DEGREE PROJECT IN ELECTRICAL ENGINEERING,
SECOND CYCLE, 30 CREDITS
STOCKHOLM, SWEDEN 2017

Develop healthy building infrastructure for KTH LIVE-IN-LAB

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TRITA 2017:092
ISSN 1653-5146

Master of Science Thesis

Develop healthy building infrastructure for KTH LIVE-IN-LAB

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Acknowledgments

I would like to reserve this space to thank my supervisor Elena Malakhatka for her endless support and dedication and for the brainstorming sessions that offered me guidance throughout all the stages of the project.

I would also like to express my gratitude towards my thesis examiner Prof. Carlo Fischione for the subject the guidance and the opportunity to work in this field at the KTH Live-in Lab.

Most of all, I would like to thank my mom Daniela, my dad Valentin, my girlfriend Henna and to all my firends for their support.

Abstract

The following master thesis is conducted on behalf of The Royal Institute of Technology and KTH Live-in Lab with the purpose of proposing a healthy building infrastructure for the KTH Live-in Lab. The Lab will serve as a testbed for products and services that can be tested and verified within an optimal space that can simulate a real life usage of the tested products or services. Since the KTH Live-in Lab proposes to create a smart environment in order to fulfill its goal, this thesis proposes to design a system that measures the key factors that influence the user's health while living in the building.

The problem that this thesis is solving is that of understanding the relevant metrics that affect the person living in the building, then identify and place the sensors that can measure the health metrics and finally encapsulate the result in a WSN, paying close attention to the topology and the communication protocols used, capable of monitoring and collecting all the relevant data for further use.

The most difficult part of the thesis is translating the health parameters into the optimal quantifiable metrics so that a developed system could become a feasible solution for a home automation. The attempted way of solving this problem is through literature review of health studies in order to understand which are the quintessential parameters that should be measured.

The system considers different health factors from 9 different domains Ventilation, Air Quality, Thermal Comfort, Moisture, Dust and Pests, Safety and Security, Water Quality, Noise and Lighting and Views. Each of these domains will be analyzed and the best metrics for monitoring will be selected. The solution will be tailored on the KTH Live-in Lab as the sensor placement is done on the schematic of the Housing Design, of the Fall Semester 2017. In order to choose the optimal way to implement the wireless sensor network, several topologies and communication protocols are compared, the chosen one being ZigBee as protocol while the topology was separated in how sensors

are organized in every room which will be a mesh topology and how they are organized in the whole building for which the chosen topology is the Two-tier hierarchical cluster topology. The system also proposes a security encryption algorithm for data protection and a way to evaluate the system based on the standard of the WELL Building Institute.

Future work will consist in implementing all the features that are designed in this paper while finding the perfect trade-off between the cost and technology accuracy when this project will be scaled for a whole apartment building.

As a conclusion, there are certain variations that one can follow when implementing the designed system as the implementation will be a trade-off between the quality of the equipment used which translates into the accuracy of the measurements and the financial and social constraints. This thesis proposes a set of core elements that cannot be replaced in monitoring and also provides approximations for other less common metrics.

Sammanfattning

Följande masteravhandling har utfärdats på uppdrag av The Royal Institute of Tecnology och KTH Live-in Lab med syftet att föreslå en hälsosam byggnadsinfrastruktur för KTH Live-in Lab. Labbet kommer att fungera som en testbädd för produkter och tjänster som kan testas och verifieras inom ett optimalt utrymme som kan simuleras till en verklig situation för användandet av de testade produkterna eller tjänsterna. Eftersom att KTH Live-in Lab föreslår att skapa en smart miljö för att uppfylla sitt mål, föreslår denna avhandling att man designar ett system som mäter huvudfaktorerna som påverkar användarens hälsa under den tid som användaren vistas i byggnaden.

Det problem som denna avhandling ämnar lösa är att skapa en förståelse för de relevanta mätvärden som påverkar den person som bor i byggnaden och därefter identifiera och placera de sensorer som kan mäta hälsomätvärden och slutligen sammanfatta resultatet i en Trådlöst sensornätverk, men också ägna stor uppmärksamhet till topologin och kommunikationsprotokollen som använts, som är kapabla att monitorera och samla all relevant data för vidare användning.

Det svåraste med denna avhandling är att översätta hälsoparametrarna till optimala kvantifierbara mätvärden så att ett utvecklat system kan bli en genomförbar lösning för en hemautomatisering. Tillvägagångssättet för att lösa detta problem är genom att granska litteratur om hälsostudier för att förstå vilka parametrar som är väsentliga och som bör mätas.

Systemet tar hänsyn till olika hälsofaktorer från 9 olika domäner; Ventilation, Luftkvalitet, Temperaturkomfort, Fukt, Damm, Säkerhet, Vattenkvalitet, Ljud och Ljus och Syn. Var och en av dessa domäner kommer att analyseras och de bästa mätvärdena för monitorering kommer att bli utvalda. Lösningen kommer att skräddarsys på KTH Live-in Lab medan sensorplaceringen är utfärdad på schematik av husets design, höstterminen 2017. För att kunna

välja det mest optimala sättet att implementera det trådlösa sensornätverket har flera topologier och kommunikationsprotokoll jämförts. Genom att göra detta har ZigBee valts som kommunikationsprotokoll medan topologin har delats upp i hur sensorer är organiserade i varje rum, vilket kommer att vara en "mesh"-topologi, och hur de är organiserade i hela byggnaden och därav är den valda topologin"Two-tier hierarchial cluster topology". Systemet föreslår också en säkerhetskrypteringsalgoritm som dataskydd och som ett sätt att utvärdera systemen som är baserade på standarden av "the WELL Buliding Insitute".

Framtida arbete kommer att innefatta implementering av alla funktioner som är designade i denna avhandling medan det perfekta utbytet mellan kostnad och teknologiprecision hittas då detta projekt kommer att skalas för en hel lägenhetsbyggnad.

Som slutsats, finns vissa variationer som en kan följa vid implementering av det designade systemet då implementationen kommer att vara ett utbyte mellan kvalitet av utrustningen som används som översätts i noggrannhet av mätningar och finansiella och sociala begränsningar. Denna avhandling föreslår ett set av kärnelement som inte kan bytas ut i monitorering och som också bistår med approximationer för andra mindre vanliga mätvärden.

Abbreviation List

U.S. – United States of America

WWF - World Wildlife Fund

WSN -Wireless Sensor Network

SBS – Sick Building Syndrome

HVAC - Heating, Ventilation and Air Conditioning systems

WSN – Wireless Sensor Network

IoT – Internet of Things

VOC – Volatile Organic Compounds

PM – Particulate Matter

LEED - Leadership in Energy and Environmental Design

TVOC - Total Volatile Organic Compounds

PID – Photo Ionization Detector

FID – Flame Ionization Detector

LED – Light Emmiting Diode

IAQ – Indoor Air Quality

MERV – Minimum Efficiency Reporting Value

NTU - Nephelometric Turbidity Unit

SDWA - Safe Drinking Water Act

PH - Potential of Hydrogen

IR -Infrared

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Chapter 1

Introduction

The following chapter will cast an overview of the factors that will come to shape the end result of this thesis such as the working environment, the personal motivation and the attempted way of solving the problem. It also contains a description of the problem and the steps needed to be taken in the attempt of solving it.

1.1 Outline

Nowadays, most people end up spending up to 90% of their time into indoor environments. Even if it is the office one has to work in or the apartment where one sleeps in or even training in the gym, it all sums up to a huge portion of our time which we spend indoor. Considering that, it is very important to assess the fact that no factors from within the indoor environment can have a long term negative effect on people's health and that the best conditions are ensured in order for people to work, have meetings or rest. According to many research studies, the environment we live in influences our behavior and performances more than we previously knew. As it can be seen from [1] "In the U.S. alone the savings and productivity gains from improved indoor environments are estimated at 25 to 150 billion per year". That is why special attention is need to be paid to the environment that surrounds us when we are at home and that is why the concept of a healthy building is researched more than ever.

A healthy building is a building that does not affect in a negative way the health of the occupants as well as the surrounding environment. To make sure that KTH Live-in Lab does not have undesired effects, and to lead the way to further research, the healthiness of every room will be monitored by sensing the performance of different systems (such as the HVAC system) and making sure that they are within the optimal limits.

As it is known, technology is starting to play a bigger role in our everyday lives. As we become more aware of our impact concerning the environment, it is important that we measure it within all our activities including when we are at home. That is why future homes will have a system of deployed service-oriented architecture over a heterogeneous Wireless Sensor Networks infrastructure to create smart environments. These monitoring technologies are indispensable for developing the next generation of smart houses which will help us to reduce the negative impact that we have on the environment and that some negative factors of the environment have on us. That is why KTH being part of the future is investing in the Live-in Lab to reduce the lead times between test/research results and market introduction. In this way, KTH Live-In Lab aims to facilitate the advent of the sustainable and resource-effective buildings of the future. KTH Live-In Lab is also a unique node for development and collaboration between industry and academia. The subject of sustainable home automation is interesting because it has the potential to help all stakeholders of a small building. Letting the system to take care of all he surrounding parameters and increase the user's comfort can improve the living standards and also the life quality of the persons inhabiting the building while having a positive environmental impact by reducing the carbon footprint of the whole building.

1.2 Problem Statement

Motivated by the desire to improve people's lives and to create better and safer conditions for people to live in, the aim of this thesis is to design and implement a Wireless Sensor Network that monitors and collects the vital data from a building that has the biggest impact of the user's health.

In more concrete words, the aim of the thesis is to identify the parameters that influence people's health when they live inside a smart room, and to design a Wireless Sensor network that can monitor these parameters, for future applications, such as control or data extraction studies. Since the aim of the KTH Live-in Lab is to enhance the collaboration between the industry and academia, and to offer a platform of for collecting real time data about the persons living in the lab for further studies, it is imperative that an appropriate sensor infrastructure is developed that can be exploited for scientific gain. Moreover, the sensors must not interfere with the daily activity of the inhabitants and also must blend naturally in the environment so that the usual pattern of daily activities is not changed.

I have no doubt that the result of the thesis will be an improvement in creating the first step towards an accessibility and greater ease of research regarding different aspects of living conditions. To sum up, I will attempt to propose a design of a Wireless Sensor Network by following the mentioned steps:

- Understand the health related metrics that are needed to be monitored in the KTH Live-in Lab
- Identify sensors that measure the aforementioned metrics
- Compare different network topologies and protocols (WiFi, ZigBee and Bluetooth) for the presented environment and identify the best solution
- Place the sensors and elaborate the design of the wireless sensor network in order to develop a fully sustainability monitoring system

Chapter 2

Methodology

The methodology of the research process used in creating this thesis can be broken down into 5 different parts:

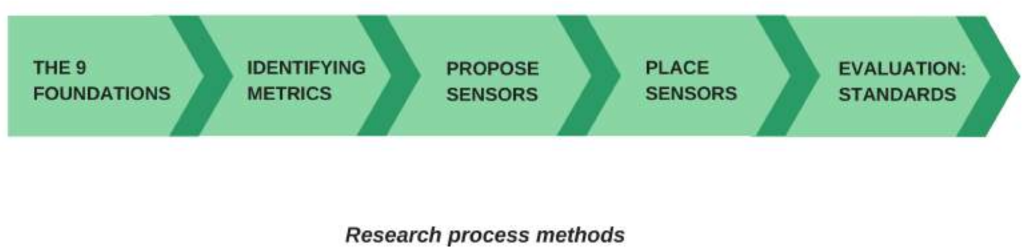

Figure 2.1: The methodology graph

First part of research consists of a literature review concerning the health principles that need to be taken into account when building a healthy infrastructure. This research is about what factors influence the human health while they are living in a building and what are the effects on it. This corresponds to the first rectangle symbolizing the first step in my research methodology which is named “The 9 Foundations” in the above image, since the Harvard document with the same name [1] is a central part in the incipient part of my research. It breaks down all the factors that need to be taken into account when monitoring health in a building into 9 categories which are afterwards used in creating the proposed infrastructure.

The transition to the next part of the scheme is marked with a green arrow and took me to the stage where it was needed to identify the actual parameters that I needed to measure in order to propose a concrete infrastructure. Since the terminology used in The 9 Foundations is mostly medical it requires an additional step, of literature review, to identify the quantifiable metrics that will be measured in order to monitor all aspects identified by The 9 Foundations.

The next part of my methodology consists of a system design part, where having identified the metrics that need to be measured and also after some additional literature review I proposed the specific sensors for every metric. Giving the specific environment and economic conditions behind the KTH Live-in Lab project, I also proposed less accurate but more economical alternatives for some of the parameters due to a possible difficulty in implementation.

A pure system design part was placing the sensors in different optimal areas of the KTH Live-in Lab followed by the motivation of the placing.

At last the final stage of the project was the evaluation part which was done by comparing with existing standards. Since a designed system like this is very difficult to evaluate until implementation, I reached out to several companies that offer green building accreditations. They pointed towards the standards they used in offering the accreditations, thus my evaluation method became comparing what they check when inspecting the building to offer a healthy building accreditation to what the proposed system provides in measurements that are accessible to the user at any given time. Of course the standard is wider and incorporates several features that go beyond the scope of the proposed system, so that is why the comparison was reduced only to the common fields that were verified by the standard and could also be measured by the designed system.

Chapter 3

Background

3.1 Why "Healthy"?

A healthy building is a building that creates an environment that has profound effects on human health and the world around. If planned and build properly the building as well as the communities that are formed around can be powerful catalyzers of health and well-being. If not, they can contribute to some of the key public health concerns of modern society, from asthma to cancer to obesity.

As more research is done, there are more and more proofs that link the indoor conditions (where we spend around 90% of our time) to several health benefits such as the people who work in well-ventilated offices with below-average levels of indoor pollutants and carbon dioxide (CO2) have significantly higher cognitive functioning scores, especially in crucial areas such as responding to a crisis or developing strategy while in some studies, there have been 11% gains in productivity from improved ventilation and 23% gains in productivity from improved lighting design. [2] It is becoming clearer that man can influence the place where he lives to a point where life becomes better and people become more productive just by manipulating the living conditions to assure the healthiest conditions to live in.

Key factors like Air Quality, or ventilation are often overlooked and they could have a devastating effect on the health and efficiency of the people that inhabit those buildings. These effects are known as the Sick Building Syndrome which is better explained as a phenomenon affecting building occupants who claim to experience acute health and comfort effects that appear to be linked to time spent in a building, but where no specific illness or cause can be identified. SBS is also used interchangeably with "building-related symptoms", which orients the name of the condition around patients rather than a "sick" building. [Wikipedia]

Sick building causes are often traced down to improper installation and management of the heating, ventilation and air conditioning (HVAC) systems. Among other causes that have been identified can be particulate matter, extremes of thermal comfort, reduced humidity, insufficient fresh air supply, excessive air movement, poor lighting, microbial contamination, volatile organic compounds and noise or lack of adequate fresh-air intake/air filtration. [Wikipedia]

The work of Harvard University aforementioned in this chapter [1] will be a starting point in the research of this paper, since it explores the effect of different indoor factors that influence a person's health while at home.

The selected parameters will be analyzed closely in the next chapters.

