Aalto University
School of Engineering

Serge Skorin

IoT based monitoring and control of concrete drying conditions in construction phase of new-production residential buildings

Master's thesis

Espoo 12.02.2018
Supervisor: Professor Jouni Punkki
Instructor: M.Sc. Jan Lund NCC Suomi Oy

Aalto-yliopisto
Insinööritieteiden korkeakoulu

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

Diplomityön tiivistelmä

Tekijä TkK Serge Skorin

Työn nimi IoT pohjainen betonin kuivumisolosuhteiden hallinta uusien asuinrakennuskohteiden tuotantovaiheessa

Koulutusohjelma Master's Programme in Building Technology

Pää-/sivuaine Building Technology / Indoor Environment **Koodi** ENG27

Työn valvoja TkT Jouni Punkki

Työn ohjaaja(t) DI Jan Lund

Päivämäärä 12.02.2018 **Sivumäärä** 105 **Kieli** Englanti

Tiivistelmä

Viime aikoina etenkin uudehkojen asuinrakennusten kosteus- ja homeongelmat ovat saaneet huomattavaa näkyvyyttä mediassa, minkä seurauksena lukuisia uusia tutkimuksia on tehty selvittääkseen ongelmien perimmäiset syyt sekä pystyäkseen ehkäisemään tulevia ongelmia. Kosteusvaurioiden syiksi on todettu mm. uusien energiamääräysten mukaiset erityisen haasteelliset arkkitehti-, rakenne- ja talotekniikkasuunnitelmat, rakennustuotannon ylikuumentuminen ja sitä kautta kasvanut riski työmaalla tapahtuviin virheisiin sekä vääränlainen käyttö ja ylläpito. Yksi isoimmista yksittäisistä syistä on kuitenkin rakennuskosteus eli rakennusmateriaalien kuten betonielementtien valmistuskosteus ja rakenteisiin rakennusaikana päässyt kosteus, jota pitäisi pystyä hallitsemaan nykyistä paremmin.

Diplomityön tavoitteena on selvittää, voiko reaaliaikaisella, IoT-teknologiaan perustuvalla työmaan rakennusaikaisten ulko- ja sisäolosuhteiden seurannalla ja betonin kosteuden mittauksella aktiivisesti ohjata työmaan johtoa betonin kuivumiselle optimaalisten olosuhteiden ylläpitämisessä sekä täydentämään tai jopa mahdollisesti korvaamaan nykyistä kosteudenmittausprosessia. Toissijaisena tavoitteena on selvittää, mikä langaton tiedonsiirtoverkko sopii kyseisten tavoitteiden saavuttamisessa parhaiten, sekä tekniseltä toteutukseltaan että kustannustehokkuuden näkökulmasta, ottaen huomioon haastavat ja muuttuvat työmaaolosuhteet.

Tutkimuksen teoreettinen osuus on toteutettu kirjallisuuskatsauksena. Tämän tutkimuksen lähteinä on käytetty pääasiassa Suomen rakentamismääräykokoelman, Rakennustiedon (RT), Betoniteollisuus Ry:n ja Betoniyhdistys Ry:n (BY) betonirakenteiden ohjeita ja määräyksiä, johtuen siitä, että Suomessa ja muissa pohjoismaissa rakennusolosuhteet ovat hyvin haastavat, mikä tarkoittaa myös sitä, että suomalainen betonitekniikka on laadullisesti hyvin korkealla tasolla. Tutkimuksen empiirinen osuus koostuu IoT-arkkitehtuurin rakentamisesta ja asentamisesta pilottityömaalle, sensorien datan keräämisestä, analyysistä ja talletuksesta sekä työmaahenkilöstölle tarkoitetun verkkopohjaisen applikaation kehittämisestä.

Tutkimus osoittaa, että reaaliaikaisella kuivumisolosuhteiden seurannalla voidaan saavuttaa projektista riippuen hyvinkin merkittävää taloudellista hyötyä lyhentämällä rakennusvaiheen kestoa, tehostamalla lämmitysenergian käyttöä ja vähentämällä perinteisten kosteusmittausten määrää. Pilottiprojekti osoittaa, että työnjohto hyötyy selvästi applikaation käytöstä ja se auttaa ennen kaikkea nuoria ja vähemmän kokeneita työnjohtajia ymmärtämään työmaan rakennusfysiikan merkityksen betonin kuivumisprosessissa.

Avainsanat IoT, kosteudenhallinta, betonin kuivuminen, Wirepas, LoRa

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School of Engineering

Aalto University, P.O. BOX 11000, 00076 AALTO
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Abstract of master's thesis

Author B.Sc. Serge Skorin	
Title of thesis IoT based monitoring and control of concrete drying conditions in construction phase of new-production residential buildings	
Degree programme Master's Programme in Building Technology	
Major/minor Construction management/Indoor Environment	**Code** ENG27
Thesis supervisor D.Sc. Jouni Punkki	
Thesis advisor(s) M.Sc. Jan Lund	
Date 12.02.2018 **Number of pages** 105	**Language** English

Abstract

Recently, moisture related problems, particularly in relatively new residential buildings, have drawn a significant amount of media attention. Consequently, numerous researches and studies have been conducted in order to detect, analyse, and prevent future moisture problems from occurring. Unwanted moisture in the structures has been found to cause both considerable financial losses and severe health issues due to potential growth of mold, dust mite presence and VOC emissions. There are many causes to the above-mentioned problems throughout the building life cycle, including inadequate design, negligent construction and inappropriate use and maintenance. One of the major single causes is construction moisture that is not properly controlled and removed during the construction phase.

The aim of this Master's thesis is to determine whether it is technically possible and financially feasible to actively steer the construction site management to maintain at all times indoor conditions that are optimal for drying of concrete with the help of real-time IoT-based monitoring technology, and additionally support or even replace current humidity measurement process. Secondary aim is to determine which wireless area network (WAN) is best suited for achieving the former aim, both from technical and financial point of view, taking into account the constantly changing construction environment conditions.

The theory section is compiled as a literature survey containing previous studies and literature on concrete including the Finnish building code, the Building Information Ltd and the Confederation of Finnish Construction Industries (CFCI) the as the main source, due to the fact that the concreting conditions in Finland and other Nordic countries are rather challenging, also implying that the quality of Finnish concrete technology is very advanced. The empirical part consists of building, testing and installing the IoT-architecture on the pilot construction site, collecting, analysing and storing sensor data, and developing a web based application designed for the construction site management.

The thesis proves that real-time control of drying conditions provides significant financial benefits by cutting down construction time, by optimizing the use of heating energy and by reducing the need for traditional moisture measurements. The case study also shows that the construction management is benefitting greatly from a supplementary mobile web application highlighting the importance of building physics in the drying process.

Keywords IoT, moisture control, moisture mechanics, drying of concrete, Wirepas, LoRa

Preface

This research was initiated by the IT-department of NCC Suomi Oy as a part of a new digital strategy in order to renew the industry and create innovative, sustainable and efficient construction supporting methods that provide ground for future development of feasible production. The research was funded by and executed in cooperation with KIRA-digi and MBR Oy (Peab Industry). The thesis was supervised by professor of practice in concrete technology, Jouni Punkki and the thesis advisor was Jan Lund, who is responsible for production support services at NCC Suomi Oy.

I would like to thank Jan Lund and Jouni Punkki for valuable assistance and ideas, development engineer Esa Eklund and IT-manager Ari Törrönen from IT-department for technical support and whole AR-team for the motivational and pleasant trainee period at NCC. Finally, I would like to thank my family and friends for mental support throughout the project.

This has been without doubt the biggest professional challenge for me so far and it has taught me many new skills that I will utilize in my future career.

Espoo 30.12.2017

Serge Skorin

Contents

Annotations

D	[m^2/s]	Vapor diffusivity in air
P	[Pa]	Pressure
Q	[m^3/s]	Air flow rate
R		Ideal gas constant
RH	[%]	Relative humidity
T	[°K] / [°C]	Temperature
g	[kg/(m^2·s)]	Flow / drying rate
g	[m/s^2]	Gravitational acceleration
k_v	[kg/sm^2Pa]	Vapor permeability
n	[mol]	Amount of substance
p	[Pa]	Partial vapor pressure
w	[kg/m^3]	Moisture content
x	[kg/kg]	Vapor ratio
β		Evaporation rate coefficient
β	[°K^{-1}]	Air compressibility
ρ	[kg/m^3]	Density

Abbreviations

API	Application Programming Interface
IoT	Internet of Things
UI	User Interface
LoRa	Long Range
WAN	Wireless Area Network
JSON	JavaScript Object Notation
HTML	Hypertext Markup Language
HTTPS	Hypertext Transfer Protocol Secure
BLE	Bluetooth Low Energy
LTE	Long Term Evolution
SDK	Software Development Kit
IDE	Integrated Development Environment
SAS	Shared Access Signature
AMQP	Advanced Message Queuing Protocol
MQTT	Message Queue Telemetry Transport
SMB	Server Message Block
SQL	Structured Query Language
URL	Uniform Resource Locator
BY	Betoniyhdistys, Finnish Concrete Association
ISM	Industrial, Scientific and Medical
NFC	Near Field Communication
RFID	Radio Frequency Identification
UHF	Ultra High Frequency (300 – 3000 MHz)
EPC	Evolved Packet Core
CSS	Chirp Spread Spectrum
CFD	Computational Fluid Dynamics
IP	Ingress Protection (Rating)
KPI	Key Performance Indicator
PDF	Portable Document Format

1 Introduction

Consistent environment condition control at a construction site is crucial for the overall success of a project, since it greatly affects both the schedule and the budget objectives. The more time is spent on drying the concrete structures during the framework phase, the more the project costs for the general contractor. Naturally, rain water penetration must also be limited to a minimum. Furthermore, the less attention is paid on keeping the building envelope as airtight as possible at all times, the more money is spent on heat energy. In fact, temporary building heating represents one of the biggest add-on production costs (Niemi 2017).

Real-time condition control enables creation of new innovative service concepts, significantly promotes consistency and predictability of production process and improves quality. There are three main general requirements for the implementation of new technologies: feasibility, reliability and convenience for the end users. Achieving all the above-mentioned requirements guarantees success.

The thesis is organized as follows: In Chapter 1, the research problem and the aims of the project are discussed. In Chapter 2, the theory of concrete structures, physical and chemical properties of concrete, heat and mass transfer mechanics, drying techniques and IoT networks are presented. In Chapter 3, the research methods, including the implemented hardware and software solutions are presented. In Chapter 4, the results of the case study research are presented. In Chapter 5, the research analysis is carried out. Finally, in Chapter 6 the conclusions are drawn and recommendations are made about potential commercial applications and further research. Primary stress of the thesis is on the empirical research.

1.1 Background

The initiation for the case study of this thesis came from the IT-department of NCC Suomi Oy as a part of their new digital strategy. The aim is to integrate new innovative technology into the production process in order to increase productivity, improve quality, consistency and reliability, and add convenience to the employees by providing digital tools, with accordance to the new tightening regulations regarding moisture control (Ministry of the Environment 2017). To achieve these goals, the technology needs to be cost efficient, easy to introduce and easy to use.

Currently, there already are many management systems that the construction site management needs to use daily, including drawing, access control, quality control, schedule planning, safety and budget management. Hence, it would be beneficial if a new system was easily integrable with the existing software in the industry, since moisture control is essentially a part of production control. For example, Congrid is a versatile and intuitive software widely used for quality control on construction sites in Finland and in Sweden, and is also suitable for direct API applications. Also, RamiSmart, developed by Ramirent Finland Oy and currently used mainly for access control, would provide a solid platform for cooperation towards more efficient and more accurate moisture control.

1.2 Research Problem

Construction site environment is exceptionally challenging, since there are many internal and external factors in the production process that often cannot be affected or predicted. Weather conditions, design and assembly challenges and human errors are common problems that need to be considered already in the planning phase. Consequently, integrating highly sensitive digital tools into the construction environment for better control of the production process is demanding for many reasons: the electronic components are sensitive to moisture, temperature fluctuations and dust, the transmission rates of wireless devices are affected by the massive concrete structures, the power outages are common, the accidental physical damages and lastly the general attitude that digital tools are unreliable, difficult to use, time consuming and obsolete.

Timing is also very important for the overall success of a project. In earlier days, the projects were generally scheduled so that the framework phase was completed during summer, thus minimizing rain exposure and the need for temporary building heating during the most energy-intensive phase of production process. Similarly, the interior works were completed during winter, at which point the indoor conditions were under control (Figure 1). Nowadays, the construction demand, especially in the Helsinki metropolitan area, is steadily growing (Helsingin kaupunki 2014) and projects are started throughout the year, thus the condition control has become ever more important.

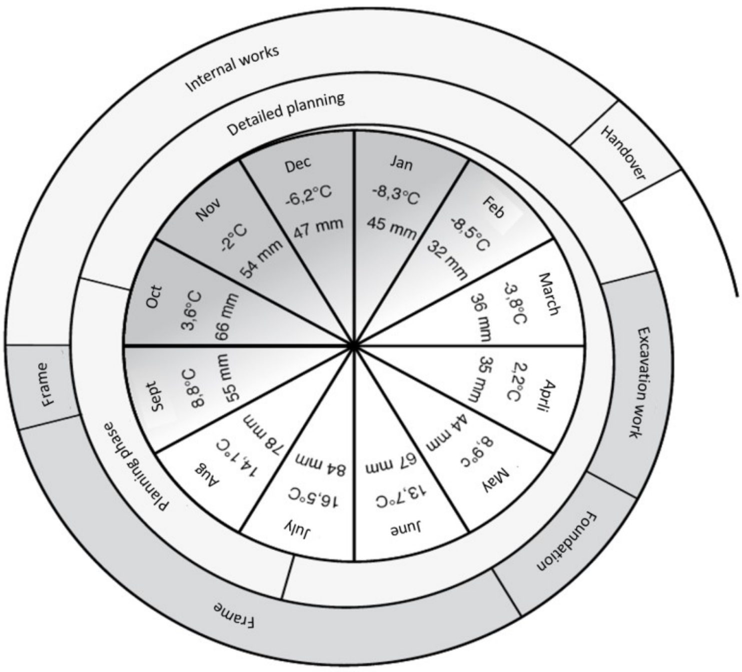


Figure 1 Recommended construction timing (modified from Ratu S-1232 2013).

Besides potential moisture related problems, one of the most important factor for controlling concrete conditions is strength development of cast-in-situ concrete structures and thus safety of a building. Casting conditions significantly affect the initial activation of setting and hardening process of concrete as well as the whole drying process.

There are also challenges related to the measurement process of temperature and relative humidity of concrete structures needed to ensure that the surface is ready for coating. Current established measurement procedures, in accordance with the RT-standard 14-10984, using Vaisala measurement equipment are only accurate when measuring momentary values. This, however, presents following limitations: To get adequate results, the measuring conditions need to be optimal, which is rarely the case, since indoor air conditions may fluctuate significantly due to sudden change in weather conditions, or simply because a window was left open, which can quickly upset the prevailing indoor conditions. Hence, the measuring error due to temperature difference or fluctuation between the concrete and the indoor air causing change in vapor pressure gradient, meaning that the moisture transfer can potentially be reversed, can be up to +/- 15 % RH. Ideally, the temperature difference between the concrete and the indoor air at the time of measurement must be below 2 °C. Also, the traditional measurement methods are extremely time-consuming and labor-intensive, which often leads to insufficient amount of measuring points and thus inadequate representation of the actual moisture distribution in the structures. (RT 14-10984 2010)

Additional complications are caused by the tightness of modern reinforced concrete structures. The measurements cannot be carried out if, for example, there is too much reinforcement steel, plumbing pipes and floor heating system components in the way in a cast-in-situ bathroom floor. Hence, the measurements often need to be taken from the concrete just outside the bathroom, where the floor structure is usually slightly different and thus the drying process is also different.

There are also some new trends in the industry: floor heating throughout the apartment and geothermal heating systems. While they add comfort and are cost efficient (Figure 38), they also require different approach regarding planning of condition control. For example, a geothermal heating system often eliminates the possibility to use temporary district water-heating systems for drying purposes, and the permanent heating can be activated relatively late in the production phase.

There are many research and literature available on the subject of moisture and condition control in buildings. The problem is that the information is scattered, often vague and sometimes contradictive. Also, in my opinion, the problem lies within common attitudes and habits in the industry: according to the CEO of a big Finnish construction company, “weather cover does not promote drying, since the drying only starts when the proper heating begins” (Mölsä 2014). Hence, in order to increase productivity that has not improved much in the past 50 something years, more radical measures are needed, also in the field of moisture control (The Economist 2017). The prerequisites to be able to maintain the conditions optimal for drying need to be ensured, and documentation of the prevalent conditions in all parts of the building should be carried out throughout the construction phase.

1.3 Aims and Objectives

The main aim of the thesis is to research whether the drying conditions can be effectively controlled with IoT based monitoring system and, consequently, whether by doing so the drying process can be positively affected. In the case study, new wireless sensors are tested at a pilot site to measure both environment conditions and conditions inside the structures. Additionally, different wireless networks are tested and compared, to find out how well they are suited for construction site environment.

In order to achieve optimal conditions for drying of concrete, the moisture control needs to be planned carefully prior to construction phase, possibly with the help of consultants, taking into account the location of the building, weather conditions, technical properties, schedule, safety requirements etc. In the construction phase, the conditions need not only to be monitored, but to be improved actively. This could, in theory, be achieved by active guidance of site supervisors, who are largely responsible for the success of the production process. In the thesis, the design principles of an algorithm that is supposed to help the supervisors to control the drying conditions by giving them concrete instructions that are calculated based on the moisture mechanics are discussed.

When considering the functionality of wireless sensors, it is important to determine how convenient the installation process is, how much time it takes and how reliable and accurate the sensors are. When choosing a network, it is important to consider safety, reliability and cost aspects. In case of a construction site, the data transmission rates do not necessarily need to be very big, since an individual signal does not generally contain a lot of data, especially when monitoring only temperature and relative humidity. The latency and the transmission frequency are also not very critical, since the drying process is relatively slow by nature. This helps save costs compared to, for example, the highly automated machine industry, where the data is transmitted several times per second and the reaction time needs to be very fast. However, the transmission range properties need to be very good in order to ensure adequate reception of all sensors.

From a financial perspective, the main goal is to cut production costs, first of all by optimizing the duration of the framework phase and, secondly, by optimizing energy consumption, since the better the conditions are controlled, the less energy is wasted on heating and dehumidifying outdoor air. By analyzing the actual drying process, we can better predict the optimal duration of the framework and thus decrease the need for time buffers. Also, by providing accurate real-time monitoring of concrete structures, the need for traditional relative humidity measurements is reduced. So called drill hole measurements present, indeed, a significant expense: each drill hole measurement can take up to 3 weeks. Additionally, by providing a good documentation of the drying process, we can minimize the risk of moisture problems in the use phase and thus reduce warranty costs.

1.4 Research Framing

In this thesis, the main focus is on common characteristics and properties of new-production residential buildings and how the IoT based service can support them. However, the outcomes of this thesis can also be applied to refurbishment projects, where controlling the drying process is also very important.

The design of the IoT architecture, including the sensors, the networks and data transmission properties, is presented in detail, but the data transfer security is discussed very briefly. However, in case of a commercial application, the data transfer security is naturally a crucial factor.

In this thesis, the complete operational model of moisture control during the construction process, the Kuivaketju10, or other extensive moisture control plans are not discussed. Also, drying techniques designed to prevent or fix moisture damage, such as drying hollow-core slabs from the inside, the use of floor radiator plates and matts, and microwave drying are out of the scope.

2 Concrete, moisture mechanics and IoT networks

In order to be able to thoroughly improve the condition control, it is essential to understand the structural physics behind the construction process and how they affect the condition control. In this chapter, main theoretical elements of the frame work process are discussed in chronological order, including the properties of concrete, the different types of concrete frame structures, the hygrothermal behavior of a building, the drying equipment, and the measurement solutions. Additionally, the newest wireless IoT technologies and the behavior of a radio signal in a building are discussed.

2.1 Properties of Concrete

Concreting is a rather complex process that happens essentially in seven stages:

1. mixing
2. transporting
3. placing
4. consolidating and compacting
5. setting and hardening
6. curing
7. drying

For the purpose of this thesis, the last three stages are discussed in this chapter. Also, basic ingredients of concrete are presented, and properties related to the drying time are discussed. In Chapter 3, the ingredients of the different concrete mixes used in the case study are presented.

2.1.1 Basic Ingredients

Concrete consists of three main ingredients: cement, aggregate and water. Cement and water form a paste that binds aggregate into the final product, concrete. Additionally, various admixtures can be added if needed.

2.1.1.1 Cement

The share of cement in concrete is normally 8–16 w% (Betoni 2017c). Cement, usually a Portland cement, named after the Isle of Portland in England, rich in limestone, is the most important ingredient, since it acts as a hydraulic binder, binding all the other ingredients together by a chemical-mechanical process (Neville 1995 p. 2). Cement also provides strength and impermeability.

Portland cement is produced by pulverizing a clinker, "a heterogenous mixture of several compounds" produced by reactions between calcium oxide (CaO), silica (SiO_2), alumina (Al_2O_3), iron oxide (FeO) and a calcium sulfate ($CaSO_4$). Since Portland cement has multiple components, the hydration, more thoroughly discussed in Chapter 2.3.2, is a process of several reactions happening both in parallel and successively. As a result, two principal solid phases are formed: *Calcium Silicate Hydrate* ($nCaO\cdot SiO_2\cdot mH_2O$, abbreviated to C-S-H) and *Calcium Hydroxide* ($Ca(OH)_2$, abbreviated to CH) (portlandite) (Figure 2), forming from

- tricalcium silicate ($3CaO\cdot SiO_2$, abbreviated to C_3S), the single most important component controlling setting and hardening
- dicalcium silicate ($2CaO\cdot SiO_2$, abbreviated to C_2S)
- tricalcium aluminate ($3CaO\cdot Al_2O_3$, abbreviated to C_3A)
- calcium aluminoferrite ($4Ca\cdot Al_2O_3\cdot Fe_2O_3$, abbreviated to C_4AF) (Mehta 2014 p. 26; Odler 1998 pp. 243–270)

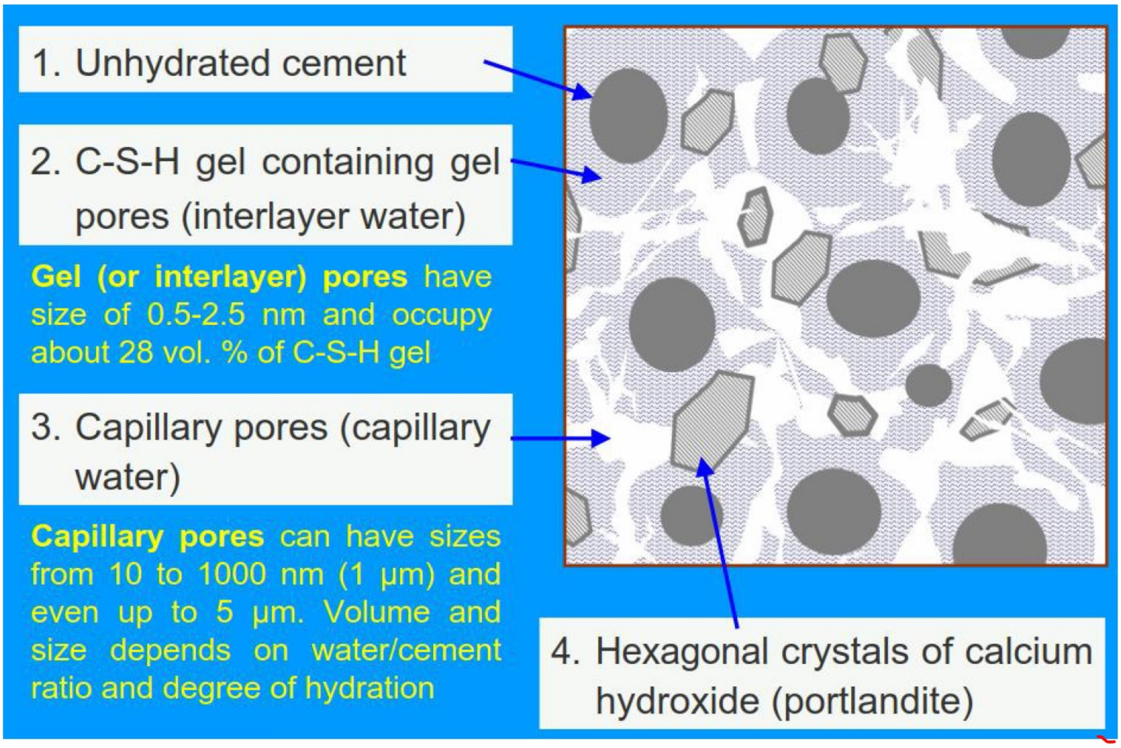


Figure 2 Hydrating cement (Selis 2013)

2.1.1.2 Aggregate

The share of aggregate in concrete is about 70 vol% (Betoni 2017c). Aggregate can be divided into two categories, fine and coarse aggregate based on their size. Aggregate of size smaller than 5 mm are considered fine and consist mainly of either natural or artificial sand, and aggregate over 5 mm are considered coarse and consist generally of gravel and crushed stone. The function of a coarse aggregate is to increase crushing strength of concrete and that of a fine aggregate is to fill the voids in the coarse aggregate and to reduce shrinkage and cracking of concrete. Aggregate is considered a non-reacting ingredient in concrete, but it is believed that some chemical reaction may occurs between the silica of the sand and the hydrating cement. (Neville 1995 pp. 108–148)

2.1.1.3 Water

Water reacts chemically with cement resulting in setting and hardening process, discussed more thoroughly in Chapter 2.1.2. Water/cement (w/c) ratio is crucial for hydration and drying process and for workability. Workability is described by two properties: consistency that is usually measured by a slump-cone test, indicating the ease of flow, and cohesiveness, meaning the water-holding (the opposite of bleeding) and the coarse-aggregate-holding (the opposite of segregation) capacity (Mehta 2014 p. 340). High water content significantly reduces the strength of concrete and increases drying time. On the other hand, low w/c ratio produces more resistance to vapor diffusion. (Laticrete 2017)

2.1.1.4 Admixtures

Admixtures are used to modify certain properties of both fresh and hardened concrete. Following properties related to strength and drying properties of concrete can be modified:

- Workability can be enhanced without increasing water content and thus without decreasing strength by using *plasticizers.*
- Setting time can be affected by using *retardants* or *accelerators*. Accelerators are generally used in cold weather.
- Air content can be affected by *air entrainers* to increase freeze-thaw durability. However, compressive strength is reduced (1 % increase in air content equals approximately 5 % loss in strength).

- Water content can be reduced to increase strength without sacrificing workability by *water-reducing admixtures*.

