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Rimante Valancauskaite

Prototype for Indoor Air Quality Monitoring

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Supervisors: Alo Peets,

Rainer Paat

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Prototype for Indoor Air Quality Monitoring

Abstract:

The purpose of this thesis is to analyse data reliability collected by do-it-yourself indoor air quality monitoring solution and give a comparison overview with a commercial off-the-shelf product called "Smart Home Weather Station" by Netamo. As a result of this thesis a prototype was constructed that was able to collect and store real time readings of temperature, humidity, CO_2 and air pressure. The prototype used ESP32 microcontroller together with 2 additional sensors SCD30 and BMP280. All data was stored in a cloud-based database using MQTT bridge for connection. Measured readings resembled reference data gathered by Netamo and despite minor offsets in the data the prototype was concluded reliable.

Keywords: air quality, Netamo, ESP32, SCD30, BMP280

CERCS: P170 Computer science, numerical analysis, systems, control; T120 Systems engineering, computer technology;

Siseruumide õhukvaliteedi mõõtja prototüüp

Lühikokkuvõte:

Antud töö eesmärgiks on analüüsida isetehtud siseruumide õhukvaliteedi mõõtjalt saadud andmete usaldusväärsust ning võrrelda neid kaubandusliku lõpptootega Netamo "Smart Home Weather Station". Töö käigus valmis siseruumi õhukvaliteedi mõõtja prototüüp, mis oli võimeline lugema temperatuuri, niiskuse, CO_2 ja õhurõhu tulemusi reaalajas. Prototüüp koosnes ESP32 mikrokontrollerist ja kahest lisa sensorist SCD30 ja BMP280. Kogutud andmed hoiustati pilve põhises andmebaasis, kasutades MQTT tehnoloogiat ühendusena. Prototüübi poolt kogutud andmed olid sarnased Netamo omadega ning väikestest nihetest hoolimata võis neid lugeda usaldusväärseteks.

Võtmesõnad: õhukvaliteet, Netamo, ESP32, SCD30, BMP280

CERCS: P170 Arvutiteadus, arvutusmeetodid, süsteemid, juhtimine; T120 Süsteemitehnoloogia, arvutitehnoloogia;

Contents

1 Introduction

Fast paced growth in metropolitan cities has contributed to a rise in air pollution. Densely packed apartments located next to busy roads preclude air flow and opening windows to get some fresh air brings in pollution instead. Since this issue does not get enough attention many disregard air filtering and effective ventilation when looking for housing [1]. Contrarily to popular opinion research conducted by Chen and Zhao [2] showed that the air indoors had up to 2/3 higher ratio of particle pollution than outdoors.

Even though carbon dioxide (CO_2) is not an air pollutant, it has an important role in monitoring indoor air quality (IAQ). Due to direct relation to occupants indoors with each exhaled breath containing some amount of CO_2 it can be used to get an overview of buildings ventilation and air flow [3]. Unfortunately, not many IAQ monitors measure CO_2 and those few commercial off-the-shelf (COTS) products that do cost between 100 and 280 euros [4].

Internet of Things (IoT) is an ecosystem between machines, where connections are made using internet. It allows users to use, control and automate one machine with another. IoT is currently playing an important role in real-time data collection solutions and therefore improving our quality of life [5].

Because of the fast-paced development of IoT it is now feasible to build self-made monitoring solution. There is multiple research that show how to create self-made low-cost monitoring solutions. Most solutions use ESP32 microcontroller with additional sensors [6,7]. Because the ESP32 microcontroller is cheap, popular and relevant it will be used in this thesis as well.

The purpose of this thesis is to analyse data reliability collected by do-it-yourself (DIY) IAQ monitoring prototype and give a comparison overview with a COTS product called “Smart Home Weather Station” by Netamo. The prototypes hardware will consist of ESP32 microcontroller and two additional sensors. Collected data will be stored on Google Cloud Platform. During this research an IAQ monitoring prototype will be developed and a comparison between the solution and Netamo will be carried out.

In addition to “Background information” and “Conclusion” this thesis will provide: an overview of existing solutions, explanation of the parameters that the solution has to meet, description of the hardware solution and implementation steps, comparison of the prototype against Netamo and suggestions for further development.

2 Background Information

In this section, importance of indoor air quality will be described first (Section 2.1). Secondly, a summary is given of related research (Section 2.2). Thirdly, an overview of software and hardware components used in this thesis is provided (Section 2.3 and 2.4).

2.1 The Importance of IAQ

United States Environmental Protection Agency (EPA) considers poor IAQ to be the top environmental health risk [8]. Many believe that air pollutants such as NOx, SO_3 and O_3 only exist outdoors and are no harm indoors. Turns out, that’s not true and actually even short-term exposure can bring out symptoms. These symptoms vary, but common are nose irritation, itchy throat and allergies, all these effects are called sick building syndrome (SBS) [1]. EPA lists these as causes that can contribute to SBS: inadequate ventilation, chemical contaminants from indoor sources, chemical contaminants from outdoor sources and biological contaminants. To minimize SBS there are a few simple measures that can be taken like removing pollutant source and increasing ventilation, for example changing your filters and opening windows after using chemicals [9].

Indoor air quality also affects our logical thinking and not only health. In 2015 Strøm-Tejsen, Zukowska, Wargocki and Wyon [10] experimented how bedroom air quality affects sleep and next-day performance. The results were that just by opening a window or using an air supply fan subjects felt better the next day, weren’t as sleepy and their logical thinking improved.

2.1.1 Temperature

Temperature has an important role in performance and health. In 2011 Valancius and Jurelionis from Kaunas University of Technology [11] showed how fluctuation in air temperature can influence work performance by asking subjects to perform text typing, arithmetic calculations and Tsai-Partington tests and the results showed that subjects were indeed affected by temperature changes, for example when temperature dropped from 22°C to 18°C productivity improved by 5.2% [11]. Even though recommended temperatures vary in season and are occupant specific being between 20°C - 26°C, a relationship between room temperature being over 22°C and SBS symptoms has been found in multiple studies. Temperature fluctuation can also affect air pollution and increase occupant sensitivity [12].

2.1.2 Humidity

Humidity also known as relative humidity (Rh) shows the level of water vapor in the air. Rh's negative impact to body, health and living environment are well known. Too dry air can cause irritation in eyes and nose, too moist air can affect body's ability to regulate temperature and is known to boost mites, fungi and even viruses. Low humidity amplifies influenza viruses and high humidity poliomyelitis viruses [12]. Optimal Rh according to United States Consumer Product Safety Commission is 30-50% [13].