3.2 Links to Sustainability

Even though a healthy building is not necessarily a sustainable building by definition the two concepts are beneficial and from one you can easily achieve the other.

According to the United States Environmental Protection Agency, sustainability "creates and maintains the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations."

The important aspect about sustainability is that the accent is put on future factors and developments, and that means that the designers and engineers have to respect a stricter policy than the one used for green buildings.

The main characteristic of sustainable products is that they reduce the impact on the environment by being created only from materials that have a low footprint on the environment; which translates into renewable materials (for example sources of energy) or materials obtained in a sustainable matter. If materials are obtained in a sustainable matter it means that they are obtained in an environmental friendly way, without negatively impacting the area of origin either by pollution of any kind or by drastically decreasing the natural resources. The concept of sustainability describes the link between the well-being of the environment and the well-being of people that are exploiting it. If the exploitation is done in a sustainable way while giving time to the environment to regenerate, our needs will be fulfilled without causing any permanent damage.[28]

Nowadays the buildings themselves create new indoor environments that present new environmental problems and challenges. For example, it has been observed that within a building, the occupant's health and comfort are starting to get influenced in a negative way by the extensive use of synthetic materials solvents and mechanical systems of environmental control which seem a very normal part of one's everyday life. It has been shown that keeping a high standard regarding the conditions from within a building leads to improvements in the health of its occupants. In the light of that it then becomes clear that, one of the key objectives in sustainable architecture will be assuring the right environmental conditions in buildings so that the occupant's health, comfort and safety are not affected by his/her time spent in the designed building.[3]

Moreover the importance of energy efficient buildings has assumed great urgency due to fast depleting energy resources, energy scarcity and increasing environmental pollution. According to WWF SWEDEN: An Analysis of Sweden's Carbon Footprint (2008), "Emissions from Swedish consumers is the carbon dioxide emitted based on the domestic consumption of goods and services, rather than production. By far, the single largest contributor to consumer CO2 emissions is households, making up 76% of Swedish consumption. CO2 emissions from residential energy demands include emissions from the direct demand for energy (heating, electrical appliances and private transport) as well as emissions from the energy needed to manufacture consumer goods and services the household indirect energy demand. This means that in the case of purchasing a car, the environmental impact is not caused in driving the car alone, but also through the raw material extraction, manufacturing, distribution, use and disposal of the car. In Sweden, these indirect emissions through consumption currently contribute to 64% of the total household emissions, with direct consumption contributing to 36% household emissions. Swedish household emissions are driven by energy and transport which make up 70% of household emissions." Thus it can be concluded that major contributions towards a sustainable way of living can be achieved by improving the energy efficiency in the built environment which is a topic that has been actively researched by both the academia and the industry.

3.3 Wireless Sensor Networks

In the light of the recent progresses that have been done in the information technology field newer and better ways of solving the challenges mentioned above have been proposed. One of the potential solutions is the Wireless Sensor Networks (WSNs) technology that due to the amount of research invested in it has shown an incredible development in the last decades. Its special characteristics can bring many advantages in improving buildings' energy efficiency and control and measurement of the indoor environment.

As it is well formulated in [4] "WSNs are small, non-intrusive and configurable sensor platforms that can operate for significant lengths of time on low energy supplies, and automatically configure themselves to form a data reporting network on deployment. Through this network, collected wireless sensor data can be transmitted to users in real-time and on a continuous basis. Since its development for military applications, WSNs have been widely used in a variety of fields, such as bio-medical, remote medical care, and environment monitoring.

In Building Management area, WSNs can play an important role in energy management by continuously and seamlessly monitoring the building energy use, which lays the foundation of energy efficiency in buildings. WSNs can also benefit building management practices in a variety of other ways. For example, status of major building components can be monitored by analyzing the sensor data; Various building management systems, currently used for automating different tasks, can be integrated to achieve higher management efficiency by making better use of a web enabled central platform."

For Building Management, a preferred Wireless Sensor Network framework is consisting of the following elements: sensor nodes, a gateway, a central node with internet access, which are the central ones and furthermore one can add a server to host the database where all the measurements shall be stored and another mobile device can also be added so that the monitoring can be verified remotely.

The sensor nodes should be deployed in the areas of interest so that they can measure the specific parameters they were designed for, and process it at the node level before transmission. Gateways (or sink nodes) are used to gather the data from all the nodes and to make it available for external applications such as the central node.

The information flow of the Wireless Sensor Network described above will take this course: the sensor nodes have the task to collect data from the

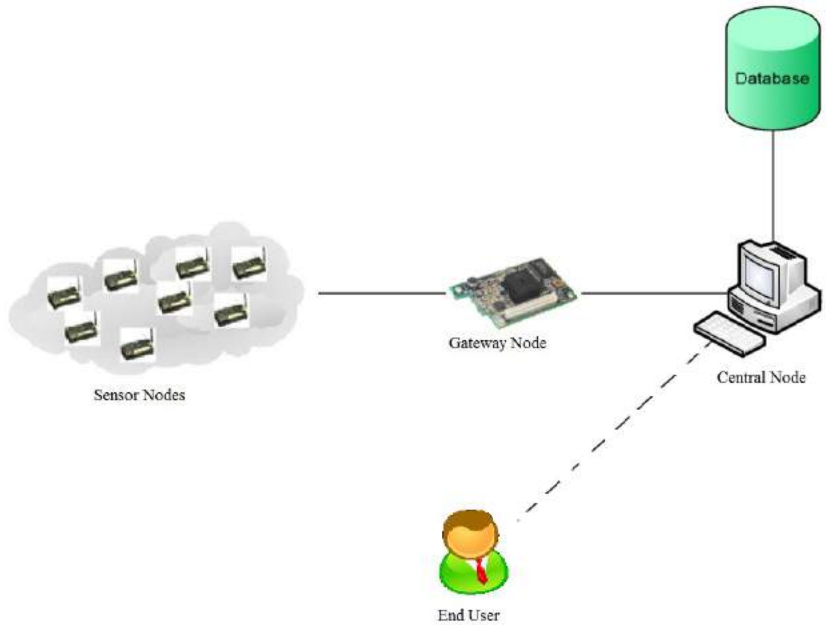

Figure 3.1: The general structure of a WSN [4]

environment where they have been deployed upon the orders they received from the gateways and process the collected data with preloaded programs at a preliminary level so that they can store it locally or forward it to the gateway node. The gateway node gathers the data from the sensor nodes and either processes it further or it sends it to the central node where the final processing is being done and then the information can be stored in a data base.

A huge advantage of Wireless sensor Networks in the home monitoring case is that of the easiness of deployment and removal since no wiring work is needed for the implementation of the sensors. Another advantage is that of the robustness of the whole network since sensors can be places in harsh environments where wires would be impractical or in remote locations such as ceilings.[4]

3.4 Ethics and Society

Given the nature of the project that will happen in the KTH Live-in Lab, it is very important to allocate some space to talk about the eventual ethical conflicts and the impact of this project on society.

Since the project will accommodate different people that will be monitored, and further deductions will be done based on the data recorded from their behavior, it is imperative that all the scientifical research and experiments must be done with their consent and blessing and that all the parts of the experiments and all the data that is collected regarding every individual is presented to every individual in advance so that the person knows what to expect on the period of the staying. Since this is just the early phase of the IoT, sensor and control systems such as the one that it is trying to be developed are not yet accessible to all households that may want to implement them without a serious financial stretch but in the future, this technology may become more and more common and while doing so, it may end up transforming the society as we know it.

If one can imagine an automated house, where the control algorithms take care of the health parameters so that they are according to the user's preference, one must imagine the amount of data that must be collected, stored and processed so that the algorithms can perform their task. In my opinion, a first obstacle in implementing these types of systems on a large scale is the capability of guaranteeing the cyber security of the data that is being collected and of the confidentiality of the process. The task is even more difficult since as long as new hacking techniques are developed or as long as encryptions are being unwillingly decrypted in less and less time, the security algorithms will always have to be updated, which may pose problems regarding eventual security settings that might be hardcoded on each controller of every system. Also, not upgrading the security measures of the wireless sensor networks is not an alternative, since the data that the system works with is far too important to leave it "unguarded".

Also, one might argue that the cost of such a technology and its implementation is too high to have it implemented on a large scale and so, it won't have a great impact on society. But if we follow the latest trends in the development of new technologies, we can see that as technological advance is done, components are getting smaller and easier to produce.

Chapter 4

Design and implementation

In the following chapter the design of the system will be explored in a deeper manner by proposing the sensors for the designed system and placing them in the KTH Live-in Lab. Following there will be a discussion about the topology of the WSN as well as the protocols that can be used.

4.1 Design

In order to design a Wireless Sensor Network for the aforementioned purpose, the first thing considered, was to determine which of the conditions from an indoor environment influence the health of the inhabitant and afterward backtrack them to some quantifiable parameters that can be sensed and controlled so that valuable data can be extracted for various purposes.

A valuable insight has been taken from [1] but, as they describe the 9 Foundations of a Healthy Building, one can observe that the aspects that are investigated are the effects of different concepts such as Air Quality or Water Quality of a building on the health of the people living inside it. Obviously the concepts from the health point of view are not quantifiable and are used to encapsulate a multitude of factors that can be traced back to specific areas of building management. In order to design a Wireless Sensor Network, one must know what to sense, therefore some quantifiable parameters are needed that can accurately define the concepts identified from the 9 Foundations of a Healthy Building.

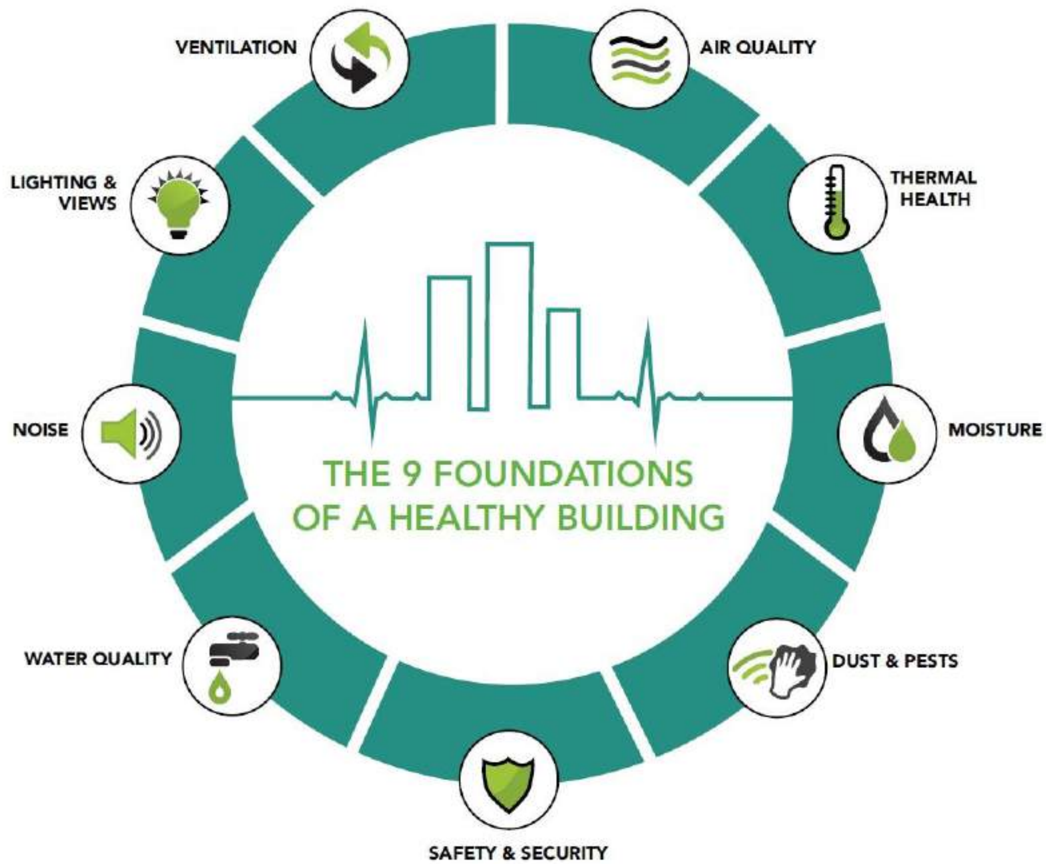

Figure 4.1: The Nine Foundations [1]

The next part of this chapter focuses on tracing back the quantifiable parameters that can be sensed and that can accurately express each of the 9 foundations.

4.1.1 Ventilation

General Description

According to the ANSI/ASHRAE, 2001, by definition, "Ventilation is the process of supplying air to or removing air from a space, for the purpose of controlling air contaminant level, humidity, or temperature within the space".

The ventilation system plays a center role in every room of every building and is a part of the bigger HVAC systems (Heating Ventilation and Air Conditioning) that provide a complete solution for the indoor comfort of the inhabitant. As it shall be seen from the next subchapters, the HVAC components are all part of the same solution because of the degree of interdependence of the parameters that they control.

Influencing also temperature humidity and air pressure, and completing the definition given above, ventilation also provides high indoor air quality which also implies temperature variations, oxygen replenishment, and removal of unpleasant impurities like moisture, odors, smoke, heat, dust, airborne bacteria, carbon dioxide, and other gases. Among some of the ventilation's functions it can be reminded: removal of unpleasant smells and excessive moisture, introducing outside air, keeping interior building air circulating, and preventing the stagnation of the interior air. The ventilation process can be split into two major parts: the exchange of air to the outside and the circulation of air within the building. It is one of the most important factors for maintaining acceptable indoor air quality in buildings. [Wikipedia HVAC]

Health Impact

Bad ventilation rates can have a profound effect on human health. Firstly it can allow the accumulation of carbon dioxide and lack of oxygen that can cause fatigue and affect the ability of the people within the indoor space to concentrate. It can also allow the accumulation of other hazardous substances into an indoor area that may result in a bad air quality that can have devastating long term effects on human health, while on the short run it can lead to headaches fatigue, allergies, dizziness, coughing or nausea. Ventilation also affects temperature and can cause heat to build in which may result in extreme discomfort for the people that have to interact in that environment. It also interacts with humidity, contributing to dry throat or dry skin if it is not enough humidity or to bacterial and mold growth if it is too much. [1]

A common term used for a consequence of poor ventilation is the Sick Building Syndrome that includes irritation of eyes nose and throat, headaches, fatigue and a susceptibility to cold and flu.