2.1.2 Hydration, Setting and Hardening

In cement chemistry, hydration is defined as a spontaneous exothermic reaction of water with Portland cement. There are currently two determined reaction mechanisms; Through-solution hydration means that anhydrous (do not contain water) compounds dissolute into their ionic constituents, after which formation of hydrates occurs. The formed hydrates are poorly soluble and thus eventually precipitate from the solution. According to studies, the through-solution "is dominant in the early stages of cement hydration". The second mechanism is solid-state / topochemical hydration of cement, where the reaction happens directly at the surface of the anhydrous cement compounds without the compounds going into solution. The second mechanism happens at later stages of hydration, "when the ionic mobility in the solution becomes restricted". The progress of the hydration reaction depends on various factors: w/c ratio, affecting the consistency of the produced suspensions, fineness and particle size distribution of cement, hydration and curing temperature, curing conditions, presence of admixtures and additives and the presence of possible foreign ions. (Mehta 2014 p. 214)

Hydration process consists of five stages according to Figure 3.

1. In the first stage, minutes after the cement is mixed with water, an initial hydrolysis of C_3A and a hydration of C_3S occurs.
2. The second stage is an inactive stage (dormancy stage) that lasts around 1–2 hours, allowing the transportation of concrete.
3. The third stage is an acceleration stage that starts about 3–12 hours after mixing. It contains initial setting, determining the rate of hardening, after which the final set happens. Setting means the start of solidification of a plastic cement paste, and is controlled by hydration. Hardening that follows the setting means the development of concrete strength. The silicates play an important role in hardening process.
4. In the fourth stage, the post-acceleration period, hydration decelerates and the rate of early strength gain is determined.
5. Finally, the stage five starts around 12 hours after mixing, at which point temperature has little effect on hydration. The hydration, however, continues as

long as there is free water available. At low w/c ratios the hydration may stop prematurely, leaving a significant amount of non-reacted material (Odler 1998 p. 267). After hydration is complete, ageing of the hydrated material begins.

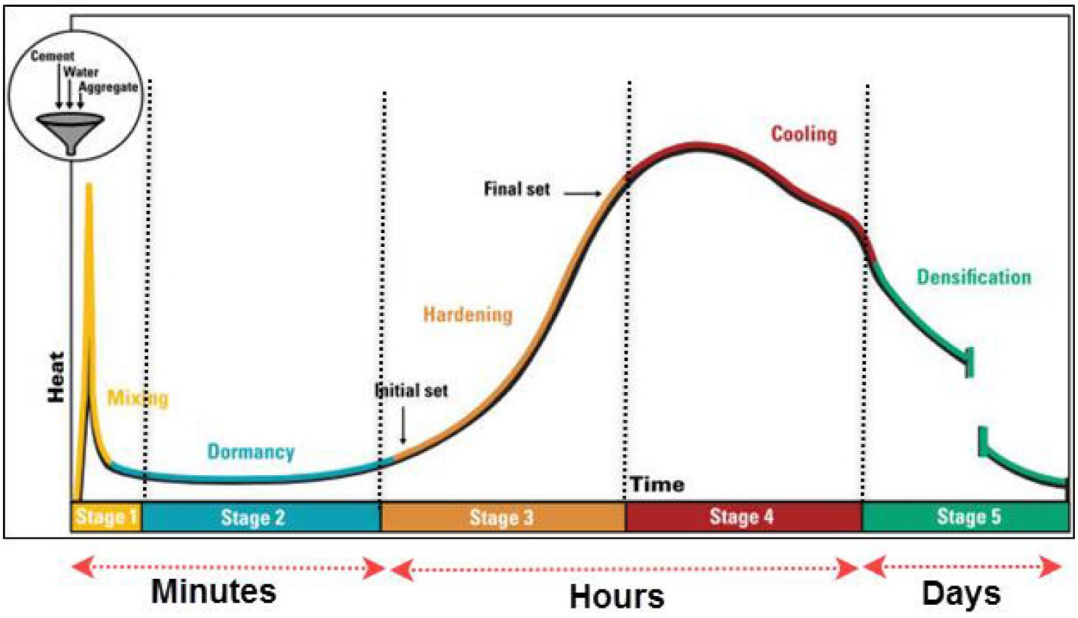


Figure 3 Hydration process (Taylor et al. 2007)

2.1.3 Curing Process

At early age, about 7 days after production, adequate attention needs to be paid on curing process of concrete to achieve adequate strength gain throughout hydration to achieve a desired strength level to be able to remove possible framework and to prevent too rapid loss of moisture often resulting in cracking of the surface (Mehta 2014 p. 338). Curing process should be initiated immediately after casting. Curing is usually done by using an impermeable-membrane or water curing depending on the prevailing conditions (temperature, relative humidity and air flow velocity) and the type of concrete. (Rudus 2017a)

2.1.3.1 Impermeable-Membrane Curing

Polyethylene sheets or membrane-forming curing compounds can be utilized to prevent moisture loss by sealing the surface of concrete. Unlike moisture-retaining polyethylene sheets, cotton or burlap sheets also allow cooling through evaporation and thus can be used in hot-weather concreting (Mehta 2014 p. 338). Sheets must be placed on the surface as soon as it is hardened enough to be walked on. According to Rudus (2017a), a curing compound is the best alternative, since placing the sheets is more labor-consuming and sheets are usually placed after troweling. Curing compound is applied before and after troweling. (Rudus 2017a)

2.1.3.2 Water Curing

If the temperature of the environment is well above freezing, ponding, immersion or spraying of the surface of concrete can be used. However, in case of Rapid concrete, water curing is not advised. Water curing should be done continuously during the curing period due to rapid evaporation of water from the surface. (Betoni 2017a)

2.1.4 Drying Process

Concrete is a hygroscopic material and thus it can absorb and release water by desorption (Merikallio 2002 p. 34). Figure 4 shows typical sorption isotherms of concrete. In a hydration process, water is chemically bound to the clinker. Additionally, there is always physically bound water, located in the pores that is capable of desorption. Figure 5 shows the distribution of moisture and air in concrete. (Rauhala 2014)

The relative humidity inside the pores always tends to achieve hygroscopic equilibrium (to reach the same % RH) with the environment. Essentially, drying process takes place if the relative humidity of ambient air is less than 100 % and lower than that of a surface. Depending on the concrete type and the drying conditions, the total mass of evaporated moisture from mixing water can be as high as 80–85 kg/m^3 (RIL 250-2011 2011). Additionally, excess moisture due to curing, rain water etc. must be removed by desorption. (Rauhala 2014)

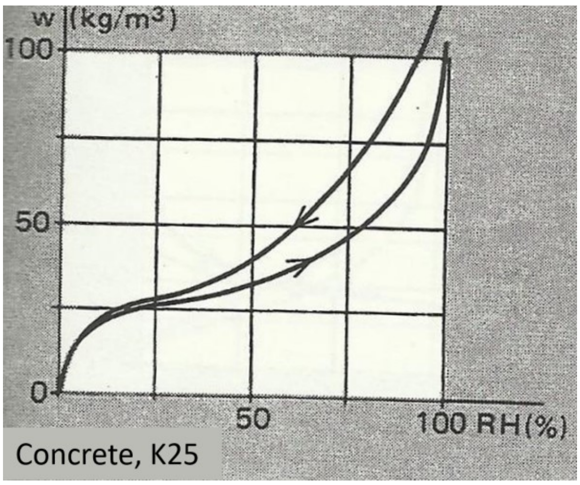


Figure 4 Adsorption and desorption isotherms of K25 concrete (modified from Björkholz 1997)

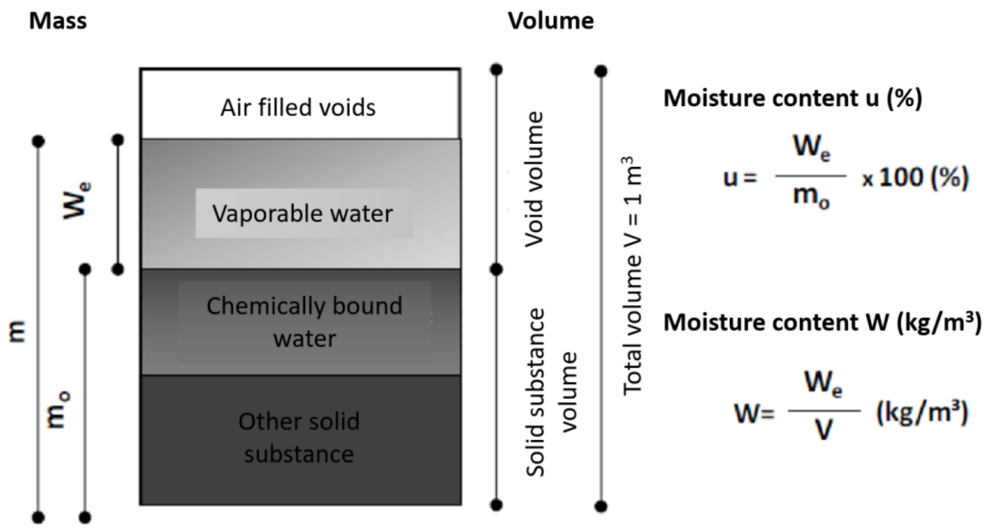


Figure 5 Distribution of chemically and physically bound water and air in concrete (modified from Merikallio et al. 2008)

Drying happens essentially by two methods, by evaporation and by diffusion, and thus the drying process can be divided into two stages (Hens 2012 p. 237). However, in some literature, three stages (Figure 6) are presented due to the overlapping nature of the two methods (Laticrete 2017). Generally, desorption is slower than absorption, as can be seen from Figure 4.

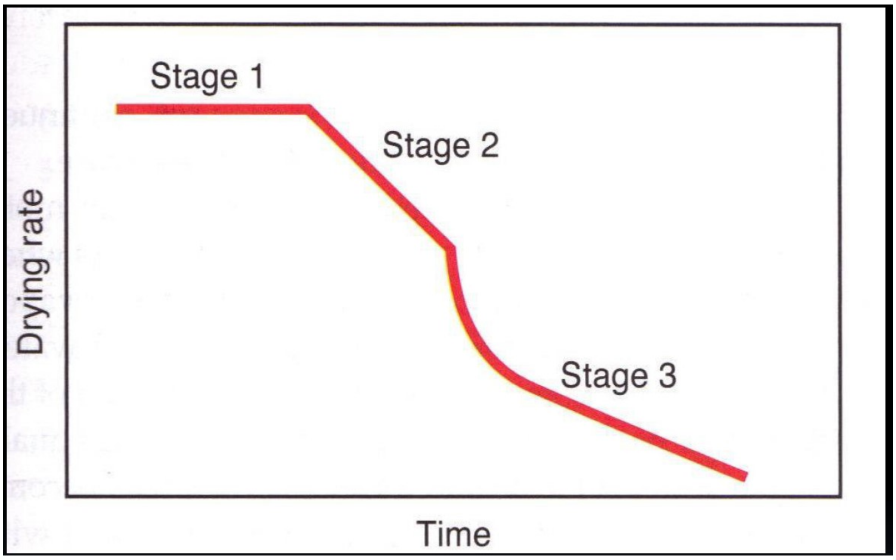


Figure 6 Drying stages of concrete (VersaFlex 2008)

In stage 1 (Figure 7), when the pores on the surface of concrete are either saturated or partly filled with water due to capillary flow, the drying happens mainly by evaporation. Stage 1 can be enhanced by increasing temperature, reducing relative humidity and increasing air flow rate. The rate of stage 1 is constant and the drying time can be estimated as follows: (Hens 2012 pp. 238–239; Lu-Tervola 2016)

$$t_{dry-I} = d(\frac{w_{capillary} - w_{critical}}{g_s}), g_s = \beta(P_{sat} - P_c) \tag{1}$$

where,

t_{dry-I} is the drying time [s]
d is the thickness [m]
w is the moisture content [kg/m^3]
g_s is the drying rate [kg/s]
β is the evaporation rate coefficient
P is the pressure [Pa]

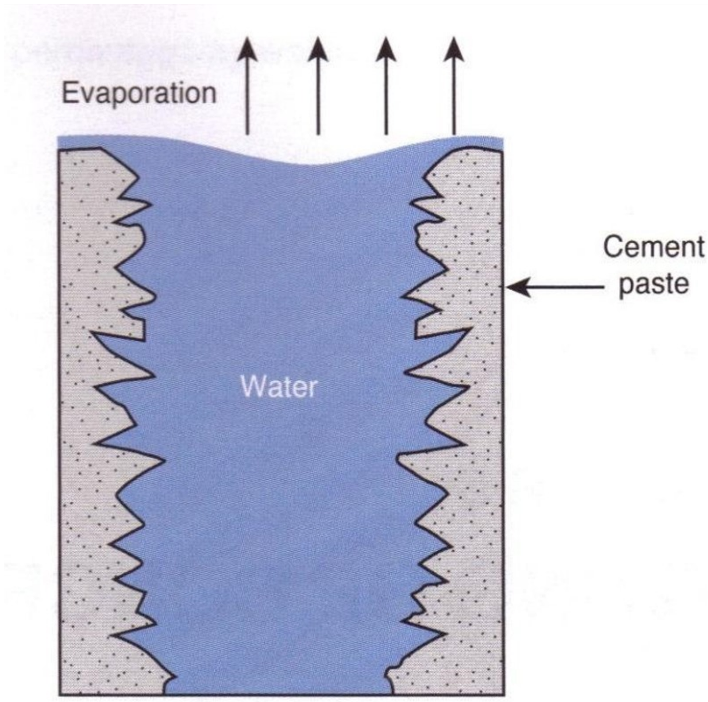


Figure 7 Stage 1 evaporation (VersaFlex, 2008)

In stage 2, when moisture is retreated below the surface and the pores are no longer filled with water, the moisture transfer happens mainly by diffusion through the concrete. Hence, in stage 2, the drying rate depends less on temperature, relative humidity and air flow rate and more on the properties of the cement paste. Generally, stage 2 is significantly slower than stage 1, and can last years. The rate of stage 2 is decreasing and the drying time can be estimated as follows: (VersaFlex 2008; Lu-Tervola 2016)

$$t_{dry-II} = d(\frac{w_{critical} - w_{air}}{\bar{g}_s}) = d(\frac{w_{critical} - w_{air}}{g_o})(1 + \frac{d\beta}{2k_v}) \approx \frac{w_{critical} - w_{air}}{2(P_{sat} - P_c)} \frac{d^2}{k_v} \tag{2}$$

where,

$t_{dry\text{-}II}$ is the drying time [s]
d is the thickness [m]
w is the moisture content [kg/m^3]
g is the drying rate [kg/s]
β is the evaporation rate coefficient
k_v is the vapor permeability [kg/sm^{2}Pa]
P is the pressure [Pa]

2.1.5 Requirements and Potential Issues

Especially in early life of concrete, in order to achieve the designed structural properties, the concreting conditions must be measured and controlled. Also, both concrete temperature, w/c ratio and the environment temperature are vital and must be taken into account when casting.

In cold weather, low ambient temperatures during curing and setting process negatively affect the rate of strength development. Heat produced in the hydration process, especially in case of small casting sections, might not be sufficient and cooling effect of frozen soil or a slab and reinforcement needs to be acknowledged. In case the mixing water freezes, there will be no water available for hydration. Thus, the set will not occur as can be seen from Table 1. After thawing and revibration to eliminate excessive pores that occurred due to expansion of water after freezing, the set will continue without loss of strength. However, revibration is not always possible. (Mehta 2014 p. 340–355)

Table 1 Setting time in relation to temperature (Ayyavu 2018)

Temperature	Approximate Setting Time (hours)
100°F (38°C)	1-2/3
90°F (32°C)	2-2/3
80°F (27°C)	4
70°F (21°C)	6
60°F (16°C)	8
50°F (10°C)	11
40°F (4°C)	14
30°F (-1°C)	19
20°F (-7°C)	Set will not occur

If freezing occurs after the concrete has set, but before it has developed sufficient strength, at least 3.5 MPa, the expansion due to formation of ice will cause irreparable loss of strength. Hence, controlling temperature of concrete in the early stage is crucial. In general, the more advanced the hydration, the less the concrete is vulnerable to frost and the more freezing-thawing cycles occur, the bigger the risk of damaging the concrete permanently. Table 2 shows ages of different cement types at which frost does not cause damage. (Neville 1995 pp. 359–402)

Table 2 Safe age of concrete in terms of frost damage probability (Neville 1995 p. 402)

Type of cement	Water/ cement ratio	*Age (hours) at exposure when preceding curing temperature was:*			
		5° C (41°F)	*10° C (50°F)*	*15° C (59°F)*	*20° C (68*
Ordinary	0.4	35	25	15	12
Portland	0.5	50	35	25	17
	0.6	70	45	35	25
Rapid-	0.4	20	15	10	7
hardening	0.5	30	20	15	10
Portland	0.6	40	30	20	15

In hot weather conditions, the water demand during curing is bigger due to high ambient and concrete temperatures, high wind velocity, high solar radiation and low relative humidity accelerating the drying process. The temperature during setting process must also not be too high due to too rapid initial hydration resulting in excessively porous structure and thus lower long-term strength. Additionally, there is a risk of plastic shrinkage cracking. Generally, rapid-hardening cement and low w/c ratio require lower temperatures. (Neville 1995 pp. 359–402)

According to Kosteudenhallinta (2017), drying conditions are optimal, when temperature and relative humidity of the environment are above 20 °C and below 50 % RH, respectively. Comparing these value with the average Finnish outdoor temperature and relative humidity values (Figure 8), it can be stated that heating and / or drying of concrete is required at all times during the production process in order to insure the best conditions that consequently lead to faster lead times and lower construction costs.

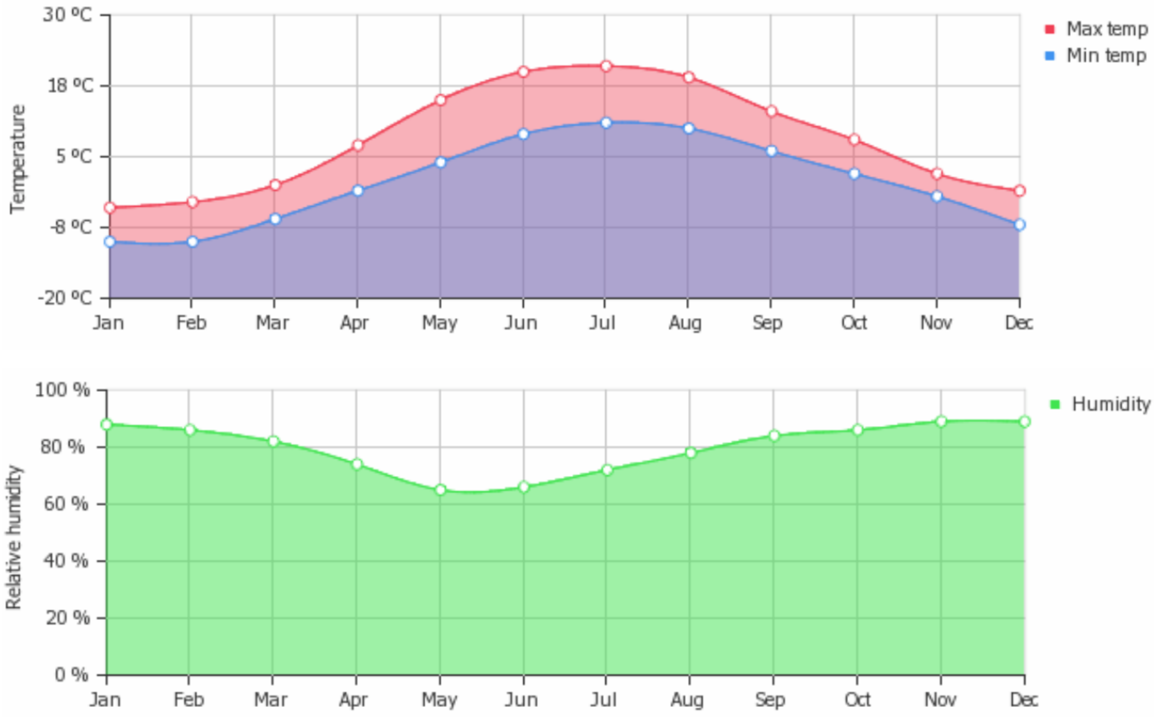


Figure 8 Average temperature and relative humidity in Helsinki, 2016 (World Weather & Climate 2016)

2.2 Concrete Frame Structures

Concrete frame structures are made using two methods: as cast-in-situ structures or by using prefabricated concrete elements. Usually, both methods are used in a project, depending on the design objectives; For example, a building can have cast-in-situ base and intermediate floors but prefabricated sandwich wall elements. Alternatively, it can have hollow-core slabs as intermediate floors but some indoor walls need to be cast-in-situ. In this thesis, the characteristics of the two methods in terms of drying properties and strength development are discussed.

2.2.1 Cast-In-Situ Concrete

Generally, cast-in-situ structures provide the freedom to design more complex and durable structures. Casting is done by using removable molds to form a structure, after which steel reinforcement, building services equipment, such as plumbing, ventilation ducts, electrical pipes and possibly floor heating are installed. Finally, the concrete is placed and vibrated to achieve even spread. Concrete curing is also very important as stated in Chapter 2.2. (Rakennustieto 2001)

To achieve adequate setting and strength development, the temperature of the environment and the concrete should be monitored, as can be seen from Table 1. The strength development can be estimated using the Sandgrove equation presented in Chapter 2.5.1. To accelerate strength development, following measures can be taken:

- using faster hardening concrete (more expensive)
- increasing strength class (more expensive)
- increasing the temperature of the environment (requires more energy)
- increase the temperature of the concrete mix (the easiest alternative)
- adding accelerators or water reducing admixtures (more expensive)

Additionally, when using water reducing admixtures, there is a risk of excessive air content. Hence, ideally, to ensure sufficient strength, also the air content of the concrete should be monitored during the casting process.

Also, to optimize the drying rate, the correct type of concrete type must be chosen. The type is usually determined by a structural engineer. However, the final decision is made on construction site depending on the prevailing casting conditions, especially during casting and the next few days, and on the desired drying rate. (Rakennustieto 2001)

It can be stated that in case of cast-in-situ concreting, choosing the right type of concrete and ensuring adequate casting conditions is crucial for feasibility, schedule, as well as for quality and safety of a structure.

2.2.2 Precast Concrete

Pre-cast of pre-fabricated concrete elements are manufactured in a factory in controlled conditions. The manufacturing process itself is very similar to cast-in-situ on site. However, the outdoor conditions do not affect the quality of the elements. Also, structures made with precast elements are less sensitive to weather conditions during assembly compared to cast-in-situ structures. Even so, the moisture must be controlled at all times in compliance with Kuivaketju10 (2017).

Usually, even if the building is made completely out of prefabricated elements, there are some sections that need to be cast on site; Because the width of a hollow-core slab is standardized, there usually remain some sections that are too narrow for a hollow-core slab (Elementtisuunnittelu 2017). Also, if a gap is an unusual shape, such as a triangle, it needs to be cast. Additionally, in a so called pre-fabricated bathroom slab or in balcony installations (Figure 9), there are sections that need to be cast. Unlike in case of load-bearing cast-in-situ concrete structures, the strength development of a pre-fabricated bathroom slab is not relevant.

Figure 9 Significant amount of steel reinforcement is needed to fulfill the strength requirements of Schöck - balcony joints in the case study project

2.3 Heat and Mass Transfer

A building is submitted to various loads and climate effects such as sun, rain, wind and differences in temperatures resulting in partial vapor and air pressure. These loads can be either attenuated or used to an advantage. Understanding these hygrothermal properties of the building and the heat and mass transfer principles between the system (the building) and the environment is crucial for efficient condition control. In this chapter, the basic physics of the heat and mass transfer are discussed separately.

In this thesis, the general principles of heat and mass transfer are discussed from a viewpoint of practical condition control, and thus the calculation methods are discussed only briefly. Also, all calculations are presented in 1D. In case of a construction project, it is important to acknowledge what the transfer methods are, how they can be controlled, how they are applicable to the construction phase of a construction project and how they can be actively affected throughout the construction phase. Additionally, to determine, what drying equipment to use and how, the movement of the heat and mass inside the building needs to be estimated and predicted. That can, in theory, be done using computational fluid dynamics (CFD) simulations. However, in reality, heat and mass transfer are intertwined and exact mathematical model of the process is not possible due to changes in material characteristics such as density, pore distribution etc. (Hens 2012 p. 267)

2.3.1 Heat transfer

Heat is considered an amount of mechanical energy produced by movement of atoms and is used to describe how energy is transferred between a system and its environment. Heat transfer is a spontaneous reaction where the energy is transferred due to temperature gradient from a warmer object (higher potential) to a colder one (lower potential) according to the second law of thermodynamics.

Heat exists in two forms: a temperature related sensitive form and a latent form related to phase transformations. In this thesis, we discuss the former. Sensitive heat transfer between two materials or places happens by three methods: conduction, convection and radiation. Controlling heat flow reduces energy consumption and accelerates drying process by allowing the indoor air to receive more moisture. (Hens 2012 pp. 13–15)

2.3.1.1 Conduction

Conduction means transfer of energy that occurs due to a temperature gradient in a solid material between two points at different temperature and also between two solid materials in contact with each other. Although the conduction also intervenes with convection when heat is exchanged in liquids and gases, the conduction process is applied mainly to solid materials and thus is more dependent on the material properties of the building, which is more relevant to the use phase that is not in the scope of this thesis. (Hens 2012 p. 13)

2.3.1.2 Convection

Convection means transfer of energy that occurs due to a temperature gradient on the contact point between a liquid or a gas at one side and a solid at the other. Convection always requires fluid motion. Hence, convection produces a current that carries the heat. Three types of convection can be distinguished: natural, forced and mixed convection. Natural convection happens spontaneously solely due to a temperature gradient causing density differences and thus buoyancy forces. Forced convection is produced by an external work; e.g. wind accelerates the convection process, in which case the heat may transfer also from low to high temperatures. Thus, the driving forces of natural and forced convection are temperature gradient and air pressure gradient respectively. Mixed convection contains both. Convection is discussed more thoroughly in Chapter 2.3.2.2 under mass transfer. (Hens 2012 p. 14)

2.3.1.3 Radiation

Radiation occurs due to a temperature gradient between two surfaces at different temperatures emitting and absorbing electromagnetic waves. Thus, compared to conduction and convection, radiation does not need a medium. The influence of heat transfer via radiation during construction phase is relatively small and is not discussed in this thesis. (Hens 2012 p. 14)

2.3.2 Mass transfer

Mass transfer means the transfer of air, solid water and water vapor between the building and the outdoor environment. Mass transfer is modelled by similar mathematical equations as heat transfer in terms of diffusion and convection. Air and mass transfer in a capillary-porous material such as concrete can sometimes be complicated to model, since the complex and constantly changing pore system of concrete is not easily quantifiable as “hydraulic network” and all related physical laws are not yet known. (Hens 2012 pp. 123–128)

The key factor for proper moisture condition control is the water vapor transfer inside the building. Vapor is a gas mixture that contains dry air and water molecules. The dry air itself consists of nitrogen (N) (78 %), oxygen (O) (21 %) and other gases (CO2, SO2, Ar, Xe) (1 %), and its molecular weight is 28.96 g/mol. The molecular weight of water (H_2O) in turn is 18.02 g/mol, thus the bigger the concentration of water, the lighter the vapor actually is. The amount of moisture in the air can be expressed using partial vapor pressure (Pa), relative humidity (% RH) and absolute humidity (g/m^3). Figure 10, the psychometric chart, illustrates the relationship between air temperature, relative humidity and moisture content at a steady pressure of 100 kPa. Dew point is achieved, when the partial vapor pressure is equal to the maximal vapor pressure.

