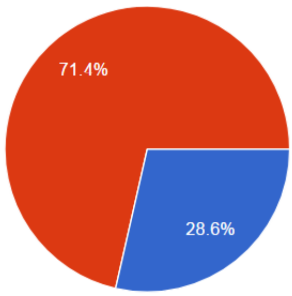
3. Are you satisfied in your HVAC system operation?



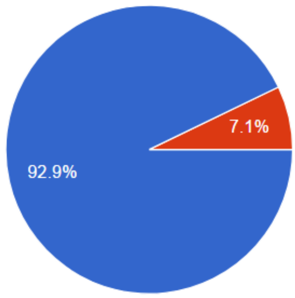
4. Would you like to have remote control and monitoring option for indoor climate on your property?

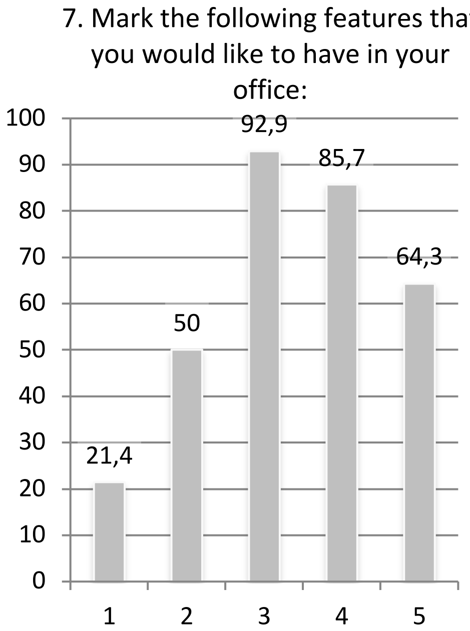


5. Are you ready to give space tenants and occupants rights for managing the rented space indoor conditions?

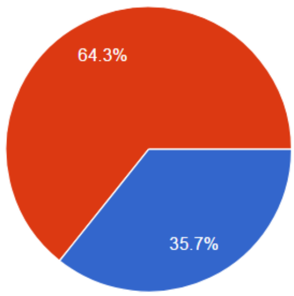


6. Are you ready to give indoor condition information to space tenants and occupants?





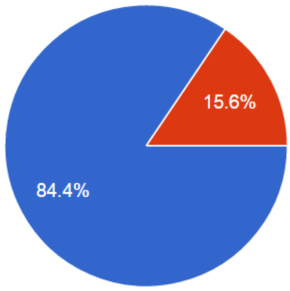
8. Would you prefer to pay the costs from the system as a one-time payment or monthly as a service?



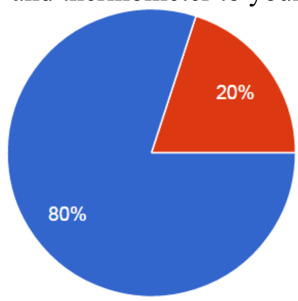
1. Individual room device energy consumption monitoring in real-time
2. Space tenant energy charging due to exact energy consumption
3. Real-time information of indoor climate stability and response capability in changing situation
4. Automatic fault detection and location
5. Booking and schedule viewing of meeting rooms

Appendices X: Office user questions and answers. (Red = no, blue = yes).

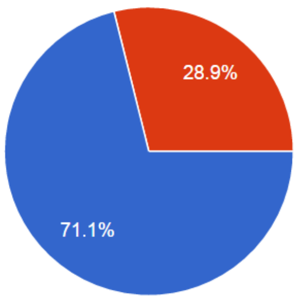
1. Have you ever felt uncomfortable in office due to bad air quality or temperature?



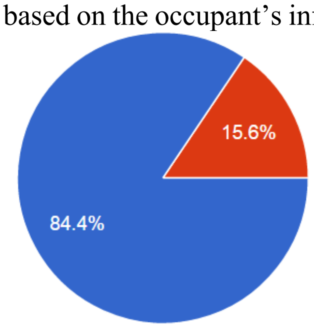
2. Would you like to get remote readable air quality- and thermometer to your office?



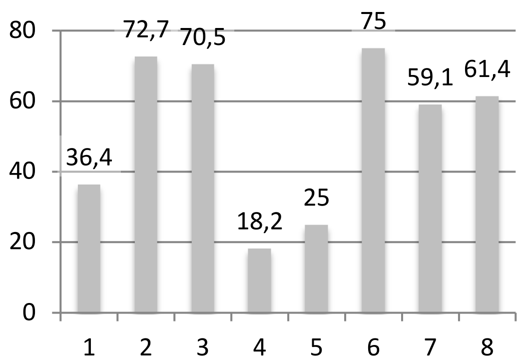
3. Do you think that individual preferences should be taken into account in office temperature control?



4. Would you use (mobile or browser) application, where every occupant in your office sets the own temperature preference and location, and the office temperature is controlled automatically based on the occupant's information?