Monitored Parameters

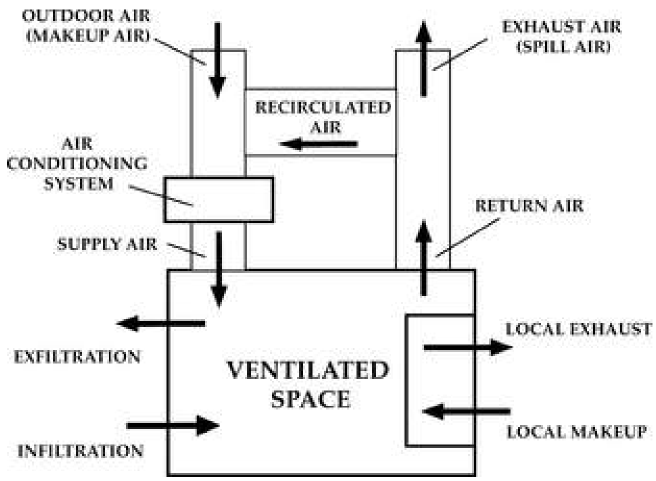

Figure 4.2: General image of a ventilation system [9]

From [9] it can be seen that when measuring ventilation in a room/building there are several ventilation metrics that must be taken into account:

- **Outdoor air change rate** (measured in $1/h$, l/s, l/s per person, $l/s/m^2$ of floor area) - the total rate at which the outdoor air enters a building including both infiltration (the air that comes in the room without the support of the mechanical ventilation) and ventilation
- **System outdoor air intake rate** (l/s, l/s per person),
- **System supply airflow rate** (l/s, $l/s/m^2$ of floor area),
- **Exhaust airflow rate** (l/s),
- **Envelope Infiltration Rate** ($1/h$)
- **Indoor carbon dioxide concentration** (mg/m^3)

But for the last metric even though according to [5] it can be seen that "based on the analysis of CO_2 and ventilation rate data, it was concluded that the peak and predicted values of both CO_2 and ventilation rate were highly correlated. The uncertainty related to CO_2 values is estimated to be ± 280 ppm based on mean 95%CI for predicted CO_2 values; and the uncertainty related to ventilation rates is ± 1.0 l/s per person based on median 95%CI for predicted ventilation rates." which means that an indicator that had good results in measuring the ventilation rates is CO_2.

From the same paper we also find out that using CO_2 as an indicator might have its challenges since the estimation of the ventilation rate might be affected by the levels of activity that usually can happen in a room and there are cases in which the CO_2 level does not reach a steady state in order for measurements to be accurate.

The Ventilation Systems that use outdoor air as a source of clean air which are the ones that are the most common and recommended for residential buildings are of 3 types:

- Exhaust-only systems which are the most problem prone because the source of outdoor-air is not known. Possible sources might be problematic places places like the garage, ground, and attic or through building cavities containing mold which are a threat to the air quality standards which will be discussed in the next subchapter.

- Supply-only systems which are less risky because in contradiction to the exhaust-only systems in this case, outdoor-air is supplied from a known location. The problem is that the location of where the indoor air exits the building is unknown so if it is humid and inside some hidden building cavities are cold surfaces, the escaping, condensation will occur on these cold surfaces which may favor the apparition of mold and rot.

- Balanced systems are a combination of the positive factors of the two above systems and are the most energy efficient outdoor-air ventilation systems. Both the location in which the air enters and exits the building are known so that the risks that are reminded in the previous cases are mitigated. [29]

Of course any of these systems can have particle filters that prevent the pollution of the outside and inside environment.

Proposed Solution

Therefore, for measuring the outdoor air change rate this thesis proposes a system that releases a fixed amount of tracer gas in the room but only in predefined conditions so that the measurement is as unbiased as possible.

After the release, the system should keep track of the level of tracer gas that is recorded in the room and approximate its decay rate that should be exponential until there is only a constant level of the tracer gas left in the atmosphere, thus approximating the ventilation rate. The predefined conditions may include that the air change rate is constant throughout the measurement period, but can also imply the presence of motion sensors to assert that there is no person in the room or movement sensors to assert that no person from the room is doing an activity that can affect with the tracer gas measurements.

Supply Airflow Rates and Exhaust Airflow Rates are typically measured by using velocity transverse methods. These methods involve measuring the air speed at multiple points across a duct cross section to determine the average air speed, which is then multiplied by the cross-sectional area of the duct to yield the volumetric airflow rate. In many ventilation systems, there are not adequate lengths of ductwork to support accurate traverse measurements. In these cases, one can use a constant tracer gas injection approach in which tracer is injected at a constant rate in the duct and the concentration is measured as far downstream as possible [9]

4.1.2 Air Quality

General Description

Indoor Air Quality is a term used for defining several factors that may influence one's comfort and health while breathing the air of an indoor environment. The air quality can be affected by a variety of indoor pollutants such as nitrogen oxides, carbon monoxide, ozone, particulate matter (PM), and volatile organic compounds (VOCs) such as formaldehyde, limonene, benzene and radon which are all toxic towards the human health.

Air quality standards and parameters are also closely connected to the ventilation system (since the ventilation system is responsible for the air movement that happens within a room replacing old and "contaminated" air from the inside with fresh clean filtered one from the outside) and both are part of the same mechanical and thermo dynamical system of HVAC.

Health Impact

As suggested in [8] if the same people are exposed on a longer period to conventional indoor environment that contains high levels of CO2 and VOCs and other factors that lower the air quality, and are also exposed to healthier environments, critical differences can be observed in the cognitive scores of the experiment subjects that raise in the case of the green and green+ (green levels combined with enriched ventilation) buildings up to 61%.

Also a higher risk when ignoring Indoor Air Quality is possessed by children, which are more susceptible to a large spectrum of diseases the most common being the respiratory health diseases when exposed to poor Indoor Air Quality conditions. The group that is exposed to a higher risk is consistent of the allergic individuals both children and adults.

Therefore there must be a special attention accorded to meeting the LEED standards regarding VOC (LEED TVOC guidance concentration of $500\frac{\mu g}{m^3}$ and the BASE mean concentration of $450\frac{\mu g}{m^3}$) and CO_2 standards (approximately 950 ppm).

Of course, the position of the building plays an extremely important role in the level of exposure to different dangerous air pollutants, higher risks are being taken if the building of residence is located near an industrial center or an area that has a high level of pollutants because some zone specific extra hazardous parameters (SO2) must also be taken into account and mitigated.

Monitored Parameters

From [6] it is said that “Indoor air quality is a complex entity to measure. Various time-dependent physical and chemical parameters (such as **relative humidity, temperature, level of air contaminants**) are constituents of IAQ. These parameters are affected by outdoor conditions (climate), building conditions (material, structure and construction), buildings’ HVAC systems (Heating, Ventilation and Air-conditioning systems), the indoor space arrangements (furnishing, furniture, equipment) as well as occupants’ productivity patterns. Indoor air quality can be managed either by increasing the ventilation rate or by reducing the air pollutant load in the air. Ventilation is used to exchange the indoor air and remove carbon dioxide and other contaminants in the air.” which shows that Indoor Air Quality is also deeply connected to the Thermal Comfort parameters which we will explore in the next subchapter and Ventilation parameters and also that it can be managed either by managing ventilation (that in this specific case can take care of indoor air pollutants such as radon, tobacco smoke, the effect of mold or cooking and heating's unwanted gasses) which was covered in the above subchapter or by measuring the air pollutant load in the air and finding the problematic substances . Increasing the ventilation rate is done by having a trade-off with the noise and temperature systems and requires ongoing monitoring.

Proposed Solution

Since the purpose of the thesis is to design a system that continuously monitors a changing environment the proposed solution will focus on managing ventilation according to some key indicators that signal the accumulation of hazardous substances.

Out of the parameters that are monitored, humidity and temperature have a straightforward method of being measured and dedicated systems can be found for optimal prices on the market. The challenge of this chapter is posed by measuring the level of air contaminants which are more diverse and require a more specific infrastructure for each parameter.

After a market study, one can find that there are multiple embedded systems proposed by companies that monitor the air quality parameters that were described in the previous subchapter and many of them come with integrated solutions about displaying the measurements. The downside is that it might be difficult to integrate the in the sensor network that this paper proposes. From [18] it can be seen that there are alternatives for measuring VOC using a Polymer-based VOC sensor module. From [19],[20] it can be seen that a more standard approach in measuring VOC would be colorimetric tubes, Infrared Detectors, Photo Ionisation Detectors (PIDs) and Flame Ionisation Detectors (FIDs) and sampling followed by laboratory analysis. Since the clorometric tubes cannot be included in a wireless sensor network, and sampling and analyzing it at a laboratory would defy the purpose of the network, the only viable methods of accurately measuring VOC are the PIDs and the FIDs. The correct choice between the two aforementioned sensors for a wireless sensor network for room would be the PID since it is smaller lighter and more reliable than the FID whose flame can sometimes go out and the hydrogen cylinder needs to be refilled on a regular basis. The PID is also cheaper.

If specific devices are not needed due to special or financial constraints, it can be concluded from [7] that "After controlling for the effect of the microenvironment and classroom-level characteristics, the models investigated the effect of ventilation and infiltration rates, and indoor CO2 levels on indoor VOCs concentrations. It was found that higher infiltration rates may remove VOCs with indoor intermittent sources, such as toluene and limonene. Lowering indoor CO_2 levels during teaching activities may control VOCs levels emitted from continuous sources, such as formaldehyde and toluene, and prevent the build-up of VOCs with outdoor sources, such as benzene." measuring and controlling the level of different CO_2 levels from different sources can be a very good indicator for measuring the level of VOC in the room. Measuring the CO2 is done with dedicated instruments that can be found within reasonable prices and are financially optimal for implementation in every apartment of a building.

Other pollutants that were considered for monitoring are CO that should be measured separately if the financial situation allows it and other ones such as Polycyclic Aromatic Hydrocarbons that would be an encouraged element to measure for people who select housing in places where air quality could be poor from wild fires, industry or motorways, or NO_2 or Ozone but the implementation would not be feasible for a whole building because of financial constraints. Another parameter that must be taken into consideration is Radon which if accumulated in high quantities in an indoor space can lead to lung cancer (it is the first reason for lung cancer for non-smokers) even though it can be mitigate by ventilation.

4.1.3 Thermal Comfort

General Description

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation (ANSI/ASHRAE Standard 55). Thermal comfort is the last concept that affects the inhabitant's health that is included in the HVAC system. It is also strongly linked to the ventilation part as it is suggested by [6] in "Achieving thermal comfort in a building requires energy consumption by the heating and ventilation systems in a building" and also in [7] "Overall the model shows that increased CO_2 levels in the classroom indicate that high internal gains and reduced ventilation patterns may result in overheating.".

Health Impact

When people are dissatisfied with their thermal environment, not only is it a potential health hazard, it also impacts on their ability to function effectively, their satisfaction at work, the likelihood they will remain a customer and so on.

Our body has a mechanism to cope with the difference of temperatures and it is by dilating and constricting blood vessels and also through sweating or shivering. Humidity influences the evaporative cooling mechanisms of our physiology. That is, if the humidity is too high, and the air more saturated, our body has a reduced capacity to cool itself through sweating. [1]

Thermal discomfort can have a strong impact on certain groups such as the very old (around over 65 years old) and the very young, for which in a living area there should be a temperature of minimum 20°C, studies suggesting that ambient air temperatures below 12°C can pose a serious risk to the health of these susceptible groups.

If one sets up the environment conditions too warm, specific symptoms might be seen to appear more often to the occupants of the building like, negative moods, heart rate, respiratory symptoms, and feelings of fatigue.[10] Furthermore factors like temperature and humidity have a toll on the way and speed diseases are transmitted. For example of an environment is cold and dry certain virus particles are more advantaged to stay longer in the air and some virus shedding period might end up being prolonged. On the other hand, if an environment is warm and humid, there is a risk of growth of mold and fungi.

Monitored Parameters

Moreover in [6] it is stated that thermal comfort is influenced by six factors. These factors are **air temperature, air velocity, relative humidity, mean radiant temperature, clothing insolation and metabolic rate**. Since the latter two factors are independent of the room structure and are closely related to the human factor they will be ignored for the point of this paper. As it can be observed some of the parameters that need measuring are the same as some of the ones that are measured for air quality. This suggests a close connection between the two systems and their impact on the controlled environment.

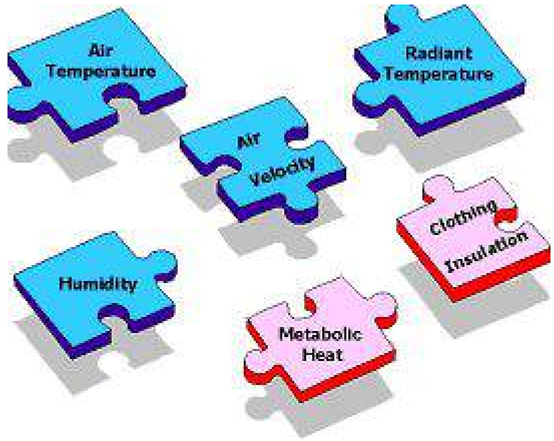

Figure 4.3: Components of thermal comfort [31]

Proposed Solution

From looking at other factors it can be stated that Air Temperature and Relative Humidity (which are also important factors for measuring the Indoor Air Quality and are also affected by ventilation) can be measured straightforward by specific instruments while for Mean Radiant Temperature and Air Velocity even though there are specific technologies that can measure them, they require some tradeoffs in terms of space used, accuracy and price.

According to [16] the most optimal way financially and from the point of computation to measure the mean radiant temperature would be the direct measuring method based on a globe thermometer since it uses compact equipment, of low cost and standard dimensions and has a direct assessment of the radiative thermal load on the person. The same paper presents the drawbacks of this measuring method which are that it might present uncertainties and the reaction time is relatively long (20-30 min). But since all the other methods require additional equipment that might increase the financial effort and additional space in order to setup such a system in every room of the KTH Live-in Lab, Even though all the parameters that need to be measured have dedicated sensors, thermal comfort is a very subjective concept, so that each user should be treated differently according to its own preferences and the system should create a profile for monitoring and learning the preferred setup for the environment. Several questionnaires are an excellent method for assessing the thermal comfort of an individual.

4.1.4 Moisture

General Description

Rather than defining moisture, it is probably better to take a look at the cause and the effects to get a better understanding of what this concept implies. Common sources of moisture in buildings can include: leaks from plumbing, roofs, and windows; flooding; condensation on cold surfaces (e.g., poorly insulated walls and windows, non-insulated cold water pipes, toilets); poorly maintained drain pans; or wet foundations from landscaping or gutters that direct water into and around a building. Secondary sources of moisture include water vapor from inadequately vented kitchens, showers, or combustion appliances [1]. Excessive moisture collection in buildings creates favorable conditions for mold growth, which, if left unchecked, can destroy the surfaces they grow on. Moisture and mold growth can accumulate in materials such as wallboard and carpeting without being noticed even in buildings with good housekeeping and maintenance.

From [23] it can be seen that dampness results from water incursion either from internal sources (e.g. leaking pipes) or external sources (e.g. rainwater). Dampness becomes a problem when various materials in buildings (e.g., rugs, walls, ceiling tiles) become wet for extended periods of time. Excessive moisture in the air (i.e., high relative humidity) that is not properly controlled with air conditioning can also lead to excessive dampness. Flooding causes dampness. Dampness is a problem in buildings because it provides the moisture that supports the growth of bacteria, fungi (i.e., mold), and insects. In the presence of damp building materials the source of water incursion is often readily apparent (e.g., leaks in the roof or windows or a burst pipe). However, dampness problems can be less obvious when the affected materials and water source are hidden from view (e.g., wet insulation within a ceiling or wall; excessive moisture in the building foundation due to the slope of the surrounding land).

Connected with Air Quality, a study on American households claims that stuffy air was reported from 22.3% and 42.8%, moldy odor in 3.9% and 5.8% and perception of dry air in 17.3% of the single-family houses and 33.7% of the multifamily houses, respectively.