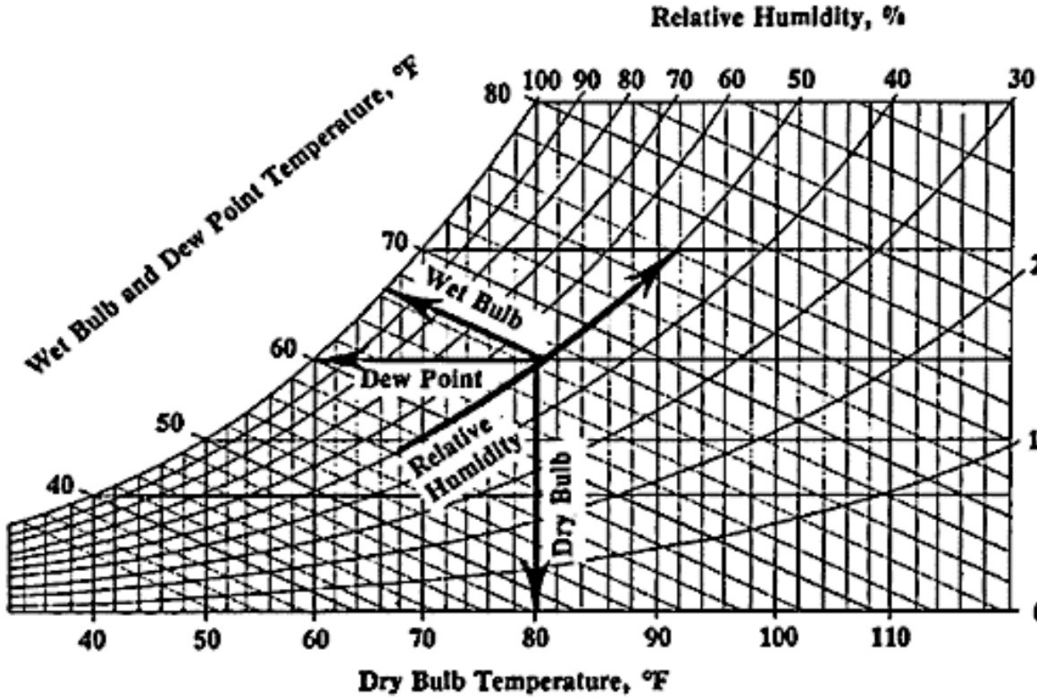


Figure 10 Psychometric chart - the values on the right show the moisture content (g/m3) (Orme 2017)

Air transfers spontaneously only due to the air pressure gradient acting as a driving force. Air pressure gradient is caused by difference in temperature and air composition, or alternatively by external forces such as wind or ventilators. Wind effects are not discussed in this thesis, since they cannot be easily affected or estimated. However, wind itself is a result of pressure differences in the air due to temperature gradients produced by the solar energy. The temperature gradient, in turn, affects both air volume and air pressure according to the ideal gas law (3). Moisture transfer happens by four methods: diffusion, convection, capillary suction and gravitational transfer. In buildings, four dominating mechanisms of moisture transfer are vapor diffusion, air leakage convection, capillary from the ground and rain penetration. Mass transfer methods are compared in Table 3. (Hens 2012 p. 132)

$$PV = nRT \tag{3}$$

where,

P is the pressure [Pa]
V is the volume [m^3]
n is the amount of substance [mol]
R is the gas constant
T is the temperature [°K]

2.3.2.1 Diffusion

Diffusion of water vapor happens due to vapor pressure gradient according to the second law of Newton. Generally, water vapor pressure is significantly bigger than air pressure, and thus is a dominant factor in buildings. The direction of diffusion is from higher to lower pressure. Relative humidity equals to the ratio between partial vapor pressure and maximal vapor pressure at the same temperature. However, if there is a temperature difference, the vapor pressure gradient changes. (Hens 2012 p. 178)

Vapor flux equation (4) for estimating the moisture transfer due to diffusion in the air according to Fick's law (analogous to Fourier law of conduction) is presented below: (Hens 2012 p. 178)

$$g = D\frac{\Delta\rho_v}{d} \tag{4}$$

where,

g is the diffusion rate [kg/(m^2·s)]
D is the diffusivity of vapor in air [m^2/s]
ρ_v is the partial vapor density [kg/m^3]
d is the layer thickness [m]

2.3.2.2 Convection

As stated in Chapter 2.3.1.2, convection is caused by the movement of the fluid, in this case, the (moist) air mass, and there are two types of convection: natural convection and forced convection. Convective mass flow equation (5) is presented below: (Hens 2012 p. 273)

$$g_v = g_a x_v = \frac{0{,}622\ g_a p}{P_a - p} \approx \frac{0{,}622\ g_a p}{P_a} \approx 6{,}21 \cdot 10^{-6}\ g_a p \tag{5}$$

where,

g is the air and vapor flow rate [kg/(m^2·s)]
P_a is the air pressure [Pa]
p is the partial vapor pressure [Pa]
x is the vapor ratio [kg/kg]

So-called stack effect is based on natural convection and is caused by the movement of the air mass due to buoyancy that occurs due to a difference in temperature and thus air mass density between indoor and outdoor air. Consequently, stack effect also induces natural convection. Stack effect is the bigger the taller the building is and the bigger the temperature difference between the indoors and outdoors. Stack effect is enhanced in stairwells and elevator shafts. Stack pressure (6) and air flow rate (7) equations are presented below: (Hens 2012 p. 134, Walker 2016)

$$P_{stack} = \rho_a g h \beta \Delta T \tag{6}$$

where,

P_{stack} is the stack-induced pressure [Pa]
ρ_a is the air density at 273,16 °K [kg/m^3]
h is the height [m/s^2]
β is the air compressibility 1/273,16 [°K^{-1}]
ΔT is the temperature difference between outdoors and indoors [°K]

$$Q_{stack} = C_d A (\frac{2gh\Delta T}{T_{in}})^{0,5} \tag{7}$$

where,

Q_{stack} is the air flow rate [m^3/s]
C_d is the discharge coefficient (0,65)
h is the height [m]
ΔT is the temperature difference between the indoor and outdoor air [°K]
T is the temperature indoors [°K]

Additionally, the housing typology affects, how powerful the stack effect is. The two common typologies are lamella and side corridor (Figure 11). The typology largely defines how effectively the air mass can transfer upwards through the building and thus is important for condition control during the construction phase. (Aalto-yliopisto 2011)

Lamella type means that there are several apartments on the same floor connected to each other by a stairwell. The air sucked in from the bottom floor of the building (e.g. from the main entrance) can relatively freely transfer to the top floor, thus allowing efficient exhaust through the roof. Also, the apartments can be compartmentalized if needed, in which case the conditions in each apartment can be controlled individually. Also, a potential atrium space can be used to an advantage (Figure 12).

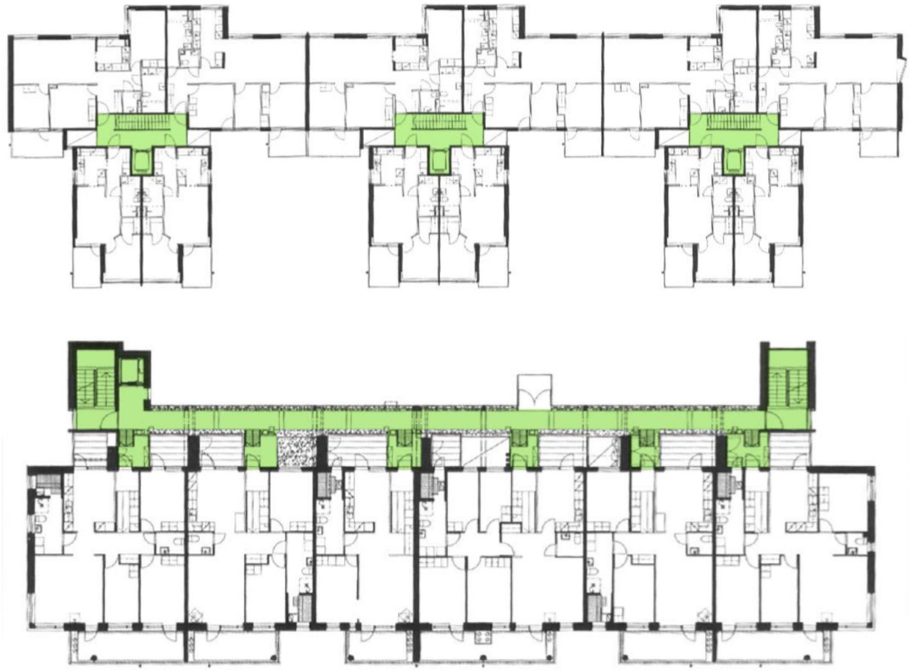


Figure 11 Housing topologies - lamella (upper) and side corridor. The green area represents the stairwell/corridor through which warm and moist air mass can transfer upwards. (Aalto-yliopisto 2011)

Side corridor type means that the apartments are connected to each other by a corridor. In terms of air flow, side corridor typology is more challenging for natural convection, since the flow of the air is restricted on each floor and stack effect is mitigated.

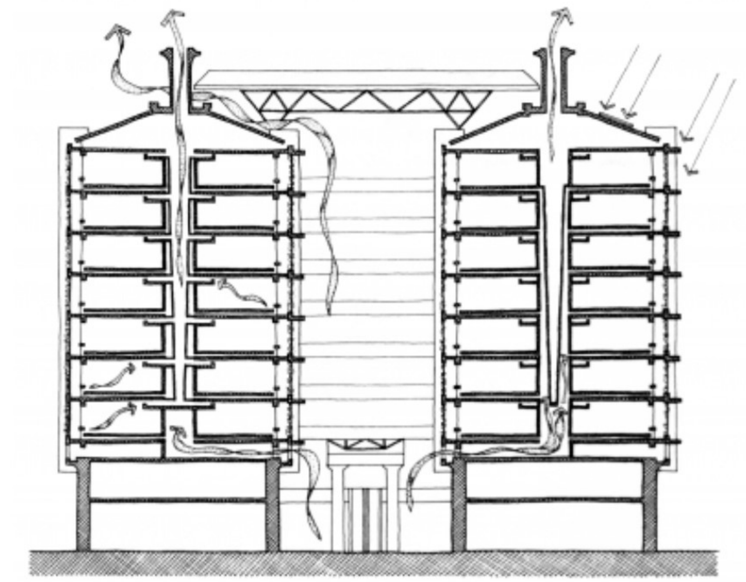


Figure 12 An example of an effective use of an atrium space for or stack induced natural ventilation (DeKay & Brown 2014)

2.3.2.3 Capillary action

Capillary action transfer method, also called capillary suction, happens in air-water-filled concrete pores due to interaction of surface tension (due to cohesion) and adhesive forces between the liquid and the surrounding solid hydrophilic porous material. The transfer direction in case of intermediate concrete floor structures is upwards. Capillary transfer in a porous material happens, when the relative humidity of a material is between 98 and 100 % RH (Figure 13). Capillary force in inversely proportional to the diameter of the tube-like pores. (Hens 2012 pp. 211–213)

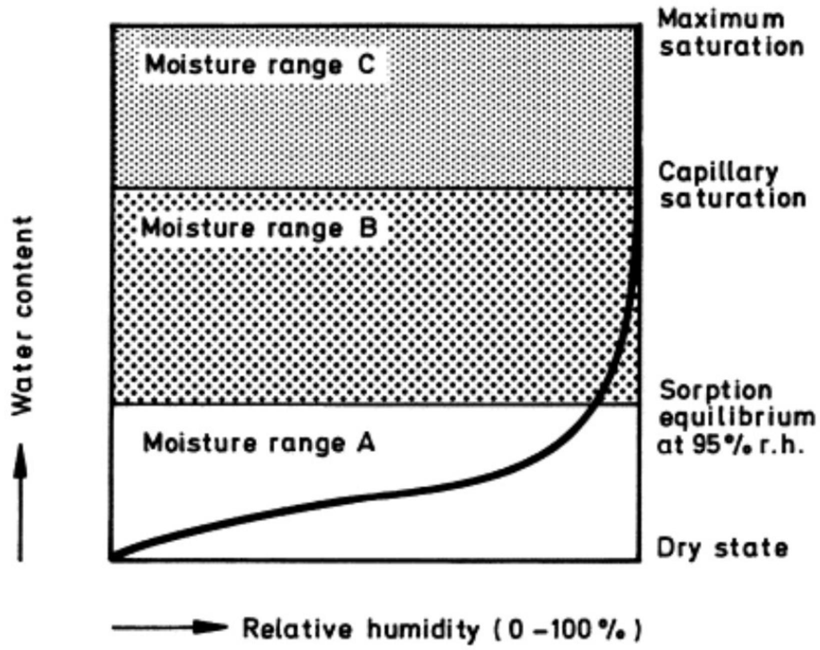


Figure 13 Water content: range A - diffusion up to 95–98 % RH, range B - capillary 98–100 % RH, range C - saturated > 100 % RH (Künzel & Kiessl 1996)

2.3.2.4 Gravitational

Gravitational transfer means liquid flow due to gravity. In case of a building project it mainly contains rain penetration and represents the range C in Figure 13.

Table 3 Summary of mass transfer methods

substance	*mechanism*	*driving force*	*direction*
air	convection	air pressure gradient	high to low pressure
water vapor	diffusion	vapor pressure gradient	high to low pressure
	convection	air pressure gradient	high to low pressure
water	capillary action	capillary pressure gradient	upwards
	gravitational transfer	gravity	downwards
	external force-induced transfer	total pressure gradient	high to low pressure

2.3.3 Applications

Based on the building physics, following actions should be taken to optimize the drying process and energy consumption, depending on the prevailing conditions (Koistinen 2016; Ratu S-1232 2013; Rudus 2017b):

In *winter*, the outdoor air is cold (-7,7°C on average in Finland, Figure 1), which has a negative effect on setting and initial strength development, as can be seen from Table 1. Thus, during casting, both the ambient temperature and the temperature of casting surfaces should be sufficient. Also, the properties of the concrete mix, such as the strength class and the strength development rate should be considered.

Drying process in winter requires significant amount of heating energy. Thus, in order to keep the energy consumption at a feasible level, the heated space should be kept as airtight as possible. Average relative humidity in winter is high, at around 88 % RH on average. However, according to the psychometric chart (Figure 10), the moisture content of the air is low, approximately 2–4 g/m^3. In comparison, the maximal moisture content at +30 °C is 30,4 g/m^3. Hence, for the most efficient drying process, the cold intake air should first be heated up near the intake opening and then redirected indoors. When the air heats up, its relative humidity decreases according to the psychometric chart. Consequently, the moisture holding capacity of air increases, which creates a vapor pressure gradient between the concrete and the indoor air, which, in turn, allows the moisture to transfer from the concrete into the indoor air, thus increasing its relative humidity. Ideally, in order to minimize heat loss, the heated space should also be kept underpressured compared to outdoors. Mechanical drying of indoor air in not necessary, since the vapor pressure gradient is more efficiently achieved by heating.

In *spring*, the average temperature of outdoor air is approximately +2,4 °C and the average relative humidity is 74 % RH. Hence, the curing conditions are generally adequate. The moisture content of the outdoor air is relative low (4–6 g/m^3).

In *summer*, the average temperature of outdoor air is approximately +13,8 °C and the average relative humidity is 73 % RH. Due to relatively high outdoor air temperatures and solar radiation during the day time, in addition to heat development through hydration, special attention needs to be paid on curing to prevent too rapid shrinkage and cracking. Also, the properties of the concrete mix, such as the temperature, should be taken into account.

Even though the relative humidity of the outdoor air is low, the moisture content can reach up to 30,4 g/m^3 at 30 °C. Consequently, due to small gradients in relative humidity and temperature between indoors and outdoors, heating the indoor air will not increase its moisture holding capacity significantly. Hence, in addition to moderate heating, the use of dehumidifiers should be considered to remove the moisture from the indoor air, in which case the airtightness of the envelope should be ensured to minimize the transfer of moist outdoor air to the inside. Ideally, to minimize the diffusion and convection of vapor from the outdoor air, the building should also be kept overpressured compared to outdoors.

In *autumn*, the average temperature of outdoor air is approximately +3,5 °C and the average relative humidity is 87 % RH. The conditions are similar to those in the spring and the drying is carried out by heating the indoor air.

Generally, the default requirements and guidelines are as follows:

- The envelope should be kept as airtight as possible at all times.
- The drying process can be accelerated by
    - heating the space
    - increasing the air flow
    - lowering the moisture content and the relative humidity of the indoor air.
- The indoor conditions should be monitored at all times to provide optimal drying conditions and optimize energy consumption.

Also, it is important to understand and control where the moisture from the concrete is transferring. Additionally, attention should be paid on potential condensation on cold surfaces.

When considering an individual apartment with outdoors and a stairwell as boundary conditions (Figure 14), following applied measures can be undertaken in compliance with efficient condition control principles utilizing real-time condition monitoring:

- The need for additional heating can be calculated based on the volume of space, and the appropriate heating equipment can be recommended.

- The need for dehumidifiers can be evaluated based on the vapor pressure and relative humidity gradients.
- The release of moist indoor air through windows or balcony doors based on the vapor pressure and relative humidity gradients can be recommended.
- Evaluating the evaporation rate (kg/s) from the concrete based on the vapor pressure gradient between the concrete and the indoor air, and estimating the moisture transfer rate (kg/s) due to diffusion (4) and convection (5, 6 and 7).

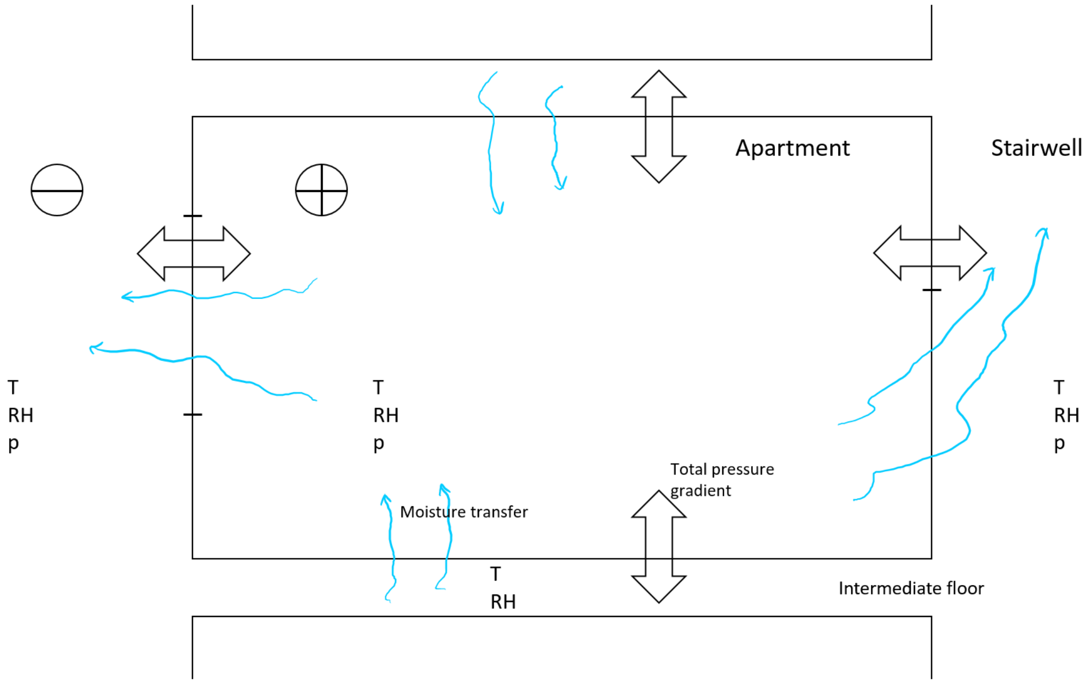


Figure 14 Moisture transfer principle

2.4 Heating and Drying Systems

Portable heating and drying systems are used to ensure optimal building conditions and to accelerate the drying process. The system costs consist of rental and operational costs. Operational costs depend largely on the energy source of the system. The rental costs alone represent a significant item of expenditure throughout the production phase. Hence, it is important to optimize the duration of use and the power output of the systems. In this chapter, common heating, drying and ventilation systems are presented. Additionally, weather protection equipment is discussed.

2.4.1 Heaters

Heaters are used essentially to raise the indoor air temperature, combined with added ventilation function. The efficiency of heaters depends largely of the environment conditions. The higher the outdoor – indoor temperature gradient, the more effective the heaters are. Hence, the heaters are best suited for winter conditions. Heaters can be categorized based on their energy source. In this chapter, water heating system, electrical heaters and fuel heaters are presented. However, the working principle is the same (Figure 15), independent of the energy source. (Niemi 2017)

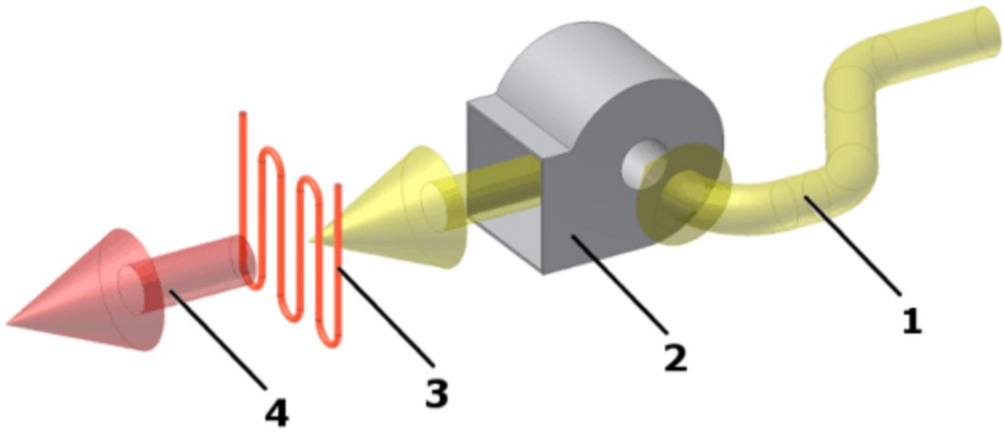


Figure 15 Working principle of heaters: 1 – intake air, 2 – extractor fan, 3 – heater, 4 – heated air (modified from Master Climate Solutions 2017)

2.4.1.1 Water Heating System

Water heating system uses district heating as the main heat source, and utilizes the heat exchanger of a building. Thus, water heating systems only work in buildings with a district heating system. The working principle is straightforward: according to Figure 16, the intake air is passed through the heater, in this case through a water comb that transfers the heat energy into the air from the water coming from the heat exchanger. The cooled-down water is delivered back to the district heating grid. The system additionally requires electrical energy for the air pump. For even distribution of air, hoses can be used (Figure 16). As soon as the building's own heating system is ready for exploitation, the temporary water heating system is usually removed. (Master Climate Solutions 2017)

Water heating systems produce power between 15 to 260 kW and they are capable of airflow of 1000–22 000 m^3. (El Björn 2017)

Figure 16 El Björn TF 250HWI - TVS, one of the most powerful water heating systems on the market (El Björn 2017)

2.4.1.2 Electrical Heaters

Electrical heathers (Figure 17) use electricity to heat up the heating comb. Otherwise, the working principle is the same as that of a water heater. Electrical heaters can heat up spaces up to 600 m^2 and the power output is up to 36 kW. The produced air flow is up to 3900 m^3/h. Electrical heaters are an efficient and versatile solutions for buildings without district heating. (El Björn 2017)

Figure 17 El Björn TF 36EL, a powerful electric heater (El Björn 2017)

2.4.1.3 Fuel Heaters

Fuel heaters use diesel or liquid gas as a heat source. Additionally, fuel heaters require electricity to power the air fans. Fuel heaters are generally more cost-effective than electrical heaters and are best suited for heating large areas. However, especially diesel heaters are considered less environmentally-friendly than electrical heaters. (Niemi 2017)

2.4.1.3.1 Diesel

TF 300DI form El Björn (Figure 18) is a typical diesel heater. It generates a maximum power output of 300 kW and the produced air flow is 21000 m^3/h. There are also smaller diesel heaters available, ranging from 30 kW to 120 kW. The smaller heaters do not have an own fuel container and the fuel is led by a hose from a separate container located outdoors. In this case, the combustion gases need to be led outside. Although energy efficient, this kind of system is rather complicated to install and maintain. The diesel heater used in the case study project generates up to 400 kW of heating power and consumes up to 36 l of fuel per hour, which is approximately 900 € per day (excl. taxes) according to current fuel prices. (El Björn 2017; Niemi 2017)

Figure 18 El Björn TF 300DI – TVS (modified from El Björn 2017)

2.4.1.3.2 Propane or Natural Gas

Liquid gas heaters use propane or natural gas as a heat source. Gas is delivered to the construction site by a gas provider, usually in cooperation with a rental company (Figure 19). Gas heaters are very efficient: one kg of liquid gas produces 12,88 kWh of heat energy. Gas is also more environmentally-friendly energy source than diesel due to a cleaner combustion process. (Aga 2017)

Figure 19 Liquid gas container on construction site (Aga 2017)

It must be noted that when burning any type of gas, the combustion product is essentially carbon dioxide (CO_2) and water (H_2O). Thus, when using gas heaters, the air humidity increases along with the temperature (Master Climate Solutions 2017). However, since the heated air can bind significantly more moisture than the combustion process produces, this is generally not a problem (Figure 20) (Aga 2017).

