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Air-quality sensor with 10-years lifespan

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Sammanfattning/Abstract
Sensors with very low power consumption are required so that they can last a long time without the need to replace the batteries very often. Low power sensors can save significant cost and time incurred in battery replacement, especially in establishments and organizations that span over several buildings, floors and rooms. In this thesis, we investigate the use of the low-power wireless protocol Z-wave for sensors solutions that can last for approximately 10 years. An algorithm was created and we concluded that 10 years on a 480 mAh battery is not possible and the expected years need to be lowered or we need to increase the battery capacity.

Keywords
Air-quality sensor, Z-wave, carbon dioxide sensor, VOC sensor

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1. Introduction

1.1 Objective

Develop and create an algorithm for a wireless air quality sensor with 10 years lifetime using the low-power wireless protocol Z-wave [1].

The sensors measure air quality of the room and also measure the lights and the temperature in the room, and then send the data wirelessly to a gateway.

This means the work had to be both about selecting what kind of sensors to use and develop the algorithm for the sensors, so that the battery can last for 10 years. In this project we concentrate only on the battery life span and we do not count on the life span of other component in the air-quality sensor.

This project was given to us by a company called Sensative AB, this is the project description that they gave us:

"Create and evaluate a smart wireless indoor environment sensor with a 10-year battery life. The thesis used the Sensative Strips Z-Wave platform. The main work is to evaluate sensors and develop smart algorithms for reading and transmitting sensor values that balances sensor performance with the extreme current consumption requirements."

1.2 Motivation

High levels of CO_2 is shown to have negative effects on the human body, for example: researchers found that people working in buildings with below-average carbon dioxide showed better cognitive function than workers in offices with typical CO_2 levels. In schools they found a direct correlation with reduction in decision-making performance and high CO_2, it is also linked to increase of health symptoms like headaches and mucosal irritations.[2]

There have also been shown that too high or low humidity favor the survival and transmission of influenza viruses and can causes asthma like symptoms.[3]

Temperature also shown to affect the cognitive performance of students in a room, a study [4] shows that having the temperature between 20-25 celsius increases the performance of the students.

According to the Public Health Authority in Sweden [5], having low VOC indoors gives better air quality, they write in an article about air quality "although if the content of VOC is low can give an unpleasant odor and VOC can change into more aggressive substances that can affect human body".

Therefore, having a smart air quality sensor that controls the ventilation in a room so that there is good air quality, is important to increase the productivity and comfort of the people in the room.

But the problem is that it could be very costly for a school or some establishment to install wired sensors in all rooms especially if they have a large number of rooms because wires are needed for all the sensors to power them up.

The solution to this problem is having a battery powered wireless sensor, but then the sensor needs to have very low power consumption so that it lasts a long time and the batteries does not need to be replaced very often, because this could be a problem for an establishment especially if they have many rooms, then they have to replace a large amount of them.

1.3 Research Questions

In order to meet our objectives, the thesis covers the following research questions::

Q1. Which sensors and air properties are relevant for achieving good air quality in a room?

Q2. How can we manage an air-quality sensors battery so it can work for at least 10 years?

Q3. What scenarios and sensors are relevant in different situations?

1.4 Methods

This work is based on a literature study which is present in chapter 2 and experiments which are presented on chapters 4 and 5.

1.5 Thesis structure

1. Introduction: We explain the objective, motivation, research questions, methods and the thesis structure of the thesis.

2. Literature study: Gives background to indoor air quality and sensor technologies and references other theses.

3. Empirical study: We explain how select the sensor that should be included in our system, what air properties should be focused on and how we get the current readings.

4. Implementation: Gives an overview off the system and how we read the current..

5. Results: We present the result of the current readings from the selected sensors and a flowchart is created from these readings. An analysis of the flowchart is also presented.

6. Conclusion: We give our thoughts about the presented results.

7. Ethics and Social aspect: Thoughts about the social and ethical effects off our system is presented.

8. Future Work: Our thoughts off how the system can be improved.

2. Literature study

2.1 Indoor air quality

Indoor air quality relates to the air quality in and around buildings and greatly affects the health of people in a building. There are both short and long term health effects for bad air quality. Short-term effect of bad air quality can cause irritation to eyes, nose and throat, headaches, dizziness, and fatigue. Long term effects of bad air quality can cause respiratory diseases, heart disease and cancer.[6]

Bad indoor air quality can be caused by outdoor pollutants like car traffic and industrial activities, which enter the ventilation of a building. It can also be caused by indoor contaminants, that are created through combustion(like burning fuels, wood and tobacco). Other factors for bad indoor air quality are cleaning products, pets and electronic equipment.[7]

Table 1 shows threshold values different air properties,where ppm = parts per million and Bq/m^3 becquerel per cubic meter.

Table 1. Threshold values for different air properties

Topics	**Normally indoors**	**Actions must be taken if the value rises**
CO_2	600–800 ppm [8]	1000 ppm for a long period [9]
VOC	100 $\mu g/m^3$ [10]	200 $\mu g/m^3$ [11]
humidity	45–55% [12]	75% for a long period [13]
Temperature	20 – 24 °C [14]	26°C or the value becomes less than 20°C [14]
CO	0-9 ppm [15]	10-24 ppm [15]
Particles	15 $\mu g/m^3$ [16]	50 $\mu g/m^3$ [14]
Nanoparticles	10 $\mu g/m^3$ [16]	25 $\mu g/m^3$ [14]
Radon	40 (Bq/m^3). [17]	200 (Bq/m^3). [18]

2.2 Sensor technologies

Non Dispersive Infrared Sensor

Non dispersive infrared (NDIR) sensors can be used to measure the concentration of gas in a chamber. An infrared light is sent from a source to a detector, and you get the gas concentration by checking how much infrared light has been absorbed by the gas in the chamber. NDIR sensor can be configured to recognize a specific gas because all elements and compounds absorb light at different wavelengths, and therefore a filter can be used to target a specific wavelength so that the sensor has a high sensitivity for a specific gas and ignores all other gases.[19]

CO_2 for example has high absorption of infrared at the wavelength: 4.2 µm.[20]

Solid Electrolyte Sensor

Solid Electrolyte sensors uses a metal oxide surface made out of a thin film of heavy metal. The exact metal that is used will depend on the gas is measured and the film overlies a layer of silicon and is heated to a temperature between 200 and 400 celsius depending on the application. [21]

2.3 Related work

There are many research papers about creating battery friendly wireless air quality sensor. For example there is paper [22] that talks about creating a battery free smart sensor system for air quality monitoring. It uses RF Energy harvesting to charge up a super capacitor, however it only has a range of 2 meter, and we plan on using the Z-wave protocol, which has a range of 30 meters indoors.

[23] revolves around creating a low-power temperature and humidity sensor using the Zigbee protocol. Similar to our work it talks about removing wires and therefore creating a wireless sensor network that is easier to install and maintain. But this solution does not have readings for CO_2, VOC and other elements that are important for measuring the indoor air quality.