Health Impact

It is common knowledge that untreated mold can be very damaging on the long term bringing several health hazards and destroying the wall on which it grows.

"A study conducted in Sweden in 2000 found that self-reported moisture-related problems in office buildings were positively associated with asthma, allergic symptoms, and airway infections."[1] The most common disease associated with mold is asthma and the most vulnerable categories to mold related sicknesses are the infants, the children, the elderly and the people that have a compromised immune system. "Mold exposure has also been positively associated with hypersensitivity pneumonitis, allergic rhinitis, eczema, toxic mold syndrome, bronchitis, and lung tumor development." [1]

Monitored Parameters

From the general description it can be understood that building moisture can result into mold growth which can be characterized by an abnormal **humidity** in different local areas of the room.

Proposed Solution

Moisture requires immediate attention. It is a system that should have a top priority in alerting the user that a problem has appeared in a certain area of the house.

Moisture can be sensed by different humidity sensors that should have values that are compared, and drastic increase in humidity in just one area might signal a problematic spot. Also high moisture levels can be mitigated by proper and adequate ventilation.

4.1.5 Dust & Pests

General Description

According to Wikipedia, dust is fine particles of matter. It generally consists of particles in the atmosphere that come from various sources such as soil, dust lifted by weather (an Aeolian process), volcanic eruptions, and pollution. Dust in homes, offices, and other human environments contains small amounts of plant pollen, human and animal hairs, textile fibers, paper fibers, minerals from outdoor soil, human skin cells, burnt meteorite particles, and many other materials which may be found in the local environment. Alongside pests dust, is a very spread element that people take into consideration when living in a place. Both of the elements are known as toxic and people usually have high level of awareness when dealing with them.

Health Impact

The primordial concern that comes from owning a pet or having pests is the one of introducing allergens into the living environment. It can have devastating consequences especially to children or people that are particularly susceptible to certain type of allergens like dog hair or cat hair. It is known that for pests like rats or mice the dangerous compound is their urine that can cause allergies, while insects like cockroaches are also responsible for introducing specific allergens that become active after exposure.

Dust mites are microscopic parasites that feed with dead human cells and live in bedding or mattresses. They are one of the most spread allergens and are being known to cause allergic reactions ranging from mild symptoms like runny nose and watery eyes, to more severe responses such as asthma attacks.

Monitored Parameters

From [7] it can be seen that a good metric for measuring **dust (Particle Matter)** concentrations is Indoor CO2 concentrations which remained a significant predictor for indoor PM levels after controlling for the effect of occupancy; therefore the relation between CO2 and PM extends beyond the resuspension of particles, and is possibly related to low ventilation rates, which were unable to purge indoor concentrations.

Proposed Solution

Particle matter concentrations can be measured by particle counters and integrated filter samplers but for the purpose of a wireless sensor measurement the perfect suggestion would be using the Optical Dust Sensor - GP2Y1010AU0F. The principle of functioning is having a diode infrared emitting diode and a phototransistor diagonally arranged so that it can detect the reflected light on the dust in the air while the output is an analouge voltage proportional to the measured dust density. In [21] this sensor is tested and gives excellent results while being situated in a very available price range.

As pointed out in the above subchapter, a possible metric for measuring dust can also be the level of CO2 but just as explained in the ventilation part approximation by CO2 measurement can have its own flaws that have to do with the activities that are occurring in the measured environment and the stabilization of the CO2 level.

Furthermore, the dust protection can be increased by placing dust filters at ventilation areas so that clean air is ensured to come in the environment and that dust is also filtered out at the exhaust air part so that it will be filtered out of the system.

Figure 4.4: Optical Dust Sensor - GP2Y1010AU0F

4.1.6 Safety & Security

General Description

Safety and Security is an important aspect in one's everyday life that needs to be taken care of everywhere in society, including in the places where one live. As Maslow's need pyramid suggests, among other basic needs, the security is fundamental for the healthy development of the individual.

The safety aspect can refer mostly to a physical part of one's life which can be for example the health of the person as well as its physical and mental integrity. Safety is the concern and measures that none of the terms mentioned before are violated in any way.

The security aspect can refer to more non personal crime such as privacy violation, or violation one's private space and stealing or just data stealing.

Health Impact

Low levels of safety and security have been associated with increased level of stress, depression or sleeping difficulty or even panic attacks as it is in people's biological structure to feel threatened and worried when basic security conditions are not assured. This happens for people that have not yet been victims due to the lack of security, but these are just symptoms that one can manifest by just perceiving a threat to one's safety.

Once one becomes a victim, the aforementioned symptoms can amplify, leading even to Post Traumatic Stress Disorder. All these factors can also contribute to a gradual withdrawal of the affected person from social activities and having less contact with friends which in turn has been linked with the increase of fear of crime. [1]

Monitored Parameters

The monitored parameters in a security system can vary from just motion sensors to detect unwanted movement to a full system with video cameras in different key positions, to video calling when ringing the door and smart locking systems that are password protected and are connected to the police.

Proposed Solution

The safety and security can be guaranteed by an alarm system that functions when the house is empty, which can be formed of motion sensors that detect if there is unwanted presence in the home and video cameras that can start functioning when the sensors detect an intruder.

4.1.7 Water Quality

General Description

Water quality refers to the chemical, physical, biological, and radiological characteristics of water. It is a measure of the condition of water relative to the requirements of one or more biotic species and or to any human need or purpose. It is most frequently used by reference to a set of standards against which compliance can be assessed. [Wikipedia]

The quality of every surface or ground water is influenced by both natural factors (microorganisms, radionuclides, nitrates and nitrites, heavy metals, fluoride) and human factors (bacteria and nitrates, heavy metals, fertilizers and pesticides, industrial products and wastes, household wastes, lead and copper, water treatment chemicals - improperly handled or stored). "A contaminant is defined by the Safe Drinking Water Act (SDWA) as "any physical, chemical, biological, or radiological substance or matter in water" (U.S. Senate, 2002; 40 CFR 141.2). This broad definition of contaminant includes every substance that may be found dissolved or suspended in water everything but the water molecule itself. The presence of a contaminant in water does not necessarily mean that there is a human-health concern. "[24] Contamination is the introduction into water of microorganisms, chemicals, toxic substances, wastes, or wastewater in a concentration that makes the water unfit for its next intended use. A contaminant in drinking water may make it unpalatable or even unsafe.

Health Impact

As of 2007, around 1.1 billion people were still using unsafe drinking water (World Health Organization, 2007). Pathogenic microorganisms in drinking water, the leading causes of diarrhea, have drawn a lot of attention in public health and other related fields, while improving water quality was shown to decrease mortality in some areas. [25]

Exposure to polluted water can also cause skin irritation, respiratory problems and other pollutant specific diseases for example lead- affects the nervous system, most dangerous when pregnant women and children are exposed to it, fluoride – can cause yellowing of the teeth and damage to the spinal cord, Nitrates – were proven to be linked to digestive tract cancers and heavy metals can cause damage to the nervous system and the kidneys.[30]

Monitored Parameters

There are several key ways water quality may be compromised in a home. Firstly, corrosion on the pipes can be a important factor for water pollution since the metals of which pipes are made of can dissolve and contaminate water as they react with it leading to lead or copper contamination. For example, the risk of lead contamination from pipes is higher particularly in water with high acidity, low mineral content, and hot water systems. Secondly, drinking water may be contaminated by improper treatment of its infrastructure; poor maintenance of distribution systems; malfunctioning wastewater treatment systems; accidental sewage releases; pesticides, fertilizers. Thirdly, the amount of time that unused water is stored within a system may affect its quality. This particular condition is called water age Examples of issues that can be related to water age:

- Rapid loss of disinfectant (such as chlorine) added to keep water safe
- Increased corrosion of plumbing components such as copper pipes, iron pipes, or brass fixtures
- Development of unpleasant tastes and odors in water
- Increased growth of microorganisms, including those that cause disease in humans, damage plumbing materials, or are harmless [26]

One way of verifying water quality is to measure the **electrical conductivity** of the water that is tested. It is essentially a measure of its purity since when the water is more pure it is less conductive as impurities that might be situated in the water make it conductive.

Other metrics can be the **turbidity** of the water (how clean the water is) as well as the **PH levels** of the water, **dissolved oxygen** and **oxygen reduction potential** (measure of the tendency of a chemical species to acquire electrons and thereby be reduced).

Proposed Solution

Water is the only parameter that will not be suggested to be measured in every room, but rather measured once while entering the building. The advantage of this situation is that the sensor does not have any more the constraint of size since it will be placed in an uninhabited place. Because of this aspect these sensors differ from the others in the network since they do not necessarily need to be wireless or have an optimal energy source since it can be plugged in the building's power network. All parameters are specific and sensors measuring them can be procured individually, but it might affect the budget as specific sensors can have a high cost depending on the wanted performance. The most important metrics that should be measured in a home are turbidity, electrical conductivity and PH level.

For turbidity, the measurement can be done in pipe; with the help of turbidimeters using an insertion probe with an IR based LED. A possible solution would be the Libelium Waspmode smart water whose parameters measured include pH, dissolved oxygen (DO), oxidation-reduction potential (ORP), conductivity (salinity), turbidity, temperature and dissolved ions (Fluoride (Fluoride ($F-$), Calcium (Ca_2+), Nitrate (NO_3-), Chloride ($Cl-$), Iodide ($I-$), Cupric (Cu_2+), Bromide ($Br-$), Silver (Ag+), Fluoroborate (BF_4-), Ammonia (NH_4), Lithium ($Li+$), Magnesium (Mg_2+), Nitrite (NO_2-), Perchlorate (ClO_4), Potassium ($K+$), Sodium ($Na+$) which covers all the aforementioned parameters and more while it may use cellular (3G, GPRS, WCDMA) and long range 802.15.4/ZigBee (868/900MHz) connectivity to send information to the sink.

For quality maintenance a filtration system needs to be implemented before the water goes into every room so that pipe damage or corrosions can be mitigated (carbon filters for agricultural contaminants such as herbicides or pesticides or fertilizers or activated carbon filters to filter out the inorganic pollutants).

4.1.8 Noise

General Description

Noise is unwanted sound judged to be unpleasant, loud or disruptive to hearing. From a physics standpoint, noise is indistinguishable from sound, as both are vibrations through a medium, such as air or water. The difference arises when the brain receives and perceives a sound. [Wikipedia]

Health Impact

Noise pollution or noise disturbance is the disturbing or excessive noise that may harm the activity or balance of human or animal life.

"The presence of background noise can also be disruptive and interfere with an individual's ability to communicate and clearly perceive speech at a normal speaking volume. Thus, a building occupant may need to raise their voice to compensate. High noise levels outside schools and self-reported poor acoustics in the workplace have been significantly associated with teachers' voice symptoms such as vocal fatigue, dry throat, hoarseness, and voice loss.

Noise exposure can alter the function of many of the body's internal organs and systems. Multiple studies on the non-auditory effects of noise exposure have observed that increased noise levels are associated with higher systolic and diastolic blood pressure, changes in heart rate, and hypertension. In children, environmental noise exposure has been associated with fatigue, irritability, emotional symptoms, behavioral conduct problems, increased hyperactivity, higher blood pressure, increased levels of stress hormones such as adrenaline and noradrenaline, poorer well-being, and noise annoyance among students. Noise annoyance, which is a form of psychological stress, encompasses feelings of irritation, discomfort, distress, or frustration. In adults, long-term transportation noise annoyance has been associated with lower levels of physical activity."[1]

Monitored Parameters

Usually, **noise** enters building interiors from outside sources such as aircraft, road traffic, trains, lawn mowers, snow blowers, and the operation of heavy equipment at construction sites. Indoors, noise can be generated from a building's mechanical and HVAC systems, office equipment, vacuum cleaners, industrial machinery, or conversations among occupants. [1]

From [11] we can see that external noise exposure metrics are generally used in studies of noise effects on children's health. These measure the average sound pressure over a specific period using dBA as the unit (dBA is the unit of A-weighted sound pressure level in decibels where A-weighted means that the sound pressure levels in various frequency bands across the audible range have been weighted in accordance with differences in human hearing sensitivity at different frequencies)

Proposed Solution

Noise has straight forward means of measurement and well defined sensors. The aspect that needs the most attention when measuring noise is the placement of the sensors which have to be as close to the source as possible if the source is internal, or as close to the point where the noise enters the environment if the source is external.

Thus, this thesis proposes that sound measuring devices should be placed near the HVAC or washing machine devices which are the biggest noise sources that are located on the inside, and for noise coming from outside, sensors should be placed on the outside walls that neighbor busy roads or other noise sources, so that if the noise exceeds a safety level, the system can take measures to mitigate it.

4.1.9 Lighting & Views

General Description

The lighting system is comprised of all the light sources and their adjacent infrastructure that are responsible for illuminating a certain environment.

Health Impact

As it can be seen from [13] "Workers in windowless environments reported poorer scores than their counterparts on two SF-36 dimensions, role limitation due to physical problems and vitality, as well as poorer overall sleep quality from the global PSQI score and the sleep disturbances component of the PSQI. Compared to the group without windows, workers with windows at the workplace had more light exposure during the workweek, a trend towards more physical activity, and longer sleep duration as measured by actigraphy", light is a very important element, when it comes to work performance and sleep duration. It induces not only visual responses but also non-visual effects; indeed it affects performance, mood, and attention and influences the synchronization of the biological clock. Duration, timing, intensity and the spectral power distribution of the light that reaches the eyes can have influence on human circadian rhythm and consequently on health. [27]

Bright light sources can also lead to bad working conditions since it can exhaust one's eyes.

Monitored Parameters

When talking about light the first metric that has to be controlled is the **light brightness** and the **light intensity**.

A good lighting system should harvest the maximum amount of available sunlight to reduce the artificial lighting energy load. It is recommended to incorporate day lighting factor, glare index and luminance values when developing daylight design for an indoor environment. [12]

Proposed Solution

The main sensors that has to be installed for sensing the lighting system is the light brightness sensor alongside the light intensity one. With the input from both of the sensors one can control the quantity of light that is needed to illuminate a room.

If illumination is done by LED it is important to consider that with the ever growing success of LED lighting a need has arisen for specialized LED Light Meters. LED lights produce white light very differently to incandescent lights. A traditional lux meter may give an accurate reading of 500 lux, but the human eye can't visibly see all 500 lux and may actually only be able to see 300 lux. Ultimately this can result in inaccuracies. One can get around this by using a specialized LED light meter.

A very important aspect is to balance the sunlight with the artificial light so that the inhabitant can get the most out of the natural light, for that brightness sensors must be implemented to sense the available amount of sunlight and to take it into account when calculating. In this matter a shading device could be installed on the windows to offer more control over the light that is needed to come from outside the room.

For a sophisticated illumination, from [14] "subjects benefited from lighting conditions with more blue-enriched white lighting either at testing or in the classroom the previous weeks. The difference between standard and acute conditions for concentration performance indicates that there is an acute stimulating effect of blue-enriched white lighting. The subjects who took their tests under blue-enriched white lighting showed more improvement in their concentration performance than the subjects under standard lighting" that if the home is used also as a work environment, the system might help boosting the inhabitant's performance by switching to a blue-enriched white lighting. Also out of environmental concerns, adjacent to the lighting system, motion sensors can be installed so that the lighting system can maximize its savings when there is no person standing in the illuminated area.