2.1.3 Carbon dioxide (CO_2)

CO_2 is not a pollution particle; humans breathe out with each exhale between 35 000 – 50 000 parts per million (ppm) of CO_2 [3]. CO_2 is an indicator used to measure ventilation reliability and IAQ. Because CO_2 level rises in correlation with occupants per room, it is directly related to human activity and high level means also high levels in unhealthy components [12]. Most commonly known symptoms that appear when CO_2 level is high are drowsiness, nausea and headaches [14].

According to Satish et al. [15] even CO2 levels at 1000 ppm can significantly reduce decision-making performance. To test this, six groups were exposed to 600, 1000 and 2500 ppm in three 2.5-hour sessions. Ventilation and temperature rates were held constant and only CO_2 was increased. Subjects were asked to complete computer-based test on decision-making performance and fill questionnaires on health symptoms and air quality. The results showed that relative to 600 ppm, even at 1000 ppm significant decrease occurred in six of nine scales of decision-making performance and compared to 2500 ppm it was decreased in seven of nine scales with some levels decreasing down to dysfunctional performance margins [15]. While confirmation of those findings is still needed, the effect CO_2 has on occupant's cognitive health cannot be denied.

Usual CO_2 level outdoors is 350-450 ppm, optimal CO_2 level indoors should be not more than 600 ppm above outdoor level [12]. According to European standards indoor air quality is high when CO_2 levels are up to 400 ppm, medium standard between 400-600 ppm, moderate when between 600-1000 ppm and low when 1000+ ppm above outdoor level [16].

2.2 Related Research

There have been many related researches done on IAQ impacting subjects, but few are concentrating on the self-made hardware and software solutions that are used to measure given changes. From Manisa Celal Bayar University Tastan and Gökozan [6] created a portable air measuring device called E-Nose. Similarly, to this research they used ESP32 module with built-in Wi-Fi and 4 additional sensors to create real-time monitoring. Tastan and Gökozan concentrated on relations between 4 gases (CO, CO_2, NO_2, PM_{10}), time, temperature and humidity and found out that not only is the number of people living in the household related to IAQ, activities like cooking and sleeping also have significant effect on gas concentrations. Trying to construct a low-cost, DIY solution they used sensors which's price-points varied between 5-25$. Because they used pre-programed application like Blynk to display information for users, their total costs came up even 100$ [6].

In National Institute of Technology Warangal Sarjerao and Prakasarao [7] also created "A Low-cost smart pollution measurement system using REST API and ESP32". Tastan and Gökozan also did some measuring using their DIY solution, while Sarjerao and Prakasarao focused only on sensors and creation of the device. They used ESP32 and also 4 additional sensors. Their device detected 9 different air components. CO, LPG, CH_4, temperature, humidity, NH_3, sulphide, Benzene and dust. To display all these components, they use Thinger.io that is connected to the ESP32 using device to device communication protocol REST. "REST protocol (Representational State Transfer) is used for development of web services. In the REST protocol broker component is not used (like MQTT protocol) and an end to end device communications happens directly" [7:3]. Because of their end goal to mount made devices to public transportation, it made sense to read 9 different air components and use REST API with device location option [7]. Different from this research where there is no need to detect gas that is emitted from transportation and is enough to just read the main components that are found indoors.

2.3 Internet of Things

IoT is communication network between machines, where connections are made using the internet. It has brought out a technological revolution and a new way of life. IoT's advancements have created the smart home reality that is currently existing [5]. To create these connections an MQTT network protocol will be used in this thesis.

2.3.1 MQTT Network Protocol

Message Queuing Telemetry Transport (MQTT) supports Machine to Machine (M2M) communication, that is based on publish-subscribe communication model. MQTT can be characterized as open and simple lightweight protocol [5].

Publish/subscribe communication means there is a publisher who provides the information and a subscriber who gets the information. The advantage of MQTT compared to traditional point-to-point patterns is that neither publisher nor subscriber have to know anything about the other.

This is accomplished using three essential concepts: topic, broker and a client. To catalogue the message sent from the publisher a *topic* is used. Topic defines the category of the message and contrary to point-to-point protocols, a subscriber will subscribe to a particular topic to receive the message. *Broker* is the intermediate for messages. The *broker* receives all the messages from the *client* and routes it forward to destination *client*. A *client* is subscribed to a certain *topic* and can publish or receive information forwarded by the *broker* [17].

2.4 Hardware Components

Base components for creating an IAQ monitoring device are any module that has pins where you can connect sensors and built-in either Bluetooth or Wi-Fi functionality. For example, Arduino Uno, ESP32, ESP8266 or Arduino Nano. Many choose ESP32 because of its low price point and small size despite being packed with powerful features. Second components would be the additional sensors. For temperature and humidity there is wide variety of modules, but most common are DHT22, BMP280 and AHT10 since their price point varies from 2.00-7.00 euros. The reason why most IAQ detectors have high prices is because they have to use nondispersive infrared (NDIR) CO_2 sensors [18]. Most common are SCD30 and MH-Z14A, their price-point varies from 22.00 – 65.00 euros. For any other additional gas detection there is a variety of additional modules to choose from. In order to get the information from the base module to users' phone or cloud-service there has to be a power supply and implementation of desired device to device protocol like REST. For easy real-time data visualization user can either program their own application or use pre-programmed apps like Blynk as done by Tastan and Gökozan [6].

2.4.1 ESP32 Microcontroller

ESP32 is a system on chip microcontroller developed by Espressif Systems. It can be integrated with Wi-Fi and dual mode Bluetooth through SPI/SDIO or I2C/UART interfaces. The microcontroller has low power consumption and can operate in temperature ranging –40°C to +125°C [19]. Because the microcontroller packs all the features that are needed for the prototype it will be used in this thesis as well. While the Espressif Systems original ESP32 board costs 13.5 euros, the one used in this thesis is a cheaper board by DOIT that costs 6 euros [20].

ESP32 has the ability to connect to Wi-Fi over user datagram protocol (UDP) and transmission control protocol (TCP). Connection to Wi-Fi will be done over TCP for data transmission and to get accurate timestamp on readings a network time protocol (NTP) will be used with UDP. Two different protocols are used because for NTP UDP is a bit more reliable regarding network speed but being easily hackable is not recommended for data transmission [21].

2.4.2 SCD30 Sensor

SCD30 by Sensirion is a NDIR CO_2 sensor. Along with CO_2 detection there are also humidity and temperature sensors inside. SCD30 uses dual channel principle to maintain stability in readings. It can be integrated with HVAC equipment, air conditioners, IoT devices, smart homes and air purifiers. SCD30 also uses UART and I_2C interface for communications.

Table 1: SCD30 specifications [22].