L.Tan et al. in [24] present a battery powered wireless sensor with an impressive 250 meter transfer distance and a shelf life of up to 20 years. But similar to the previous article this work has sensors only for temperature and humidity.

Another research paper which is very similar to our "Design of A Low-Cost Wireless Indoor Air Quality Sensor Network System"[25], they used Zigbee and Arduino Uno as a microcontroller which is not very power efficient compared to what we used. But the main similarity is that the used VOC sensor TGS2602, CO_2 sensor MG811, CO sensor MQ7, Ozone sensor MQ131, temperature and humidity sensor RTH03. All the sensors they used are not power efficient like ours, for example they used VOC sensor TGS2602 which takes 5 times more current then our [26], and our VOC sensor can also read temperature, humidity and CO. The CO_2 sensor MG811 they used we have already compared with 4 others in the table 3, and it is not the best one if we compare power draw and accuracy error. But in this research paper they have Ozone sensor which we do not have.

3. Empirical Study

Learning about air properties

By reading research articles about air quality and air properties. We have figured out which components in the air are interesting to measure, and the limit value of each air property inside a room, and when they become harmful to people and when they are safe.

Selecting Sensors

The most important factors when choosing the sensors for the air quality monitor is that they should have very low operating current while still managing to be as accurate as possible.

Therefore we have searched the market via various websites for many different kind of sensor and learn about them and compare them with each other and then choose the ones sensors that are the most suited for our project. The most important parameters we looked at when selecting the sensors where: accuracy, average current consumption and price.

Testing the Sensors

After we selected the sensors we tested them and measured the real power consumption of all sensors by using an oscilloscope and a resistor shunt, more description in “Current readings” paragraph. Then we figured out an algorithm that can save as much current as possible and give us a good air quality inside a room.

System

Our system have a microcontroller that is based on Intel 8051 and is named C8051F996. This microcontroller was selected by the company Sensative AB because it has been already tested in other projects. The microcontroller has very low operating current of 10 nA when in sleep mode, so we can save power by putting the microcontroller to sleep as much as possible.

Because the system is designed to draw as little power as possible, we used switches that are connected from the microcontroller to each sensor and the wireless module. So we save power when the sensors are not in use by disconnecting it from the power supply.

Current readings

An Oscilloscope was used to measure the current consumption of our system. Oscilloscope is an instrument that allows observation of voltage levels then output it as a graph on a display where we have an X-axis which represent the voltage level and Y-axis which represents time. Because Oscilloscopes normally are not used to get the current readings of a circuit, we need to use a resistor shunt which is resistor with very low resistance that puts in series with any system. We then read the voltage over the resistor shunt and then we can get the current measurement of your system by using Ohm's law.

4. Implementation

4.1 Microcontroller

The microcontroller we used is the C8051F996 [27] which is a variant of the Intel 8051. The microcontroller is chosen because of its very low current consumption it draws 150 µA per MHz (max frequency is 24.5 Mhz) on active mode and 50 nA in sleep mode with the CPU running at 32.768 kHz.

The microcontroller is connected to the development board C8051F996-DK by Silicon Labs [28]. The microcontroller has a port for connecting a debugger, which is used to program the microcontroller with the help of the IDE: Simplicity Studio 4.0 by Silicon Labs. The programming language that is used to program the microcontroller is C.

The development board gets power through USB or connecting the VDD pin on the board to 1.8-3.3 V. For this project we connected an external power source of 5 V that can be regulated down to 3.3 V and connected to VDD.

We use the lowest possible active frequency by using the internal clock divider to divide the maximum frequency 24.5 MHz by 32. We get a frequency of 765625 Hz and we get a current draw of 114.8 µA on active mode.

4.2 Switches

To get as low power consumption as possible, we need turn off parts of the system that are not in use. For this purpose, we make use of Transistor switches which can cut the current flow from a part of the system. A transistor has 3 pins called: Gate, Source and Drain, where Source and Drain is connected to in series with the part of the system we want to disconnect and Gate is used to turn on/off the switch by lowering or raising the potential under or over a specific threshold voltage.

The Transistor that is used is IRLIB9343PBF [29] which is a P-channel MOSFET transistor with a threshold voltage of 1.0 V. Figure 1 shows how a switch is connected.

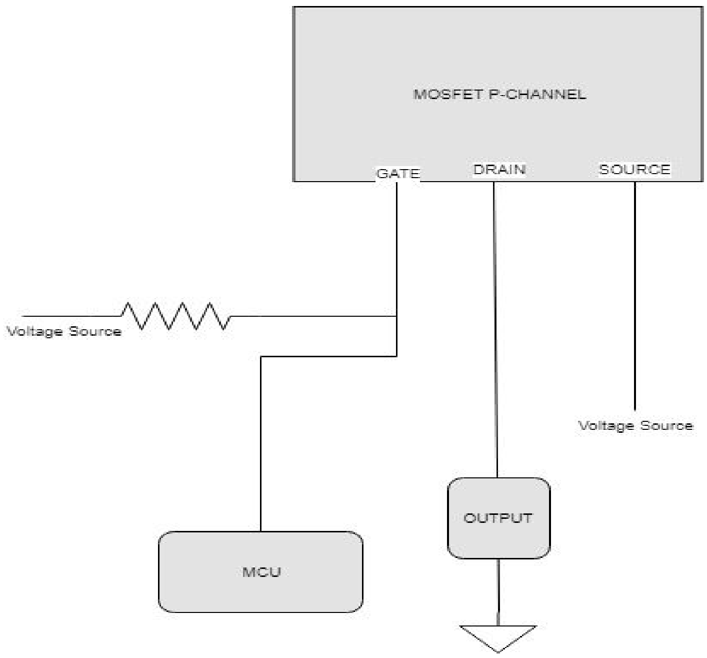

Figure 1. Schematic of Switch connection

4.3 Battery

The battery that is going to be used as the power source is a 480 mAh battery with the voltage of 3.7V and wattage hour of 1.776 wh.

4.4 Regulators and Level shifter

The battery and the different components uses different voltages, therefore voltage regulators are needed. The battery has a voltage of 3.7V the CO_2 sensor runs on a voltage of 5.0V and the rest of the components uses 3.3V.

A regulator is connected directly after the battery, this regulator is called AP2205-33Y-13 and it takes down the voltage from 3.7V to 3.3V, it has a Quiescent Current of 10 nA.

To power the 5V CO_2 sensor we used the step-up regulator U1V11F5 that will pull up the voltage from 3.7V to 5V. This regulator has an efficiency loss of 10% and 3 mA Quiescent Current and it will be connected with a switch so that it will only be powered when we read from the CO_2 sensor.

The CO_2 sensor and the microcontroller communicate through the i2c protocol and because they both have different voltages a level shifter is needed. The level shifter is called SN74LV1T04DCKRG4, and it is connected between the CO_2 sensor I2C and microcontroller I2C, and it uses an operating supply current of 1.35 mA.