A better view of the dependence of the nine analyzed parameters can be seen on this diagram. The orange arrows mark the ways one parameter influences another while the common area of the circles symbolizes that the two or three parameters have common metrics:

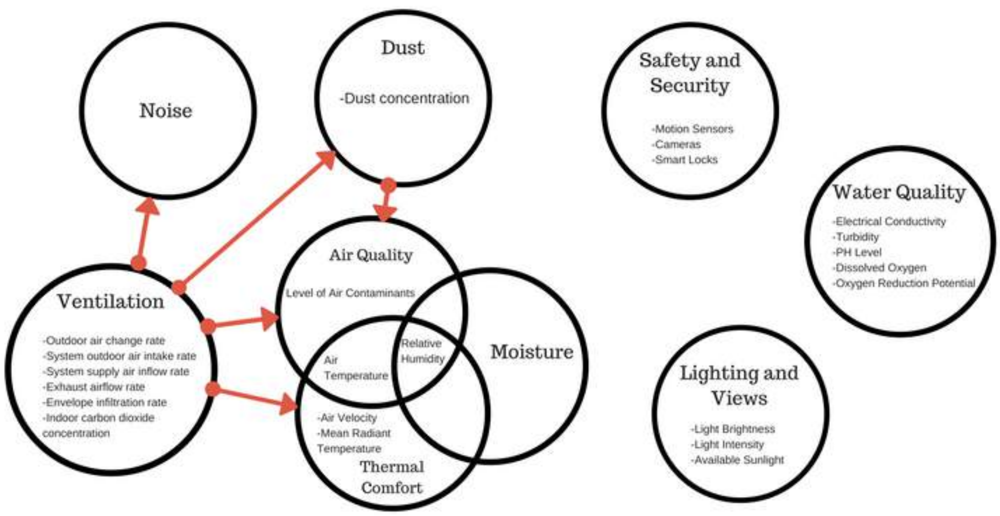

Figure 4.5: Diagram Of the dependencies between parameters

4.1.10 Wearables

General Description

Until this part, this paper disregarded the parameters collected from the human body that can give clues about one's health situation, and focused more on the environmental aspects that have a beneficial or adversary effect on people's health, but in this subchapter the focus will be shifted towards the so called "human parameters" and how could sensing them and incorporating the information into the designed system might benefit the overall result.

The plan is to include a self-monitoring technology that the inhabitant of the building can wear like a clothing item but which can read a certain metric of importance and send the readings to the central node of the designed system.

Health Impact

The biggest impact that the wearable will have will be that since the human body will be monitored directly the system can react if there is an imbalance in the well-known areas in which the parameters are supposed to be situated. So the system can detect an unhealthy lifestyle or just some minor affection that would need to be treated on the spot.

The implementation of this system will also help in having the better understanding of how the human is feeling in the proposed environment, without any personal intervention such as questioners. It can be regarded as a voluntary automated feedback that the user is permanently inputting into the system so that it can validate the correctness of the user's lifestyle.

Monitored Parameters

The monitored parameters can vary since they can be related to several of the aforementioned subchapters. For example the most common wearable applications can measure the human body temperature, heart rate and the galvanic skin [22], or as it is known on the market there are several fitness smart bracelets that can track the number of steps done in a day and several other fitness related parameters.

Proposed Solution

The desired wearable should be as small as possible so that the wearer does not need to break his or hers normal routine when using it and should not feel any discomfort while doing so. That is why the best wearable to be used is a wristband which qualifies both as size and easiness to use as well as from the point of view of the measured parameters.

The market has several alternatives of smart wristbands that measure the movement as well as the body temperature and heart rate and which send the data to the cloud which makes the viable for this project.

The following part will be a summary of the most important elements presented in this part of the chapter:

	General Description	Health Impact	Monitored Parameters	Proposed Solution
Ventilation	Ventilation is the process of supplying air to or removing air from a space, for the purpose of controlling air contaminant level, humidity, or temperature within the space	- Headaches - Fatigue - Allergies - Dizziness - Coughing - Nausea - Fatigue	- Outdoor air change rate - System outdoor air intake rate - System supply airflow rate - Exhaust airflow rate - Envelope Infiltration rate - Indoor carbon dioxide concentration	- Velocity transverse methods - Tracer gas injection approach
Air Quality	Indoor Air Quality is a term used for defining several factors that may influence one's comfort and health while breathing the air of an indoor environment	Respiratory health diseases	- Level of air Contaminants - Air Temperature - Relative Humidity	- Temperature Sensors - Humidity Sensors - Photo Ionization Detectors

Thermal Comfort	Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation.	- Ability to function effectively - Temperature and humidity have a toll on the way and speed diseases are transmitted - Sweating or Shivering	-Air Velocity - Mean Radiant Temperature - Air Temperature - Relative Humidity	- Direct measuring method based on a globe thermometer - Velocity transverse methods
Moisture	Several parts of the living area are affected by high humidity over long periods of time which can lead to mold growth	- Hypersensitivity pneumonitis - Allergic rhinitis - Eczema - Toxic mold syndrome - Bronchitis - Lung tumor development - Asthma	- Relative Humidity	- Humidity Sensors

Dust	Dust in homes, offices and other human environments contains small amounts of plant pollen, human and animal hairs, textile fibers, paper fibers, minerals from outdoor soil, human skin cells, burnt meteorite particles, and many other materials which may be found in the local environment	- Allergy - Asthma	- Dust Concentration	- Optical dust Sensor

Safety and Security	Refer mostly to a physical part of one's life which can be for example the health of the person as well as its physical and mental integrity. - Refer to more non personal crime such as privacy violation, or violation of one's private space and stealing or just data stealing.	- Increased level of stress - Depression - Sleeping difficulty - Panic attacks - Post-Traumatic Stress Disorder	- Motion Sensors -Cameras -Smart Locks	- Alarm System

Water Quality	Water quality refers to the chemical, physical, biological and radiological characteristics of water. It is a measure of the condition of water relative to the requirements of one or more biotic species and or to any human need or purpose	- Skin irritation - Respiratory problems - Affections of the nervous system - Yellowing of the teeth - Damage to the spinal cord - Digestive tract cancers - Damage to the nervous system and the kidneys	- Electrical Conductivity - PH Level - Turbidity - Dissolved oxygen - Oxygen reduction potential	- Turbidimeter - PH sensor - Conductivity Sensor
Noise	Noise is unwanted sound judged to be unpleasant, loud or disruptive to hearing.	- changes in heart rate - hypertension - fatigue - irritability - higher blood pressure - increased levels of stress	Noise	Noise Sensor

Light and Views	The lighting system is comprised of all the light sources and their adjacent infrastructure that are responsible for illuminating a certain environment	- Performance - Mood - Attention - Influences the synchronization of the biological clock	- Light Brighteness - Light Intensity -Available Sunlight	- Brightness Sensor - Light Intensity Sensor
Wereables	Sensing human body parameters and incorporating the resulted information into the designed system	-Better control	- Human Body Temperature - Heart Rate - Glavanic Skin	- A smart wristband

Table 4.1: Summary

4.2 Implementation

4.2.1 Topology

Before detailing the implementation, an important aspect that must be addressed is the topology of the network that will be implemented to collect the measurements. The topology represents the structure of the wireless sensor network and it can vary between several forms and designs.

For a structure as complex as a building, hosting several residential apartments a single topology is not enough therefore the network must be split into the network inside a room and the network that encapsulates the whole building. The two parts will have two different topologies that will be combined in one wireless sensor network.

When referring to the room, the best topology for spreading small sensing devices and have them sent back the measured data to a central node is the mesh topology depicted in the figure below:

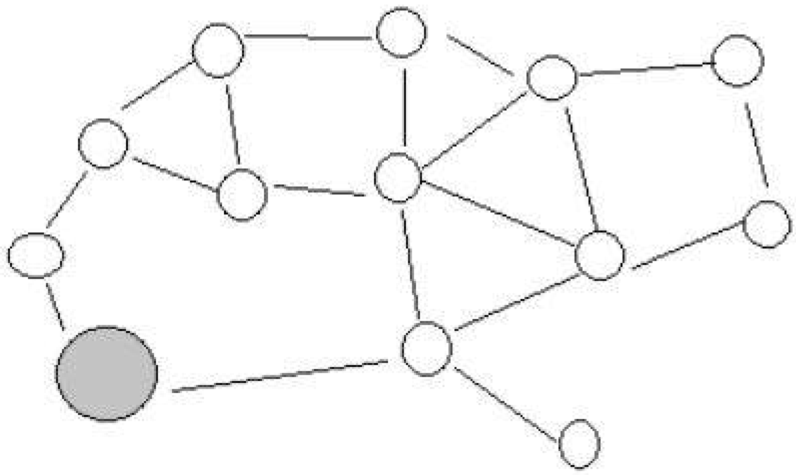

Figure 4.6: Multi hop mesh topology [15]

One of the many benefits of this kind of topology is that it is very robust. As it can be observed in the figure above, for many peripheral nodes there is more than one route that the message can take in order to deliver the information to the sink (gateway) node. If one of the intermediary nodes becomes offline due to some unforeseen circumstances, the other nodes can take on the load and direct the messages around the offline node. Another advantage is that since there is no fixed structure to respect, the network is scalable and new nodes are easy to add.

Of course, the data gathered from every room must be sent to a special unit where they can be stored and processed according to the owner's needs. This implies that another network must be created that links all the rooms and that allows the transportation of the information to the central node. For this purpose the Two-tier Hierarchical Cluster topology must be used, so that every sink node of every room becomes a peripheral node in the network responsible to take the data to a central node.

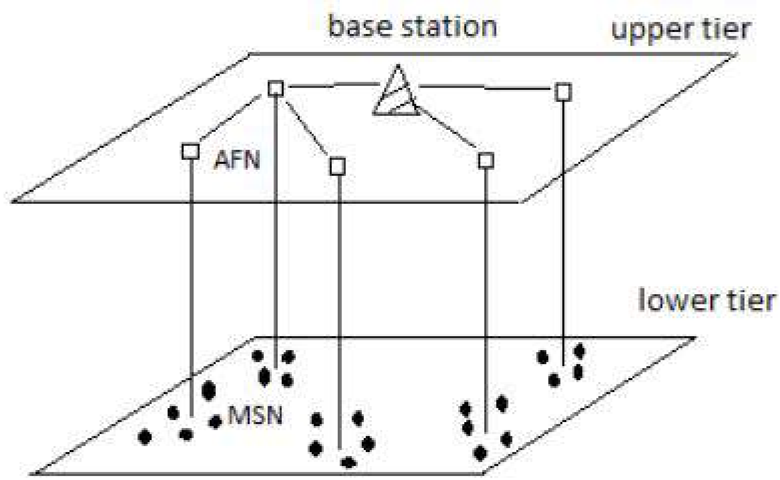

Figure 4.7: The Two-tier hierarchical cluster topology [15]

Each sink node from every room will be a part of the upper tier, and each room's wireless sensor network will be part of the lower tier.

When designing a network the choice of the communication protocol can be taken by considering many options such as WiFi, ZigBee, Bluetooth and many others. As the enumerated ones are the most famous when designing a Wireless Sensor Network, they shall be analyzed according to the advantages and disadvantages of each protocol. WiFi is the most spread, it is available almost everywhere, in every household, it is very suitable for large data transfer applications, but the downside is that it needs a lot of energy in doing so. ZigBee is predominantly used for low data rate communication and low power consumption having also a smaller range of transmission, while Bluetooth has a moderate data rate communication and does not require a gateway for communication with other devices but the downside is that it does not support the communication between enough nodes as needed for the designed system and that it is more oriented towards point to point communication.

For the purpose of home automation applications and Wireless Sensor Networks, the recommended protocol to be used is ZigBee since it blends better on the requirements. Another advantage of ZigBee is that it supports a mesh network topology which can maximize the scalability of the network to a dimension of more than 64000 wireless nodes, way more than one could use in a home. An advantage of the mesh topology as presented above is that it assures redundancy so if a relay nodes suddenly becomes unoperational, the information can travel through another route through the network, to reach the sink node.

Since the application is designed for a building it is expected that the topology of the network once deployed to remain unchanged because too many interventions may interfere with the comfort of the user of the home. Thus, it is suggested that the routing should be static for every network in every room since each individual network is small and the information does not need to travel many hops to get to the sink node.

4.2.2 Sensor Placement

1. Ventilation

    - Outdoor air change rate – measured by injecting a tracer gas into the room and measuring its decay rate which means that the sensors must be placed throughout the monitored room so that they can sense the tracer gas
    - Supply Airflow Rates and Exhaust Airflow Rates – measuring the air speed at multiple points across a duct cross section to determine the average air speed, which is then multiplied by the cross-sectional area of the duct to yield the volumetric airflow rate which means that the anemometers are placed inside the ducts that are being measured

    As the first parameter is measured, the thesis proposes to place the sensors for the tracer gas in the red circles, which are drawn in the figures below representing one living room and the basement of the KTH Live-in Lab. They are spread so that the gas measurement is uniformly taken so that a higher concentration of the gas in one side of the room is sensed.

    The Supply and Exhaust Airflow Rates must be measured at two or more distinct points that are placed on the ventilation ducts where the anemometers are placed. In order to make air velocity measurements in a duct, it is best to measure at least 7.5 duct diameters downstream and at least 3 duct diameters upstream from any turns or flow obstructions. It is possible to do a traverse as little as 2 duct diameters downstream and 1 duct diameter upstream from obstructions, but measurement accuracy will be impaired.[32] The idea was that one measurement will be taken at the basement level and one at every floor the sensors being placed in the dark circles where the arrow points. In the images shown below there will be no differentiation between the Supply and Exhaust parts because in both cases the same parameter is measured.