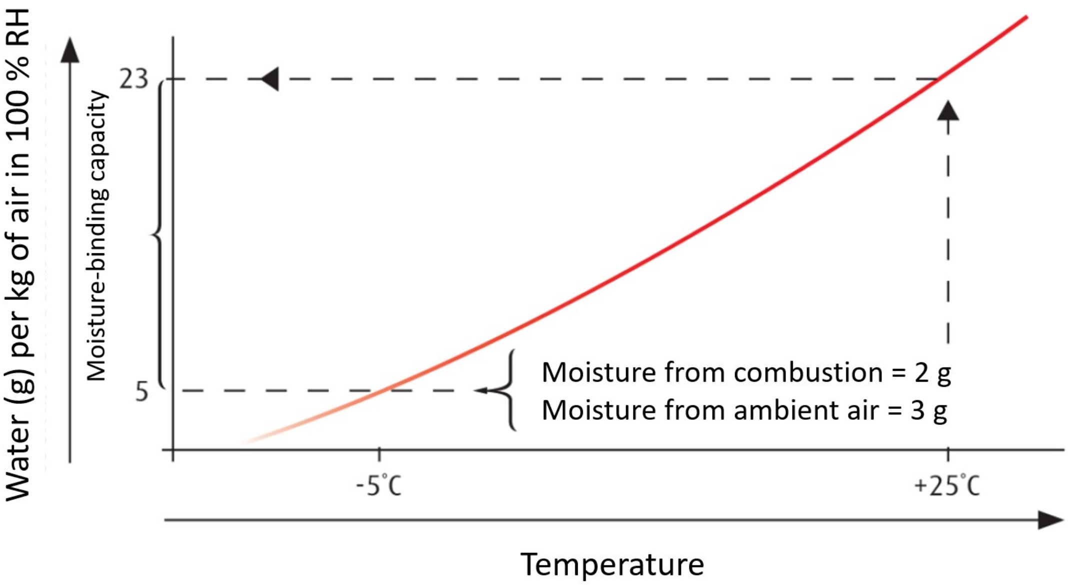


Figure 20 Additional humidity due a combustion process (modified from Aga 2017)

2.4.2 Dehumidifiers

The working principle of a dehumidifier is based on separating water molecules from the air by either desorption or condensation. There are also so-called combination dehumidifies that use both desorption and condensation. The two methods are suited for different environment conditions. The use of dehumidifiers generally requires closed system, meaning that the building envelope is airtight and the indoor air is circulated inside the building while the dehumidifiers are operating. By neglecting the airtightness, the moist outdoor air enters the building continually thus prolonging the drying time and increasing costs. The use of dehumidifiers is justified especially in summer and in autumn, when the total humidity of the outdoor air is big and the temperature and relative humidity gradients between outdoors and indoors are small. The water gathered by the dehumidifiers must also be taken care of. In Figure 21, efficient operational zones of the two dehumidifying methods are presented. (Lamminen 2015)

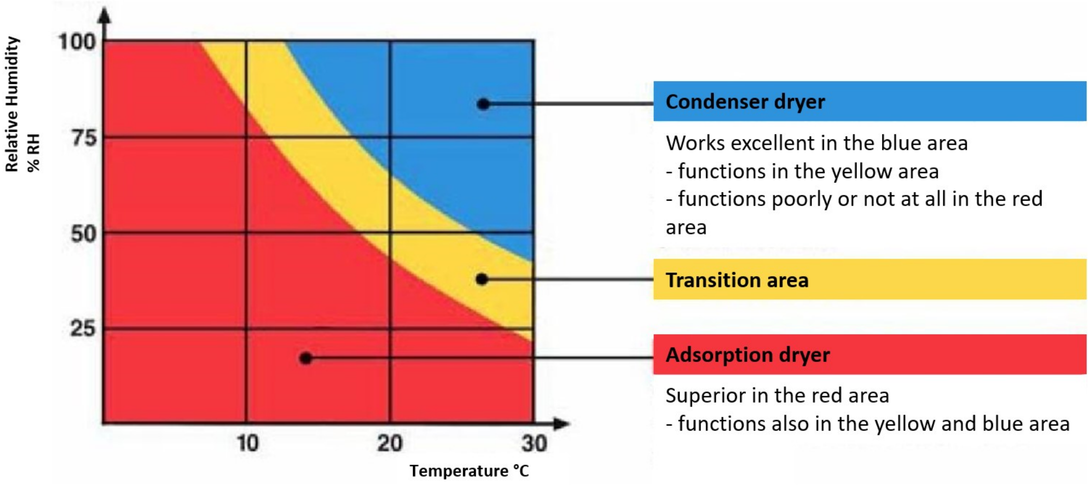


Figure 21 Efficient operational zones of desorption (red) and condenser (blue) dehumidifiers, Gles Oy (modified from Lamminen 2015)

2.4.2.1 Condenser Dryer

Condenser dryer is utilizing condensation principle (Figure 22) for removing excess moisture from the air. As can be seen from Figure 10, the warmer the air is, the more moisture it can contain. The condensation happens when the air is cooled down to the dew point temperature, thus when the relative humidity is 100 %. The intake air is led through a cooling cell, where the moisture condensates and the water is collected. Then, the air is heated, which lowers its relative humidity. Hence, the outflowing air has both lower relative and absolute humidity. The warmer and the moister the intake air is, the more water can be retrieved and the lower the relative humidity of the outflowing air is. The water is collected either in an internal container or led into the drain. As can be seen from Figure 21, the condenser is the most efficient in extremely warm and moist conditions. If the relative humidity and the temperature is low, the condenser is irrelevant. (Lamminen 2015)

Condensers manufactured by El Björn (Figure 23) are suitable for spaces up to 680 m^3, the effective working range is +7–34 °C and 35–95 % RH, and the drying capacity is up to 55 l/24h at 30 °C and 80 % RH, power consumption being 710 W. The efficiency depends on the ambient conditions. Some condensers also have a hygrostat: the target relative humidity value can be set, at which point the device automatically turns itself off. (El Björn 2017)

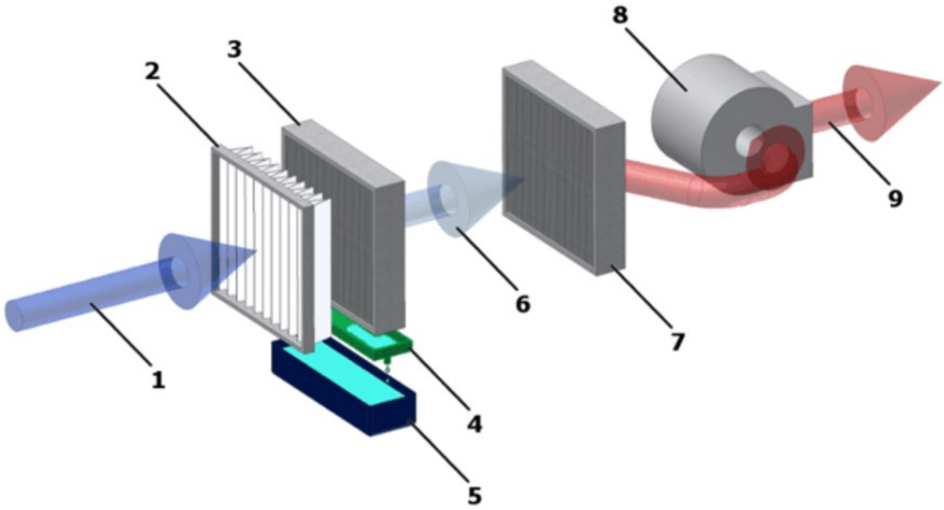


Figure 22 Working principle of a condenser: 1 – humid intake air, 2 – filter, 3 – evaporator, 4 – dripping tray, 5 – condensate tank, 6 – dehumidified and cooled air, 7 – condenser, 8 – extractor fan, 9 – dehumidified and heated air (Master Climate Solutions 2017)

Figure 23 El Björn AD 620E (El Björn 2017)

2.4.2.2 Adsorption Dryer

Adsorption dryer utilizes a hygroscopic material to absorb the moisture. The material is usually a silica-gel or other material with good adsorption and desorption capabilities. The material is placed inside a cell or a rotor (Figure 24) whose surface is covered with the material to maximize the adsorption area. The device is divided into two sections, the dehumidifying and the regenerating section: the first incoming air stream is dehumidified and released into the indoor air, and the second, so called regeneration stream, is heated and led through the rotor to remove the humidity from the hygroscopic material, after which the humid regeneration air is led outside. (Lamminen 2015)

Adsorption humidifiers made by El Björn are effective in conditions between -30 °C and +40 °C and the drying capacity is 33,6 l/24h, power consumption being 2100 W. Thus, an adsorption dryer is less efficient than a condenser dryer. (El Björn 2017)

The operating range of an adsorption dryer is larger than that of a dehumidifier. However, since an adsorption dryer is designed for an environment with low moisture content and low temperature, it is not the most efficient way to remove moisture in new construction projects. Adsorption dryers are mainly used in refurbishment projects for damage control or, for example, for keeping the crawlspace dry in order to minimize the risk of mold growth. (Lamminen 2015)

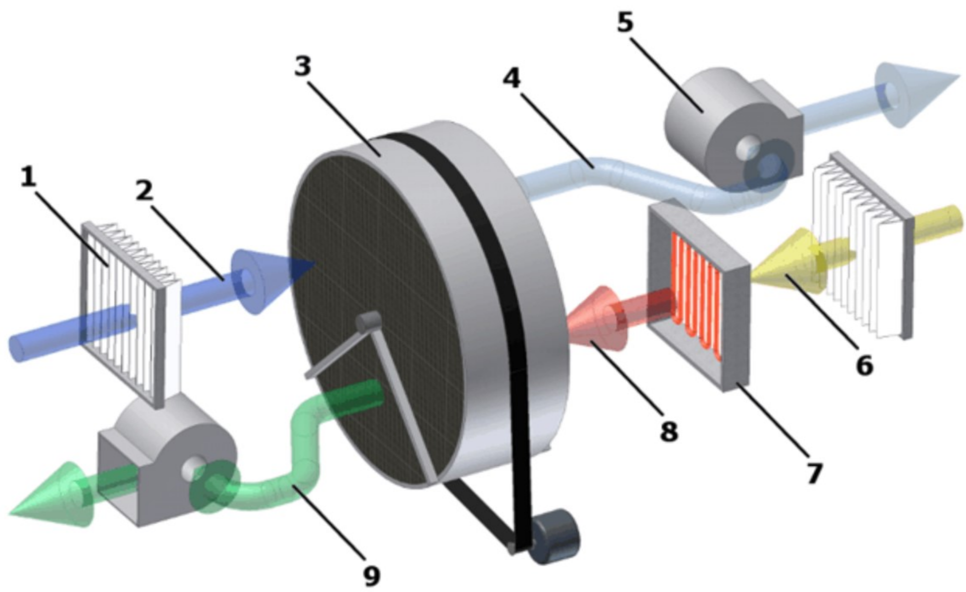


Figure 24 Working principle of an adsorption dryer: 1 – filter, 2 – humid intake air, 3 – rotor containing hygroscopic material, 4 – dehumidified air, 5 – extractor fan, 6 – regeneration air, 7 - heater, 8 – heated regeneration air, 9 – humid regeneration air (Master Climate Solutions 2017)

2.4.3 Ventilation Equimpment

Ventilators are used for three purposes, to control and steer the air flow, for pressurization of spaces, and to increase the drying process by creating forced convection. There are two types of blowers, axial and radial. One of the biggest manufacturers of construction ventilators is the German company Heylo. (Heylo 2017)

2.4.3.1 Axial

Axial ventilators produce high air pressure and can achieve good air transfer across long distances and produce air flow of up to 10550 m^3/h. Ventilators can be connected to hoses to better direct the air flow where it is needed. Heylo PowerVent 1200 (Figure 25) has a diameter of 550 mm and produces an air flow of 8603 m^3/h and compression of 744 Pa. Maximum power consumption is 3.7 kW. (Heylo 2017)

Figure 25 Heylo PowerVent 1200 (Heylo 2017)

2.4.3.2 Radial

Radial ventilator is mainly used in case of a water damage, due to its low outflow opening designed to produce maximum air flow at surface level. They are also suitable for drying hollow spaces. The air flow rate is significantly lower than that of an axial ventilator. For example, Heylo TD 300 (Figure 26) has a maximum air flow rate of 445 m^3/h. (Heylo 2017)

Figure 26 Heylo TD 300 (Heylo 2017)

2.4.4 Weather protection

Temporary weather protection is used to keep rain water, snow and wind away from the structures. By using proper protection at a proper time, the drying process can be accelerated, the need for hollow-core drying is reduced, the installations on the roof are easier and there is less risk of moisture getting inside the structures via through holes for e.g. ventilation ducts. Weather protection can be carried out using blankets, weather covers and façade protection. It this thesis, only the former two are discussed, since façade protection is used mainly in refurbishment projects. (Rakennustieto 1992)

2.4.4.1 Blankets

Weather blankets are used for covering critical areas, usually on the top floor of the building. They are made from PVC and common dimensions are 4x6, 5x7 and 6x9 m. The weight of the blanket material is 600–680 g/m^2. Blankets are especially useful in the winter to protect the freshly cast concrete from wetting and freezing. They are easy to install due to a relatively light weight. However, they are somewhat prone to wind and they cannot possibly stop all the rainwater from entering the lower floors due to multiple joints. In addition, the rainwater needs to be channeled outside the building, which is challenging without using the drainage system of the building. Blankets are also used to protect construction material on site. (Pajulahti 2017)

2.4.4.2 Weather Cover

Weather covers are made using a steel or an aluminum beam frame with a PVC-blanket on top (Figure 27). Weather covers are assembled on site and can be installed on top of the building frame with a crane. The covers usually come in 6 m long modules and in many different widths, from 5 m to 15 m, and shapes depending on the geometry of the building. There are also extra-large covers up to 45 m in width. According to Rakennustieto (1992), weather covers are suited well for foundation works, frame element installations and casting work. Weather covers are designed to either stand on their own feet, or they can be attached to a scaffold. In the design phase, it is also technically possible to integrate holders into the façade elements for weather cover installation. In terms of weather protection properties, weather covers are superior to weather blankets. However, they are much more expensive. Also, as was thoroughly discussed in the Willman's (2015) bachelor's thesis, the installation process challenges and the logistical challenges of weather covers are significant. (Willman 2015; Ramirent 2017; Pajulahti 2017)

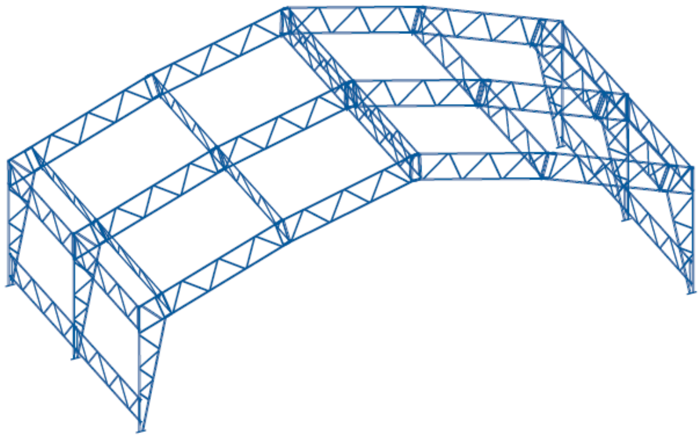


Figure 27 M-Weather cover by Ramismart (2017)

2.5 Measurements

In this chapter, the compressive strength and the moisture content measurement principles are presented.

2.5.1 Compressive Strength

Compressive strength development measurement can be done using the Sadgrove equation (8). The method is based on measuring the temperature of the early age concrete, during casting and curing process. The equation determines the equivalent age of concrete at 20 °C. (Newman & Choo 2003 p. 4/24)

$$t_{20} = \sum\left\{\left[\frac{T+16\,°C}{36\,°C}\right]^2 * t\right\} \quad (8)$$

where,

t_{20} is the equivalent age at 20 °C [d]
T is the temperature during setting time t [°C]
t is the setting time [d]

2.5.2 Relative Humidity

Relative humidity measurement of a concrete structure is done to ensure that the relative humidity of a surface corresponds to the requirements of a specific coating. Different material specific requirements are presented in Table 4. If the relative humidity value is higher than advised in the table, major complications may occur during the use phase of the building. The potential complications contain mold growth and so-called secondary VOC emissions. Hence, it is important to always ensure that there is no excess moisture in the structure prior to coating. In case of extremely sensitive materials, such as polymer matts, it is also essential to know the history of the concreting process, including casting and curing conditions, wetting etc., to be sure that the measurement values are adequate. (Hätönen 2016)

Table 4 Maximum % RH values of concrete surface prior to coating (J+J Flooring Group 2014)

Max. % RH	Cover Material
60%	Parquet board with no plastic film between wood & concrete
80%	Mosaic parquet on concrete Carpet with rubber, PVC or rubber-latex coated Broadloom carpet
85%	Plastic carpet with felt or cellular plastic base Rubberized carpet Cork tile with plastic film barrier Carpet with non-PVC Carpet made of natural fibers
90%	Plastic tiles Plastic carpet with no felt or cellular plastic base Linoleum
95%	Textile Composite Flooring
The Finnish SisaRYL 2000 Code of Building Practice.	

The measurements are done according to the RT 14-10984 (2010) card by two methods: drill hole and concrete sampling. Both methods can be used on site to measure the temperature and the relative humidity of concrete. For more thorough analysis, a concrete sample can be sent to the laboratory. If coating instructions are implying the moisture content of concrete, other measurement methods, such as weighing, drying and the carbide-method can be implemented. However, these methods are out of the scope of this thesis. (RT 14-10984 2010)

2.5.2.1 Drill Hole

A drill hole is performed according to the ASTM-F2170 standard (ASTM 2017). The drill hole method is the most common way to determine the relative humidity of concrete. First, a hole of 16 mm is drilled and thoroughly cleaned by blowing or by a vacuum cleaner. The hole size can differ depending on the equipment provided by the manufacturer of a measuring device. The minimum diameter is 10 mm to ensure an appropriate diameter/depth ratio. The hole needs to be exactly the right depth, down to the millimeter. Then, a tube (e.g. an electrical tube) is inserted into the hole and sealed at perimeter to the concrete and from the top (Figure 28). The hole is left to set for at least 3 days. It is recommended to insert an insulating material inside the tube for the setting period to prevent condensation. Finally, the plug is removed, the measuring device is inserted into the tube, and the humidity value is registered. It should be noted that when the plug is removed, some of the moisture might escape. Thus, after inserting, the sensor requires approximately 1 hour to adapt to the prevalent tube conditions for accurate results. Also, to achieve maximum accuracy, the hole can only be used for a single measurement. Generally, the precision of the insertion and the sealing of the sensor is crucial to the accuracy, as can be seen from Figure 28. (RT 14-10984 2010)

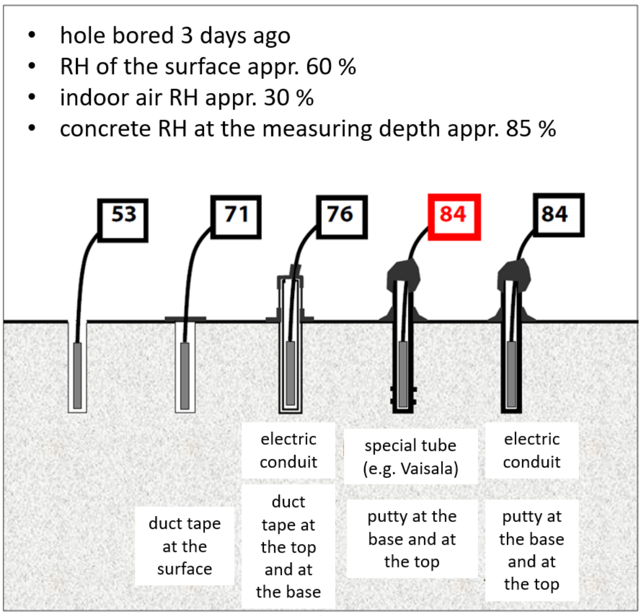


Figure 28 How different sensor installation methods affect the accuracy of results (modified from RT 14-10984 2010)

Additionally, following requirements according to the RT 14-10984 (2010) are to be considered:

1. The sensor head needs to be clean; dirt and e.g. dried out concrete on the tip of the sensor increases the moisture capacity and thus the setting time.
2. The tube needs to be airtight to prevent the moisture from escaping through the hole.
3. The condition fluctuations between the concrete and the indoor air must be minimized in order to prevent condensation inside the tube, and the temperature

difference between the concrete and indoor air must be below 2 °C. Also, the temperature inside the structure needs to be even.

4. The sensor needs to be calibrated.
5. Sensor's accuracy is adequate, usually ±1–3 % RH.
6. Optimal measuring temperature is +15–25 °C.
7. The minimum measurement depth is 10 mm and the maximum is 70 mm. The depth depends on the type of the structure (Figure 29). Generally, a measurement from two depths is required to determine the moisture gradient (Figure 30) and thus to ensure that the humidity of the surface humidity is lower than that of the deeper spot, and that it is low enough to receive the moisture from the float or the adhesive.

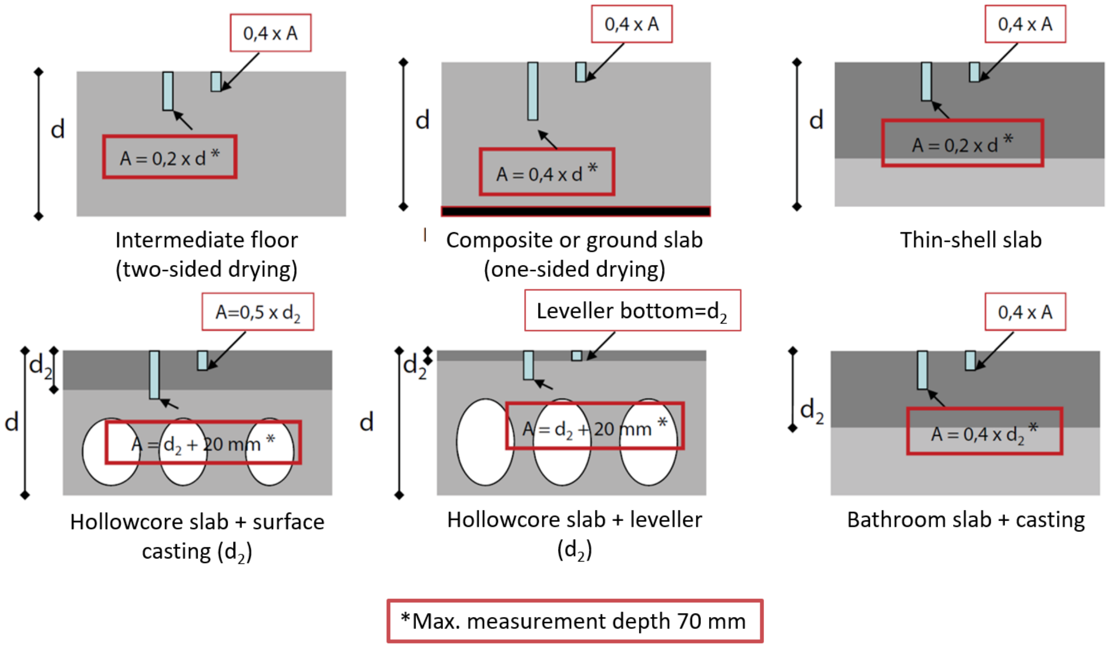


Figure 29 Different intermediate floors and the measurement methods (modified from RT 14-10984 2010)

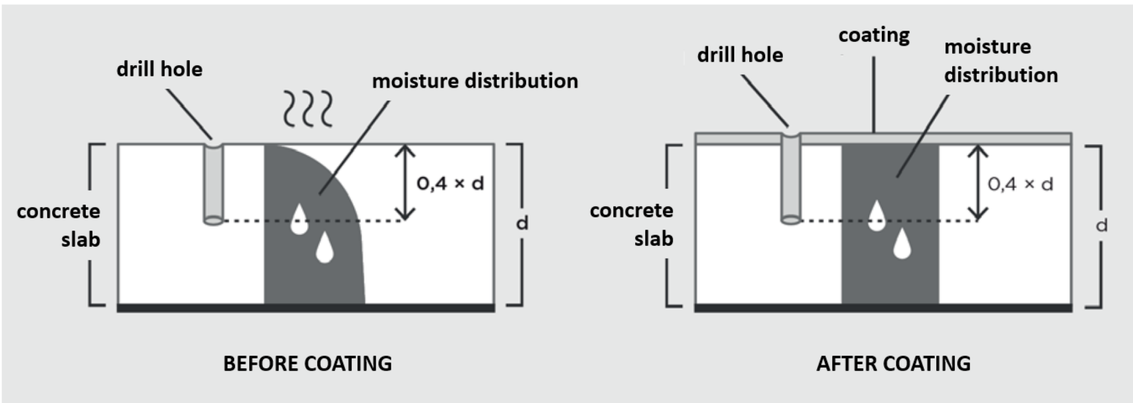


Figure 30 Moisture gradient before (left) and after coating (modified from Vaisala 2017)

2.5.2.2 Concrete Sample

The concrete sampling method (Figure 31) is usually faster and more flexible than the drill hole method. The concrete sampling method is recommended if the ambient temperature is fluctuating significantly, or either the concrete or the indoor air temperature is below 15 °C or above 25 °C. Sampling can be performed in temperatures between -20 °C and +80 °C, and the temperature differences between the concrete and the indoor air are not relevant. Following requirements according to the RT 14-10984 (2010) must to be taken into account:

8. The minimum sampling depth is 2 mm.
9. The amount of sample (> 1/3 of the tube volume) and the setting time (> 5–12 h) are adequate.