4.5 The system

A regulator is used because the CO_2 sensor uses 5.0V to power on while the VOC/CO sensor and Microcontroller uses 3.3V, we use a power source that is 3.7V that we connect to a regulator that brings down the voltage to 3.3V and we connect a step-up (or boost) voltage regulator between the CO_2 sensor and a switch.

We implemented a light sensor, that can be used to check if there is ambient light in the room, so that the system does not read from the sensor for example in the night when the lights are switch off because no one is in the office.

Figure 2 shows the block diagram for the system overview.

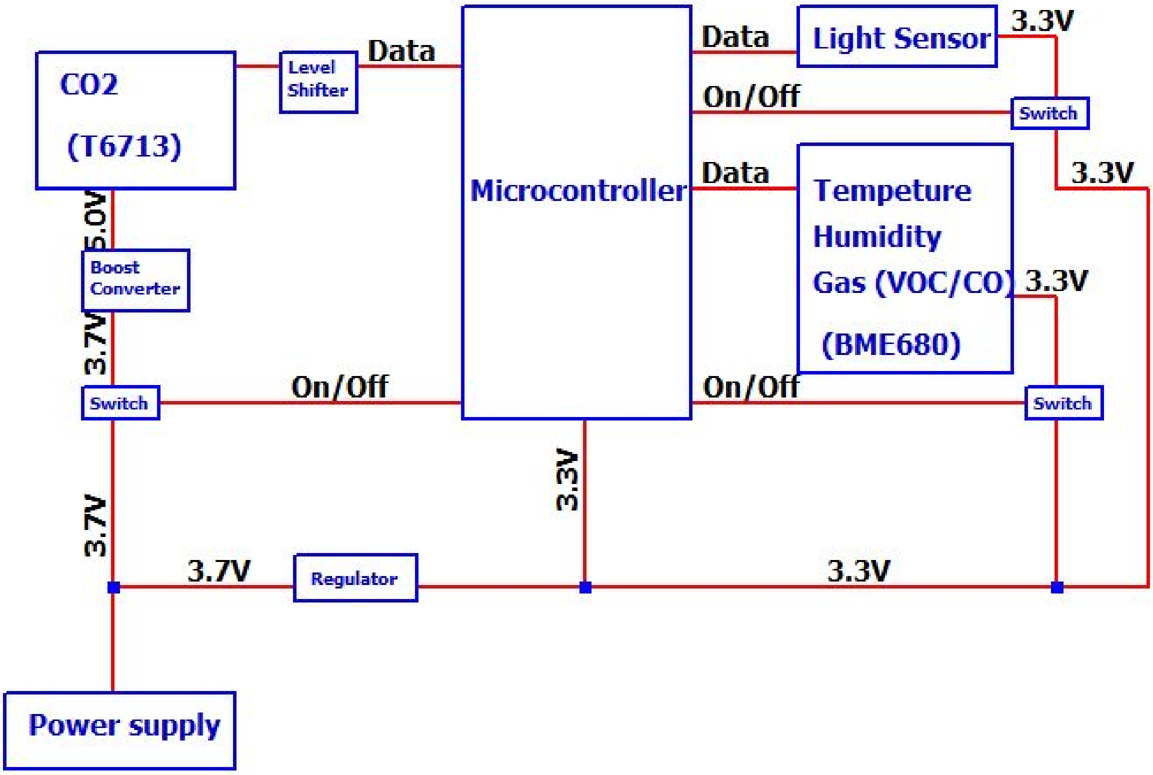

Figure 2. Block diagram of System

4.6 Current reading

An oscilloscope is used to observe the change of voltage over time, so because we are only interested on the current consumption we need use a resistor shunt. This is a resistor that is connected in series with a specific load we want to measure the current consumption of. We then measure the voltage over the resistor shunt with the oscilloscope and then to get the current that goes through the load we use Ohm's law, which is:

$$\text{Current (I)} = \frac{V\,oltage\ over\ the\ resitor\ shunt}{Resistance\ of\ the\ shunt}$$

The resistance shunt itself will also resist the current from the load, therefore it needs to be very low, we use a shunt with a resistance of 1 Ohm. Figure 3 shows how the shunt and oscilloscope is connected.

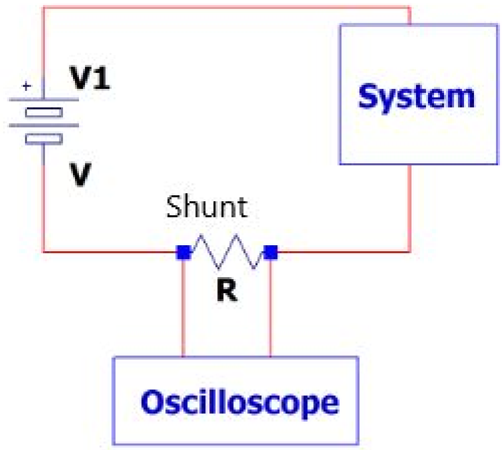

Figure 3. Connection diagram of Oscilloscope and shunt

4.7 Z-Wave

Z-wave is a low-power wireless protocol that is used mostly in IoT (internet of things) system. It operates in 800-900 MHz frequency range means that it has low interference compared to the protocol Zigbee which has the frequency of 2.4 GHz (same as WiFi) because there are less devices that uses the 800-900 MHz frequency range.[1]

The company Sensative AB provided the data of the current consumption from products they have created, which uses the Z-Wave. Therefore we used the values that they provided instead of creating new current consumption experiments using Z-Wave.

Current draw for sending a single report through Z-wave:

Z-wave takes on average 27.5 ms to startup before transmitting, and while starting up it draws 17.5 mA (Figure 4 shows a graph of the transmission of a packet). To get the current draw we use this calculation:

$$\textit{Z-Wave startup} = 27.5\ ms * 17.5\ mA = 481\ \mu As = 0.1336 * 10^{-6}\ Ah$$

Where µAs is micro Ampere seconds, and Ah is Ampere Hours.

After startup the Z-wave will begin transmitting, this will take on average 17.5 ms, the average draw is 34.5mA:

$$\textit{Z-Wave transmission} = 17.5\ ms * 34.5\ mA = 604\ \mu As = 0.1677 * 10^{-6}\ Ah$$

$$Total = 0.1336 * 10^{-6} + 0.1677 * 10^{-6} = 0.3013 * 10^{-6}\ Ah \text{ per packet transmission}$$

The different packet sizes that have been tested are from 10 bytes to 200 bytes, and there are no noticeable difference in the current consumption when sending a packet with the size of 10 bytes or when sending a packet with the size of 200 bytes. While the Z-wave is not transitting anything it will draw 750 nA.

Figure 4. Wave of the current consumption of sending one packet with Z-Wave. First part from the first red line to the second redline is the startup of the Z-Wave, and the second part starting from the second red line to the third red line is the consumption when sending data.