CO_2 range	0 – 10 000 ppm
CO_2 accuracy	±30 ppm ±3% (25 °C, 400 – 10 000 ppm)
CO_2 repeatability	10 ppm
CO_2 temperature stability	2.5 ppm / °C (0 – 50 °C)
CO_2 response time (t_{63})	20 s
Temperature range	– 40 °C – 120 °C
Temperature typ accuracy (°C)	±0.5 °C (0 – 50 °C)
Temperature repeatability (°C)	0.1 °C
Temperature response time (t_{63})	>2 s
Humidity range	0 – 100% Rh
Humidity typ accuracy	±2% Rh (0 – 100% Rh)
Humidity repeatability	0.1% Rh
Humidity response time (t_{63})	8 s

The Sensor comes fully calibrated and linearized. Metrics are shown in table 1. The sensor is 35 mm x 23 mm x 7 mm in size and sold at a price of 60 euros [22]. The specifications are comparable with higher-end IAQ monitoring solutions [13-26].

2.4.3 GY-BMP280 Sensor

BMP280 sensor by Bosch is an environment sensor that tracks humidity, temperature and pressure. The sensor offers both I_2C (up to 3.4MHz) and SPI (up to 10 MHz) communication interfaces. Sensors specifications are shown in table 2 and it's starting price is 2 euros [27].

Table 2: BMP280 specifications [28].

Temperature range	-40°C - 85°C
Temperature accuracy	±1°C
Pressure range	300-1100 hPa
Pressure accuracy	±1
Humidity range	0-100% Rh
Humidity accuracy	±3% Rh

BMP280 sensors low price point and considerable accuracy cumulates into a sensor that can fulfil most users need for IAQ monitoring, but for more reliable readings higher-end sensors should be consider like SCD30.

As described in this chapter IAQ can have a significant effect on health and performance. Fortunately, fast-paced growth in the technology sector has created an opportunity to monitor IAQ conditions with self-made solutions that can be considered reliable as similar research to this thesis have brought out. Next chapter will go over existing commercial solutions that can be used for comparison with self-made prototypes.

3 Existing Solutions

There are a lot of IAQ monitoring solutions with a very wide price and measurement range. Most solutions are concentrated on industrial use. COTS products that have established reliability have become an investment therefore making customers doubt the need for them. Fortunately, residents with a minimal technical knowledge can build their own IAQ monitoring solutions from parts ordered online. By doing that, users can create a fully personalised product that can be integrated with other custom solutions.

Building custom IAQ monitoring solutions can cost significantly less than a COTS product, but two issues arise when doing so. First and foremost, there is no way to test reliability of ordered parts without having another monitoring solution for comparison. Second issue is that lower costs translate into higher effort. The combination can make building self-made monitoring solution not worth the risk, creating a need for research and testing.

This thesis will be concentrating on IAQ monitoring solution that measures temperature, humidity, air pressure and CO_2. The importance of the ability to measure CO_2 has been explained under section 2.1.3 Carbon Dioxide. To get a better overview of current market options, a selection of COTS products will be brought out in this section. The following devices are selected based on Techhives review of best indoor air-quality monitors with a condition of having over 4 out of 5 rating and ability to measure CO_2 [4].

3.1 Awair Element

Awair Element is an IAQ monitoring solution done by Awair. It is suggested to be a budget friendlier version of their product Awair 2nd Edition. Awair Element costs approximately 138 euros and is 15.5 x 4.6 x 8.4 cm in size. The device is powered by a power outlet. The product has a minimal design with a LED display which shines through a grid. The display shows bar graphs of 5 air elements and an overall air quality score with a coloured led indicating if the score is poor, fair or good. Main critique of the product is that the white bar graphs against a white grid are hard to see therefore, to get a better overview of the readings Awair Element has a mobile application. The application alerts users when readings go over recommended amount. The recommended amount is calculated based on users' "interests" and it is not known which standards are used. Additionally, to showing readings for 5 air elements, the application shows current weather overview. The Element can also be integrated with smart home systems like Google Home and Amazon Alexa [29].

The 5 air elements that Awair Element tracks are temperature, humidity, CO_2, volatile organic chemicals (TVOCs) and PM2.5 (dust). Accuracy and range are provided in table 3 [29].

Table 3: Awair Element measurement ranges and accuracies [26].

Temperature range	-40 - 125 °C
Temperature accuracy	±0.2°C
Humidity range	0-100%Rh
Humidity accuracy	±2% Rh
CO_2 range	400-5000ppm
CO_2 accuracy	±75ppm
TVOCs range	0-60000
TVOCs accuracy	±10%
PM2.5 range	0-1,000 µg/m³
PM2.5 accuracy	±15 µg/m³

Awair Element is one of the cheapest devices that tracks relevant air elements with accuracy that can be compared to higher-end devices. Only issue being a poorly designed bar graph on the device it can justify its price.

3.2 Kaiterra Laser Egg+ CO_2

Kaiterra Laser Egg+ CO_2 is a CO_2 focused IAQ monitoring solution based on Kiaterra Laser Egg+. The Laser Egg+ CO_2 costs approximately 184 euros and is a 10.6 x 8.8 cm in size, overall design is bell shaped and it is powered by a battery and is charged using a USB - Cable. The device has a 2.6" full colour LCD that displays the readings. To have a better overview of readings the device has a companion app [30]. The application shows bar charts of 4 air elements that are colour codes according to their health level based on U.S. Environmental Protection Agency standards [31].

Kaiterra Laser Egg+ CO_2 tracks PM2.5 (dust), CO_2, temperature and humidity. Accuracy and range are shown in table 4.

Table 4: Kaiterra Laser Egg+ CO_2 measurement ranges and accuracies [24].

PM2.5 range	1-999 µg/m³
PM2.5 accuracy	±3 µg/m³
CO_2 range	400 - 5000 ppm
CO_2 accuracy	±30 ppm
Temperature range	-20 ℃ - 100 ℃
Temperature accuracy	±1 ℃
Humidity range	0 - 99%Rh
Humidity accuracy	±1 %Rh

Compared to Awair Element, Kaiterra Laser Egg+ has better CO_2 accuracy, but does not track TVOCs. Also, temperature accuracy being equal to BMP280 sensor, the price cannot be reasoned based on these specifications.

3.3 Airthings Wave Plus

Airthings Wave Plus is a higher end IAQ monitoring solution based on Airthings Wave. The circular shaped device is priced at 269 euros and has a 11.9 cm diameter. The product doesn't have a display instead a light ring that lights up with a wave and changes colour according to IAQ status. Wave Plus is 2xAA battery powered and has a companion app that gets the readings via Bluetooth. Because the device reads 6 different air elements and radon is among them, it takes approximately a week to calibrate. The app takes readings in 5-minute intervals, displays a line graph with each element and colour codes them accordingly to recommended amounts. Similarly, to Awair Element they display which readings categories under what colour, but no information regarding which standards they are based on [32].