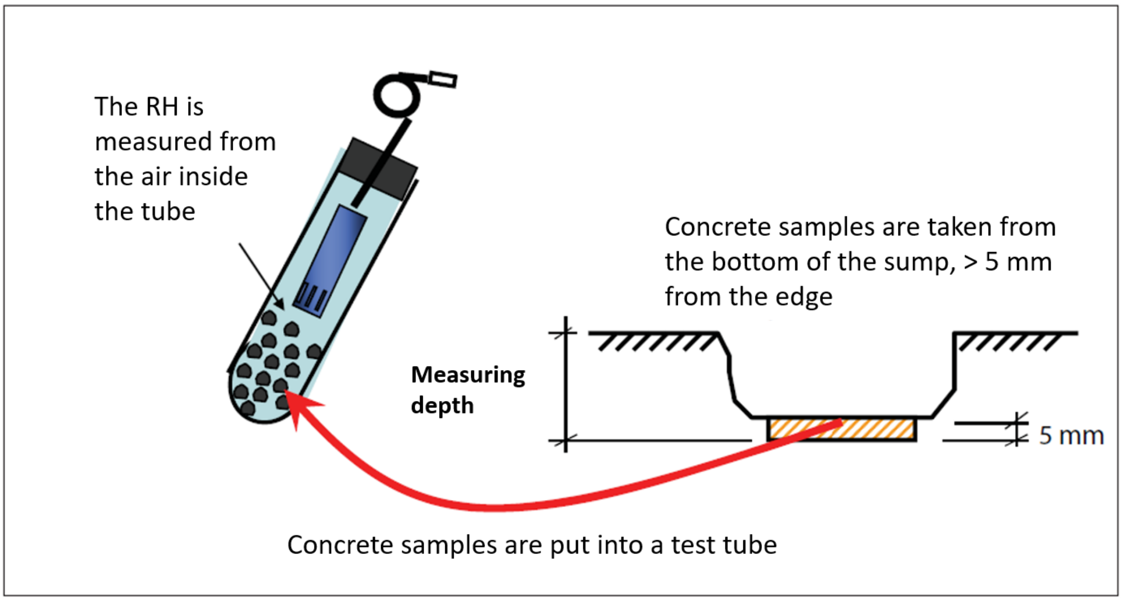


Figure 31 Concrete sampling principle (modified from RT 14-10984 2010)

2.5.2.3 Fresh Concrete

Currently, Vaisala sensors are considered the most reliable and accurate for relative humidity measurement. Vaisala sensor system consists of a sensor head and a display unit. Vaisala also provides a special installation tube. The tube can be installed into fresh concrete with the help of a height adjuster. Additionally, Vaisala provides a protective cup, where the sensor head can be stored during the setting period (Figure 32). It should be noted that the surface of the concrete on the bottom of the hole needs to be broken prior to measuring for accurate results. (Vaisala 2017)

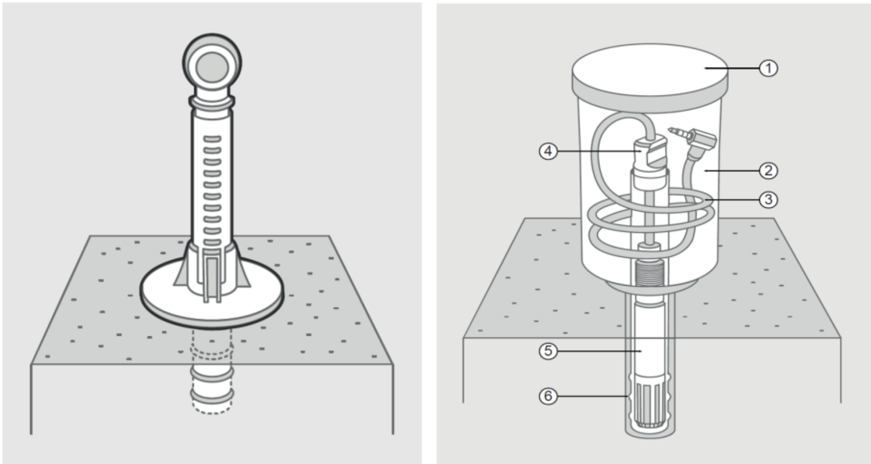


Figure 32 The Vaisala tube in the fresh concrete (left) and the protective cup containing the sensor head (Vaisala 2017)

2.6 Wireless IoT Protocols

As IoT is a rapidly growing business, there are many new wireless network solutions developed in the past few years (Columbus 2016). Modern IoT solutions require above all good scalability, long transmission ranges, good energy efficiency and good security. In this chapter, the principles of wireless networking as well as major wireless long-range protocols suitable for large scale commercial use are presented. Data security is not discussed in this thesis.

Two of the main network connection patterns, also called networking topologies, are: the mesh and the star (Figure 33). The star topology is centralized, meaning that the peripheral nodes are connected to a central node. Thus, the peripheral nodes cannot communicate with each other directly. In the decentralized mesh topology, every two nodes are connected to each other. Hence, the data can be transmitted between the nodes unrestricted. (Sosinsky 2009)

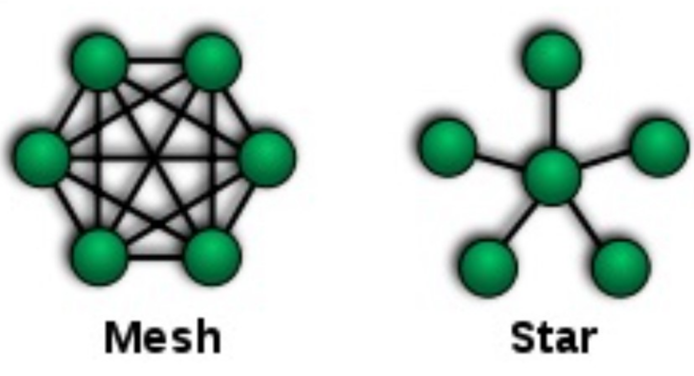


Figure 33 Wireless network topologies (IT geared 2012)

Essentially, all computer network solutions are based on an Open System Interconnection (OSI) model containing 7 abstract layers, starting with the lowest in the hierarchy (Microsoft 2017):

1. Physical layer – defines data transmission properties between a node / a device and a physical medium (e.g. radio frequency link).
2. Data link layer – a logical link between two nodes connected by a physical layer.
3. Network layer – defines network routing properties.
4. Transport layer – ensures the reliability of data transfer.
5. Session layer – manages session properties between different processes.
6. Presentation layer – formats the data for the application layer.
7. Application layer – defines the UI.

Majority of wireless network protocols are based on the IEEE 802 wireless networking standards covering the *physical and the data-link layers*. Other protocols include NFC, LoRaWAN and LTE. Wireless network systems can be divided into four groups based on their coverage, starting with the lowest coverage (Yang et al. 2017; IEEE 2017):

- Near Field Communication (NFC) – short-range
- Wireless Personal Area Network (WPAN / IEEE 802.15, e.g. Bluetooth 802.15.1, ZigBee 802.15.4.) – short-range
- Wireless Local Area Network (WLAN / IEEE 802.11, e.g. Wi-Fi 802.11g) – short-range
- Wireless Wide Area Network (WWAN) – long-range
    - Low-Power Wide Area Network (LPWAN, e.g. LoRa)
    - Cellular (e.g. LTE)

Generally, short range networks are best suited for local, within a building applications. However, by using base transceiver stations, the transmission range can be extended significantly. The WLAN and the NFC are not discussed in this thesis. (Yang et al. 2017)

2.6.1 Wireless Personal Area Network (WPAN)

2.6.1.1 Bluetooth LE

Bluetooth LE, also known as Bluetooth smart, is one of the most common protocols for IoT applications. Bluetooth is based on the WPAN standard. Compared to the regular

Bluetooth, the LE is designed for low-power network systems transferring relatively small chunks of data and provides significantly longer transmission ranges. The frequency rate is 2.4 GHz (ISM), the data rate is 1 Mbps and the range is 50–150 m. Also, the BLE can use 6LoWPAN as a separate gateway to access the Internet, or it can use a BLE supported smartphone as one. (Bluetooth 2017)

Due to the original Piconet (master-slave) architecture, the BLE transmission is generally constrained to peer-to-peer communications. In the 4.1 version, BLE introduced a scatternet topology: a master node of one or several slave nodes can simultaneously be a slave to another node. Thus, a scatternet created a network similar to a wireless mesh network. However, the communication between the nodes was not totally seamless. Currently, in the version 5.0 released in 2017, a true mesh network was introduced, significantly extending the network range and improving scaling capabilities. (Raza et al. 2015; Bluetooth 2017)

2.6.2 Wireless Wide Area Network (WWAN)

2.6.2.1 LPWAN

2.6.2.1.1 LoRa

LoRa is a proprietary, unlicensed networking technology, patented by Semtech Corporation. Essentially, LoRa is a waveform that uses chirped spread spectrum (CSS) technology, which encodes multiple bits per symbol and has integrated packetization and error correction. LoRa represents the base of a physical layer for different network systems. LoRa enables bidirectional communication capabilities, long range data transfer, and very low energy consumption due to low transfer rates. (Link-Labs 2017b)

2.6.2.1.1.1 LoRaWAN

LoRaWAN is a protocol developed and managed by the LoRa Alliance. LoraWAN is using 867–869MHz (ISM) band in Europe. According to the LoRa Alliance (2015), the energy consumption is 3 to 5 times better than that of other wireless network technologies, and the battery lifetime can be up to 20 years. Also, the transmission coverage of a single base station can, in theory, be hundreds of kilometers. LoRa is using star network topology. Thus, by using one hop mechanism, LoRa is relaying on the transfer range at the expense of data rates and flexibility of a mesh network. Lora's transfer rates are significantly lower than that of BLE, ranging between 300 bps and 5.5 kbps (in Europe). However, in case of construction applications, where the processes are generally slow, this is adequate. In Finland, a comprehensive LoRaWAN is provided by Digita (2017). (LoRa Alliance 2015; Järvinen 2017)

2.6.2.1.1.2 Symphony Link

Symphony Link is a protocol based on LoRa and developed by Link Labs. Symphony Link is suited better for the industrial use, because the package error percentage (PER) is lower than that of LoRaWAN. Symphony link also acknowledges every message in both direction as opposed to LoRaWAN and Sigfox. The firmware update is also made easier, which is convenient for startup companies. As opposed to LoRaWAN, Symphony link is a synchronous protocol and can thus utilize repeaters that cost less than an access point. Symphony link provides improved transmission quality by controlling transmission power of individual nodes: a node that is located near the base station is transmitting fast and quietly and those located further away are transmitting slowly and loudly. (Link-Labs 2017b)

2.6.2.1.2 SigFox (UNB)

Although still considered a startup company, SigFox, founded in 2009, is currently one of the biggest network providers in the industry. Sigfox developed a proprietary unlicensed Ultra Narrow Bandwidth (UNB) technology based on LPWAN. The specialty of UNB is a so-called cooperative reception, meaning that a signal from a device is jointly received by multiple base stations, thus increasing reliability. Sigfox also provides cloud platform services. Like LoRaWAN, Sigfox is using 867–869 MHz (ISM) band in Europe and only 100 Hz bandwidth. In comparison, LoRaWAN is using 125–500 kHz. (Yang et al. 2017; Brown 2017; LoRa Alliance 2015)

2.6.2.2 Cellular

Since cellular networks were originally developed for human to human communication devices being powered by high-capacity rechargeable batteries and using high data rates, they differ radically from modern LPWAN solutions. In response to rapid development of unlicensed protocols such as LoRaWAN, the 3GPP started to develop low-power and low-rate communications on top of existing LTE cellular network. As a result, following major protocols designed for IoT applications have been developed. The main advantage of the cellular technology is that is does not require separate gateways. (Yang et al. 2017)

2.6.2.2.1 LTE-M

LTE based LTE-M (Release 12 by 3GPP) was first released in 2015. It is more affordable than the regular 4G network, because it uses narrower bandwidth (180 kHz–1.08 MHz) and the maximum data rate is limited to about 1000 kbps. (Yang et al. 2017)

2.6.2.2.2 NB-IoT

LTE based NB-IoT (Release 13 by 3GPP) utilizes re-farmed GSM spectrum and uses even narrower bandwidth (3.75 kHz) than the LTE-M, and maximum data rate is limited to about 100 kbps. (Yang et al. 2017)

2.6.2.2.3 5G

The use of 5G for LPWAN IoT applications is the most recent development of cellular network providers. The 5G will support faster transmission rates and more connections for IoT devices. Final specifications will be finalized in 2019. (Hwang 2017)

Compared to the non-licensed technologies such as LoRa and SigFox, the licensed cellular technologies are generally more power-hungry and more expensive in terms of costs per amount of data transferred (Yang et al. 2017). Hence, the non-licensed technologies initially seem to be more appropriate for construction business applications, since a construction company can have thousands of construction sites, and each site can have hundreds of data sending devices.

Other promising wireless network solutions worth researching include ZigBee, Z-Wave, Ingenu, Thread, 6LowPaN and Weightless.

2.7 Attenuation of Radio Signal

The attenuation of a radio signal occurs naturally with distance and additionally in any material based on its dielectric properties. Also, attenuation is increased with frequency, and in reinforced concrete, attenuation is enhanced especially by the rebar. Additionally, according to Abbadi (2014), attenuation is further increases by moisture. Hence, construction site conditions are especially challenging for wireless network applications. Furthermore, the networks using 2.4 GHz frequency, such as Bluetooth, are likely to perform worse than the networks using 860 MHz, such as LoRaWAN. Different material specific attenuation rates can be seen from Table 5. (Digi 2010; Abbadi 2014)

Table 5 Attenuation of a radio signal in different materials (Digi 2012)

Material	Attenuation @ 900 MHz
Glass 0.25″ (6mm)	0.8 dB
Glass 0.5″ (13mm)	2 dB
Lumber 3″ (76mm)	2.8 dB
Brick 3.5″ (89mm)	3.5 dB
Brick 7″ (178mm)	5 dB
Brick 10.5″ (267mm)	7 dB
Concrete 4″ (102mm)	12 dB
Masonry Block 8″ (203mm)	12 dB
Brick faced concrete 7.5 “ (192mm)	14dB
Masonry Block 16″ (406mm)	17dB
Concrete 8″ (203mm)	23dB
Reinforced Concrete 3.5″ (203mm)	27dB
Masonry Block 24″ (610mm)	28dB
Concrete 12″ (305mm)	35dB

3 Research Methods

This thesis represents an extensive research project that required significant amount of background preparation, thorough testing and diverse product development.

First, a pilot site needs to be selected. The main requirement is that the schedule of the framework phase is suitable for testing purposes. Also, the structural specifications need to be suitable for the installation of the IoT-system, and to show the potential benefits of the system. The specifications of the pilot site are discussed more thoroughly in Chapter 3.1.

Secondly, the IoT-architecture needs to be designed and built. The work required advanced knowledge about programming, cloud computing and data analytics. Also, the sensors and the network solutions that are essential for the success of the project, needed to be assessed and selected. For that purpose, numerous negotiations with hardware and software companies were conducted. The structure of the IoT-architecture is discussed in Chapter 3.2.

Prior to installations on site, the IoT system and the sensors needed to be tested in controlled conditions. The results of the initial testing are discussed in Chapter 3.3. Final testing and installations were done on site, in order to ensure that the data is transmitting from all the sensors as planned. The installation process is discussed in Chapter 3.4.

Additionally, to examine, how different concrete mixes behave under different external conditions, and ultimately to be able to choose, prior to casting, the most suitable mix for prevalent casting conditions based on a real-time data analysis and the time reserved for the drying, five different concrete mixes were designed and delivered by MBR Oy. The mixes are presented in Chapter 3.5.

The timeline flow of the complete research process is visualized in Figure 34.

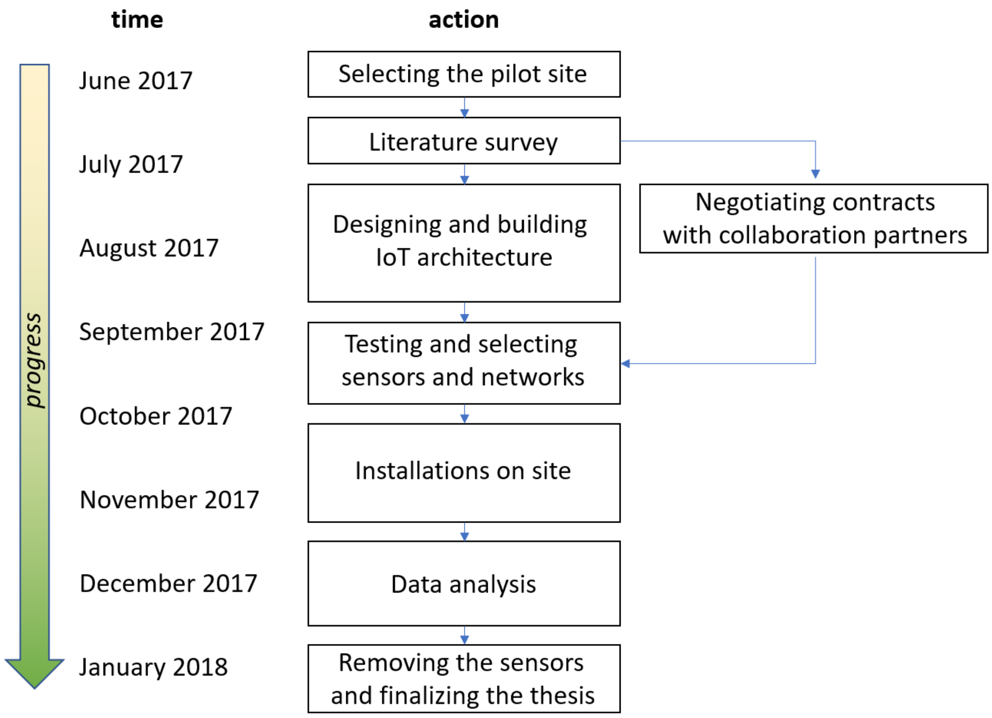


Figure 34 Timeline of the master's thesis project

3.1 Pilot Site

The pilot site selected for the case study is named Borgströminmäen Setlementtiasunnot, located in Laajasalo at Koirasaarentie 19, Helsinki. The construction project represents a traditional design-bid-build (DBB) delivery method, with Setlementtiasunnot Oy as the owner and A-Insinöörit Oy as the main consultant. Below, the 3D rendering of the building made by the general designer (Figure 35), and the general schedule (Figure 36).

Figure 35 Borgsröminmäen Setlementtiasunnot

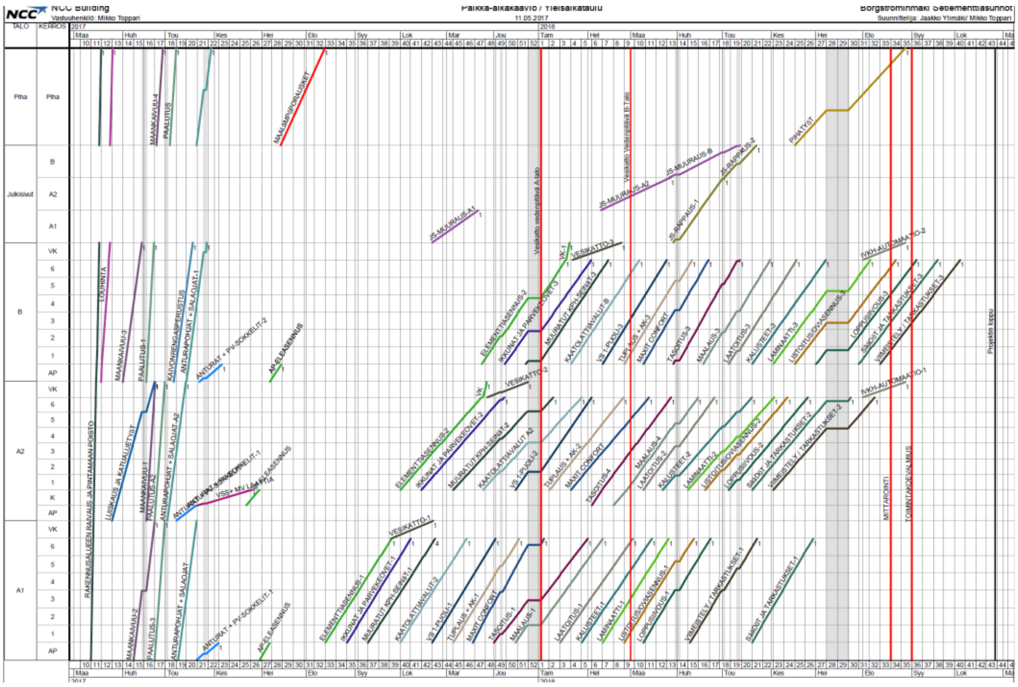


Figure 36 The building is completed in 3 separate zones

From the general schedule, following observations can be made: The time reserved for the intermediate floors to dry, before the laminate flooring installation work begins, is approximately 25–28 weeks. For bathrooms floors, in turn, the time is 14–15 weeks. By using the BY 1021 estimating software, it can be stated that in optimal conditions (+20 °C, 50 % RH, initial RH of a hollow-core slab 90–95 % and target RH 85 %, thickness of a pre-fabricated bathroom slab 185 mm, target RH 90 % and w/c ratio 0,5), the shortest estimated drying time would be 16 and 6 weeks, and in case of extremely wet and cold external conditions (+10 °C, 80 % RH, initial RH of a hollow-core slab > 95 %), the estimated time is 42 and 19 weeks, respectively. Thus, it can be stated that keeping the indoor conditions adequate for drying is essential in order to meet the schedule objectives. Also, if the drying conditions were optimal at all times, in theory, it would be possible to save up to total of 26 weeks. That would of course require all the other contracts, including the HVAC, to be adjusted accordingly, which is not always possible. Overall, the schedule is planned well and the work flow is adequate.

3.1.1 Structural Specifications

The building has 6 floors, 108 apartments and a total usable area of 8599 m^2. The frame is made mainly of precast elements. The cast-in-situ sections are limited to bathrooms and Schöck Isokorb® type balconies, which also represent the most critical places in terms of drying time. The building represents a lamella typology with three separate zones: A, A1 and B.

3.1.2 Technical Specifications

The heating system of the building contains a geothermal heat pump in combination with underfloor heating. The main difference between a geothermal heat pump and a more conventional district heating, in terms of drying control, is that a temporary water heating system cannot be used. Permanent heating was planned to be switched on only in May 2018, and thus cannot be used for the most energy consuming phase of the drying process. The underfloor heating has proved to be more comfortable and ultimately more affordable than a conventional radiation heating system in terms of construction costs (Figure 37) and is becoming more popular in residential buildings. The moisture measurement process, however, is slightly different from a traditional drill hole measurement process of a hollow-core floor slab due to different floor structure.

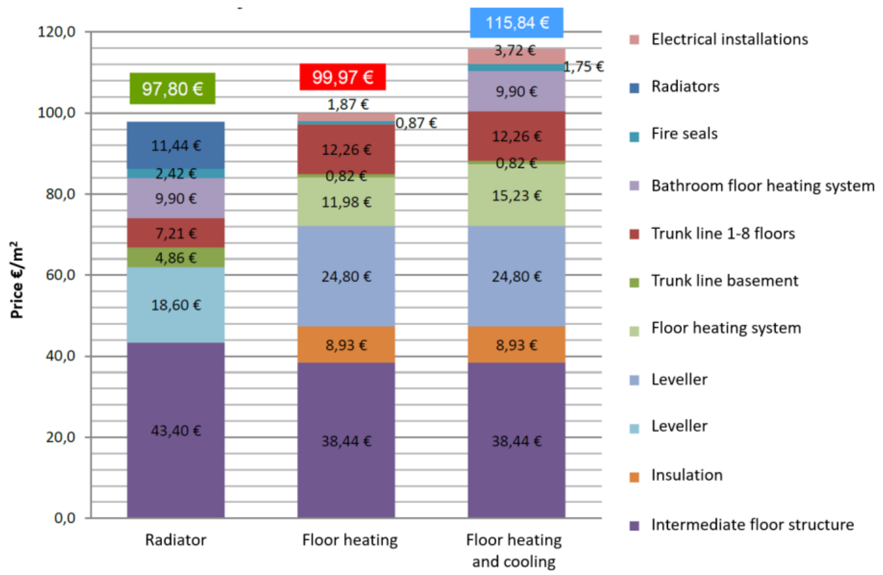


Figure 37 Heating system comparison (modified from Uponor 2017) - the construction costs of a floor heating system (middle) are almost equal to those of a traditional heating system, however, with lower risk of costs increase due to the potentially bigger amount of levelling concrete

3.1.3 Measured Data

In order to compile a comprehensive picture of prevalent drying conditions, following data was measured:

- outdoor conditions including temperature, relative humidity and barometric pressure
- indoor conditions including temperature, relative humidity and barometric pressure

- temperature and relative humidity of the most critical concrete structures

The so-called raw data is filtered and analyzed before exporting to the web application. The visualized data is presented more thoroughly in Chapter 3.2.2.3.

3.2 IoT Architecture

IoT Architecture means a configuration of a digital service build on top of IoT objects. The architecture can be divided into multiple layers that have clear boundaries between each other. Each layer is responsible for a certain task and is usually independent of other layers. For this thesis, it is purposeful to use five-layer principle (Figure 38). (Pallavi & Smruti 2017)

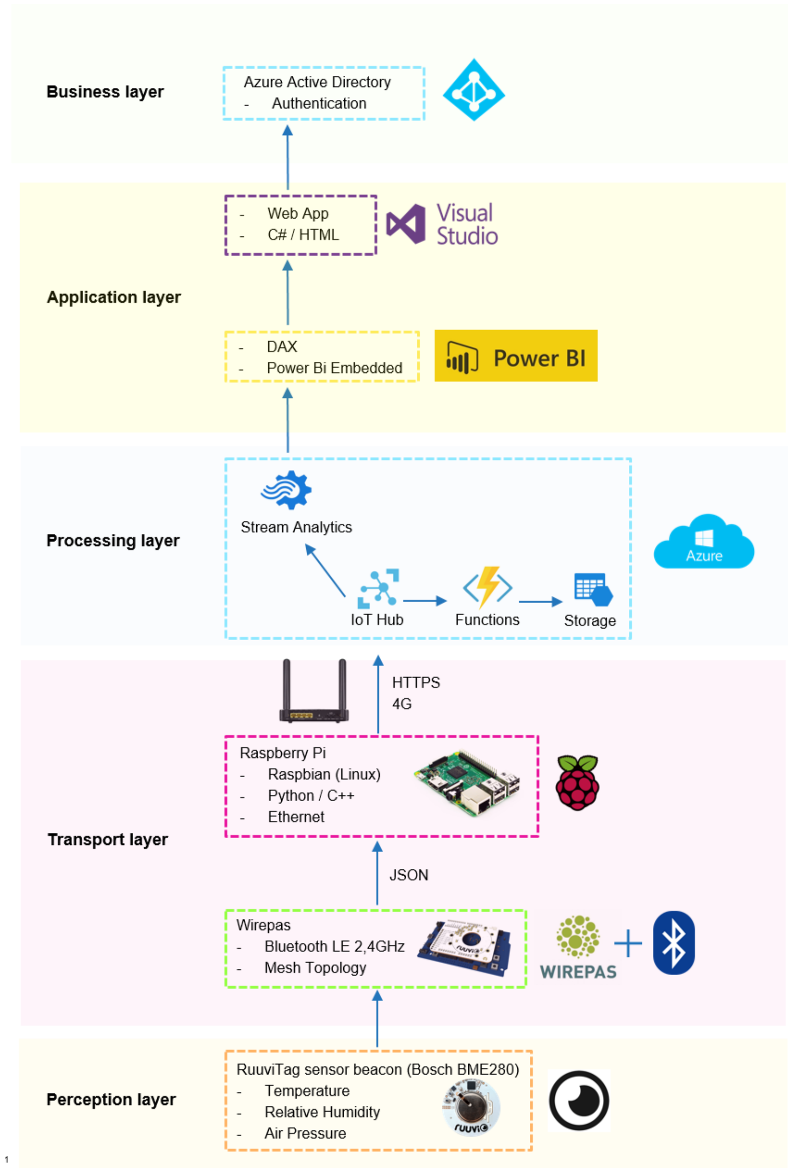


Figure 38 The IoT architecture

The perception layer consists of physical sensors that can collect, transmit and receive specific digital information such as temperature or relative humidity from the environment. Sensors are a part of a hardware setup that is discussed below in Chapter 3.2.1. *The transport layer* uses networks to transmits the data from the perception layer to the processing layer, and in the opposite way. *The processing layer* analyzes and stores the data. *The application layer* visualizes the data for the user in form of a user interface (UI). *The business layer* manages the application, the business model and the authentication. The software, including the networks, the cloud cervices and the application is presented in Chapter 3.2.2. (Pallavi & Smruti 2017)

3.2.1 Hardware

The hardware refers to physical electronic components that are controlled by a software and require a power source to function. In this chapter, the hardware is presented in detail, however, without discussing the settings used for the case study of this thesis.