5. Results

5.1 Air properties

This part is answering the first part of research question 1.

CO_2

CO_2 is a very common gas that is all around us. It has no colour or smell and is naturally present in the atmosphere. All humans and animals exhale carbon dioxide when they breathe, and plants absorb it during a process called photosynthesis in order to grow.[30]

VOC

Volatile organic compounds (VOC) are emitted as gases from certain solids or liquids. VOCs include a variety of chemicals, some of which may have short- and long-term adverse health effects. Concentrations of many VOCs are much higher indoors and they are emitted by a wide array of products numbering in the thousands.
Organic chemicals can be found used in many different products that exist in a normal household like for example: paint products, cleaning products, cosmetic products, degreasing products and hobby products. Fuels are also made up of organic chemicals and all of these products can release organic compounds while we are using them, and while leaving them on some shelf. [31].

Humidity

Humidity is a measure of the amount or percentage of the water vapor in the air. There is a high risk for higher humidity in buildings with poor or ineffective ventilation, which leads to higher risk for mites. High humidity (over 55%) affects human experience of heat or cold, and low humidity(under 45%)leads to problem with dry skin and dry trachea. [32]

Temperature

The indoors temperature is one of the important factors to reach a good thermal indoors climate. The lowest accepted indoors temperature is 20 degrees but if it is lower than that you will become sensitive and stressed in the body, on the other side the highest accepted indoors temperature is 24 degrees but if it is higher than that on a long time you may lose fluid and get dehydrated. [32]

CO

Carbon Monoxide or CO (also called the "silent killer") is a colourless and odourless poisonous gas. CO is created from the combustion process off fossil fuel. In worst case scenario CO can kill human in less than 3 minutes if levels are very high more than 12 800 PPM [33].

Particles and nanoparticles

Particles and nanoparticles affect health, irritation symptoms may occur in direct contact with the skin. In case of elevated particle levels, the respiratory system and eyes are affected.

The main source to particles indoors are traffic emissions such as street dust and exhaust gases. there are other source for particles like tobacco smoking, pets, the amount and quality of textiles as well as cleaning habits [34].

Particle sensors that currently exist consume too much current, so we will exclude it from our implementation.

Radon

Radon is a radioactive gas that forms naturally in the bedrock when radium decays. Only in Sweden radon inside causes about 500 lung cancer cases per year and it is primarily smokers who are affected [18].

Radon sensors are currently very expensive to buy (more than 2000 kr), and we can therefore not implement it on our system.

5.2 Selecting CO_2 Sensor

This part is answering the second part of research question 1.

We compared 5 different CO_2 sensors with 2 of them being NDIR sensors and the others being solid electrolyte sensors (Table 3 shows the sensor that we compared). These values are taken from the data sheets of the different sensors.

We found that the NDIR CO_2 sensors are both more accurate and have lower operating power compared to the sensors that uses solid electrolyte sensors. All the NDIR CO_2 sensors had very similar accuracy but the sensor "T6713" had the lowest operating current of all the sensors that we compared.

Table 3. CO_2 sensors

CO_2 Sensors				
Name	Accuracy error (+/- %)	Operating current (mA)	Size (mm^3)	Price (Euro)
MQ-135 (solid electrolyte sensor)[35]	45	160	2596,608	13
MG-811 (solid electrolyte sensor)[36]	15	200	2596,608	27
T6613 (NDIR sensor)[37]	3	33	27132,000	67
T6713 (NDIR sensor)[38]	3	25	4029,480	67
TGS4161 (solid electrolyte)[39]	20	50	1049,536	30

5.3 Selecting VOC and CO Sensors

This part is answering the second part of research question 1.

When searching for VOC and CO sensors we found that there were many sensors that did both and we therefore compared a list with these kind of sensors (Table 4 shows the sensor that we compared). These values are taken from the data sheets of the different sensors.

We found that sensors BME680 had the lowest operating current compared to the other sensors, this sensor also records the temperature and humidity and therefore is a good fit for our air quality monitor.

Table 4. VOC, CO sensors

VOC, CO Sensors			
Name	**Operating current (mA)**	**Size (mm^3)**	**Price (Euro)**
AS-MLV-P2 (solid electrolyte sensor) [40]	25,00	372,645	14,00
CCS811B (solid electrolyte sensor) [41]	26,00	10,800	5,77
CCS801B (solid electrolyte sensor) [42]	23,60	6,000	3,75
BME680 (solid electrolyte sensor)[43]	10,00	8,370	5,23
MICS-6814 (solid electrolyte sensor) [44]	0,21	54,250	10,00

5.4 Response time

Every sensor needs a specific amount of time to get a reading. This time is relevant to our research because the longer time a sensor needs to be on to get a reading the more current it draws from the system.

Temperature

The sensor BME680 is a temperature, humidity and VOC/CO sensor in one, and how much current it draws depends on what you want to read.

When reading the temperature, we found with the help of a oscilloscope (see Figure 5) that it will read for approximately 40 ms and has roughly a current draw of 10 mA

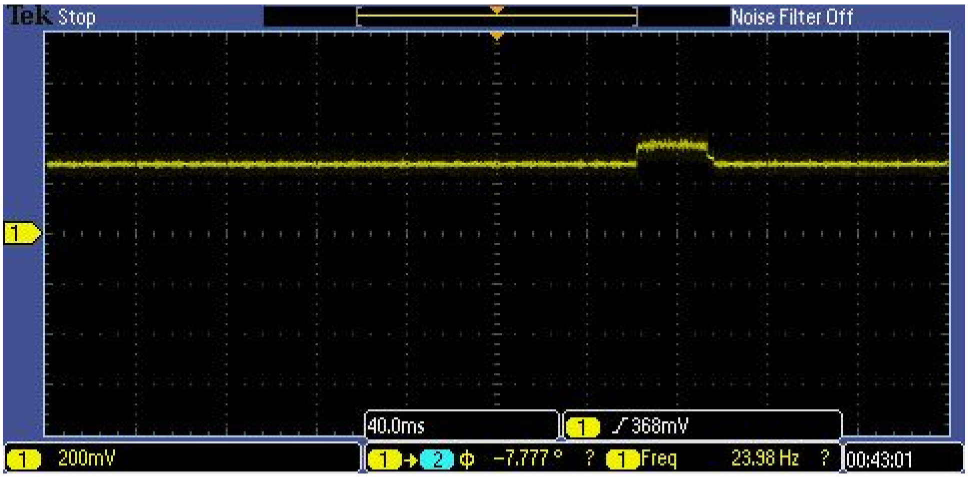

Figure 5. Oscilloscope image when reading the temperature sensor

Humidity

For the humidity sensor, the current draw is 10 mA and warm up time is 30 ms (See Figure 6 for oscilloscope image).