Airthings Wave Plus tracks Radon, CO_2, TVOCs, temperature, humidity and air pressure. Accuracy and range are shown in table 5. According to Wave plus the optimal measurements are shown in table 6.

Table 5: Airthings Wave Plus measurement ranges and accuracies [25].

Radon range	0 – 20000Bq/m3
Radon accuracy	±200Bq/m3
CO_2 range	400 – 5000ppm
CO_2 accuracy	±30ppm
Temperature accuracy	±0.1°C
Humidity accuracy	±1%Rh

Table 6: Optimal IAQ levels according to Airthings Wave Plus [25].

Radon	<100Bq/m3
TVOCs	<250ppb
CO_2	<800ppm
Humidity	≥30 and <60 %
Temperature	≥18 and ≤25 °C

Airthings Wave Plus is the most expensive device out of the listed solutions, the price comes from ability to measure Radon. Considering that commercial Radon measurement devices are priced up to 1799 euros, Airthings Wave Plus can actually be considered cheap. While Airthings was most transparent regarding their optimal readings, they were the only device not to have a datasheet.

3.4 Netamo Smart Home Weather Station

Netamo Smart Home Weather Station is a base IAQ monitoring system that can be integrated with a ran gauge and a wind gauge. It comes with two modules, indoor and outdoor, to compare IAQ against outdoor readings and get as accurate results as possible. The base station excluding rain and wind gauge is priced at 169 euros [33]. The indoor module is 4.5 x 4.5 x 15.5 cm sized cylinder and the outdoor module is a bit smaller in height at 10.5 cm. The indoor device has a light stripe instead of a display that shows colour according to CO_2 levels when tapped on top. The product has a web and mobile app for data display. The mobile application shows an overview of current locations weather and recent readings with colour indications. There is also an option to see line graphs of the 5 readings. In addition to IAQ monitoring the device also measures sound [23]. Netatmo uses colours for recommended IAQ levels from region regulations, e.g. from The European Citeair for Europe [34].

Netamo Smart Home Weather Station tracks temperature, humidity, pressure, CO_2 and Sound. Accuracy and range are shown in table 7.

Table 7: Smart Home Weather Station indoor module sensors accuracy and range [23].

Temperature range	0 to 50°C
Temperature accuracy	± 0.3°C
Humidity range	0 to 100% Rh
Humidity accuracy	± 3% Rh
Pressure range	260 to 1260 mbar
Pressure accuracy	± 1 mbar
CO_2 meter range	0 to 5000 ppm
CO_2 meter accuracy	± 50 ppm
Sound meter range	35 to 120 dB
Sound meter accuracy	± 0 dB

Netamos Smart Home Weather Stations price and accuracy are comparable with higher priced devices, but as name indicates the device is meant more for weather enthusiast rather than in depth IAQ measurement. Netamo is one of the very few devices that measures sound making it a suitable device to use for sleep environment analysis.

All commercial products have a unique feature over others and integration options with known smart home systems. While a non-technical user can find a suitable solution from those listed above, a customer with basic tech knowledge that would like to have fully personalised product for a lower price should consider self-made solution.

4 Prototype overview

The solution consists of two parts; hardware IAQ monitoring solution and cloud-based database. The hardware solution can be set anywhere using a power supply – that being either a portable power bank or an electric socket to collect data. Cloud-based database from Google Cloud Platform called BigQuery is used to store and access collected information. This chapter defines the parameters the solution has to meet, describes different parts of the program and implementation steps. The hardware serves as a proof-of-concept and is not designed to be consumer-friendly. Link to the full source code can be found in appendix I.

4.1 Parameters

Based on the purpose of this thesis to compare and test reliability against Netamo Smart Weather Station indoors the following criteria's have to be met:

- Microcontroller used for the IAQ monitoring solution has to be able to connect to Wi-Fi, ability to store temporary data and connect 2 additional sensors.
- Sensors have to measure temperature, humidity, CO_2 and pressure.
- Temperature sensors accuracy has to be equal or better than ± 0.3°C. Range has to be at least between 0°C - 40°C.
- Humidity sensors accuracy has to be equal or better than ± 3%. Range has to be 0-100% Rh.
- CO_2 sensors accuracy has to be equal to or better than ± 50 ppm. Range has to be at least 0 – 3000 ppm.
- Pressure sensor accuracy has to be equal to or better than ± 1 mbar or hPa. Range has to be at least 400 – 1200 mbar or hPa.
- IAQ monitoring solution has to record data every 5 minutes, store data in a cloud-based database for real-time access and device cost cannot exceed 100 euros.
- The solution has to run unendingly when connected to a power supply.

4.2 Hardware

IAQ monitoring solutions hardware consist of one ESP32 microcontroller connected with SCD30 and BMP280 sensors. While SCD30 can measure temperature, humidity and CO_2, BMP280 is needed to measure pressure. Detailed description of the sensors and microcontroller can be found under sections 2.3.1-2.3.3. The price of the solution totals at 68 euros. Figure 1 shows prototypes design and wiring schematics.

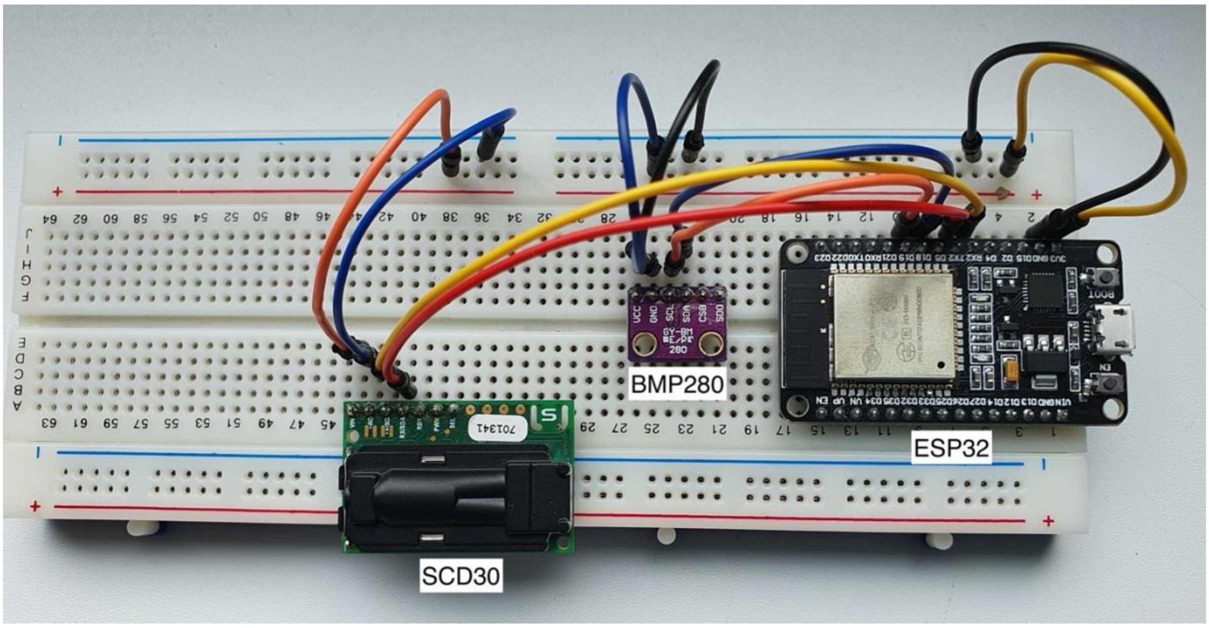

Figure 1: IAQ monitoring solution prototype.