3.2.1.1 Sensors

Modern semiconductor sensors output binary pulses depending on the intensity of the physical or chemical input. The pulses are then translated into readable data. Wireless IoT sensors are controlled by a firmware that is programmed on an electric circuit. An electric circuit of a wireless sensor also contains an own power source, usually a battery, and a radio transmitter. Firmware is a part of a software and defines, for example, which data is transmitted and how often. (Randy 2013)

For the case study, four different wireless sensors were selected. Two of the sensors, RuuviTag and Thingsee, are using Bluethooth LE (BLE) data transmission protocol in combination with a Wirepas mesh network. The other two sensors are manufactured by Wiiste Oy. One of Wiiste's sensors is using the relative new LoRaWAN protocol. Additionally, Vaisala HMP40s was used as a reference sensor.

3.2.1.1.1 RuuviTag

RuuviTag (Figure 39) is an affordable, open-source sensor beacon developed by a Finnish company Ruuvi Innovations Ltd. RuuviTag uses 2,4 GHz BLE and has Nordic Semiconductor nRF52832 SoC chip, STMicroelectronics LIS2DH12 accelerometer, temperature and humidity sensor and Bosch BME 280 temperature, humidity and air pressure sensor. It has a 1000 mAh battery and due to the polycarbonate enclosure with a Gore-Tex vent-membrane through which the air is diffusing, it is IP67 certified, meaning it can, in theory, withstand temporary immersion (> 30 min) in water (Bisenius 2012). The manufacturer claims that the battery lasts approximately 3–5 years depending on the transmission frequency. It can operate in extreme temperature conditions from -40 °C to 85 °C, however -20 to 65 °C is recommended. (RuuviTag 2017)

Figure 39 RuuviTag measures 52mm in diameter and 12 mm in thickness (RuuviTag 2017)

The most valuable component in the RuuviTag is the Bosch BME sensor (Figure 40), which is an extremely compact environmental sensor developed by Bosch especially for mobile applications. The sensor is calibrated at the factory, it has a broad operation range (Figure 41) and it is fairly accurate:

- temperature: absolute accuracy at 25 °C is ±0.5 °C and between 0 and 65 °C is ±1 °C
- relative humidity: absolute accuracy at 25 °C and between 20 and 80 % RH, including hysteresis, is ±3 % RH
- barometric pressure: absolute accuracy between 0 and 65 °C is ± 1hPa

No information is provided about the accuracy of the relative humidity above 80 % RH. Also, it is significantly less accurate than the Vaisala HPM sensor, whose accuracy for relative humidity is ±1,5 % RH and for temperature is ±0,2 °C, but for the purpose of this thesis, the accuracy is sufficient. (Bosch 2017)

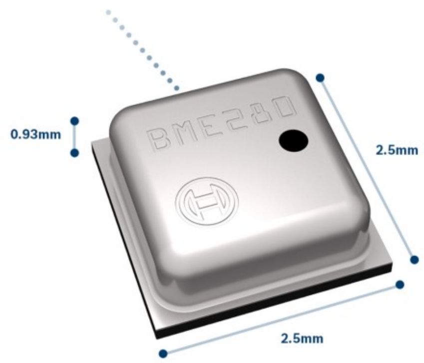


Figure 40 The BME280 is very tiny (Bosch 2017)

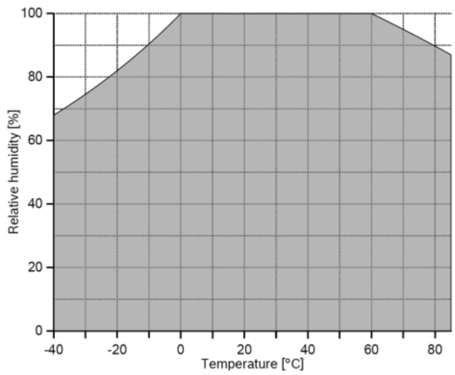


Figure 41 Operation range of BME280 (Bosch 2017)

3.2.1.1.2 Thingsee POD

Thingsee POD (Figure 42) is a compact environmental sensor developed by a Finnish company Haltian Oy. Like the RuuviTag, it also uses 2,4 GHz BLE. Thingsee POD measures light intensity, barometric pressure, relative humidity and temperature. However, no data regarding more detailed specifications of the sensor is provided. The sensor is not waterproof and thus cannot be used inside concrete. The measures are: 25 mm x 20 mm. (Thingsee 2017)

.

Figure 42 The design of the Thingsee POD is rather appealing (Thingsee 2017)

3.2.1.1.3 Wiiste SolidRH SH1

SolidRH SH1 is a concrete sensor developed by a Finnish company Wiiste Oy. Two versions of the sensors are tested: The original sensor (Figure 43) is IP57 certified, utilizes RFID based technology and requires a separate reading device to transmit the data to the cloud. A prototype of the upcoming LoRa-sensor (Figure 44) uses 860 MHz LoRaWAN transmission protocol. Both sensors have the same sensing component measuring temperature and relative humidity. However, more thorough technical information about the prototype is not yet revealed.

The sensors are designed specifically for fast and simple installation into fresh concrete during casting. The working principle is as follows: the plastic tube part that can be adjusted for length, depending on the required measuring depth of the structure is placed inside the concrete. The moist air from the concrete enters the tube from below and proceeds to the sensing component that is located on top of the device, protected by a thick layer of epoxy (> 3mm), to allow the removal of laitance. The location of the sensing component provides optimal transmission range. The disadvantage is that due to possible temperature changes between the concrete and the indoor air, the moisture inside the tube may condensate temporarily show higher relative moisture values. Also, the sensor is single-use, meaning it cannot be detached and reused for another location.

The technical specifications are listed below:

- temperature: absolute accuracy between 0 and 60 °C is ±0,2 °C
- relative humidity: absolute accuracy between 10 and 90 % RH is ±2,5 % and at over 90 % RH is ±3 % RH

Figure 43 An older SolidRH SH1 sensor that requires a separate RD1 reading device (Wiiste 2015)

Figure 44 A prototype of the upcoming LoRaWAN-sensor, the casing is 3D printed

3.2.1.2 Sink

The sink is working as a gateway for sensors using Wirepas network. It gathers all the sensor data and transfers it to the base transceiver station. Below, the sinks for RuuviTag (Figure 45) and Thingsee (Figure 46) are showed.

Figure 45 RuuviTag sink needs a USB-A to USB micro-B cable to connect (RuuviTag 2017)

Figure 46 Thingsee sink is very compact and is connected directly into an USB port

3.2.1.3 Base Transceiver Station

A base transceiver station transfers the data to the cloud. The base transceiver station prototype (Figure 47) was designed and built specifically for this project using a Raspberry Pi 3 mini computer running on Raspbian OS (a modified version of Linux). The Raspberry Pi has four USB A ports, an Ethernet port, 2.5 V power input and a HDMI output. The USB ports were used for connecting a mouse and a keyboard, and the HDMI was used for connecting a monitor during configurations on site (Figure 62). The Raspberry Pi can also be controlled with a laptop using a Putty-software, in which case the computer needs to be in the same Ethernet as the Raspberry Pi.

The Raspberry Pi is connected to a TP-LINK 4G internet router using an own sim-card, to provide optimal wireless connection to the cloud and to the sink. The script for the transmission of sensor data was written in Python and the data was sent to a server client in JSON format using the HTTPS protocol.

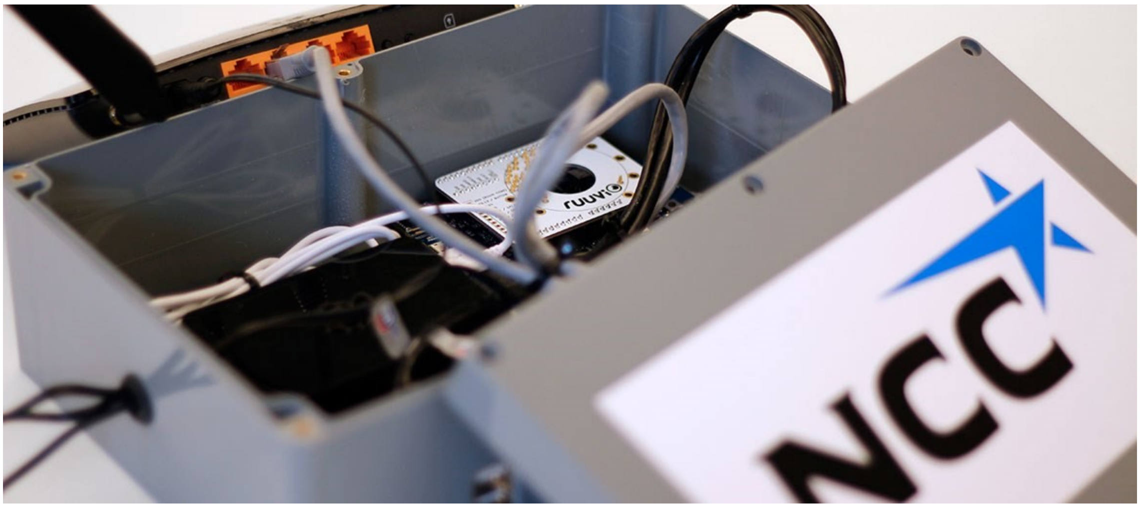


Figure 47 A base transceiver station prototype containing a 4G router, a Raspberry Pi 3 and a RuuviTag sink

3.2.2 Software

The software is essentially a package of code written in a specific programming language and designed to perform certain commands and tasks. It is also a common term for computer programs. In this thesis, following languages were implemented: Python 2.7, Python 3.4, JavaScript, C++ and C#.

Software is becoming one of the single most important element in business models based on digital construction services, since it connects the user with the physical devices. Figure 48 presents a simplified diagram containing different types of software.

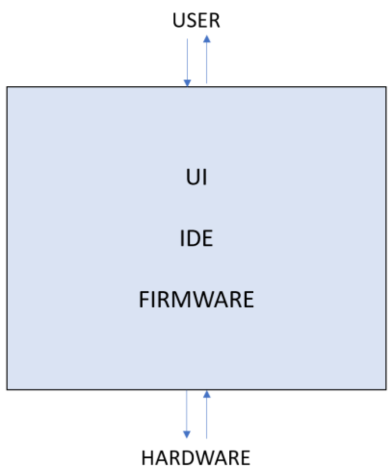


Figure 48 A simplified interaction process between a software (middle), a hardware and a user

3.2.2.1 UI

In this chapter, the UI of the web application that was built for the case study is introduced. As can be seen from Figure 39, the analyzed sensor data is transferred from Azure to Microsoft Power Bi for visualization purposes. Power Bi provides variety of interactive visualizations such as KPIs, graphs and charts that can be used separately as so-called tiles or integrated into reports and dashboards. The tiles, reports and dashboards can then be embedded (imported) into any application using appropriate APIs. The web based application used in this project was made using Visual Studio IDE and written in C# language. Visual Studio uses Azure SDK to connect to Azure.

The application has following functions:

- Home screen (Figure 49) is showing the location of the construction site, some general information, current state of the drying conditions in the building, as well as concrete instructions for the construction management, including how the drying conditions should be improved.

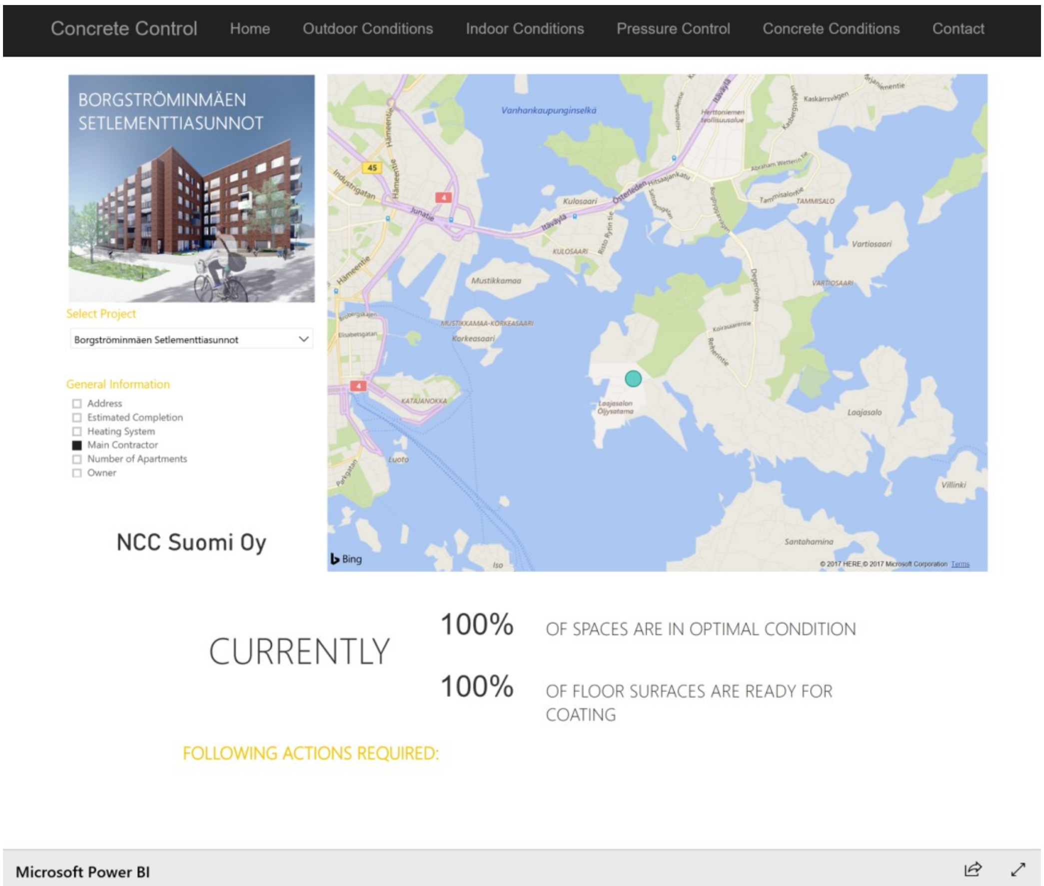


Figure 49 The home screen of the web application

- Outdoor Conditions (Figure 50) show current temperature, relative humidity and barometric pressure outside the building, as well as a 5-day weather forecast retrieved through an open source open weather data API. The weather data is also analyzed and used for the instructions.

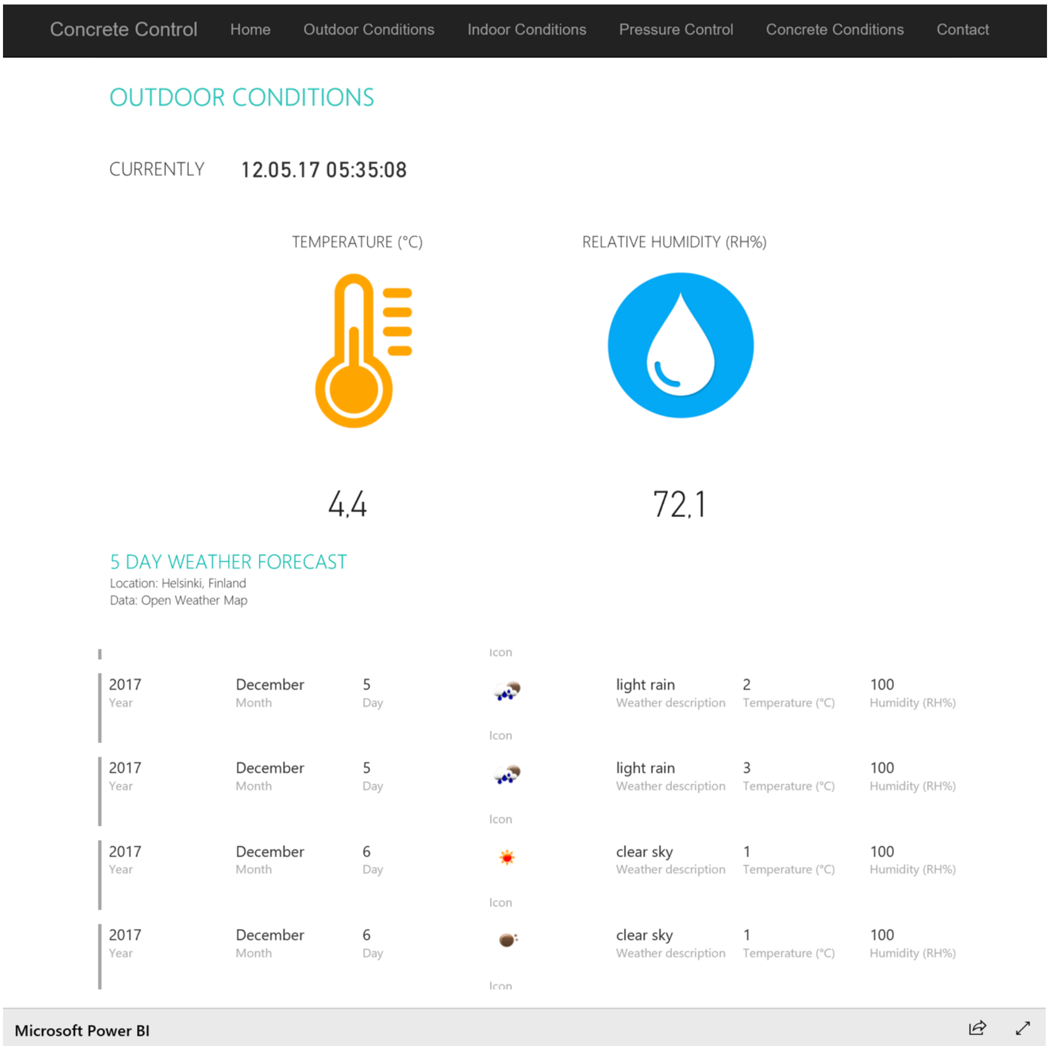


Figure 50 The outdoor conditions

- Indoor Conditions (Figure 51) show temperature and relative humidity data of different spaces in the building. The visualization is made using PDF floor plans of the building. The spaces are colored either green or red depending on the preferred index. For example, a binary index can be used to show whether the indoor conditions are optimal for the drying of concrete: If both the temperature is above 20 °C and the relative humidity is below 50 % RH, the index value is 1 (green). If either of the requirements is not met, the index value is 0 (red). Also, a mold index, developed by Viitanen (2004) can be used.

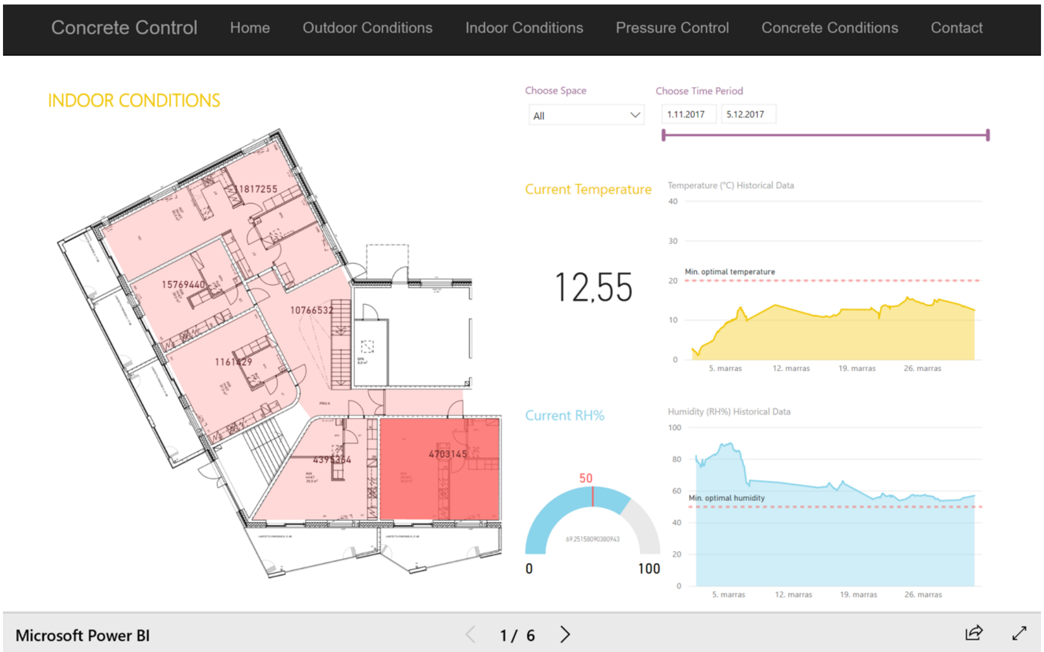


Figure 51 The indoor conditions

- Pressure Control (Figure 52) is used to visualize prevailing pressure conditions inside the building. The application can calculate air and vapor pressure gradients between outdoors and indoors, between an apartment and a stairwell, and also between indoors and a concrete floor, to show an estimation, in which direction the air and moisture are transferring, or to control the pressure conditions of compartmentalized spaces.

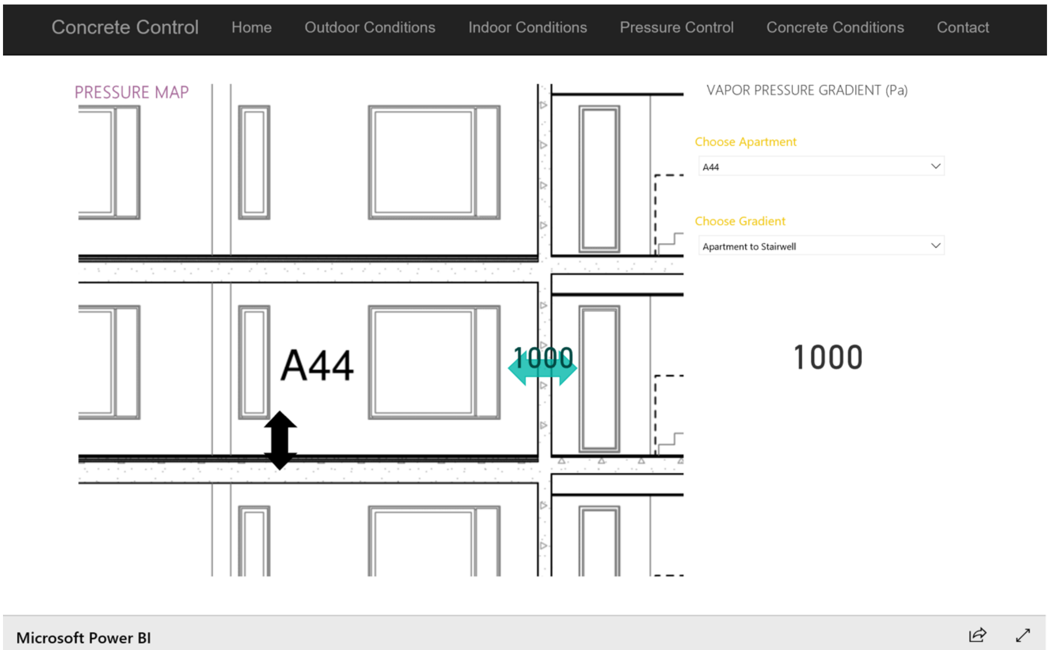


Figure 52 The pressure map

- Concrete Conditions (Figure 53) show temperature and relative humidity of concrete structures where the sensors have been installed. The relative humidity data is used to forecast the drying process and to inform the construction management, when the floor surface is ready for coating, for example by sending an email.

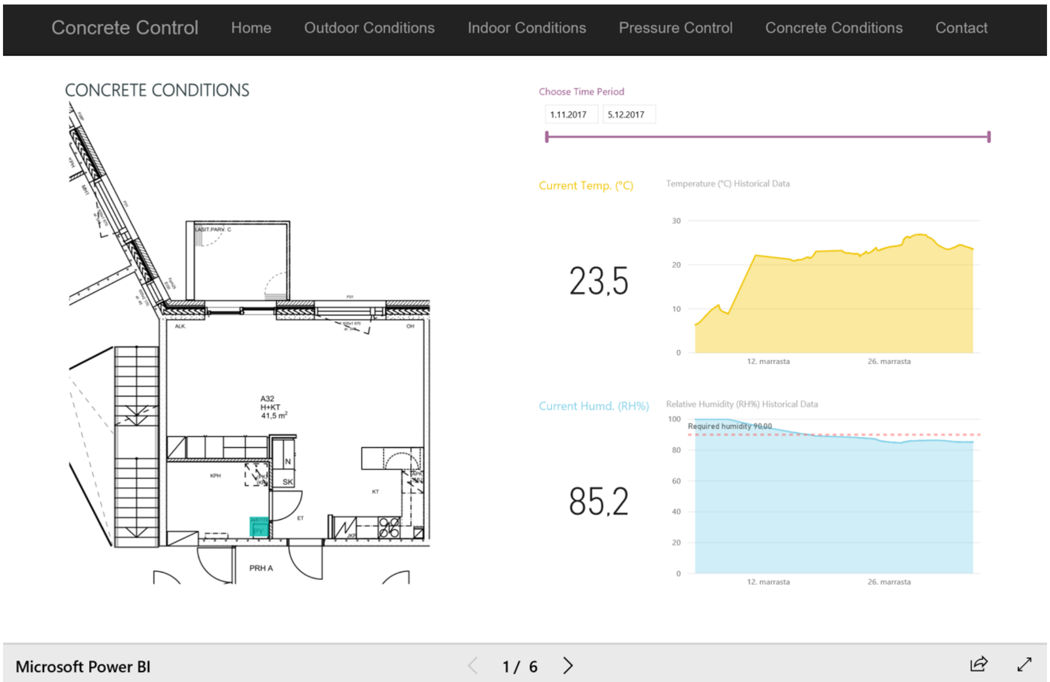


Figure 53 The concrete conditions

3.2.3 Networks

In this thesis, two different wireless network systems are compared: LoRaWAN and Wirepas. Wirepas was developed by a Finnish startup company Wirepas Oy in 2010. A LoRaWAN network, currently covering a reasonable part of Finland (Figure 54), is provided by Digita Oy. There are two main differences between the two networks. First, Wirepas always creates a network locally, and constantly optimizes the network based on the properties and the number of devices that are connected to it, which is also the main advantage compared to a regular Bluetooth Mesh, whereas LoRaWAN requires a central network management, in this case maintained by Digita. Second, they use different network topology: LoRaWAN uses a star-topology and Wirepas uses a mesh-topology. (Wirepas 2017; Digita 2017)

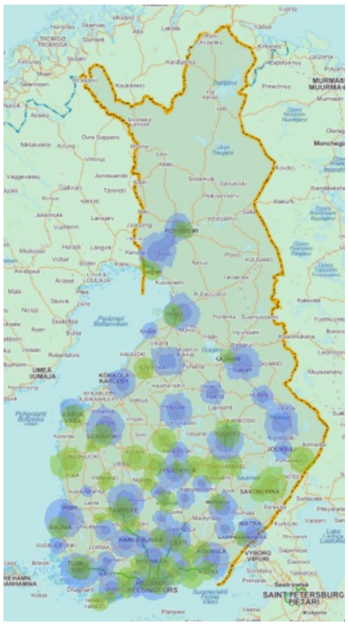


Figure 54 Current (blue) and planned (green) coverage of LoRaWAN in Finland by the end of 2017 (Digita 2017)

In this thesis, we compare the two networks in construction site conditions to determine which one is suited better applications in this environment. The theoretical advantages and disadvantages of each network technology are discussed in Chapter 2.7.