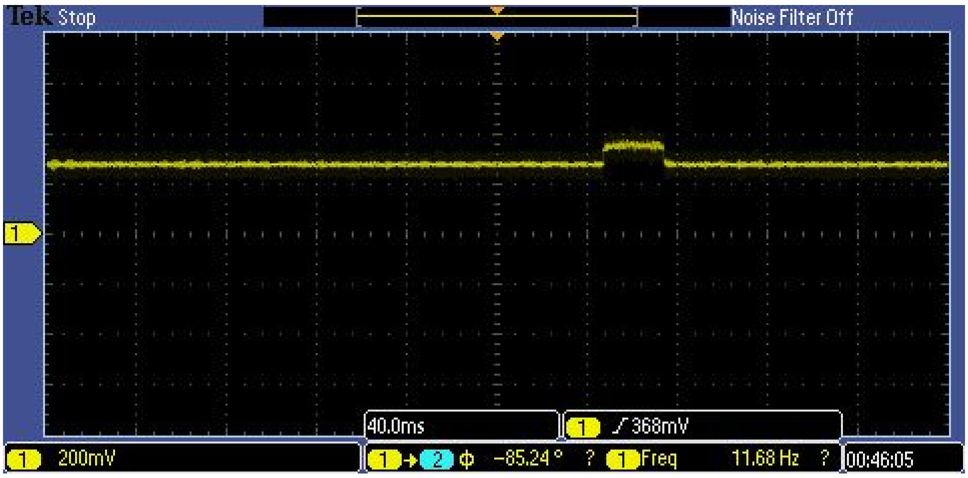

Figure 6. Oscilloscope image when reading the humidity sensor

VOC/CO

Inside the BME680 there is a gas sensor that can detect both VOC and CO. This sensor takes longer time to read from compared to the humidity and temperature sensors, because it needs to heat up a plate to get a reading.

Reading VOC gives an average current draw of roughly 15 mA and it takes 80 ms to read a value (See Figure 7 for oscilloscope image).

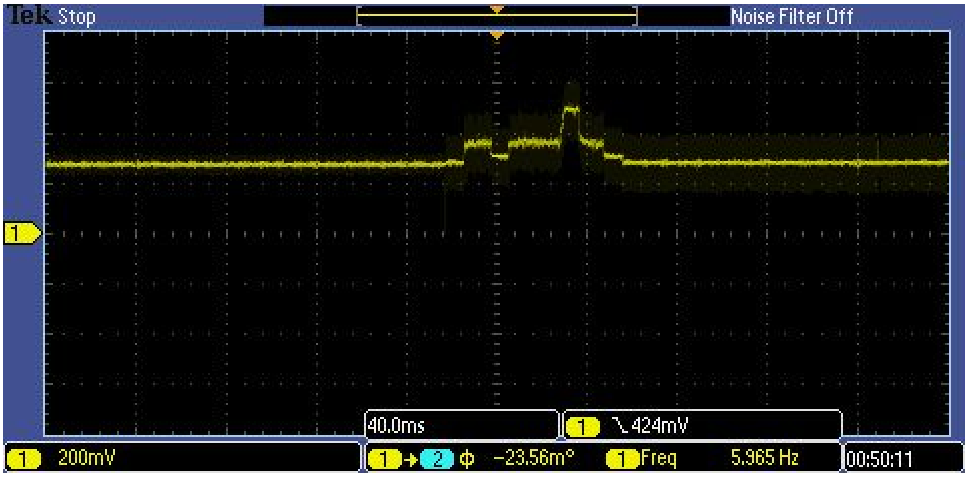

Figure 7. Oscilloscope image when reading the VOC/CO sensor

Analog light sensor

Reading of the light sensor is done by the ADC of the microcontroller, and the ADC conversion time required to get a reading from the sensor is 4.19 µs with an average current draw of 25 mA.

CO_2

According to the datasheet of the CO_2 sensor T6713, it should take roughly 2 min to warm up the sensor and get CO_2 readings. The CO_2 sensor draws on average 25 mA, and drawing that much of current under 2 min is too much. It will mean that we can not afford to read from the CO_2 sensor even once a day, if we want the battery too last 10 years.

Experiment were performed with the CO_2 sensor on 2 different locations, to see what the CO_2 values we get when we read every second up to 130 seconds. The first location (see Figure 8) was in a room with no ventilation and all the windows and doors closed. The second location (see Figure 9) was performed in a room with good ventilation and open windows and doors. We performed 10 readings (marked with different colors) on each location with 5 min wait period between each reading so that sensor can cool down.