4.3 Software

ESP32 has predefined pins for I2C serial clock signal (SCL) as GPIO22 and serial data (SDA) as GPIO21 [35]. In order to get the data from multiple sensors that have the same address using I2C bus interface, default SCL and SDA pins need to be changed using *TwoWire* objects from *Wire* library. To get data from SCD30 using *TwoWire* object it has to be set as a parameter in begin function [36]. For BMP280, a memory address to *TwoWire* object can be given to the constructor [37]. A code sample of redefined and initialized pins to the sensors objects is shown in figure 2.

```
#include <Wire.h>
#include <Adafruit_BMP280.h>
#include "SparkFun_SCD30_Arduino_Library.h"
//SCD30
//GPIO17 pin variable is defined
#define SDA_1 17
//GPIO16 pin variable is defined
#define SCL_1 16
//BMP280
//GPIO18 pin variable is defined
#define SDA_2 18
//GPIO19 pin variable is defined
#define SCL_2 19
//TwoWire instance is created with aadress defined as 0
TwoWire I2Cone = TwoWire(0);
//TwoWire instance is created with aadress defined as 1
TwoWire I2Ctwo = TwoWire(1);
//BMP280 object is created with memory aadress to I2Ctwo
Adafruit_BMP280 bmp(&I2Ctwo);
```

```
//SCD30 object is initialized
SCD30 airSensor;
void setup() {
//Twowire objects have begun to read from initialized pins
    I2Cone.begin(SDA_1, SCL_1);
    I2Ctwo.begin(SDA_2, SCL_2);
//SCD30 begin function is initalized with I2Cone object, the sensor is activated
    airSensor.begin(I2Cone);
//BMP280 is activated and I2C aadress is set to 0x76
    bmp.begin(0x76);
}
```

Figure 2: Code sample on initializing redefined SDA and SCL pins.

To read data from sensors the following libraries are used: for SCD30 *SparkFun SCD30 Arduino Library* [36] and for BMP280 *Adafruit BMP280 Library* [37]. SCD30 will provide readings for temperature, humidity and CO_2. BMP280 will provide pressure and additional temperature reading. In order to make collected data comparable with a COTS product a timestamp is needed, for that a network time protocol (NTP) will be used with a user datagram protocol (UDP) to get current time. All data will be temporarily stored on a JSON file that will be minimized and sent to Google Cloud Platform using a MQTT bridge. A code sample of the process is shown in figure 3.

```
#include <NTPClient.h>
#include <WiFiUdp.h>
#include <Adafruit_BMP280.h>
#include <ArduinoJson.h>
#include "SparkFun_SCD30_Arduino_Library.h"

WiFiUDP ntpUDP;
//NTPClient object is created and initalized with UDP object
NTPClient timeClient(ntpUDP);

void setup() {
//SCD30 begin function is initalized with I2Ctwo object and the sensor is
activated
  airSensor.begin(I2Cone);
//BMP280 is activated and I2C address is set to 0x76
  bmp.begin(0x76);
//Clock synchronization is activated
  timeClient.begin();
//Timezone is set to GMT+3
  timeClient.setTimeOffset(10800);
}
//String to temporarily store initial timestamp
String formattedDate;
//String to temporarily store date
String dayStamp;
//Long to temporarily store time passed
unsigned long lastMillis = 0;
void loop() {
//Empty buffer is created where minified JSON data will be stored
  char buffer[512];
//Empty JSON file is initalized
  StaticJsonDocument<422> doc;
//Check if 5 minutes have passed
    if (millis() - lastMillis > 300000) {
//Restart counting time
      lastMillis = millis();
```

```
//Make sure that time is up-to-date
      while(!timeClient.update()) {
//If not then update time
        timeClient.forceUpdate();
      }
//Get current time as a timestamp
      formattedDate = timeClient.getFormattedDate();
//Seperate date from time
      int splitT = formattedDate.indexOf("T");
      dayStamp = formattedDate.substring(0, splitT);
//Insert data to JSON file
      doc["device_id"] = "esp32";
      doc["date"] = dayStamp;
      doc["time"] = timeClient.getFormattedTime();
//Check if SCD30 has any data available
      if (airSensor.dataAvailable())
      {
//If true then insert it to JSON file
        doc["temperature_1"] = airSensor.getTemperature();
        doc["co2"] = airSensor.getCO2();
        doc["humidity"] = airSensor.getHumidity();
//If false then insert zeros
      }else {
        doc["temperature_1"] = 0;
        doc["co2"] = 0;
        doc["humidity"] = 0;
      }
//Insert data from BMP280 to JSON file
      doc["temperature_2"] = bmp.readTemperature();
      doc["pressure"] = (bmp.readPressure() / 100.0F);
//Create minified JSON file to send to Google Cloud Platform
      serializeJson(doc, buffer);
  }
}
```

Figure 3: Code sample of data collection on to a JSON file

4.3.1 Database configuration

In this thesis the data management pipeline is structured as shown in figure 4.