3.2.4 Cloud Services

There are a few big cloud service providers, including the Amazon Web Services (AWS), the IBM Cloud and the Microsoft Azure. They all offer basically the same core services, and there are some minor differences in pricing. In this thesis, the Microsoft Azure cloud services are used for two main reasons. First, because NCC is already using Office 365, thus the setup was familiar and there is an immediate support for Azure Active Directory (AAD) users. Second, because it integrates seamlessly with the Visual Studio IDE that was used for software development.

In this thesis, following services of Microsoft Azure are implemented:

- IoT Hub
- Function App
- Storage
- Stream Analytics

IoT Hub provides secure device-to-cloud-to-device communication including messaging and file uploads. IoT Hub is authorizing the devices by using SAS, containing identity registry security credentials. Single IoT Hub is capable of connecting up to millions of IoT devices simultaneously. IoT Hub uses following data transmission protocols: AMQP, MQTT and HTTPS. In this thesis, IoT Hub is used to receive the data from the Raspberry Pi (gateway). The data is sent via HTTPS protocol. HTTPS, also known as HTTP-over-TLS, is a widely used and secure protocol that is well suited for IoT usage due to bidirectional encryption between an IoT device (client) and a server. Prior to sending, the data is formatted to JSON, which is convenient, because it represents a simple dictionary containing a key and a value. For example: [{"device1": "Raspberry1"; "temperature1": 24.5; "humidity1": 55.5"}] means that a device named "Raspberry1" is sending following data: temperature equals 24.5 and humidity 55.5. (Microsoft Azure 2017a, S.Cirani et al. 2014)

Azure Functions is a service that allows running small scripts inside of Microsoft Azure, independent of the other services and applications. Functions can be written in C#, F#, Node.js, JavaScript, Python and PHP languages. Functions can be connected to other Azure services such as Azure Storage, Azure Event Hubs or Twilio for sending SMS messages through an API. In this thesis, a Function app written in JavaScript is used to transfer the data from IoT Hub to the Azure Storage. (Microsoft Azure 2017b)

Azure Storage is a service that provides secure and scalable data storage. There are four types of storages: Blob storage, Queue storage, File storage and Table storage. Blobs represent any type of files: pictures, excel files etc. Queue storage is used to store and retrieve messages. File storage can process files using SMB protocol in order to allow file share for multiple clients simultaneously. Finally, Table storage is optimal for storing structured, key/value data and thus is ideal for the purposes of this thesis. There are also other widely used storage options provided by Microsoft Azure, such as the SQL Database that is also suited for structured JSON data. However, the Storage is significantly less expensive. (Microsoft Azure 2017c)

Stream Analytics is used for real-time analysis of high-volume streaming data for up to 1 GB per second. Stream Analytics can read data from various sources, including the IoT Hubs. The data can be analyzed, for example, for patterns, to provide forecasting capabilities. In this thesis, the analyzed data is output to Microsoft Power Bi. (Microsoft Azure 2017d)

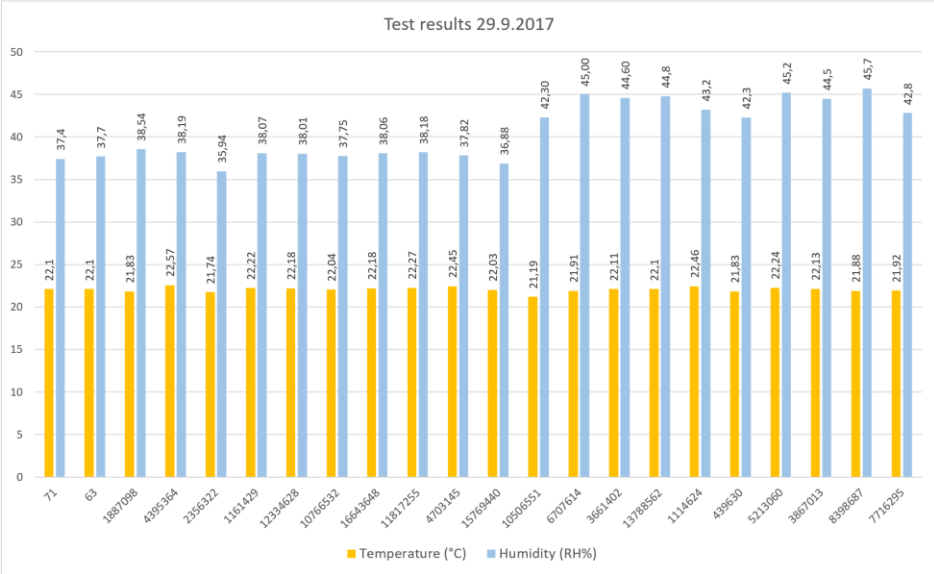
3.3 Initial Testing

The initial testing was conducted between September 26th and September 29th in the office and under steady conditions. 10 RuuviTags, 10 Thingsee PODs and two Vaisala HMP40s sensors were placed inside a polystyrene box (Figure 55) for three days. Vaisala sensor were calibrated prior to testing. A polystyrene box was used to isolate the sensors from the environment and thus provide more reliable results. Additionally, Blu-tack was used to seal the holes made for Vaisala sensors for better airtightness. The box was placed in a closet away from any heat source that could have affected the results.

The results are presented in Table 6. The result clearly show that the RuuviTag sensors performed very well: The range of variation for temperature and relative humidity was 0,83 and 2,6 respectively, and the average values of both temperature (22,15) and relative humidity (37,74) are close to those of Vaisala HMP (22,1 and 37,4, respectively). However, the Thingsee sensors presented significantly weaker results, especially in terms of relative humidity accuracy: The range of variation for temperature and relative humidity was 1,27 and 3,4 respectively. The average temperature was 21,98 and thus 0,88 higher than that of Vaisala, and the average relative humidity was 44,04 and thus 6,49 higher than that of Vaisala. Since Haltian Oy did not specify, by whom the sensing component is manufactured, it is impossible to assess, whether the accuracy of the results is in accordance with the technical specifications of the sensor. Based on the test, RuuviTags were chosen as the main sensors to be used in the case study. Also, RuuviTags are more affordable.

Figure 55 The sensors inside the polystyrene box

Table 6 Testing RuuviTag and Thingsee POD sensors



Sensor	Id
Vaisala	71
	63
RuuviTag	1887098
	4395364
	2356322
	1161429
	12334628
	10766532
	16643648
	11817255
	4703145
	15769440
Thingsee POD	10506551
	6707614
	3661402
	13788562
	1114624
	439630
	5213060
	3867013
	8398687
	7716295

3.4 Concrete Mixes

MBR Oy is delivering four different mixes of concrete that are designed to suit different casting conditions according to Table 7. Ultimately, the software could help the supervisors to choose the right mix depending on the prevalent conditions and the required drying time.

Table 7 Concrete types used in casting, some values are missing

Concrete Type	*Strength (MPa)*	*Plasticity*	*Max. Grain Size (mm)*	*Water/Cement Ratio*	*Air Content (%)*	*Additives*
Rapid	C30/37	S3	16	0,49	2	Plasticizer
SK*	C35/45	S3	16	0,41	5	Plasticizer, Air-Entraining Agent
IK**	C35/45	S3	16	0,35	5	Plasticizer, Air-Entraining Agent
NPB	C25/30	S3	16	-	-	Plasticizer, Air-Entraining Agent

* weather-resistant
** self-drying

3.5 Installations

As presented in Chapter 3.1.3, the sensors are installed to monitor three main things: outdoor conditions, indoor conditions and concrete conditions. Outdoor data contains temperature, relative humidity and barometric pressure. The data is used as a reference to the indoor conditions. Indoor data similarly contains temperature, relative humidity and barometric pressure. Finally, concrete data contains temperature and relative humidity. In order to gather sufficient amount of data for the analysis, and display the prevailing conditions as accurate as possible, it is reasonable to install as many sensors as technically possible, while maintaining feasibility.

To achieve an ideal model of outdoor conditions, and to be able to calculate accurate air pressure gradients between outdoors and indoors, the sensors need to be installed on each floor level, since the pressure value is dependent on the elevation.

Indoor data needs to be gathered from each apartment separately, because the apartments can be compartmentalized, if needed, and the differences between the apartments can be seen clearly. Also, it is convenient for the visualization, as can be seen from the UI in Chapter 3.2.2.3. Installing one sensor per apartment can be considered adequate. Ideally, the values should be measured at floor level. However, due to better preservation of the sensors during the intensive framework phase, they were attached to the ceiling (Figure 56). The differences in temperature and relative humidity between the floor and the ceiling level are taken into account: Approximately 3 % RH difference in relative humidity and 0.3 °C difference in temperature was measured under steady conditions (% RH ~ 80 % and temperature +7 °C). Altogether, 41 sensors were installed indoors.

Figure 56 RuuviTag attached to the ceiling

Originally, the data from the concrete was planned to be gathered both from the Schöck-balconies and the bathroom floors. However, due to technical difficulties with the IoT system, the sensors were installed only in the bathrooms, between floors 3 and 6. The locations can be seen from Figure 57. Altogether, 39 sensors were installed in the concrete.

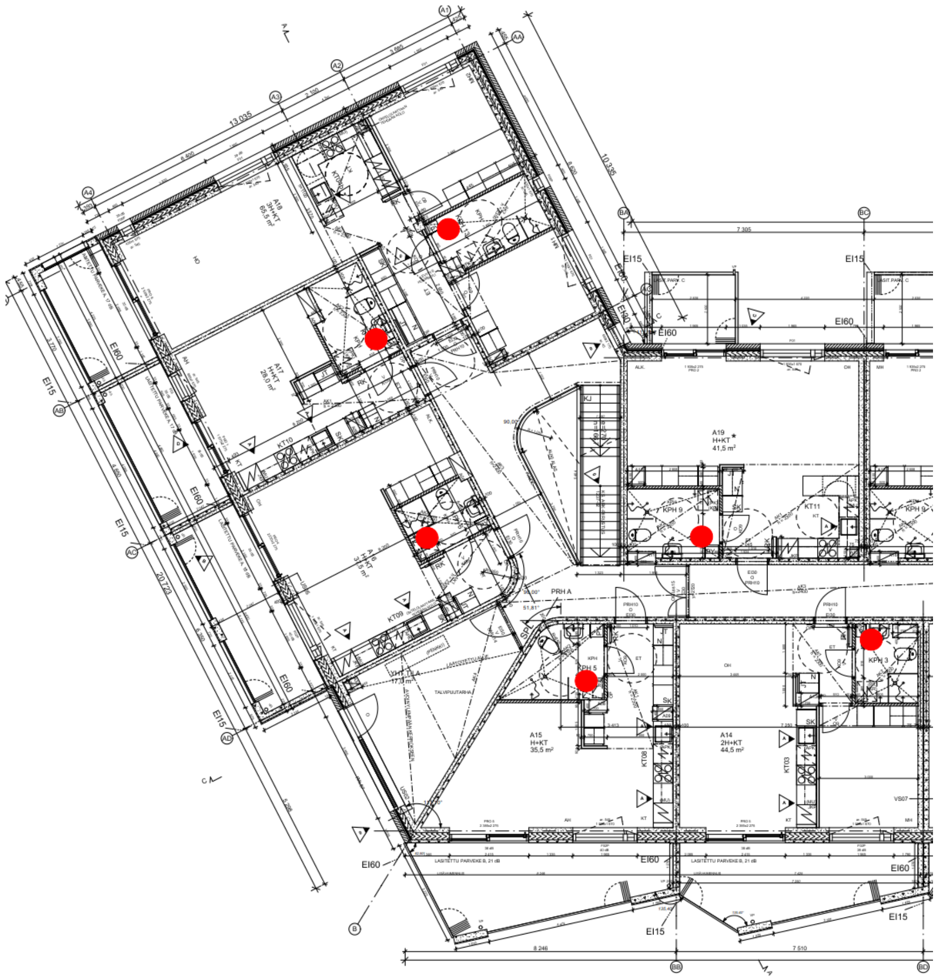


Figure 57 Sensor locations in the 2nd floor of section A. Other floors are installed similarly.

Concrete sensors are installed in three ways:

1. Directly into fresh concrete during casting.
2. On the bottom of a reservation made by a 3D printed mold, concrete casting on top.
3. On the bottom of a reservation made by a 3D printed mold, plugged by either a polyurethane or a plastic plug.

In case of first two installation methods, the sensors are left inside the concrete. In the latter case, the sensor can be easily retrieved from the structure and reused.

In the first installation method, a steel telescope stand was used, designed specifically for this project (Figure 58). The stand is attached to the floor by a 4,8-mm nail anchor, for a secure fixation. The height was adjusted to a millimeter accuracy, according to the RT-card (Rakennustieto 2010).

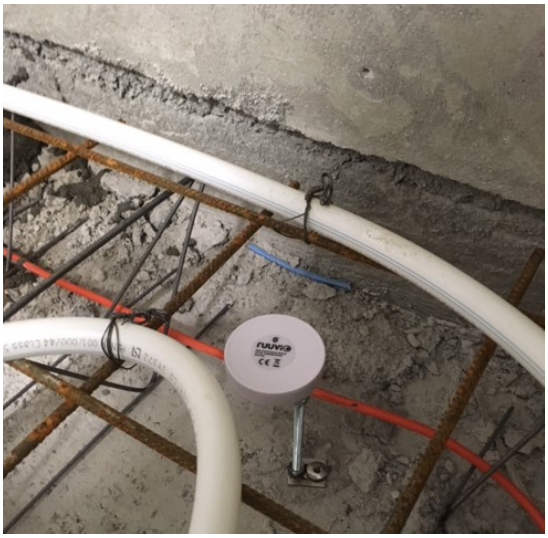


Figure 58 The RuuviTag was adjusted to 115mm, the orange curing cable can be seen

For the second and the third installation methods, a 3D printed mold was developed using Google SketchUp software and printed by extrusion using a PVC-based material (Figure 59). The height of the mold is 70 mm, which is the maximum measuring depth for this particular structure (Rakennustieto 2010). Since the diameter of RuuviTag is 52 mm, a bore hole would have been difficult to make, due to a risk of hitting the reinforcement steel or the technical hoses.

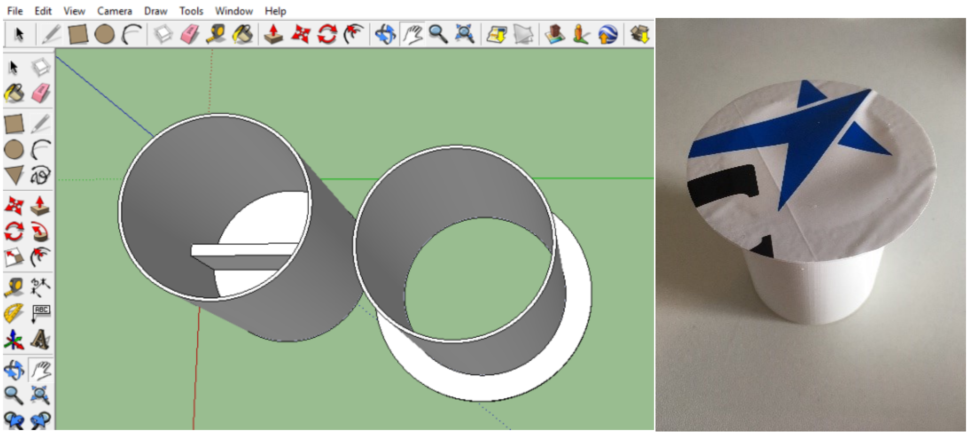


Figure 59 A 3D sketch and a ready mold (right) designed for the RuuviTag

The installation process is as follows (Figure 60):

- A 3D mold is inserted into fresh concrete after placing.
- After the concrete is hardened, the inner cylinder is removed by rotating and pulling from the middle part, and potential dust removed with a vacuum cleaner.
- A RuuviTag is placed on the bottom of the reservation and the edge/perimeter is sealed with a caulking compound.
- The hole is filled with concrete or plugged.

Figure 60 The installation process of RuuviTag sensors. In the upper left picture also the two Wiiste sensors can be seen in the concrete.

As stated in Chapter 3.2.1.1, RuuviTag has a small hole covered by a Gore-Tex® membrane to let the vapor transfer into and out of the casing. To improve the flow, and to reduce the risk of moisture accumulating beneath the casing, the RuuviTag was modified by replacing the original membrane with a larger one (Figure 61).

Figure 61 The Gore-Tex membrane was replaced

Before installing all the sensors, they needed to be tested in order to determine whether the transmission range is adequate. As stated in Chapter 2.8, the reinforced concrete structures significantly interfere with the radio signal. Hence, the transmission range is most likely not as good as stated in technical specifications of the sensors. (Abbadi 2014)

The testing showed that the maximum transmission range of RuuviTag sensors in a corridor, with no direct visual communication between the sensor and the base transceiver station, was approximately 20 m, and the maximum transmission through a bearing concrete wall was approximately 9 m. Thus, the transmission ranges are considered adequate for the purposes of this thesis. However, in case of the Wiiste's LoRaWAN sensors, a separate base station was additionally required to be installed in close proximity to the sensors (Figure 63). Figure 62 presents the testing setup.

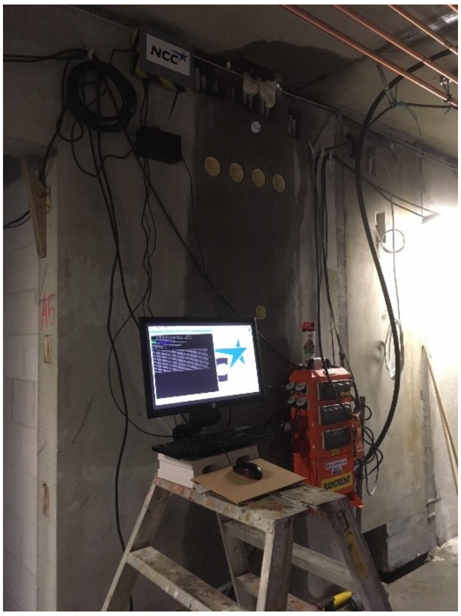


Figure 62 Testing the reception and the transmission range

Figure 63 A LoRaWAN base station is sometimes required if the transmission range is not satisfactory

4 Results

In this chapter, the measurement results of all the installed sensors, including RuuviTag and Wiiste sensors, between September 1st, 2017 and January 9th, 2018 are presented. In total, over 300.000 messages have been sent successfully to Azure. Vaisala HMP40s sensor was used for reference values in concrete structures.

4.1 Cast-In-Situ Bathroom Floors

Figures 64, 65, 66, 67, and 68 show the measurement results of the cast-in-situ bathroom floors for the comparison of different casting and drying conditions, concrete mixes and measurement methods. Due to missing reference measurements, some concrete mixes are not presented. Also, some indoor air data during casting is missing due to technical issues. The total thickness of the cast-in-situ concrete structure is approximately 185 mm, and the measuring depth is 70 mm.

Location	A45
Concrete mix	SK
Casting date	27.10.2017
Surface temperature at casting	-1,4 °C
Indoor air temperature and relative humidity at casting	-
Avg. temperature of concrete	22,0 °C
Sensor properties	RuuviTag in a 3D mold, cast

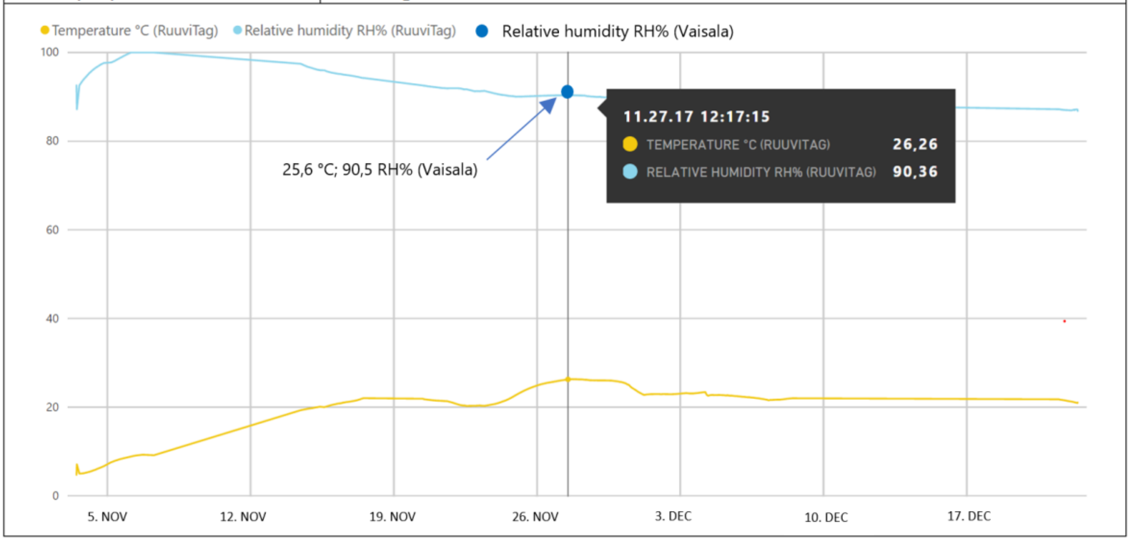


Figure 64 Apartment A45

Location	A32
Concrete mix	IK
Casting date	27.10.2017
Surface temperature at casting	-1,6 °C
Indoor air temperature and relative humidity at casting	-
Avg. temperature of concrete	21,6 °C
Sensor properties	RuuviTag in the fresh concrete

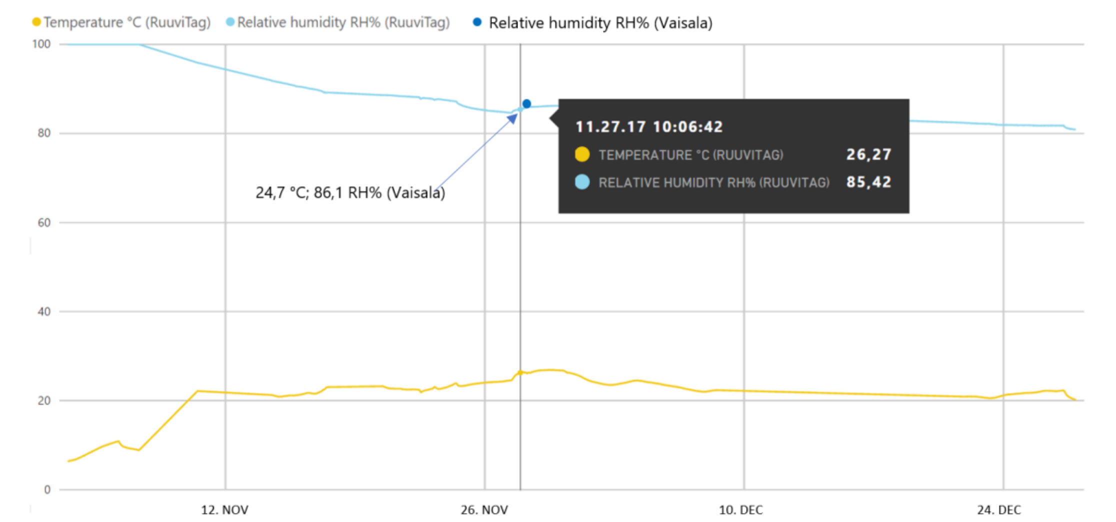


Figure 65 Apartment A32

Location	A57
Concrete mix	NPB
Casting date	10.11.2017
Surface temperature at casting	15,7 °C
Indoor air temperature and relative humidity at casting	22,8 °C, 46,6 RH%
Avg. temperature of concrete	23,8 °C
Sensor properties	RuuviTag in a 3D-mold, plugged, bigger Gore-Tex membrane

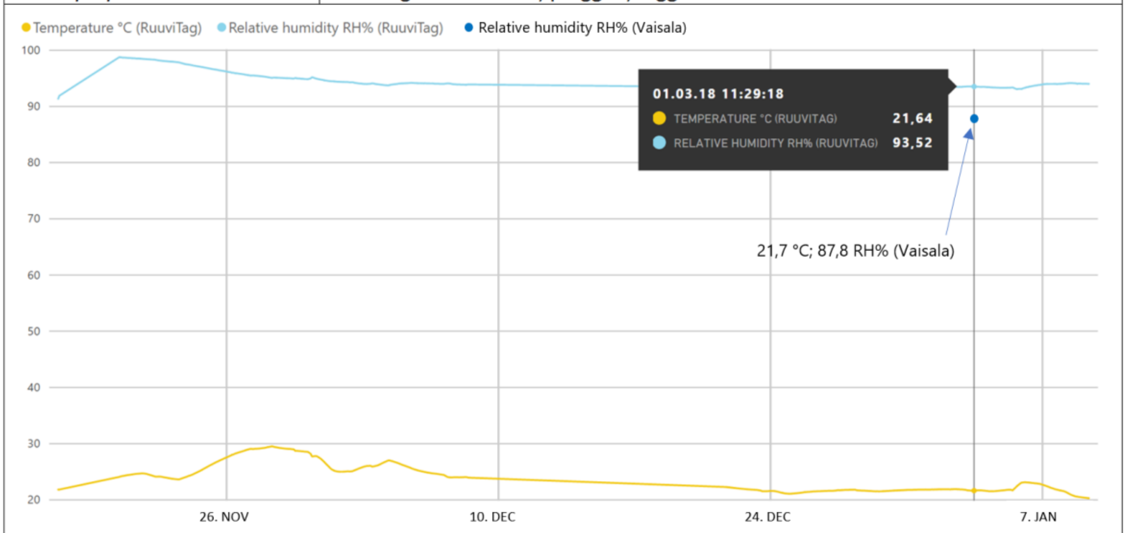


Figure 66 Apartment A57

Location	A68
Concrete mix	IK
Casting date	10.11.2017
Surface temperature at casting	11,8 °C
Indoor air temperature and relative humidity at casting	-
Avg. temperature of concrete	20,8 °C
Sensor properties	RuuviTag in a 3D-mold, plugged