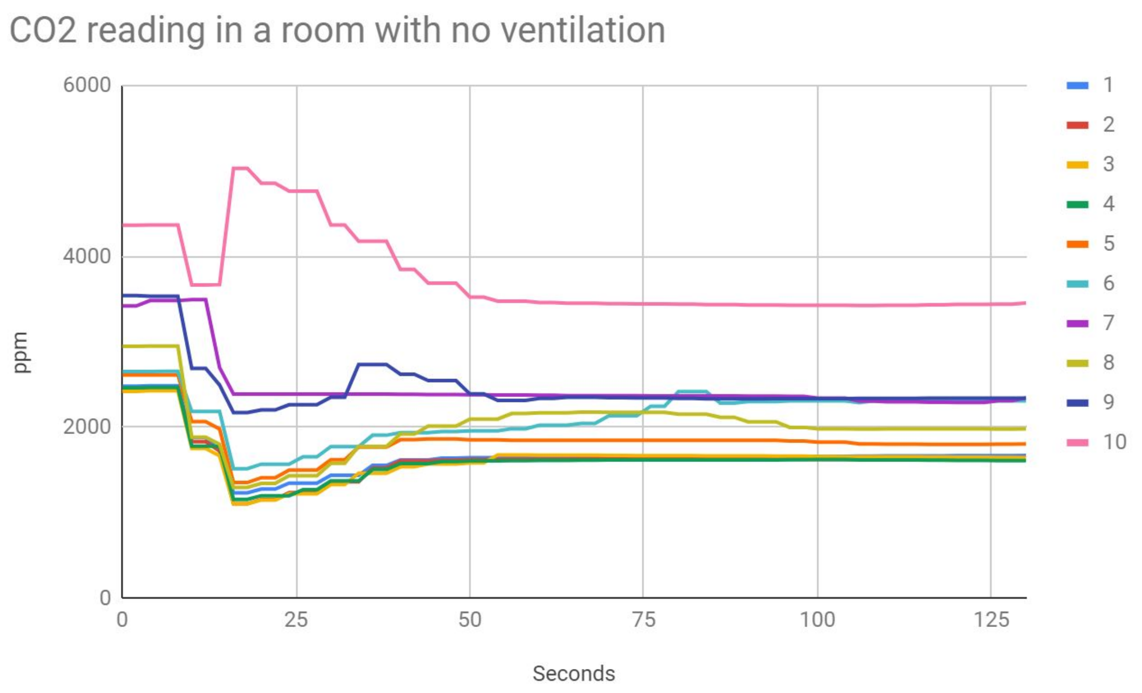

Figure 8. CO_2 readings over time in room with bad ventilation

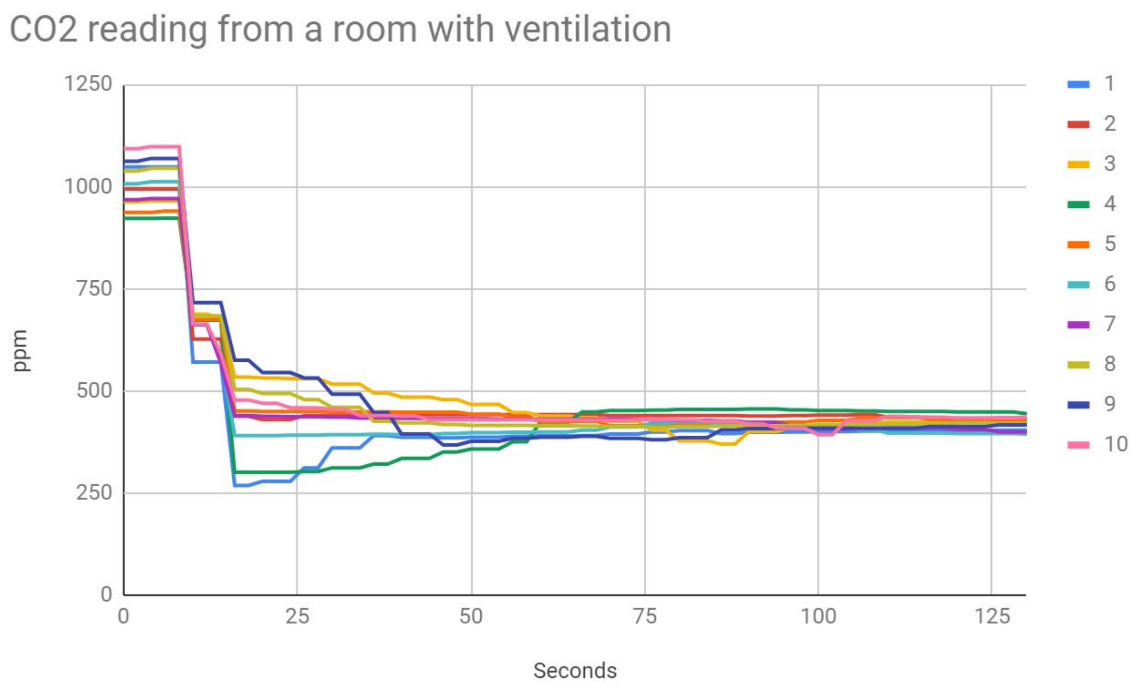

Figure 9. CO_2 readings over time in room with good ventilation

On all experiments we found that the sensor takes approximately 50 seconds to stabilize and get an accurate reading of the CO_2 in the room. 50 seconds is still a large amount of time and it would take to much current for each reading.

We then started to analyze the graph to see if there are some correlation between the experiments. We looked at the CO_2 values at 1 second and at 120 seconds and get the difference in ppm (Table 5).

Table 5, CO_2 values at 1 second and 120 seconds and the quotient of them

	1 seconds (PPM)	120 seconds (PPM)	Difference (PPM)
Average CO_2 reading in a room with good ventilation	1003,2	420,8	582,4
Average CO_2 reading in a room with bad ventilation	2934,9	2074,1	860,8

Looking at Table 5 we see that there exist a difference between the ppm readings after 1 seconds after the sensor has started compared to after 2 min when the sensor is fully functional. The difference seems to be lower in room with good ventilation compared to a room with bad ventilation where the difference is 278,4 ppm higher.

Even though there is a clear difference between the readings when the sensor is starting up and when it is fully warmed up, we are able to see a clear difference between a room with good ventilation and a room with bad ventilation when reading after 1 seconds.

We are not able to include the CO_2 sensor in our system if we want very accurate readings of the CO_2 values in a room because of the very high current draw that is required to keep the sensor on for 2 min. But if only read after 1 seconds then we can include it in our system, we will get an inaccurate reading of the CO_2 but as the results shows, we can still detect when the CO_2 becomes dangerously high.

5.5 Power draw

This part is answering research question 2.

The sensors are not the only components that draws current, we also have 3 switches that draws 0.100 µA each and the microcontroller which draws 0.05 µA when in sleep mode and 0.1148 in active mode (see Table 6). This means that the system will a total of 0.35 µA when it is not reading anything and the microcontroller is in sleep mode.

Table 6. Passive current draw of system

	Average current draw (µA)
3 Switches	0.300
Microcontroller sleep mode	0.05
Microcontroller active mode	0.1148

For our calculations we used a battery with the capacity of 480 mAh (milliAmpere hours), this is the same kind of battery Sensative AB uses for their products. Before we create an algorithm to make the system last for 10 years we need to calculate how much battery capacity it will take when the microcontroller is in sleep mode and not reading from the sensors. To do this we use the formula:

*(Current draw in mA) * Time (in Hours) = Battery capacity drained (mAh)*

We divide our calculations in 2 parts, first part is about calculating the power drain from the components that uses 3.3V and the second part is the CO^2 sensor that uses 5V.

Table 7 presents how much battery capacity drained when the microcontroller is in sleep mode and 2 switches for 10 years.

Table 7. How much battery capacity is drain when just in sleep mode for 10 years

	Average current draw (µA)	Battery Capacity drained after 10 years (mAh)
System in sleep mode	0.25	21.96

Battery capacity total so far is **21.96 mAh**. Table 8 shows a list of how much battery each sensors and Z-wave transmission drains.

Table 8. The amount of battery drain for each components action

	Response time (ms)	Average current draw (mA)	milliAmpere hours per reading (mAh)
Temperature	40	10	$0.1111*10^{-3}$
Humidity	40	10	$0.1111*10^{-3}$
VOC/CO	80	15	$0.3333*10^{-3}$
CO_2	1000	25	$6.9444*10^{-3}$
Z-Wave Transmission	45	24	$0.3013*10^{-3}$
Analog light sensor	0.00419	25	$0,00002909*10^{-3}$

By using the light sensor we assuming day and night scenario, which answering research question 3.

The light sensor is used to check if the room is filled with ambient light and then read from the sensors if there is light on or sunlight, so that the system does not read from sensors when the room is dark where we can assume that no person is in the room. One possibility to save the battery is to shorten the reading time from the sensors. However, this time cannot be long to risks cannot arise. Therefore, we read from the light sensor every minute.

Table 9 shows how much battery capacity is drain from just checking the light sensor every minute for 10 years.

Table 9. How much battery capacity is drain when reading the light sensor for 10 years

	Total amount of reading after 10 years	Battery Capacity drained after 10 years (mAh)
Light sensor	5 256 000	0.1529

Battery capacity total so far is **22.05 mAh**.