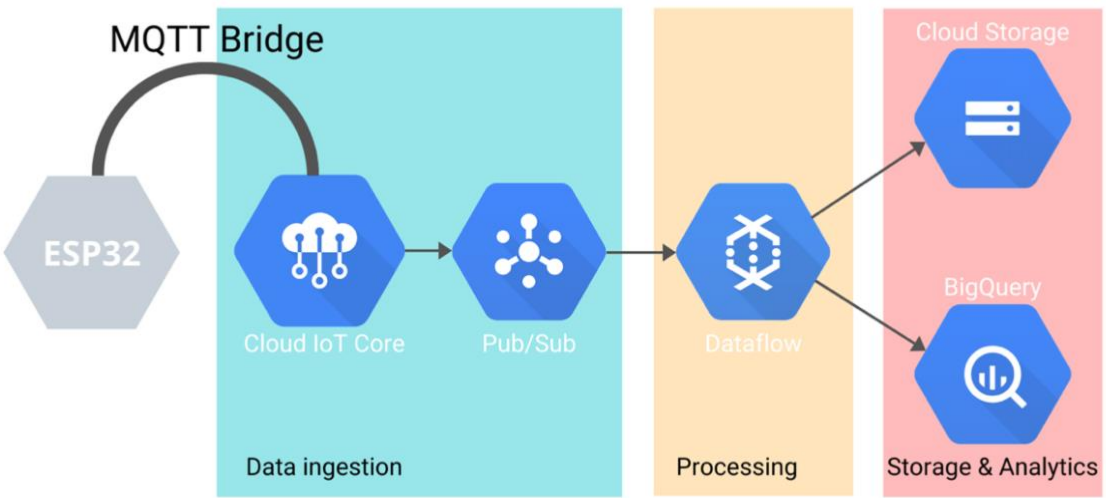

Figure 4: Data management pipeline

The configuration had to be done on either side of the MQTT bridge. On Google Cloud Platform it was done based on Google Cloud Documentation Quickstart guide and on the device a Google Cloud IoT JWT library was used for MQTT bridge creation [38,39]. For secure gateway a JSON Web Token was used. To process all incoming JSON payloads a Dataflow was set up based on dataflow template “Cloud Pub/Sub Subscription to BigQuery” that would insert information to specified rows in BigQuery dataset [40]. For comparison with Netamo Weather Station a standard SQL query was used to export data from BigQuery. Microsoft Excel was used for data analytics and visualization.

5 Reliability Comparison and Results

In order to test the reliability of the solution created during this thesis, a 48-hour long run time was conducted in parallel with Netamo "Smart Home Weather Station". During the 48-hour inquiry, first 24 hours were meant for calibration, second 24 hours were used for data gathering and comparison analysis. Both devices collected temperature, humidity, CO_2 and pressure readings in 5-minute intervals. Analysed data was collected from 13/04/20 09:50:00 till 14/04/20 09:50:00. Readings took place in a 2.4x4.6m bedroom with a single window, single door and a ventilation system. The devices were placed against the furthest wall from the window and ventilation. For data analysis 275 readings are used and Netamo readings are used as a baseline.

5.1 Temperature Results

Netamo temperature readings averaged 22.65°C with median readings at 22.7°C. Netamo also stabilizes their sensor readings for temperature. Because both of the DIY solution sensors measure temperature, both readings we're taken into comparison. SCD30 temperature readings averaged at 24.75°C with median readings at 24.78°C resulting in a +2.1°C average offset. BMP280 temperature readings averaged at 23.65°C with median readings at 23.66°C resulting in a +1°C average offset. All readings collected over 24-hour period from 13/04/20 09:50:00 till 14/04/20 09:50:00 are displayed in figure 5.

As seen in figure 5 both DIY solution sensor readings have a positive offset compared to the baseline readings. Possible reasoning for SCD30 +2.1°C offset can be that the NDIR approach used to read CO_2 can cause temperature rise in the sensor itself and therefore affecting temperature readings and although the sensor comes fully calibrated there might be a need for longer run time for calibration with the environment. BMP280 readings had an offset of +1°C which is in line with the accuracy of the sensor.

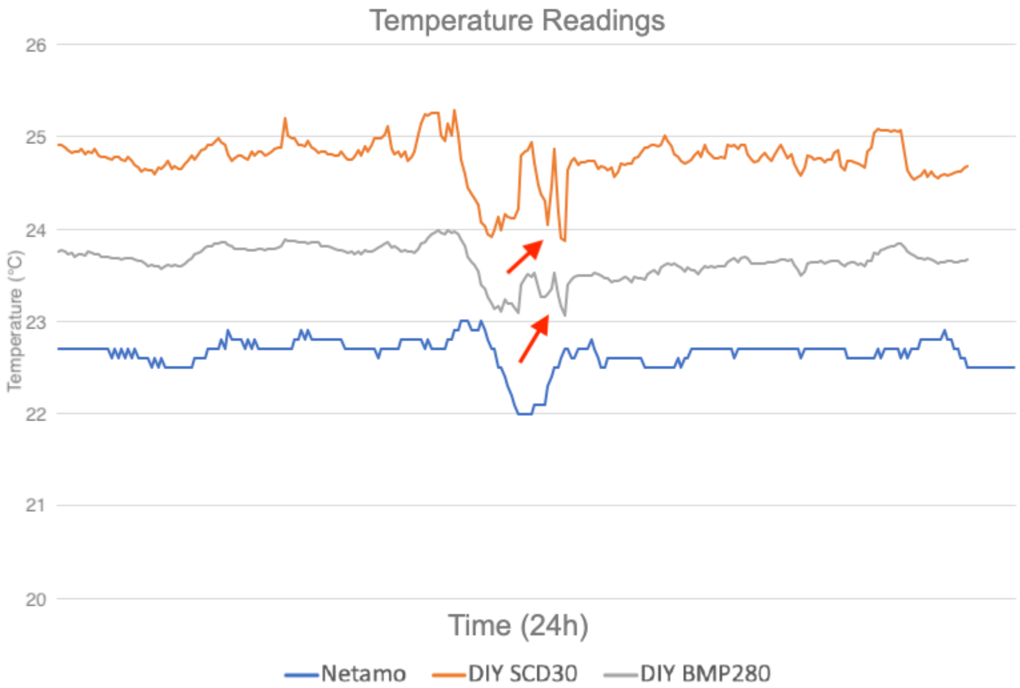

Figure 5: Temperature results from Netamo and both DIY solution sensors over 24-hour period

All sensors detected changes in temperature by opening windows or closing doors. Compared to baseline readings both sensors used in DIY solution also had an anomaly as pointed out in figure 5 with red arrows. Because the anomaly is a significant temperature drop not a rise and appears in both DIY solutions used sensors, potential reasoning can't be provided.

In conclusion since both temperature sensors had a very stable offset and comparable readings to the baseline, the temperature readings can be held reliable with a need of slight adjustments to take into consideration temperature rise in the device itself.

5.2 Humidity Results

Netamo humidity readings averaged at 31.43% with a median reading of 30%. Netamo also stabilizes their readings for humidity. For the DIY solution humidity was measured using SCD30 sensors, where readings averaged at 27.41% with a median reading of 26.23% resulting in average offset of -4.02%. All readings collected over 24-hour period are displayed in figure 6.