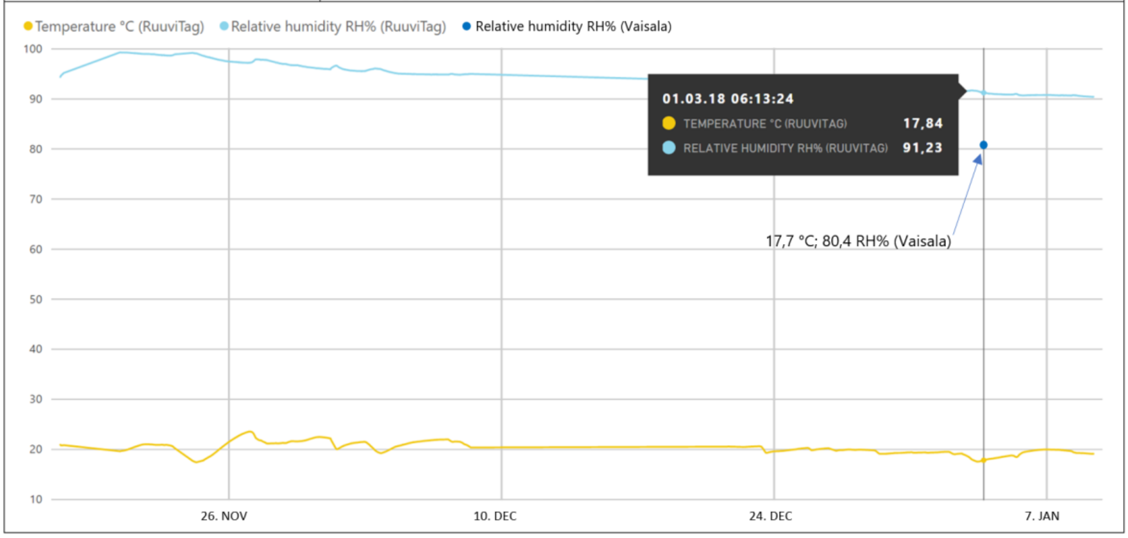


Figure 67 Apartment A68

Location	A67
Concrete mix	IK
Casting date	10.11.2017
Surface temperature at casting	11,5 °C
Indoor air temperature and relative humidity at casting	-
Avg. temperature of concrete	18,8 °C
Sensor properties	RuuviTag in a 3D-mold, plugged; Wiiste

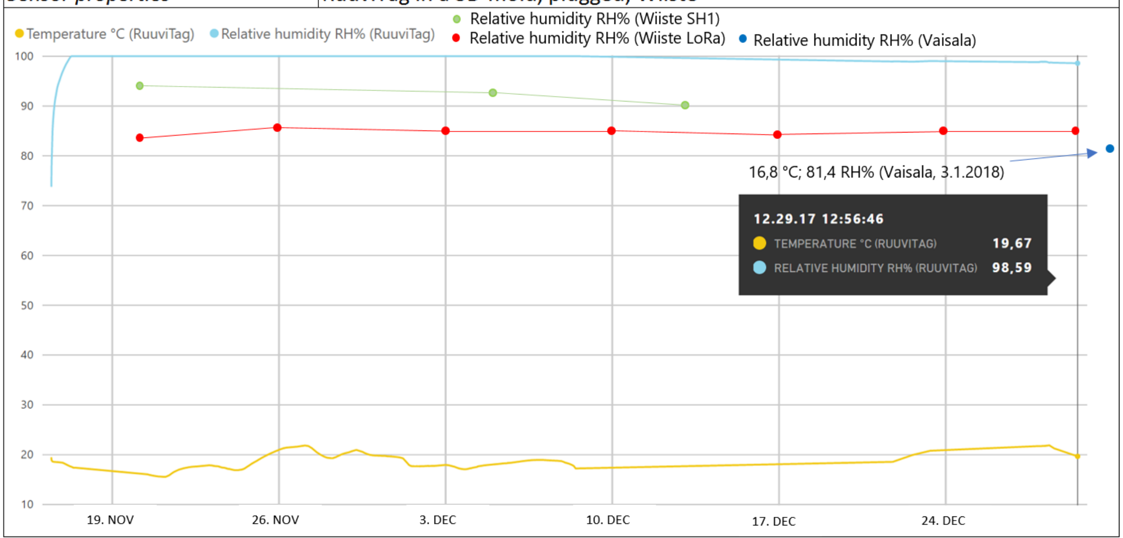


Figure 68 Apartment A67

4.2 Indoor Conditions

Indoor conditions were monitored using RuuviTag sensors. The data was gathered between September 1st, 2017 and December 28th, 2017. The heating was started on September 7th, 2017.

Average indoor temperature was 18,6 °C and average relative humidity was 47,4 % RH, thus only 1,4 °C and 2,6 % RH below the optimal drying conditions, which is remarkable. The results are showed in Table 8 below. The main heaters were located in the stairwell between the floors 2 and 5, which can be observed from the table. Also, the stack effect can be clearly seen. Overall, the indoor conditions were optimal approximately 45 % of the time. It should be noted that the ambient conditions were quite favorable: average outdoor temperature according to Ilmatieteen laitos (2017) was 2,1 °C.

Table 8 Indoor conditions

Location	*Id*	*Avg. Temperature*	*Avg. Relative humidity*	*Total Count*	*Optimal Count*	*Optimal %*
A3	4703145	11,77	69,25	1179	0	0,0
A4	4395364	14,64	56,18	3269	0	0,0
A5	1161429	14,96	59,86	2350	0	0,0
A6	15769440	16,63	47,17	1712	220	12,9
A7	11817225	12,98	67,17	1703	115	6,8
1.str	10766532	14,41	54,47	3127	901	28,8
A14	2264274	15,71	61,63	1823	504	27,6
A15	1815530	16,54	59,43	3060	679	22,2
A16	9596227	17,75	48,85	4452	1050	23,6
A17	14152445	15,62	60,94	749	359	47,9
A18	10399371	15,73	53,8	2178	699	32,1
A19	1395088	16,63	53,85	1772	492	27,8
2.str middle	15120179	19,35	38,41	44332	9275	20,9
2.str east	4279516	error	75,71	16418	3119	19,0
A28	4395364	14,64	56,18	3269	0	0,0
A29	12554082	17,69	47,36	1488	1092	73,4
A30	15048420	19,46	43,03	10669	2001	18,8
A31	1823027	19,31	45,92	2206	1339	60,7
A32	14177275	18,98	42,02	2520	1486	59,0
3.str middle	4042312	23,19	33,14	17031	16650	97,8
3.str east	8846809	22,24	36,56	3129	2560	81,8
A41	6451107	20,59	39,71	1856	1569	84,5
A42	16640649	20,5	41,09	1685	1459	86,6
A43	2999774	19,8	43,03	2446	1899	77,6
A44	2909578	21,47	38,76	1838	1622	88,2
A45	2674498	17,75	49,75	1887	1281	67,9
4.str middle	14208559	24,81	31,88	2532	2231	88,1
4.str east	16400815	22,78	35,64	1880	1624	86,4
A54	13679415	20,97	39,33	1817	1543	84,9
A55	10550732	21,67	38,21	2348	2046	87,1
A56	15526995	20,18	42,55	2025	1533	75,7
A57	6160775	23,33	40,92	2415	2188	90,6
A58	2731250	error	46,83	1790	1311	73,2
5.str middle	15074492	20,85	44,45	3287	2422	73,7
5.str east	2681266	error	35,56	1897	1567	82,6
A67	5503330	18,79	44,41	1826	1262	69,1
A68	2059408	18,87	42,72	1793	1398	78,0
A69	14894865	17,45	49,02	1664	940	56,5
A70	9352907	error	45,74	2099	1375	65,5
6.str middle	14685967	20,46	40,72	2720	2215	81,4
6.str east	11892184	19,53	41,9	2703	1997	73,9
Total average		**18,6**	**47,4**	**170944**	**76023**	**44,5**

5 Research Analysis

In this chapter, the results of the research are analyzed, and a NPV for a potential business model is calculated. Overall, the IoT system functioned adequately, and there was only little need for maintenance during the data gathering period.

5.1 Sensors and Networks

5.1.1 RuuviTag + Wirepas

The transmission success rate of RuuviTag sensors in combination with the Wirepas network was excellent both indoors and inside the concrete. In total, only 3 % (2 pc.) of sensors failed to establish a connection to the base transceiver station, which was better than expected. However, 27 % (6 pc.) of the sensors inside the concrete lost the connection during the gathering period. 100 % of these sensors were either installed into fresh concrete or cast inside a 3D mold, thus the moisture might have entered the casing and destroyed the circuit board.

The transfer frequency of some individual sensors varied significantly as can be seen from Table 8; the period between two values was several days at the worst, implying temporary connection issues or lack of optimization. The issue has been acknowledged and Wirepas is currently working on update for the network. Also, the sensors located in close proximity to the base transceiver station appear to transmit the data more frequently than others. For example, the sensor located in the stairwell on 2nd floor (no. 15120179) sent over 44000 messages. In comparison, the sensor in apartment A17 (no. 14152445) sent only 749 messages. It theory, some sensors may also interrupt the transmission of other sensors. Hence, in similar IoT applications the stability of data transfer of each sensor should be ensured, and the transfer frequency should be optimized.

In terms of accuracy inside the concrete, the performance of RuuviTag sensors is varying; Some sensors that were installed into fresh concrete and in a reservation made with a 3D printed mold and were cast showed excellent results as can be seen from Figures 65 and 66. However, the reliability was poor due to lost connection. The sensors that were plugged, in turn, showed relative humidity values that were significantly higher than the reference values, presumable due to condensation inside the casing, and poor moisture flow through the small hole. The temperature values, however, were accurate with all installation methods. As a conclusion, based on the case study, it is not recommended to use RuuviTag sensors inside the concrete at this point due to accuracy in relative humidity and reliability issues.

5.1.2 Wiiste + LoRaWAN

The original version of Wiiste's SolidRH SH1 sensor without the LoRaWAN capability has been tested previously in the master's thesis of Partanen (2015). The results were showing slightly too high relative humidity values, presumably due to the condensation inside the tube. The new version has been redesigned, i.a due to this issue. In this case study, same issues could be observed in case of regular SolidRH SH1 sensors that showed systematically significantly higher relative humidity values compared to LoRa-sensors that did not seem to have the condensation problem: the values of regular SH1 sensors were up to 10 % RH higher and on average 5 % RH higher than that of LoRa-sensors (Figure 69). However, in total, 2 of 5 LoRa-sensors lost connection (Figure 69). Also, it appears that some LoRa-sensors might not have adopted to the initial moisture content after casting, when the relative humidity should initially be near 100 % RH, based on the estimations done with BY 1021 software and on the slope of the drying curve being exceptionally flat (Figure 69).

Additionally, the LoraWAN network did not function without a separate base station (Figure 63). Moreover, the transmission range of the base station was not sufficient to gather the data from the top two floors of the building when being located in the construction site office, approximately 50 m from the sensors. Taking into account the geometry of the building and general attenuation of radio signal in reinforced concrete structures, the coverage of the whole building would potentially require multiple base stations. Range issues of LoRa-sensors should therefore be addressed prior to further construction site applications.

Table 9 Wiiste sensors on the 5th and 6th floor

Location	*Sensor type*	*Id*
A54	Regular SH1	13347
A54	LoRa	2299
A56	Regular SH1	13198
A56	LoRa	2307
A67	Regular SH1	13098
A67	LoRa	2283
A69	Regular SH1	13288
A69	LoRa	2277
A70	Regular SH1	13235
A70	LoRa	2296

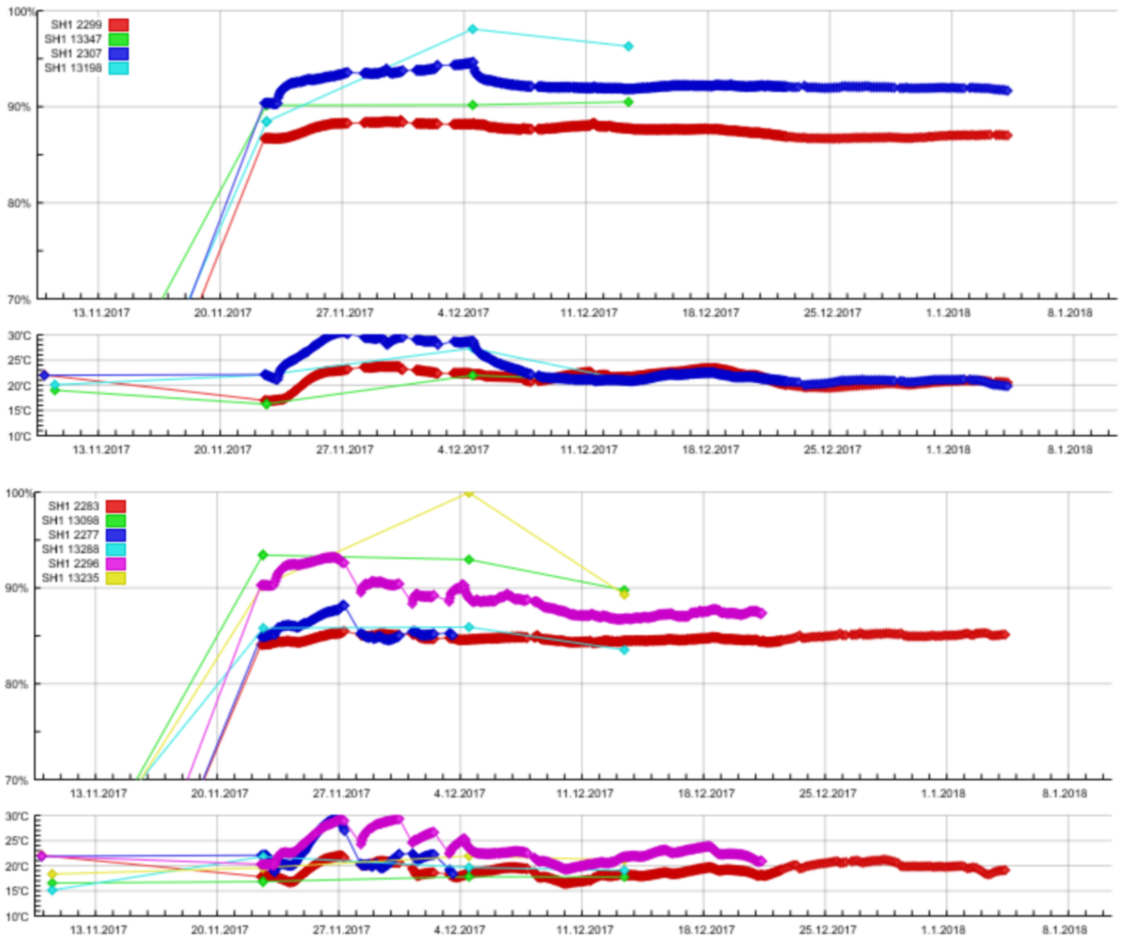


Figure 69 Wiiste sensors on the 6th floor – two LoRa sensors lost connection and the differences between the two versions in the same location are significant

5.1.3 Thingsee + Wirepas

Thingsee sensors were not used for data gathering due to the relatively inaccurate results in initial testing. However, the transmission range was adequate with ten sensors being spread around the building. All ten sensors successfully transmitted the data to base transceiver station.

5.2 Limitations and Errors

5.2.1 General

The use of heating cable in cast-in-situ bathroom floors might have produced uneven heating. Consequently, the drying rate of bathroom floors might have varied, and accuracy and reliability of sensors in general might have been compromised. Curing cable is often used in casting in winter conditions. Thus, potential issues related to humidity measurement must be acknowledged.

During casting and curing, the moisture might have entered the casing of RuuviTag sensors that were installed into fresh concrete, thus either ruining the electronics or causing false results.

5.2.2 Measurement

There were too few reference measurements conducted using the Vaisala system, which lowers the reliability of the individual values and the possibility to compare the development of drying results. Ultimately, that is the weakness of traditional measurement method.

According to the RT 14-10984 (2015) card, there are many factors affecting the accuracy of moisture measurement (Figure 70). In the case study, the issues related to a drill hole method are applicable to the installment of RuuviTag sensors inside the concrete. For example, potential dirtiness of a hole causes an error of -5 – +10 % RH. In some floors, the 3D printed mold was difficult to remove and some dust might have gotten under the sensor. Also, when sealing the sensors, the caulk might have partially clogged the hole in the casing, thus preventing adequate moisture transfer. (RT 14-10984 2015)

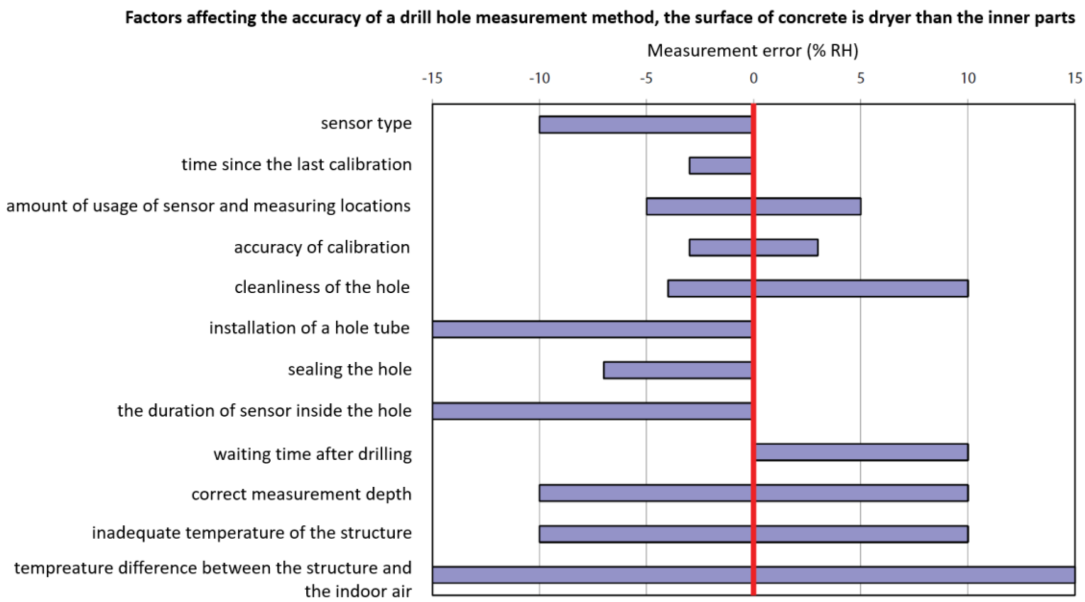


Figure 70 Factors affecting accuracy of a drill hole method (modified from RT 14-10984 2015)

The method of using of a PVC-tube cast in the fresh concrete to create a reservation for a sensor was introduced already in the 1970's with satisfactory results. The same principle is applied for the 3D printed mold used in the case study. However, it must be assured that the temperature of concrete at the measuring point is exactly the same as the sensor's. Hence, it is important that the thermal conductivity of concrete is the same as that of a plug used in some of the concrete floors. Otherwise, the relative humidity values are not necessarily comparable. The U-value of the 20-mm polyurethane plug is significantly bigger than that of a 60-mm concrete, thus it might have affected the results. (Nilsson 1980)

5.2.3 Concreting

During concreting, there were major issues with workability related to the unconventional concrete mixes. Potentially due to low ambient temperatures, some concrete mixes were too stiff, so that the mix would not come out of the batching vehicle, and additional water and plasticizers needed to be added during casting and placing process. Some, however, were too fluid, and additional layer of regular concrete needed to be cast in order to fulfill the inclination requirements. Due to that, the results are not fully comparable, and the drying process of different concrete mixes under different conditions is not analyzed.

5.3 Business Model Proposition

Setup and operation of an own IoT system, similar to that used in the case study project, requires following procedures: assembly of a base transceiver station, installment and removal of sensors on a construction site, and a project specific setup of Azure and Power Bi software. Tables 10, 11, and 12 show estimated costs per construction site. The cloud services are estimated to manage 500 construction projects simultaneously. The revenue for the service is calculated by assuming a very competitive fixed price of 5 € per sensor per month. The NPV for 500 projects, based on these estimations, is calculated in the next chapter.

Table 10 Estimated cloud service costs per month

Function	*€/mth*
Azure Hub (6 000 000 msg/day)	421,65
Azure Storage (10TB)	189,98
Azure Stream Analytics (6 SU)	444,45
Azure App Service (S3)	246,92
Total (€)	**1303**

Table 11 Estimated equipment costs per construction site

Equipment	*Price (€/pc.)*	*Pc.*	*Total (€)*
RuuviTag sensor	21	100	2100
Router (e.g. ZyXEL LTE3301)	129,9	1	129,9
Ruuvi Sink	20	1	20
Raspberry Pi 3	49,9	1	49,9
Raspberry case	14,9	1	14,9
Raspberry power supply	17,9	1	17,9
Raspberry heat sink	4,9	1	4,9
Raspberry Raspbian	19,9	1	19,9
Base station case	9,9	1	9,9
USB-cable	9,9	1	9,9
Cooling fan	6,9	1	6,9
Total (€)			**2384,1**

Table 12 Estimated labor costs per construction site

Task	*Duration (h)*	*€/h*	*Total (€)*
Installment and removal of sensors	16	35	560
Setting up the project (incl. Azure and Power Bi)	8	35	280
Total (€)			**840**

5.3.1 NPV

NPV is calculated to estimate the financial feasibility of an investment. In case of an IoT system, estimating cost-saving potential related to the improved moisture management is rather challenging, since it requires project-specific optimization of schedule, heating energy need and moisture control procedures depending greatly on the organization's size, project's properties, schedule objectives and weather conditions. Hence, the following calculations do not include the effect of reduced energy consumption, reduced need for traditional moisture measurements on site, and reduced drying time on construction costs, even though they are indeed significant. Also, the NPV does not include the possible need for technical support, and a terminal value is not calculated due to the uncertainty of IoT technology development.

Table 13 NPV calculations

Initial investment

Product	100000
Material costs	1192050
Total costs (€)	1292050

Inflation	1,5 %
Cap rate	6 %
Discount rate	7,50 %

NPV for 500 units / 10 years

Year	1	2	3	4	5	6	7	8	9	10
Year-end closing	31.12.2019	31.12.2020	31.12.2021	31.12.2022	31.12.2023	31.12.2024	31.12.2025	31.12.2026	31.12.2027	31.12.2028
Potential gross income	3 000 000 €	3 000 000 €	3 000 000 €	3 000 000 €	3 000 000 €	3 000 000 €	3 000 000 €	3 000 000 €	3 000 000 €	3 000 000 €
Utilization rate	80 %	85 %	90 %	95 %	95 %	95 %	95 %	95 %	95 %	95 %
Effective gross income	2 400 000 €	2 550 000 €	2 700 000 €	2 850 000 €	2 850 000 €	2 850 000 €	2 850 000 €	2 850 000 €	2 850 000 €	2 850 000 €
Cloud service costs	15 636 €	15 636 €	15 636 €	15 636 €	15 636 €	15 636 €	15 636 €	15 636 €	15 636 €	15 636 €
Setup and installations	420 000 €	420 000 €	420 000 €	420 000 €	420 000 €	420 000 €	420 000 €	420 000 €	420 000 €	420 000 €
Net cash flow	1 964 364 €	2 114 364 €	2 264 364 €	2 414 364 €	2 414 364 €	2 414 364 €	2 414 364 €	2 414 364 €	2 414 364 €	2 414 364 €
Net present value	1 827 315 €	1 829 628 €	1 822 724 €	1 807 877 €	1 681 746 €	1 564 415 €	1 455 270 €	1 353 739 €	1 259 292 €	1 171 435 €

Total NPV	14 481 391 €

The calculations in Table 13 show that even though the fixed costs are relatively high, running an IoT system independently can be profitable.

6 Conclusion

The research has clearly proved that there is an immediate need for real time monitoring of concrete drying conditions, and that the IoT system developed in this thesis was indeed helpful for optimizing the drying conditions by regulating the power output of the heating system, and thus for reducing heating costs. The case-study has also shown that a construction site environment is far from ideal in terms of installing and maintaining an IoT system, and in terms of data transmission reliability, especially inside the concrete. In the future, besides developing the functions and algorithms of the supplementary monitoring software for better assistance in keeping the drying conditions optimal, in order to achieve great results and ultimately get the most out the IoT system, a building needs to be better isolated from the environment. Thus, guidelines regarding overall moisture control need to be tightened: a weather cover should always be used (until the roof is water-tight) and all openings should to be closed as soon as possible.

6.1 Follow-up Research

In this chapter, potential subjects for follow-up researched are discussed, including sensor and network testing and applications.

6.1.1 Sensors and Networks

It has been proved that it is possible to achieve very accurate results with conventional and affordable environmental sensors, even when installing into fresh concrete. Hence, more elaborate testing of relative humidity measurement methods especially inside concrete structures should be carried out. Also, it is important to research whether it is possible to effectively prevent measurement errors currently occurring mainly due to inconsistency of measurement process, or at least minimize their effect on accuracy. Ultimately, the goal is to eliminate the need for traditional manual measurements on site.

Generally, more wireless sensors using different power source, data layer protocols, transmission frequencies and topologies should be tested to find the most cost efficient and reliable solution. Also, different networks should be tested and compared in order to improve reception rate and reliability. Following network solutions could potentially be suitable for construction applications and are worth testing: Sigfox, Z-Wave mesh network and Bluetooth LE mesh network.

6.1.2 Applications

In this chapter, several applications implementing wireless sensors are recommended for testing. In all the applications, RuuviTag sensor beacons using stock firmware, or other similar wireless sensors can be used.

6.1.2.1 Hollow-core Concrete Slab

Wireless sensors could be utilized in monitoring relative humidity in prefabricated hollow-core concrete slabs after levelling. The reservation for a sensor could be made in the concrete element factory during the production process to save time on site. The more sensors are installed inside the concrete slab, the better the coverage, and thus the more reliable internal moisture distribution they are presenting. Sensors could also be tested directly in the levelling layer, for example, in case of an intermediate floor structure with underfloor heating, where moisture conditions of the levelling material are decisive.

6.1.2.2 Plastering Conditions

Plastering has been used in construction for centuries and plastered façades are considered aesthetically pleasing and durable. Both plastering materials and techniques have improved significantly, especially in the past couple of decades. However, the plastering process still requires steady conditions for optimal and durable results. Hence, using wireless sensors for monitoring plastering conditions could be tested in case studies. (Suomen Betoniyhdistys 2005)

6.1.2.3 Life-cycle Management

Wireless sensors that could be integrated into the structures during the construction phase should also be implemented for the life-cycle management of a building. By placing the sensors measuring relative humidity in close proximity to the most critical structures in terms of potential moisture damage due to leakage or condensation, even the smallest changes in moisture distribution by diffusion inside the concrete could be detected, which would indicate a substantially elevated risk of moisture damage, such as mold growth, and initiate further investigations.

Such structures that are most prone to moisture damages and that are also difficult to maintain and service due to limited accessibility, are, for example, HVAC inlets of the roof, bathroom floors and façade structures in points of potential cold bridges such as in frame element joints and frame-to-balcony junctions.

Thus, using wireless sensors for life-cycle management purposes represents a lucrative market, especially for the owner of the big data produced in the process. However, it would require significant improvement of the internal power supply solutions of the wireless devices or alternatively the utilization of energy harvesting technology.

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