We intend to use this system in a workplace environment and in Sweden the average work week is 38 hours [45] and this how long we will assume that the system will be able to read from the air quality sensors. Total hours in a week is 168 hours, this means that in theory the system will only be able to read from the air quality sensor 22.6 % of 10 years (2.26 years). Because of this, the sensor will not work in an office where many of the workers have very different working hours and will only be efficient in offices where everybody has similar working hours,

We have to read from CO sensor at least every 3 min because if we wait longer than that then the people can die if they are exposed to high amounts of CO. But we will send the data in 30 minutes interval if the results are in the accepted area, if not then we send the data immediately. Therefore it's difficult to know how many times we are forced to send the data immediately every day, but we can guess 5 times every day, we guess that to come close to an estimate of battery life. Table 10 shows how much battery capacity is drain from reading the CO every 3 minute for 2.26 years.

Table 10. How much battery capacity is drain when reading the VOC/CO sensor

	Total amount of readings	Battery Capacity drained after 2.26 years (mAh)
VOC/CO sensor	395 952	131.97

Battery capacity total so far after including VOC/CO sensor is **154.02 mAh**.

If we also read the humidity and temperature sensor the same time as VOC/CO sensor then we can send all the data the same time with one Z-wave transmission. (Table 11).

Table 11. How much battery capacity is drain when reading the Temperature sensor and Humidity sensor

	Total amount of readings	Battery Capacity drained after 2.26 years (mAh)
Temperature sensor + Humidity sensor	118 785	26.39

Battery capacity total so far is **180.41 mAh**.

We have now calculated the current draw of the components that is connected to the 3.7V to 3.3V step-down regulator. This regulator dissipate power when decreasing the voltage and it needs to also be calculated. To get the power dissipation we will use the following formula:

*Battery_capacity_drained * Voltage_difference = Power_Dissipation in watt hours (wh)*

Battery_capacity_drained is how much battery capacity has been drained (**0.18041 Ah**) and *Voltage_difference* is the difference in regulator input voltage (3.7V) and output voltage (3.3V).

Power dissipation:

*0.18041 Ah * (3.7-3.3)V =* ***0.072164 wh***

The regulator also has a quiescent current of 10 nA, which will after 10 years have a power capacity drain of:

*0.000876 Ah * 3.7V =* ***0.003241 wh***

We need to know the total power draw of the 3.3V components, therefore we will translate the battery capacity that the components depleted to power capacity by using the following formula:

*Battery_capacity_drained * Voltage = Power_Capacity_drained(wh)*

Battery_capacity_drained is again how much battery capacity has been drained (0.18917 Ah) and *Voltage* is the voltage the components uses (3.3V).

*Power Capacity drained: 0.18041Ah * 3.3V =* ***0.595353 wh***

When including the power dissipation we get a total power capacity drain from of:

0.072164 wh + 0.003241 wh + 0.595353 wh = 0.670758 wh

Lastly there is the CO_2 sensor which drains the most battery of all the sensors per reading. We made a table (Table 12) what would be optimal with reading interval with the amount of battery capacity left. We choose intervals that are multiples of 10, because then we can send CO_2 sensor data together with the other air quality sensor data as one Z-wave transmission

Table 12. How much battery capacity is drain when reading the CO_2 sensor and sending data with Z-Wave for different reading interval

Reading interval (min)	Total amount of readings	Battery Capacity drained after 2.26 years (mAh)
10	118 785	860.68
20	59 392	394.55
30	39 595	263.03

We find that 30 min interval is the minimum interval because if CO_2 content increase the VOC/CO sensor will “notice” that. We humans not only emit CO_2 but also secrete microorganisms, gases and particles, we stir up dust, and not least we produces heat.

Therefore if CO_2 are increasing because of presence of human[46][47], we are many in the room for example, then the VOC/CO sensor will notice that by temperature increasing thereafter the CO_2 will be measured just before Z-wave transmission.

The CO_2 sensor needs 5V to run, therefore a boost converter is needed that brings up the voltage from the battery (3.7V) to 5V. This boost converter has has a power loss of 10% and a quiescent current of 3 mA. A switch is connected to this converter so that it will only power on when we want to read from the sensor.

First we translate the battery capacity drain (263.03 mAh) to power capacity drain:

*0.26303 Ah * 5V =* ***1.31515 wh***

Then we calculate the power loss:

10 % 1.31515 wh = 0.131515 wh

Also the drain from the quiescent current of the converter (3mA) which we get by multiplying total hours on time with the wattage:

*10.9986 hours * 0.003 A * 5V =* ***0.164979 wh***

There is a switch between the regulator and the battery that has a current draw of 0.100 µA. After 10 years this switch has power draw of:

*0.00876 Ah * 3.7V =* ***0.032412 wh***

Then lastly we also have a level shifter that is connected between the I2C pins of the sensor and the microcontroller that has supply current of 1.35 mA:

*10.9986 hours * 0.00135 A * 5V =* ***0.074240 wh***

Total power capacity drain from the CO_2 sensor part:

1.31515 wh + 0.131515 wh + 0.164979 wh + 0.074240 wh + 0.032412 wh = 1.718292 wh

Total power capacity drain from the whole system after 10 years:

1.718292 wh + 0.670758 wh = 2.38905 wh

Table 13. How much Power capacity is expected to drained by the different parts of the system after 10 years.

Components	Power capacity drain (wh)
3.3V components including regulator and switches	0.703170
5V components including boost converter and level switcher	1.68588
Whole System	2.38905

The battery has a total power capacity of **1.776 wh** and the system will draw a total **2.38905 wh**. This means that the system will not have a life span of 10 years and battery unless we increase the battery capacity by at least 35 % or decrease the expected life span by 35% to 6.5 years.