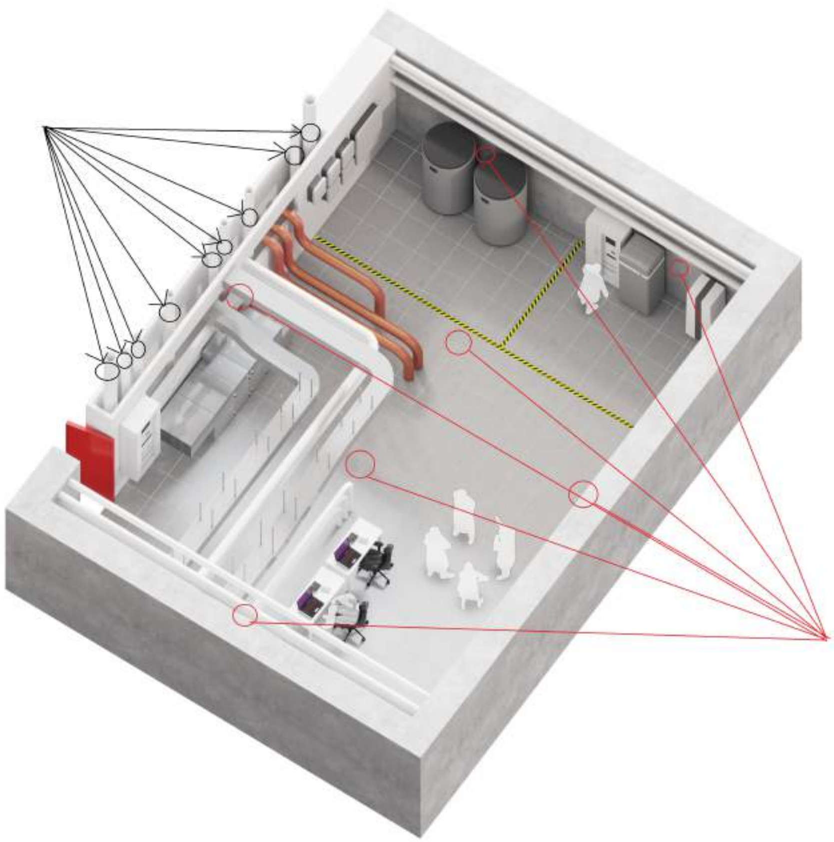

Figure 4.8: Ventilation related sensors positioned in the basement

Figure 4.9: Ventilation related sensors positioned in the living room

2. Air Quality

   - Relative humidity – in order to measure the relative humidity, the sensors must be placed far from water sources or from anything that could cause a spike in humidity
   - Temperature - in order to measure the temperature, the sensors must be placed far from factors that contribute to the increase or decrease of temperature (such as windows or air conditioners or even doors)

- Level of air contaminants – for which was stated in the previous subchapter that it will be the same as CO2 measurements or by a PID

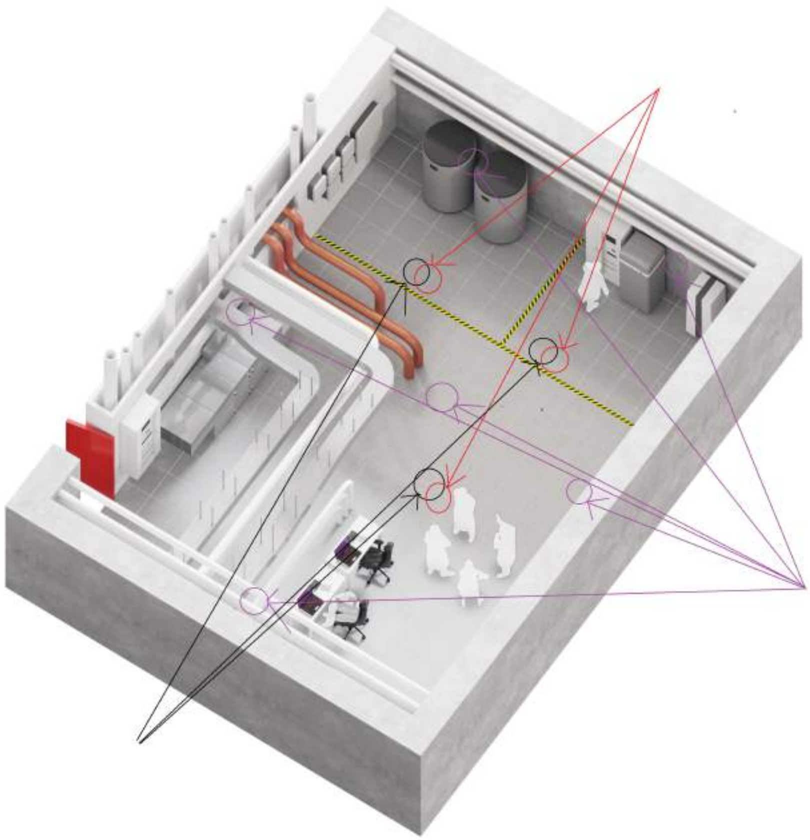

Figure 4.10: Air Quality related sensors positioned in the basement

Figure 4.11: Air Quality related sensors positioned in the living room

In order to measure CO2 the same spots have been chosen to place the sensors as the ones for sensing the tracer gas because, they work on the same principle as CO2 can be a tracer gas itself. In the images above it is shown with the help of the purple circles.

The PID's positioning can be the same as the CO2 one.

The black and the red circles are used to show the location of the temperature and respectively the humidity levels. They are placed in the middle of the room or in the middle of the basement because they will be placed on the ceiling. Since the basement covers a larger area multiple sensors have been used to measure the temperature and humidity from different parts of the room, so that the measurement can be a uniform approximation of the joint temperatures from the room.

3. Thermal comfort

    - Air temperature – this parameter has been covered in the previous subchapter
    - Relative humidity – this parameter has been covered in the previous subchapter
    - Air velocity – the anemometers which will be used to measure the air velocity should be placed in the same spots in which they were placed for the Supply Airflow Rates and Exhaust Airflow Rates because most air velocity in a room is given by the ventilation system.
    - Mean radiant temperature – the globe thermometers that were discussed, should be placed as central as possible, in the room in order to increase the accuracy of the readings. Avoid placing the instrument where relatively large air currents are expected. If the room is too big, multiple thermometers can be used that will pick up data from different sectors of the measured room.

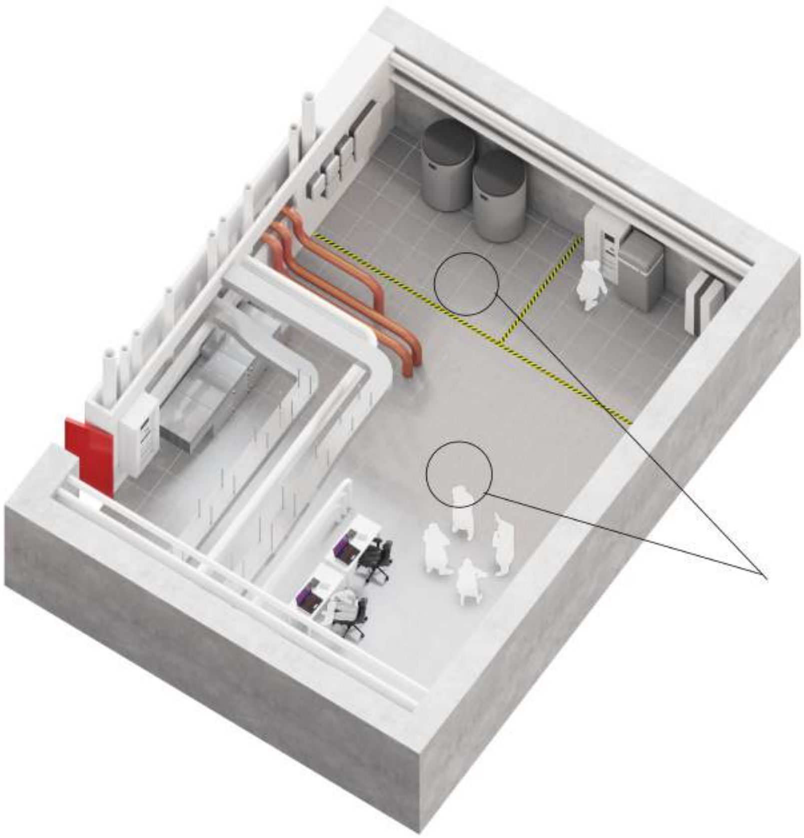

Figure 4.12: Thermal comfort related sensors positioned in the basement

Figure 4.13: Thermal comfort related sensors positioned in the living room

4. Moisture

   - Abnormal humidity in different local areas of the room – to measure moisture, one must think of the places that it is more likely mold will develop and place humidity sensors in the close proximity. If abnormal high values are registered then that might indicate thriving conditions for mold apparition

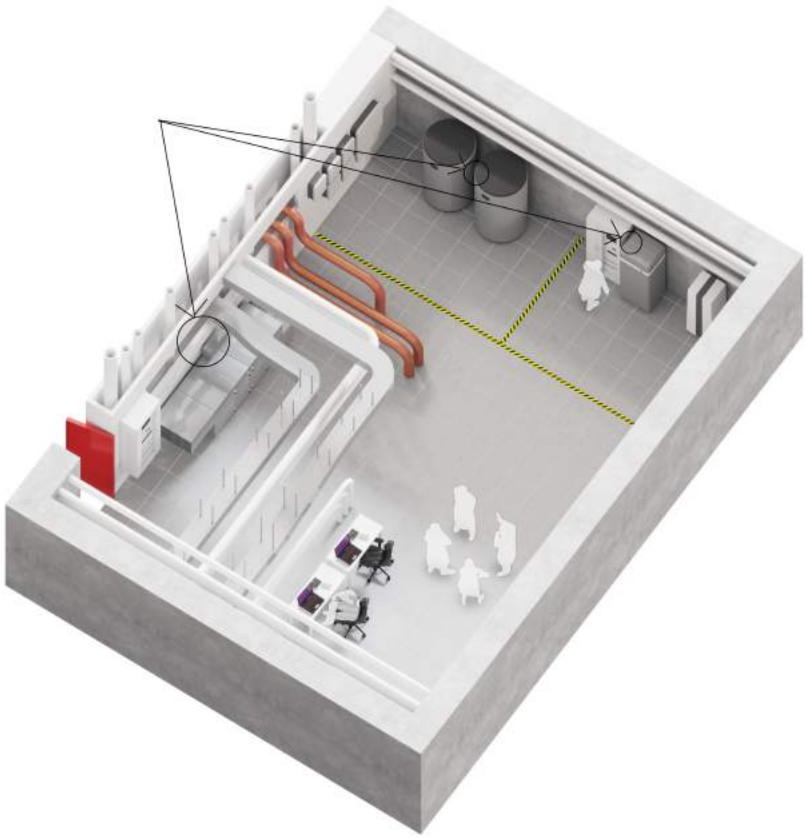

Figure 4.14: Moisture related sensors positioned in the basement

Figure 4.15: Moisture related sensors positioned in the living room

For measuring moisture, closed spaces were considered, for example behind counters, wardrobes and other pieces of furniture that are not moved that often and where a water accumulation could be least noticed. Also places where leaks of the water system were most probable to occur were also considered.

5. Dust and Pests

   - Optical Dust Sensor – this sensor should be placed on a wall in the middle of the distance between the floor and the ceiling and should be as unobstructed as possible since it would need an open area in order to maximize the efficiency of the readings.

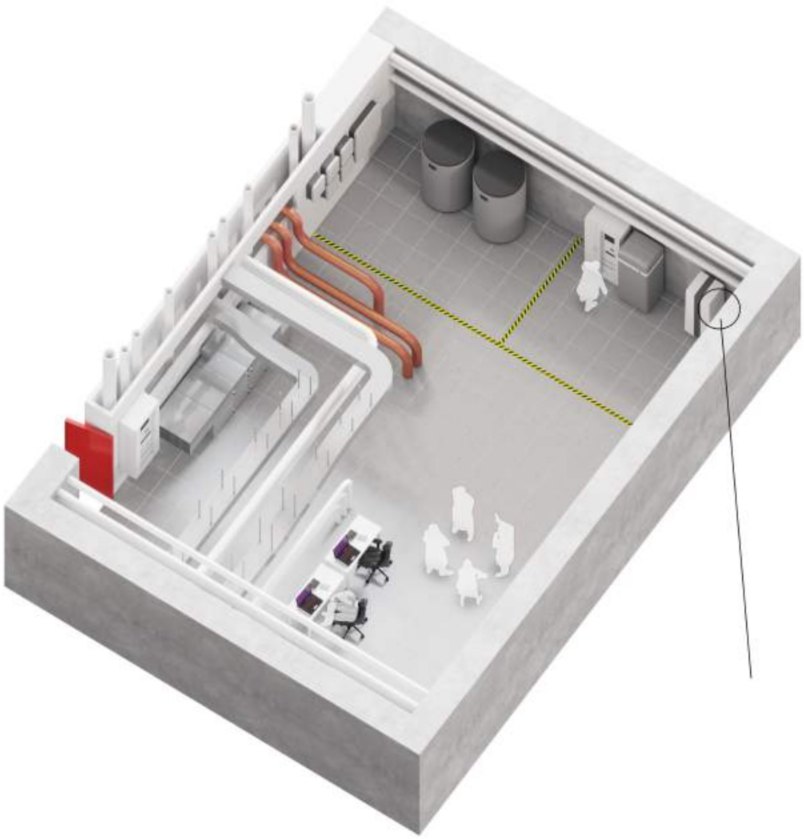

Figure 4.16: Dust related sensors positioned in the basement

Figure 4.17: Dust related sensors positioned in the living room

6. Safety and Security
    - Motion Sensors - detect if there is unwanted presence in the home
    - Video cameras - can start functioning when the sensors detect an intruder

The considered positions in placing motion sensors were around the access points such as windows and doors, but also close to the spots that may hold valuable objects like computers, or that contain a critical infrastructure.

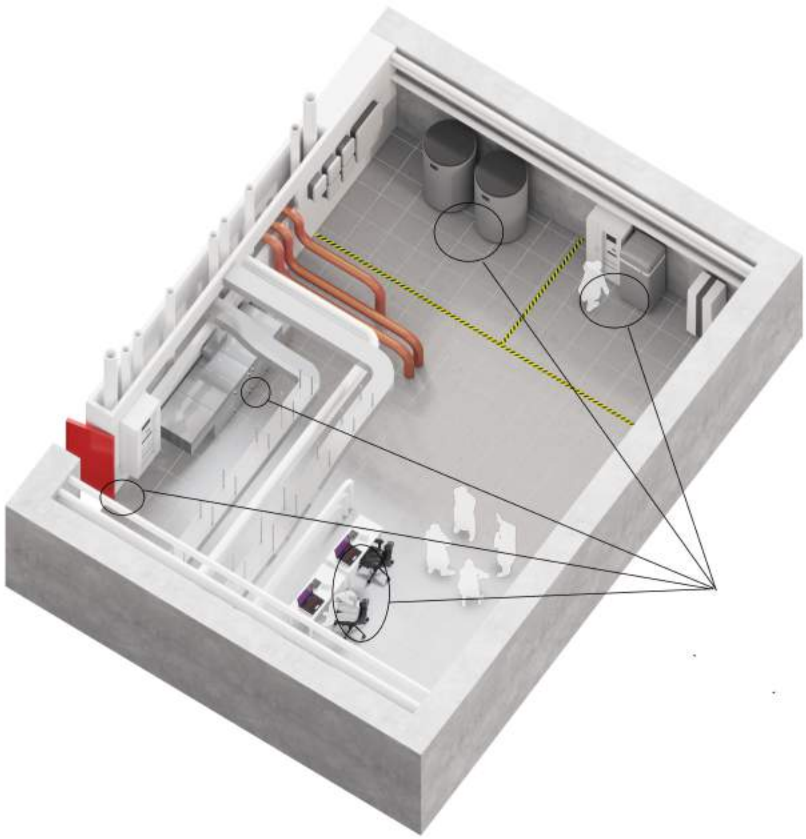

Figure 4.18: Safety related sensors positioned in the basement

Figure 4.19: Safety related sensors positioned in the living room

7. Water Quality

    - Electrical conductivity – can be measured in the pipes when the water comes into the building or where it comes in contact with the inhabitant
    - PH level – can be measured in the pipes when the water comes into the building or where it comes in contact with the inhabitant

8. Noise

- Noise sensors – placed near (a reasonable distance from) the noise sources such as washing machines or dishwashers and the exterior so that it can be seen how the person standing next to them gets affected