5. Mark the following features that you would like to have in your office:



1. Lightning control
2. Notifications of possible fault cases
3. Notifications of air quality weakening
4. Suggestions for clothing in warm or cool days
5. Booking and schedule viewing of meeting rooms
6. Possibility to have local influence on office climate by boosting the cooling or heating
7. Possibility to boost the fresh air supplying
8. Possibility to give feedback for the space tenant, maintenance or property owner

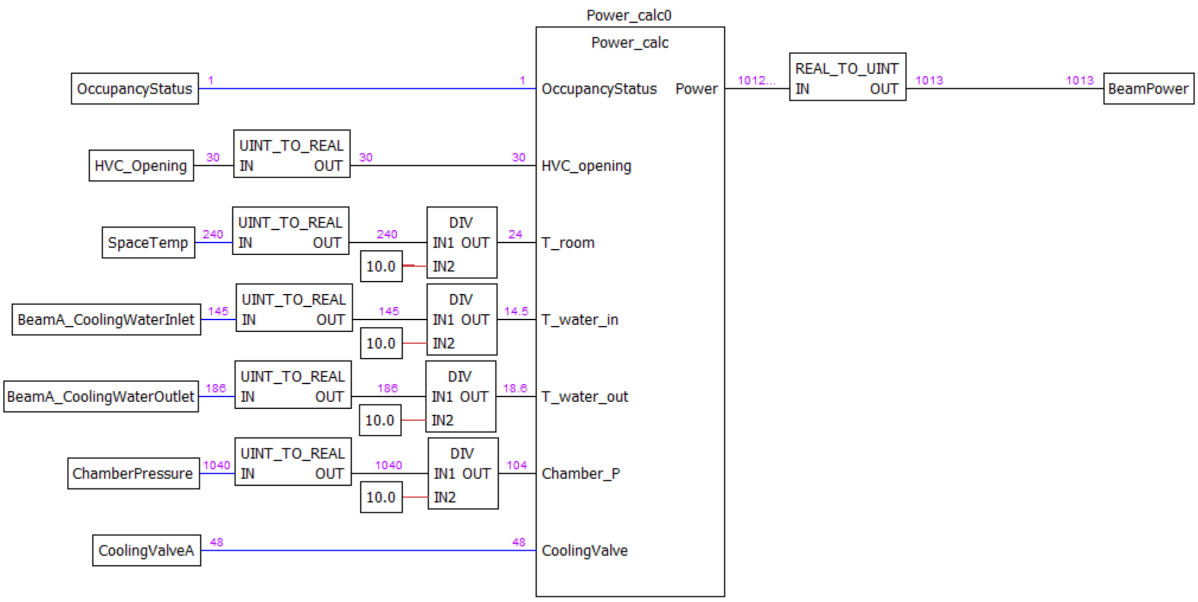
Appendices XI: Random situation in normal mode calculated with HIT and compared to function block simulation result: HIT (1034W) and Power function (1013W)

Normal Cooling	R6O/B-3000-B-2800		2013.02
Room:		Supply air flow rate:	31 l/s
Room size:	10.0 x 6.0 x 2.6 m		1.0 l/(sm2)
Occupied zone:	h=1.8 m / dw=0.5 m	Supply air temperature:	18.0 °C
Room air:	24.0 °C / 50 %	Static chamber pressure:	-
Heat gain:	-	Total pressure drop:	129 Pa
Installation height:	2.60 m	Unit sound pressure level:	36 dB(A) 10m2sab
Inlet water temperature:	14.5 °C	Total sound pressure level:	34 dB(A)
Outlet water temperature:	18.6 °C	Primary air capacity:	217 W
Water flow rate:	0.060 kg/s	Total cooling capacity:	1251 W
Coil capacity:	1034 W		447 W/m, 21 W/m2
	369 W/m	Dew point temperature:	12.9 °C
Water pressure drop:	3.8 kPa	Velocity control:	left=3, right=3
		Min flow opening:	100.0
		Normal/boost opening:	100.0 / 0.0
		L_d:	-

Velocity point	v1	v2				
Nozzle jet	~0.10 m/s	~0.20 m/s				
Nozzle jet, isothermal	~0.10 m/s	~0.15 m/s				
dt (nozzle jet-room air)	-0.2 °C	-0.4 °C				

Heat sources and their location may influence the velocity and direction of the jet

vlim = 0.20 m/s



Appendices XII: Random situation in boost mode calculated with HIT and compared to function block simulation result: HIT (1379W) and Power function (1383W)

Boost Cooling	R6O/B-3000-B-2800		2013.02
Room:		Supply air flow rate:	30+32 l/s
Room size:	10.0 x 6.0 x 2.6 m		1.0 l/(sm²)
Occupied zone:	h=1.8 m / dw=0.5 m	Supply air temperature:	18.0 °C
Room air:	24.0 °C / 50 %	Static chamber pressure:	-
Heat gain:	-	Total pressure drop:	129 Pa
Installation height:	2.60 m	Unit sound pressure level:	36 dB(A) 10m²sab
Inlet water temperature:	14.5 °C	Total sound pressure level:	34 dB(A)
Outlet water temperature:	20.0 °C	Primary air capacity:	444 W
Water flow rate:	0.060 kg/s	Total cooling capacity:	1823 W
Coil capacity:	1379 W		651 W/m, 30 W/m²
	492 W/m	Dew point temperature:	12.9 °C
Water pressure drop:	3.8 kPa	Velocity control:	left=3, right=3
		Min flow opening:	100.0
		Normal/boost opening:	100.0 / 100.0
		L_d:	-

Velocity point	v1	v2				
Nozzle jet	~0.20 m/s	~0.35 m/s				
Nozzle jet, isothermal	~0.20 m/s	~0.35 m/s				
dt (nozzle jet-room air)	-0.2 °C	-0.3 °C				

Heat sources and their location may influence the velocity and direction of the jet

vlim = 0.20 m/s