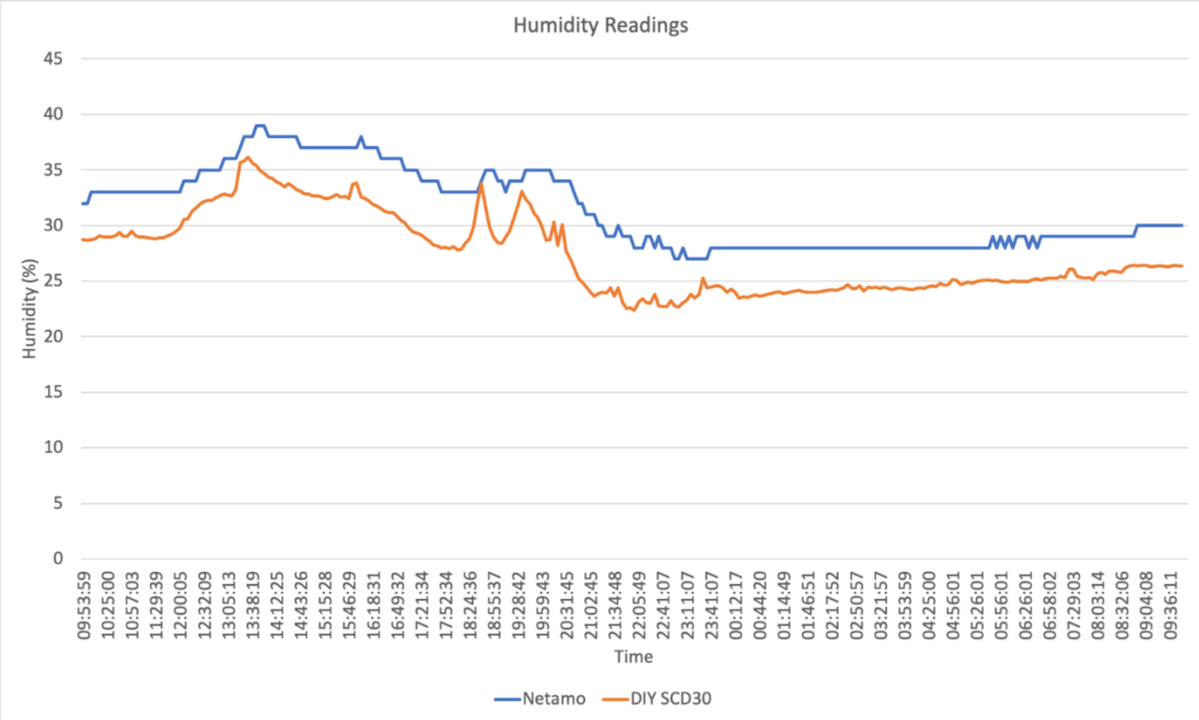

Figure 6: Humidity results from Netamo and SCD30 over 24-hour period

Compared to the temperature readings, humidity was not affected by keeping the window open or door closed. The readings show that human activity and movement creates a fluctuation in humidity. Readings flatlining at 23:41:07 when occupants went to sleep also supports this claim. In conclusion since the readings were comparable to the baseline and had a low offset, they can be held reliable with a need for more time to stabilize in the new location.

5.3 CO_2 Results

Netamo CO_2 readings averaged at 711.32 ppm with median reading of 680 ppm. For the DIY solution CO_2 was measured using SCD30, where readings averaged at 619.79 ppm with median reading of 588 ppm resulting in average offset of -91.53 ppm. The offset is most likely caused by having too short amount of time for calibration and should be given a week to adjust with the new environment [36].

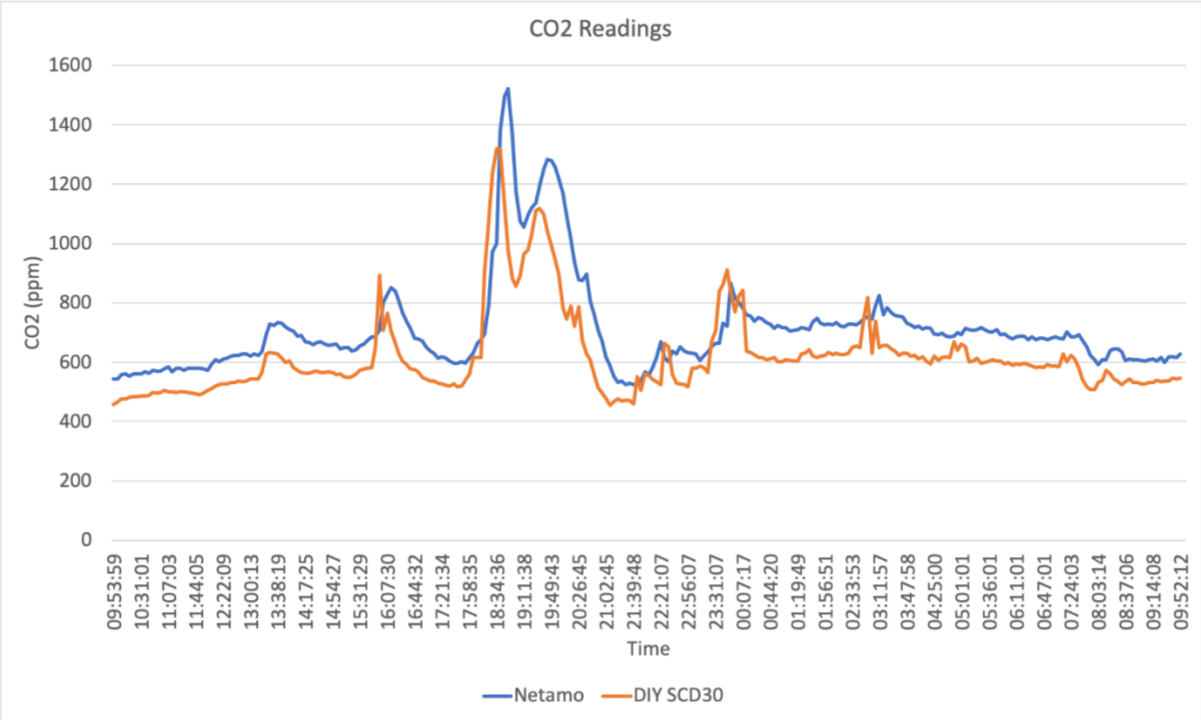

Figure 7: CO_2 results from Netamo and SCD30 over 24-hour period

All readings collected over 24-hour period are displayed in figure 7. The results support the claim of similar research done in the field, that human activity causes increase in CO_2. The readings are stable because the room has built in ventilation. Both devices were able to capture when human activity was present in the room even with the door open. The biggest spike in readings was caused by a workout with closed door and window. Because the devices were placed near the head of the bed, readings did not flatline during night-time and constant fluctuation was happening due to ventilation and door being open. In conclusion the SCD30 readings can be held as reliable and should be given a longer time to calibrate.