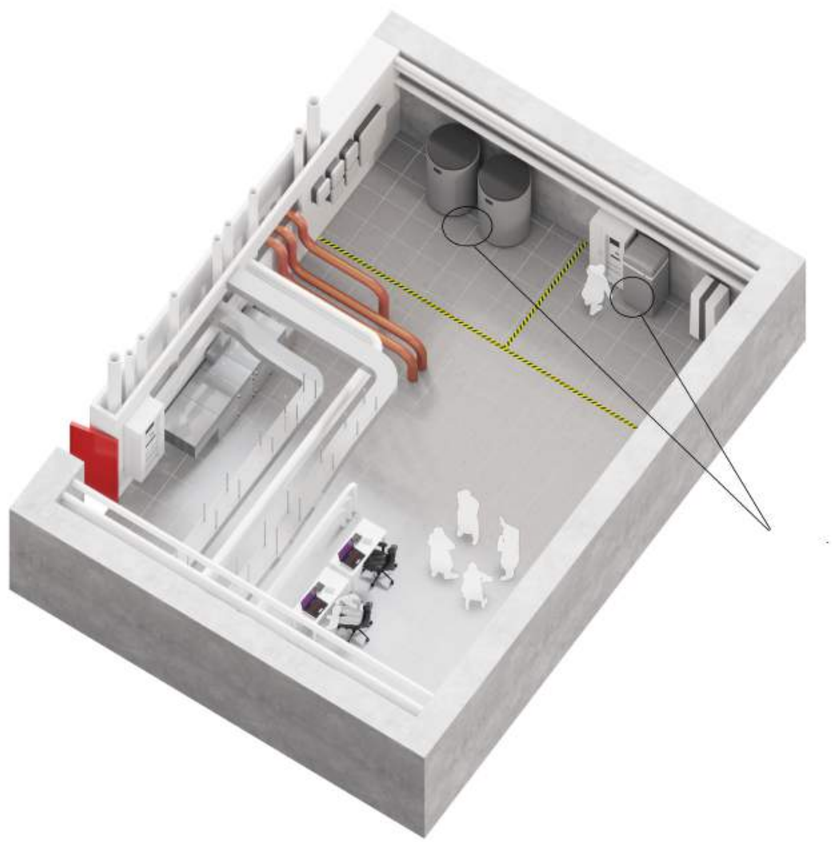

Figure 4.20: Noise related sensors positioned in the basement

Figure 4.21: Noise related sensors positioned in the living room

9. Lighting and Views

    - Brightness – the lighting brightness must be measured at the level of the user's eyesight and must be in sync with other light sources as the screen of the computer and the natural illumination so that the control algorithm can balance the sources so that the user gets as most natural light as possible
    - Intensity – the intensity sensor can be put far from other light sources except the main one, where the light that comes from the

principal light source is not obstructed

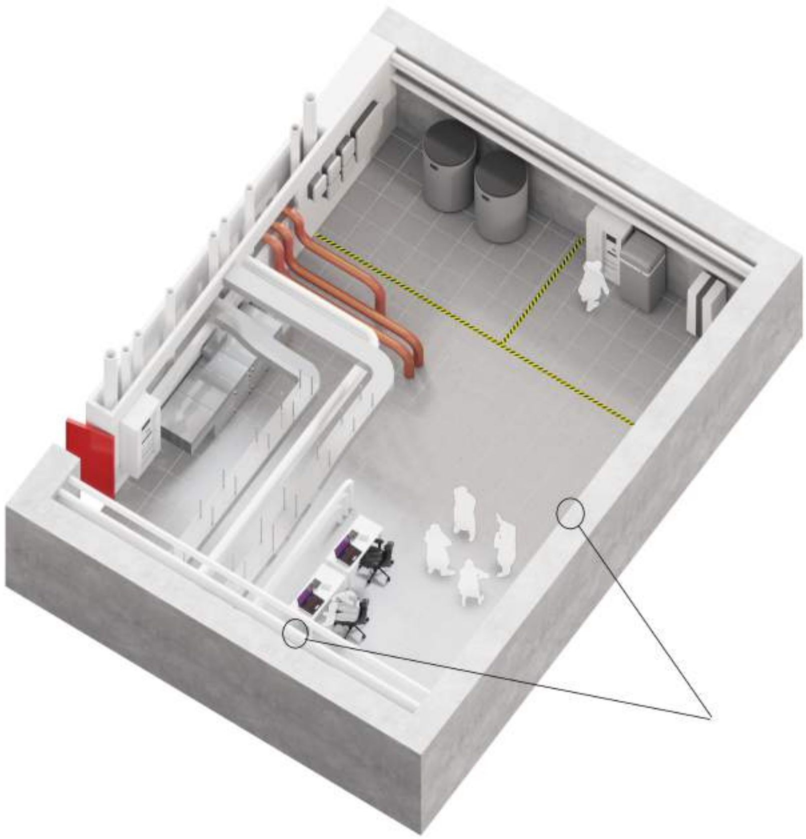

Figure 4.22: Lighting related sensors positioned in the basement

Figure 4.23: Lighting related sensors positioned in the living room

4.3 Security

In the last part of the paper the security issue will be addressed. This type of security is not the security that was mentioned in the previous part, but it is the security of the wireless sensor network itself. Since the sensors might transmit sensible data or non-sensible data, the administrator of the network has the duty to ensure that all the data is used in the desired purposes and remains confidential to the people that are not entrusted with it.

In order to obtain a sigh security level, the administrator of the network must use encryption and authentication protocols. The most used and well known encryption and authentication measure is only with a strong encryption key management which means key distribution and after that establishment discovery and update protocols.

Starting with the key distribution, the best solution is the random key pre-distribution which implies that every node will share a secure connection with their neighbors granted the fact that they will share private symmetric keys. The algorithm has an initial phase, in which to every node there is assigned a relevant number of keys out of the total number of keys (which is held by the sink) completely randomly and saved into the node's memory.

The next phase is the discovery phase which happens after the nodes are deployed. Firstly, every node checks if it shares a similar key with any of their neighbors. This is done by each node issuing a client puzzle to all of its neighbors and that any node that responds to the puzzle with the correct answer means that it can be identified as a safe neighbor. Furthermore a challenge-response protocol is used to verify that the neighbor actually holds the key. This way, the identified common shared key can become the key that encrypts the communication on that link. If it happens that two adjacent nodes do not share the same key, the nodes can set up path keys with the respective neighbors.

Since with time, this "static" encryption system can be rendered obsolete by an adversary that deduced the key that is used for the communication's encryption of a node, a re-encryption algorithm is advised. This implies that the sensor collecting the data always encrypts the information with a private key that it shares only with the sink, and that every node along the way to the sink will flip a coin to decide if it will also encrypt the message with its own key.

In order to defend against an adversary who compromises more and more nodes as it can access the data that it is stored on the node and get the encryption key and use it to decrypt further communication, the keys should be periodically refreshed. Usually this key refreshment should be done randomly, as the sink cannot know which nodes have been compromised. This could guarantee that over long periods of time an adversary will not collect keys it deschypred and use them to obtain valuable information from the system.

The drawback of adding the encryption algorythm is that it lowers the troughtput of the network, adds delay and it requires more power, so if the intention is to view real time data, these security algorythms might not be adviced but it can be adviced if the goal is only to gather and process data.

Chapter 5

Evaluation

In the following chapter the system will be undergoing an analysis by comparison with one standard used for certifying a healthy building.

5.1 WELL Building Standard

In order to evaluate such system with respect to its performance, one must turn to the organizations that inspect and certify buildings according to different criteria. One of these organizations is The International Well Building Institute, that has proposed "The Well Building Standard"[17] that in their words: "marries best practices in design and construction with evidence-based health and wellness interventions. It harnesses the built environment as a vehicle to support human health, well-being and comfort. WELL Certified™ spaces and developments can lead to a built environment that helps to improve the nutrition, fitness, mood, sleep, comfort and performance of its occupants. This is achieved in part by implementing strategies, programs and technologies designed to encourage healthy, more active lifestyles and reducing occupant exposure to harmful chemicals and pollutants."

In this standard, the factors have been classified into 8 categories: Air, Water, Nourishment, Light, Fitness, Comfort, Mind and Innovation. Each of these categories is representative for a part of factors that influence human health of the occupant of a building. Called features in [17] these parameters all have certain limits that they must be complied to in order to receive the certification.

For the system designed in this paper, many of the features that are inspected by the Well Building Institute when called to give an accreditation, do not apply since they are either architectural features (Color Quality, Surface Design) or they depend on the inhabitant (Food Storage, etc) and they will be ignored.

In conclusion while addressing how the proposed system tackles the measurable features of the Well standard, every category will be listed and every feature of the category will also be listed, but only the measurable ones will be discussed in more detail.

For a simplified view on the coverage that the proposed system has on the WELL standard, after each subchapter there is a table with all the features proposed in the standard and the ones covered by the sensing abilities of the proposed system will be marked by a “V”. The not measurable ones will be marked by an “O” and the not covered but measurable ones will be marked by an “X”.

5.2 Air

As presented in the previous parts of the paper, a very important factor that conditions the health of any inhabitant of a building is the air that the person breathes while in the building. So it is of no surprise that the same category is also found in the list of factors that are being looked at when applying for a Well certification. The air category has 29 features which are: Air quality standards, Smoking ban, Ventilation effectiveness, VOC reduction, Air filtration, Microbe and mold control, Construction pollution management, Healthy entrance, Cleaning protocol, Pesticide management, Fundamental material safety, Moisture management, Air flush, Air infiltration management, Increased ventilation, Humidity control, Direct source ventilation, Air quality monitoring feedback, Operable windows, Outdoor air systems, Displacement ventilation, Pest control, Advanced air purification, Combustion minimization, Toxic material reduction, Enhanced material safety, Antimicrobial activity for surfaces, Cleanable environment, Cleaning equipment.

Regarding the first feature Air quality standards, which is also a feature of importance related to this work, in has several parameters in its subdomain that need to be in certain limits. The first parameter used in describing the Air quality standards is the standard for volatile substances, which imposes the following conditions to be met: Formaldehyde levels less than 27 ppb and total VOC less than 500 $\frac{\mu g}{m^3}$. The second measured parameter is the standard for particulate matter and inorganic gasses where the conditions that must be met are carbon monoxide less than 9ppm, PM2-5 less than 15 ug/m3, PM10 less than 50 $\frac{\mu g}{m^3}$ and Ozone less than 51 ppb. The last parameter is radon and the standard states that it should be less than 4 $\frac{pCi}{L}$ in the lowest occupied level of the project. The proposed system deals with measuring the most important parameters of this standard. The first parameter is approximated by the level of CO_2 in the room while for the second parameter the only feasible metric to measure in a habitable room and not a laboratory is the CO level which has a dedicated sensor. A specific installation is proposed for dealing with radon measurements also but it can be overlooked since radon can be mitigated by ventilation that runs according to the control algorithm meant for the other metrics.

The next measurable feature for the presented system is the ventilation effectiveness that is regarded more as a consequence of the measurements proposed more than directly measuring the parameters. While talking about the ventilation effectiveness the first parameter is the ventilation design that needs Ventilation rates to comply with all requirements set in ASHRAE $62.1-2013$ (Ventilation Rate Procedure or IAQ Procedure) and also projects must comply with all requirements set in any procedure in ASHRAE $62.1-2013$ (including the Natural Ventilation Procedure) and demonstrate that ambient air quality within 1.6 km [1 mi] of the building is compliant with either the U.S. EPA's NAAQS or passes the Air Quality Standards feature in the WELL Building Standard for at least 95% of all hours in the previous year. The second parameter is demand for controlled ventilation which taken from the standard it is written that for all spaces 46.5 m^2 [500 ft^2] or larger with an actual or expected occupant density greater than 25 people per 93 m^2 [1,000 ft^2], one of the following requirements is met: • A demand controlled ventilation system regulates the ventilation rate of outdoor air to keep carbon dioxide levels in the space below 800 ppm. • Projects that have met the Operable windows feature demonstrate that natural ventilation is sufficient to keep carbon dioxide levels below 800 ppm at intended occupancies. The third parameter is the system balancing which refers to the testing and balancing of the system once every 5 years. The proposed system does not directly influence these parameters, it is just a tool that helps measuring them.

Moving on to the next feature, VOC reduction, it mostly refers to regulating different sources of VOC that may appear when certain activities happen such as painting the interior, or newly applied adhesives, etc. Even though this parameter has several parts such as interior paints and coatings, interior adhesives and sealants, flooring, insulation, furniture and furnishings that may produce VOCs, the system is equipped with the necessary tools of measuring and mitigating their effects even when one of these sporadic actions happen. Air filtration, is a very important feature concerning the proposed system, and the standard divides it into 3 parts: filter accommodation (Rack space and fan capacity is in place for future carbon filters or combination particle/carbon filters and the mechanical system is sized to accommodate the additional filters), particle filtration (MERV 13 (or higher) media filters are used in the ventilation system to filter outdoor air) and air filtration maintenance. Since the maintenance is a concern of the personnel it will be disregarded for the purpose of this project, but filter accommodation has been covered in has been discussed in the ventilation subchapter, while dust filters were proposed in the dust subchapter. The particle filters were also proposed to be used in the ventilation subchapter.

The moisture management feature is described more as a proactive management in order to avoid a possible hazardous situation. The standard describes the interior and exterior liquid water management as well as the condensation management (which gives the same advices that this paper has dealt with in the moisture chapter which are to monitor humidity in places prone to develop mold over time) and material selection and protection. Even though air flush can be regarded as a ventilation feature, it is in fact related to the immediate after construction period when air is forced through a building in order to remove or reduce pollutants, such as VOCs and particulate matter, inadvertently introduced indoors during construction. And air infiltration management feature refers mostly to air leakage testing which (alongside with the air flush parameter) is not the scope of the developed system.

The humidity control feature, measured by the relative humidity is a big part of the proposed system since it can be found in the ventilation air quality and also moisture subchapter. The standard states that a ventilation system should maintain relative humidity between 30% to 50% at all times by adding or removing moisture from the air. And also modeled humidity levels in the space are within 30% to 50% for at least 95% of all business hours of the year. Buildings in climates with narrow humidity ranges are encouraged to pursue this option.

The direct source ventilation feature can be misleading, it might resemble a ventilation feature but the standard specifies that it applies for all cleaning and chemical storage units, all bathrooms, and all rooms that contain printers and copiers (except those meeting the low-emission criteria of Ecology CCD 035, Blue Angel RAL-UZ 171, or Green Star) meet the following conditions: Are closed from adjacent spaces with self-closing doors and Air is exhausted so that all air is expelled rather than recirculated. Which is a building design property and is not relevant to the proposed system since it cannot be measured.

The air quality monitoring and feedback feature is at the core of the proposed system, the whole thesis proposes a solution for doing the closed loop of presenting the user the measured data about air quality and the rest of the 9 Foundations.

The pest control feature is also a proactive feature for which the user has to respect all the norms. The system cannot conduct a pest inspection or cannot verify that all the perishable food is stored in sealed containers.