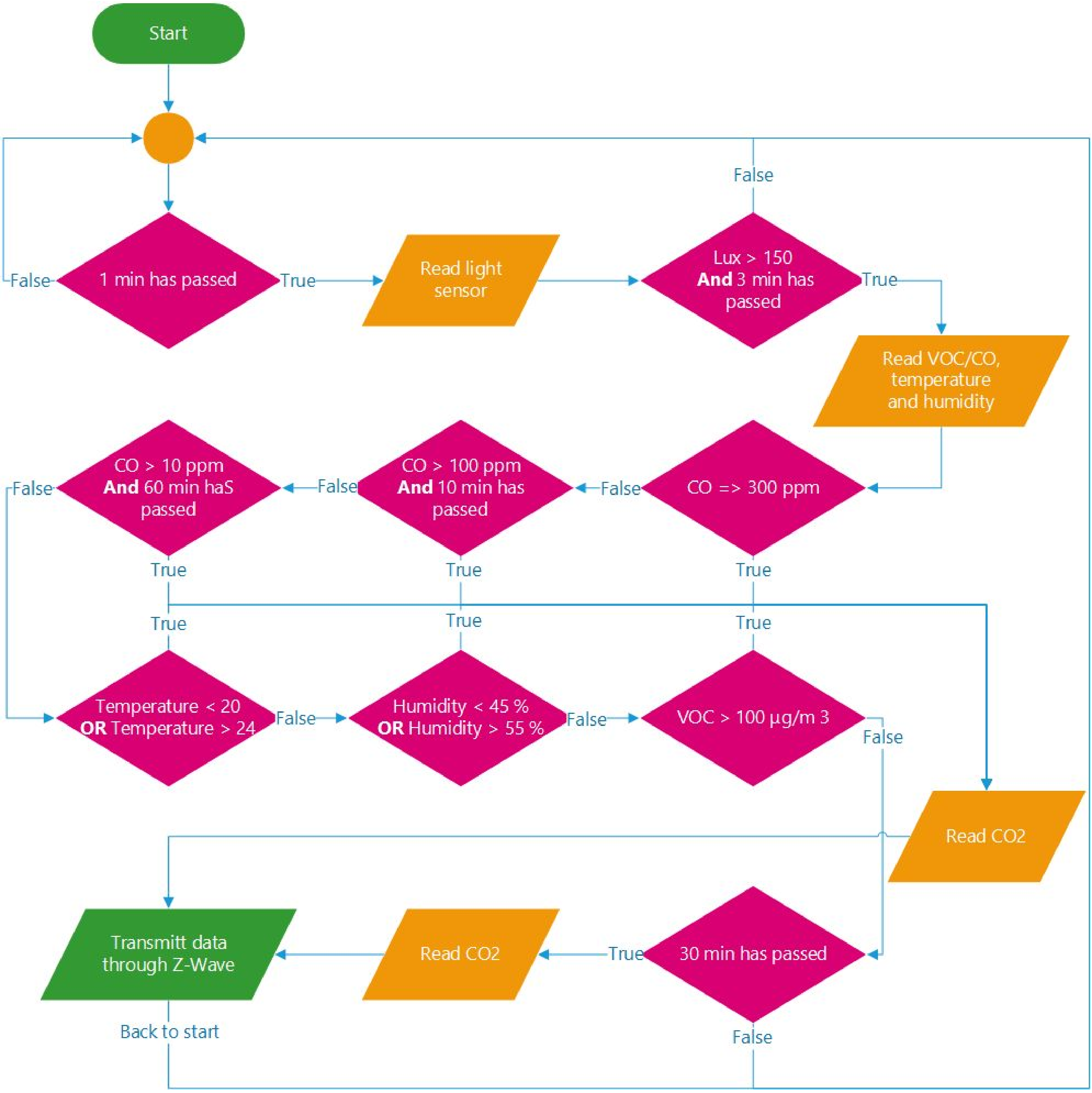

Figure 10. Flowchart for when to read from the sensors

Analysis of flowchart:

The first if-statement controls if one minute has passed, then reads the light sensor. The second if-statement is used to control if the light is on in the office and three minutes has passed.

If the second if-statement is true then it should read the VOC/CO, temperature and humidity sensors.

The next step is seven important if-statements, if one of them is true then it reads the CO2 sensor and the data transmits to the receiver which will present the data or maybe trigger the alarm.

The first three if-statements after VOC/CO reading are only about CO data, the worst case scenario is that the CO can be very high and kill people within 3 minutes. How dangerous CO is depends on mainly two things, concentration of PPM and time. CO division in our system is an inspiration of three different CO alarm systems [48][49][50].

Temperature, humidity and VOC if-statement is based on the "normal indoors" limit values in Table 1. The system reads these sensors in 3 minutes interval, in fact the system is forced to do that when it could have been a little longer periods of time. In this scenario the algorithm has a limitation caused by the hardware VOC, CO, temperature and humidity is one big sensor.

The last if-statement used to force the system to transmit the data and to read from CO2 when 30 minutes has passed. CO2 limit indoor is 1000 PPM but the limit value based on CO2 coming from people staying in the room [51], and there is a hard connection between heat and the number of people in a room [46][47], so if the CO2 will increase during a period of less than 30 minutes, the system will detect it via VOC/CO sensor.

There are always limitations in algorithms, this algorithm does not include what happens for example when battery ends, reading problem of the sensors and transmission problem.

If the battery starts to run out, a red light on the sensor should be lit with explanation text, and error message should be sent to the receiver with the battery status.

If it is not possible to read from a sensor, an error message should be sent to the receiver with the name of the sensor.

If there are transmission problems, air quality sensor should light another red light with explanation text, and there should be a control in the receiver side if the air quality sensor has not send any data in a while.

6. Conclusion

We connected the system according to the block diagram and got readings from all the sensors. We made calculations according to our algorithm we can conclude that we are not able to create a system that can last for 10 years and we need to either increase the battery capacity by at least 35% or decrease the expected life time of the system to 6.5 years.

We had major challenges during this project, the first one was to find the best sensors and to find the most important topics in the air to measure to ensure that the air in the room is good. We can say that we have found the best sensors with best power consumption and with reasonable prices. We have also done major investigations to find the best topics in the air to measure, we have found 8 air properties and we measure 6 of them with the air-quality sensor system and we are satisfied with the results.

The second major challenge was to make a good algorithm so the battery works for at least 10 years. And we did that by two ways: 1: by not reading from sensors very often and by reading from the sensor when there are people in the room (by using light sensor). 2: by using power-efficient sensor and microcontroller and by using switches.

Because we focused on making the system as battery efficient as possible, we had to sacrifice the measurement accuracy of the CO_2 sensor. It was just not possible to both get very accurate readings of the CO_2 and making the sensor system last for 10 years on a 480 mAh battery.

We believe our system should only be used to regulate the ventilation of a room to increase the productivity and comfortability of the people inside, and should not replace fire alarms. Mainly because of how dangerous CO is and how fast it can kill a person if it reaches high levels.

7. Ethics and social aspect

This system has the potential to really improve the environment in the workplace and improve the health and productivity off the people working there. By providing a wireless and battery driven air quality sensor, there will be no need to spend a lot of time and money to install wired air quality sensors in every room.

However because we had too balance sensor reading timings with battery drain, we are not confident that our system should be used to replace fire alarms that can detect when the air reaches dangerous levels immediately. We think our system should be used to increasing the productivity and comfortability of the people inside the workplace.

8. Future work

We hope we can improve the system by actually putting multiple sensor around different offices and school to see if our theory can work in a real life environment. We also hope that better and more efficient sensor technologies is created, so that we can have a CO_2 sensor that is both power efficient and accurate.

Better and more power efficient sensor technologies is also very important for shorting the interval between sensor reading without sacrificing battery life. We also hope to include more air-quality sensor to our system like for example: radon sensor and particle sensor, so that we can create a air-quality sensor system that can read all harmful properties in the air.

We also believe that implementing solar power can be used to create an even more battery efficient air-quality system, solar power could be used to constantly recharge the battery.

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