5.4 Pressure Results

Netamo pressure readings averaged at 994.88 hPa with median reading of 995.2 hPa. For the DIY solution pressure was measured using BMP280, where readings averaged at 989.53 hPa with median reading of 989.82 hPa resulting in average offset of -5.06 hPa. The offset can be considered insignificant because both devices accuracy is ± 1 hPa and the difference would not have any effect on IAQ. All readings collected over 24-hour period are displayed in figure 8.

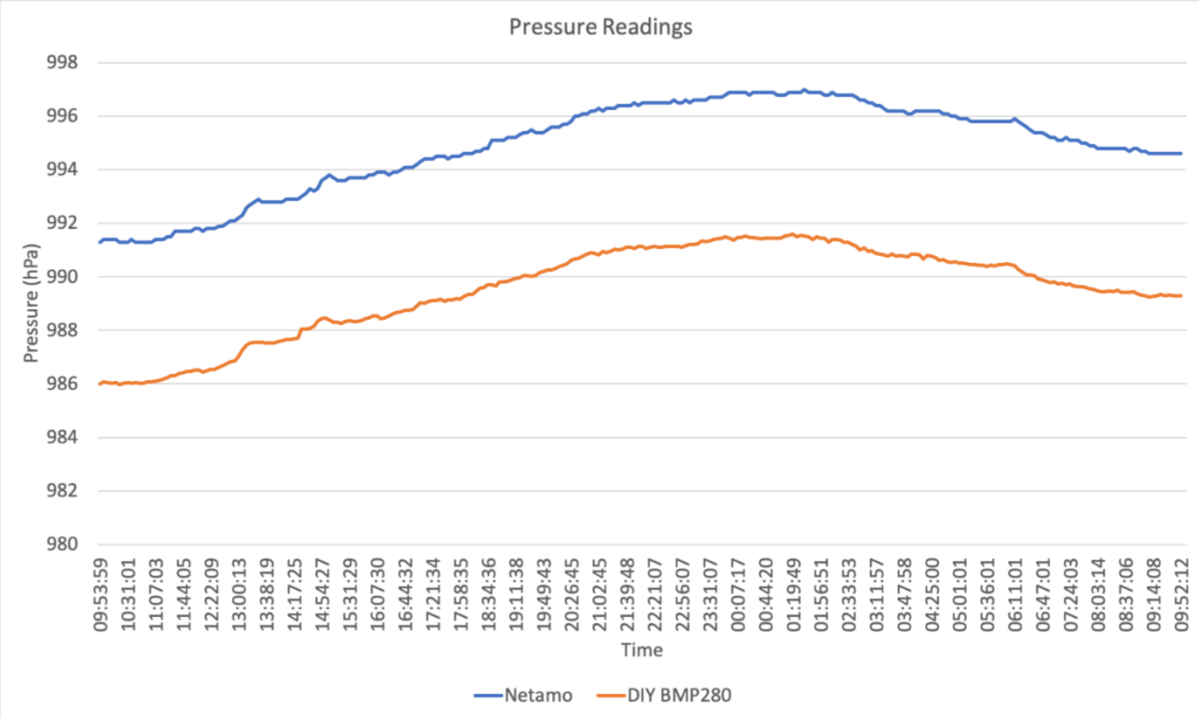

Figure 8: Pressure readings from Netamo and BMP280 over 24-hour period

Considering that the readings of BMP280 were following baseline changes and had a minor offset, they can be held reliable without even a need for calibration. Compared to other readings, pressure was not affected by human activity or presence, raising a question whether it is relevant for IAQ. Based on the purpose of IAQ monitoring pressure can be concluded as not relevant, because it is only affected by changes in weather. In conclusion, while the BMP280 can be considered reliable it is not relevant and can be eliminated in further development.

5.5 Overall Results and Conclusions

All DIY solution readings were resembling the baseline with stable offsets and taking into consideration that COTS products mentioned in section 3 have one-week calibration period, the readings can be held reliable with a need for more time in the new environment. All offsets could be compensated in the products software if a reliable reference is used. Taking into consideration that Netamo is a commercial product and not meant to use as a calibration reference, the offset should not be compensated based on Netamo readings.

With Netamo costing 169.99 euros and the DIY solution totalling at 68 euros, the price differs 101.99 euros. Netamo does include in the price a very minimal design, additional outdoor module and web and mobile application. The core purpose was to measure IAQ and get reliable feedback and both devices did that but considering a user with non-technical background Netamo or any other commercial product would be better fitted while the DIY device would need further development to become usable for a non-technical customer.

5.5.1 Further Developments

Next steps in advancing the prototypes software towards more user-friendly solution would be to create a user interface for real-time data display. Quicker solution would be to add led lights and an LCD display to the hardware itself eliminating the delay that comes from data transfer. In the database a cloud function would be a cost-free way to read incoming data compared to Dataflow which will start to cumulate costs fast if a longer period of time is used for data collection. In order to get the hardware out of the prototype stage next steps would be to transfer the prototype from breadboard to a permanent form of circuit and design and print a case using 3D-printer. Analyse the actual need for pressure readings and consider adding dust and chemical sensors for more in-depth overview.

6 Conclusion

The purpose of this thesis was to analyse data reliability collected by DIY IAQ monitoring solution and compared with a COTS product called “Smart Home Weather Station” by Netamo. As a result of this thesis a prototype was created using ESP32 microcontroller together with 2 additional sensors called SCD30 and BMP280. All data was stored in Google Cloud Platform over a MQTT bridge. The solution was able to measure temperature, humidity, pressure and CO_2 in the accuracy and range set by the parameters in section 4.

Despite needing further development, the prototype was comparable with Netamo. All data collected by the device was resembling the readings from Netamo. Small stable offsets were seen in the data. For SCD30 sensor the reasoning was a rise in temperature in the sensor itself due to approach used to read CO_2 and short calibration time. BMP280 offset was in line with the accuracy set by manufacturers and performed accordingly despite being priced at 2 euros. Based on the analysis the readings from the prototype were considered reliable.

Although the prototype is already comparable with commercial products, there is room for improvement. Next development step should be a compatible web or mobile application and for competitive advantage additional sensors for dust and chemical readings.

Given that the prototypes costs totalled at 68 euros with the possibility to fully customise, Netamos price of 169.99 euros can only be justified if customers interest lays in weather rather than IAQ. The choice of which product to use comes down to users’ background and technical knowledge. Customers who prefer low cost high effort solutions should go with a self-made product and for non-technical users Netamo or any of the devices listed in section 3 Existing solutions should be considered.

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Appendix

I Source Code

Source code without any sensitive information is located in this repository https://github.com/rimanteval/IAQmonitor.

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