Air Features Matrix	Coverage
Air Quality Standards	V
Smoking Ban	O
Ventilation Effectiveness	V
VOC Reduction	V
Air Filtration	V
Microbe and Mold Control	X (can be solved by regular inspections special infrastructure not necessarily needed)
Construction Pollution Management	O
Healthy Entrance	O
Cleaning Protocol	O
Pesticide management	O
Fundamental material safety	O
Moisture management	V
Air flush	O
Air infiltration management	O
Increased ventilation	V
Humidity control	V
Direct source ventilation	O
Air quality monitoring and feedback	V
Operable windows	O
Outdoor air systems	O
Displacement ventilation	O
Pest control	X
Advanced air purification	O(design feature)
Combustion minimization	O (design feature)
Toxic material reduction	O
Enhanced material safety	O
Antimicrobial activity for surfaces	O
Cleanable environment	O
Cleaning equipment	O

Table 5.1: The coverage of the Air properties verified by the standard

5.3 Water

The next big category that is at utmost importance is the water that is used in many important processes around the household such as drinking washing and cooking. As it is known water has a direct contact with the body of the inhabitant so that is why it is so important that it should be as clean and safe as possible. The water standard dictates that the water category has 8 features which are Fundamental water quality, Inorganic contaminants, Organic contaminants, Agricultural contaminants, Public water additives, Periodic water quality testing, Water treatment, Drinking water promotion.

The first feature is the fundamental water quality that has two parts that need to be paid attention to: the sediments which mean that the turbidity of the water sample is less than 1.0 NTU and microorganisms which should result in a total absence of all coliforms in the water sample. The turbidity issue has been addressed and while for it a special sensor is included in the solution, the system has no way of detecting if microorganisms conditions are met since it would require a sophisticated laboratory analysis instead of a smart home monitoring solution.

The next feature is inorganic contaminants, which can be traduced by dissolved metals. The standard mentions that All water being delivered to the project area for human consumption (at least one water dispenser per project) should meet the following limits: Lead less than $0.01\frac{mg}{L}$, Arsenic less than $0.01\frac{mg}{L}$, Antimony less than $0.006\frac{mg}{L}$, Mercury less than $0.002\frac{mg}{L}$, Nickel less than $0.012\frac{mg}{L}$, Copper less than $1.0\frac{mg}{L}$. The proposed system has a solution for detecting metal impurities, which is verifying the water conductivity, which means that if the water has high conductivity, there are big chances to be found dissolved metals in it.

The area of contaminants consists of inorganic as well as organic contaminants. Therefore it is very important to also check for the other half of this spectrum of contaminants. The organic pollutants enumerated by the standard are: Styrene that should be less than $0.0005\frac{mg}{L}$, Benzene less than $0.001\frac{mg}{L}$, Ethylbenzene less than $0.3\frac{mg}{L}$, Polychlorinated biphenyls less than $0.0005\frac{mg}{L}$, Vinyl chloride less than $0.002\frac{mg}{L}$, Toluene less than $0.15\frac{mg}{L}$, Xylenes (total: m, p and o) less than $0.5\frac{mg}{L}$ and Tetrachloroethylene less than $0.005\frac{mg}{L}$ In order to deal with these impurities specific carbon activated filters have been recommended.

Also for the rural areas a danger is also the risk of water pollution by agricultural contaminants. The standard states that for the herbicides and pesticides parameters, Atrazine less than $0.001\frac{mg}{L}$, Simazine less than $0.002\frac{mg}{L}$, Glyphosate less than $0.0170\frac{mg}{L}$, 2,4-Dichlorophenoxyacetic acid less than $0.07\frac{mg}{L}$, and for the fertilizers parameters Nitrate should be less than $10\frac{mg}{L}$ nitrogen. These contaminants can also be removed with carbon filters.

The periodic water testing and the water treatment, even though part of the cathegory, are not related to the measuring system and can be regarded as a proactive measure to ensure high standards of the water that the inhabitants will use.

Water Features Matrix	Coverage
Fundamental water quality	V
Inorganic contaminants	V
Organic contaminants	V
Agricultural contaminants	V
Public water additives	V
Periodic water quality testing	O
Water treatment	O
Drinking water promotion	O

Table 5.2: The coverage of the Water properties verified by the standard

5.4 Nourishment

The nourishment part of the standard is regulating the different aspects of dietary patterns and nutrition of the user of the building that are of no concern with respect to the designed system.

Nourishment Features Matrix	Coverage
Fruits and vegetables	O
Processed foods	O
Food allergies	O
Hand washing	O
Food contamination	O
Artificial ingredients	O
Nutritional information	O
Food advertising	O
Safe food preparation materials	O
Serving sizes	O
Special diets	O
Responsible food production	O
Food storage	O
Food production	O
Mindful eating	O

Table 5.3: The coverage of the Nourishment properties verified by the standard

5.5 Light

Light is a very important element of the indoor environment. It is known that multiple human bodies physiological processes are affected by light and it can directly influence people's mood and performance. That is why it was so important to have Light as an independent category with the following Visual lighting design, Circadian lightning design, Electric light glare control, Solar glare control, Low-glare workstation design, Color quality, Surface design, Automated shading and dimming controls, Right to light, Daylight modeling and Daylight fenestration.

The first feature is visual light design which tackles the core principles of illumination of a room. Part one is the visual acuity focus which implies that The ambient lighting system is able to maintain an average light intensity of 215 lux [20 fc] or more, measured on the horizontal plane, 0.76 m [30 inches] above finished floor. The lights may be dimmed in the presence of daylight, but they are able to independently achieve these levels. The ambient lighting system is zoned in independently controlled banks no larger than 46.5

m^2 [500 ft^2] or 20% of open floor area of the room (whichever is larger). If ambient light is below 300 lux [28 fc], task lights providing 300 to 500 lux [28 to 46 fc] at the work surface are available upon request. Here, there are some design aspects that the proposed system has no control over but the proposed light intensity sensor manages to measure this metric so that it respects the Well standards. Part two of this parameter is the brightness management strategies for which the standards says that the illumination system should provide a strategy that takes into consideration: brightness contrasts between main rooms and ancillary spaces, such as corridors and stairwells, if present, brightness contrasts between task surfaces and immediately adjacent surfaces, including adjacent visual display terminal screens, brightness contrasts between task surfaces and remote, non-adjacent surfaces in the same room and the way brightness is distributed across ceilings in a given room. Again in this case some aspects fall on the control algorithm that controls the brightness but, the proposed system also has a brightness sensor that makes all the future steps of the control algorithm possible.

The next measurable feature to the designed system is the automated shading and dimming controls that includes automated sunlight control, for which all windows larger than 0.55 m^2 [6 ft^2] should have shading devices that automatically engage when light sensors indicate that sunlight could contribute to glare at workstations and other seating areas. This measure is also suggested in the proposed system. Furthermore the automated shading and dimming controls also includes the responsive light control that the standard specifies that all lighting except decorative fixtures is programmed using occupancy sensors to automatically dim to 20% or less (or switch off) when the zone is unoccupied and all lighting except decorative fixtures has the capacity and is programmed to dim continuously in response to daylight. The system also proposed a motion sensor in every room to interact with the room's occupancy degree and also proposed to have a light sensor at every window to balance the amount of light that is available from outside the room with the amount of light that is complementary from the artificial illumination system so that the user has optimal illumination.

Light Features Matrix	Coverage
Visual lighting design	V
Circadian lighting design	O
Electric light glare control	O
Solar glare control	O
Low-glare workstation design	O
Color quality	O
Surface design	O
Automated shading and dimming controls	V
Right to light	O
Daylight modeling	O
Daylighting fenestration	O

Table 5.4: The coverage of the Light properties verified by the standard

5.6 Fitness

The fitness category is the one regulating the physical activity spaces and fitness equipment and programs that concern the user of the building, so it also is irrelevant to the presented system.

Fitness Features Matrix	Coverage
Interior fitness circulation	O
Activity incentive programs	O
Structured fitness opportunities	O
Exterior active design	O
Physical activity spaces	O
Active transportation support	O
Fitness equipment	O
Active furnishings	O

Table 5.5: The coverage of the Fitness properties verified by the standard

5.7 Comfort

Probably the most decisive factor for the owner of a home to continue living there is the fact that he or she can shape the interior of the room so that it feels more comfortable. Alongside this principle Well standard has several regulations that would benefit the comfort of the building user as well as his or her health. The parameters included in the comfort category are: Accessible design, Ergonomics: Visual and Physical, Exterior noise intrusion, Internally generated noise, Thermal comfort, Olfactory comfort, Reverberation time, Sound masking, Sound reducing surfaces, Sound barriers, Individual thermal control, Radiant thermal control.

In this case the first relevant feature is the exterior noise intrusion. It is very common that sometimes one has a noisy neighborhood and that all the noise that comes from outside the room is disturbing and it interferes with the occupant's activities. For that the system proposes a sensor placed near every point of possible noise access into the home (such as windows) to monitor the sound pressure level. The Well standard dictates that the outside noise intrusion should not exceed 50dBA.

Remaining into the noise topic, it is a common knowledge that the source of the noise can be inside the building that is why the next feature that will be discussed is the internally generated noise. The Well standard concerning the internally generated noise has two parts, which are acoustic planning which falls more into the design category, so that there are loud and quiet areas ensured and mechanical equipment sound levels so that it can be ensured that all the indoor noise sources cannot produce noise greater than 40 dB. In order to guarantee this, the designed system proposed the placement of noise sensors around possible noise sources to sense the intensity of the noise.

Furthermore, the next important feature that is relevant to the topic is the thermal comfort. In the Well standard it follows two options for the mechanically ventilated buildings and for the naturally ventilated buildings. Since the designed system will be mechanically ventilated, the standard regulates that all spaces in mechanically-ventilated projects meet the design, operating and performance criteria ASHRAE Standard 55-2013 Section 5.3, Standard Comfort Zone Compliance. In order to comply to that criteria, the proposed system measures air temperature, air velocity, relative humidity and mean radiant temperature whose optimal values can be found in the aforementioned criteria.

On the same topic the final feature contained by the Well standard that is relevant to the designed project is the radiant thermal comfort, which is part of the thermal comfort and has been mentioned in the previous paragraph. The mean radiation temperature which is a key metric in this case will be measured with the help of one or two globe thermometers (depending on the size of the room that is being measured).

Comfort Features Matrix	Coverage
Accessible design	O
Ergonomics: visual and physical	O
Exterior noise intrusion	V
Internally generated noise	V
Thermal comfort	v
Olfactory comfort	O
Reverberation time	O
Sound masking	O(Building design)
Sound reducing surfaces	O(Material design and building design)
Sound barriers	O(Material design and building design)
Individual thermal control	O
Radiant thermal comfort	V

Table 5.6: The coverage of the Comfort properties verified by the standard

5.8 Mind

The mind category is also mostly irrelevant to the purpose of the paper since the features that it incorporates are: Health and wellness awareness, Integrative design, Post occupancy surveys, Beauty and design, Biophilia I – Qualitative, Adaptable spaces, Healthy sleep policy, Business travel, Building health policy, Workplace family support, Stress and addiction treatment, Altruism, Material transparency, Organizational transparency, Beauty and design II and Biophilia II – Qualitative.

The only feature from this category included in the designed system is the Self-monitoring one for which the standard specifies that at least 2 of the following parameters should be made available for each occupant body weight/mass, activity and steps, heart rate variability, sleep duration, quality and regularity. The designed system has a wearable subchapter where in conformity with the standard; it proposes that the heart rate and activity of the user should be monitored by the usage of a smart bracelet.

Mind Features Matrix	Coverage
Health and wellness awareness	O
Integrative design	O
Post-occupancy surveys	O
Beauty and design I	O
Biophilia I - qualitative	O
Adaptable spaces	O
Healthy sleep policy	O
Business travel	O
Building health policy	O
Workplace family support	O
Self-monitoring	V
Stress and addiction treatment	O
Altruism	O
Material transparency	O

Table 5.7: The coverage of the Mind properties verified by the standard

Chapter 6

Conclusion

In conclusion, I would like to summarize the whole system in the end presenting some possible solutions which can be interpreted as future work in order to adjust it to user of the project which is the KTH Live-in Lab user.

Starting from the health concepts proposed by Harvard, the paper above manages to identify the metrics that need to be measured in order to have a good view over the health affecting parameters that exist in a residential building. In order to create a health monitoring system a wireless sensor network is proposed each metric having its own sensor (or couple of sensors) designed and placed on the schematics of the KTH Live-in Lab. A building specific topology of the system is also proposed in the above chapters. The paper also proposes an encryption algorithm to ensure the security of the data that travels through the network is protected against eavesdropping attacks (so that an attacker which has access to the data through illegal methods cannot properly read the data he possesses).

In order to assess the proposed system's efficiency when measuring the intended metrics, it has been compared to the specification of the WELL Standard that certifies healthy buildings. All relevant aspects of the standard to the proposed system have been approached and fulfilled with a proposed solution.

From the user's point of view, they will benefit from living in a building that respects all the health standards while being able to directly monitor all their surrounding parameters while being announced in real time if there has been a dangerous change in the factors. This has been made possible by centralizing all the data on a data base, where the values of the measurements are saved and accessed at different times for different purposes and it can also have a graphical interface application which can be for example a Java-based application or a LabView based application. Furthermore, in order to make the living in KTH Live-in Lab a more user-friendly experience, instead of showing all the data only on a computer connected to the central node, a mobile application can be created using for example Android Studio which could help the user since he/she does not need to be home in order to check the living parameters, but instead he/she could check them at any given time only by looking his/her smartphone. It can be regarded as another interface to the same database whose entries are the measurements and who is also used by the central node's interface.

Chapter 7

Future Work

This thesis is just the first step in which the proposed system is designed in order to measure all the identified parameters that affect the health of the person living in the KTH Live-in Lab. The next obvious step would be the implementation of the designed wireless sensor network in all the rooms of the building and the creation of the central node and the application which manages the data collected by the multitude of sensors.

The first challenge that arises in this part of implementation is that in order to have a uniform system all the rooms in which users will be living in should have the same monitoring equipment installed. This fact combined with the need of accurate measurements might lead up to a substantial cost of acquiring the equipment and installing it, which is why it is very important to consider the trade-off between the overall cost and the accuracy of the measurement. As it was shown in the previous chapters, in some cases the thesis proposes a measurement of a certain number of parameters, but sometimes gives the liberty of dropping some parameters in the proposed solution out of these considerations. Moreover if in some cases the equipment is considered too expensive or impractical, the thesis also gives a more inaccurate way of approximating the metric that wished to be measured but warns about the possible drawbacks (ex: Air Quality).

Concenrning the security aspect an encryption algorythm that can be used to secure the communications of sensible information withing the wireless sensor network is presented in the previous chapters but it could also be improved. A possible improvement could be the implementation of a differencial privacy algorythm. Which increases the privacy by adding some local noise to the measurement of every node but not too much so that the data can be recovered in the central node. This can be added as a form of protecting really specific data from users. The drawback of it is the same as the drawback for adding the encryption algorythm which is that it lowers the troughtput of the network, adds delay and it requires more power, so if the intention is to view real time data, these security algorythms might not be adviced.

Finally in the previous chapters a special part is dedicated to the wearables devices that help monitor the metrics that are from within the human body. If the implementation would be broken down into phases, I would suggest implementing the environment monitoring system first, and then adding the wearables component afterwords. This is why I am inclined to add the wearables part to the future work.

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