CHALMERS
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Development of an Air Quality Monitor for Increased Productivity

The full development process from problem identification to a working prototype

Master's thesis in Product Development

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Gothenburg, Sweden 2024
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Cover: Visualisation of final product modelled in Fusion 360 and rendered in KeyShot 10. Example interface and shape of the product is seen.

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Abstract

In the modern world, air pollution in densely populated areas is increasingly becoming more of a problem. This is well known to affect personal health negatively, but lesser known is also the impact on productivity and human cognition. With products for measuring air quality is a developed market the products connecting it to productivity and providing recommendations to improve it are far less. This thesis is therefore set out to explore the effects on productivity from poor air quality and to develop a product as a solution.

Air quality is found to affect productivity through many metrics; temperature, humidity, volatile organic compounds, carbon dioxide and particulate matter are some of the most impactful parameters and becomes the aim to monitor for this project. It is found that productivity in a poorly ventilated room, which is not that uncommon, can degrade by as much as 50% [1]. Creating awareness of this effect could possibly increase human productivity around the world by a significant margin and result in overall improvements.

For the product to be successful it has to comply with the current market and user needs. This is therefore an important research topic sought to understand for the development of the product. A thorough and systematic product development methodology has been used to arrive at an optimal concept solution for the air quality monitor. As a goal and for introduction to the market, a minimum viable product has been developed with the purpose of giving users an initial understanding of the monitor. This prototype is used as proof of concept and to communicate the project proposal to external parties.

Keywords: Air Quality, Air Quality Monitor, Productivity, Human cognition, Awareness, Product Development, Minimum Viable Product.

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We extend our gratitude to the Global Mentorship Program's endorsement in making the 3-month field study in India possible as well as for the insights by the mentors and the crash courses before the field study.

We would also like to thank the Indian Institute of Technology Delhi where we were able to work and meet talented people to discuss with. We would especially like to acknowledge Professor S.Paldas at the design department for his involvement both on and off campus.

Lastly, we would like to express our gratitude to our friends and family back home in Sweden who supported and energised us.

Erik Albinsson & Måns Karlsson, New Delhi, June 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Air Conditioning
AI	Artificial Intelligence
AQ	Air Quality
AQI	Air Quality Index
CAD	Computer Aided Design
CO_2	Carbon Dioxide
DC	Direct Current
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
I^2C	Inter-Integrated Circuit
IEQ	Indoor Environment Quality
IITD	Indian Institute of Technology Delhi
LCD	Liquid Crystal Display
MVP	Minimum Viable Product
PhD	Doctor of Philosophy
PM	Particulate Matter
ppm	parts per million
RQ	Research Question
RH	Relative Humidity
SEK	Swedish Krona
UI	User Interface
USB-C	Universal Serial Bus Type-C
UX	User Experience
VOC	Volatile Organic Compounds

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1
Introduction

The connection between air quality and productivity is something that has been a growing research interest during recent years. That human cognition or performance is affected by the air we breathe is an established fact, but the awareness of the public is uncertain. This Master Thesis therefore explores the area and aims to develop an air quality monitor to inform every day users of how the air quality around them affects their productivity. A structured product development process is followed which consequently arrives at a minimal viable product for proof of the product concept.

1.1 Background

Air pollution is well known to affect human health in various harmful ways. This is most prevalent in densely populated countries or cities where emissions from traffic and other consumer products are high. Another aspect that is affected by air pollution or air quality in general is productivity which is an essential metric for both individuals and organisations. This interest for good air quality can be seen through the industry of HVAC and other ventilation systems for example. But these products mostly focus on larger scale installations, and few products are seen having direct interaction with users and information regarding the air quality is very limited. With the current and increasing focus on both air quality and productivity, this is an interesting field to study and to see if a potential product could be successful. Therefore this project intends to develop a monitor that can give users information and create awareness about the air quality around them. This could be paired with suggestions on what consumers can do to easily increase their air situation to improve human cognition. A small increase in productivity, on a large enough scale, and in the long term could have great impacts on the final results. However, the market for this kind of product is not explored yet and because of this, a minimal viable product is developed to reduce risk and to give initial feedback from the market for future continued development.

For more efficient development and to help people in need, the majority of this thesis is conducted in New Delhi, India, where the air quality situation is particularly bad. Breathing the air in Delhi during one bad day can have the same effect as smoking as much as 25-30 cigarettes [2].

The development will more specifically take place at the Indian Institute of Technology [3] because of the availability of resources and research contacts. A stipend from The Global Mentorship Program [4] was received as budget for the trip regarding logistics, field studies, and materials for the project.

1.2 Scope

This thesis intends to investigate how an optimal air quality monitor for increased productivity could be designed. The main focus is on using product development methods with a systematic approach to explore as much of the design space as possible to then funnel down successively into a final result. This includes initiation from the early phases of market research and user understanding all the way to creation of a minimal viable physical prototype. UX interface, manufacturing & supply chains are however left for future exploration.

The scope also further includes the specifics regarding the fields that the product will be targeting, meaning air quality & productivity. Gathering data regarding what some prevalent air quality parameters are, what the optimal range is of these parameters, and how they affect productivity. The specific research questions that the thesis addresses are described in the following section, and the results can be found in Chapter 7.

1.2.1 Research Questions

The main research question and objective for this project is the first one in the list below. The others are all linked to this first one as milestones for the study to support the final result. While still being explicit RQs since they are key objectives for the project, they are of less importance and are therefore documented more briefly.

- **RQ1: What is the optimal design of an air quality monitor for increased productivity?**
  - This RQ focuses on a holistic way to develop the design considering what sensors should be included, how they are connected, how the casing looks, how to make it user friendly etc. It is evaluated by methods of targeting a specific market segment and satisfying the customers needs to the highest level.

- **RQ2: How interested are the main customers and users of monitoring air quality as a way to increase productivity?**
  - The product is created to be sold to generate profit and to have a positive impact globally by creating value for the end user. So the most interested user needs to be identified. The customer and user can be different and the number of these will determine if a viable market segment exists.

- **RQ3: Is there an impact from air quality on productivity? If so, what are the major parameters that have an impact?**
  - An air quality monitor could be used to improve health in general or reduce the risk of getting sick but this thesis will focus on evaluating productivity. Importance is then put on finding the most impactful parameters.

1.2.2 Delimitation's

The project employs a holistic view of product development but all aspects can not be considered since the resources needed would exceed the possible limits, like exceeding the time frame or budget of the project. To deal with this, certain delimitation's are set at the beginning of the project and are continuously updated as the project progresses. As more information is gathered and details are clarified, the scope can be updated accordingly.

Masters Thesis Limitations

The project is a master's thesis which means that the project is conducted by two M.Sc. students with a time frame of four months and with limited budget and resources. This means that compromises has to be made on where to focus, and some areas might only be explored briefly or left entirely for further work. The limited connections also have an impact on user studies not reaching a vast population leading to the data acting more as an indication than documented facts.

Focus on Productivity

This project focuses specifically on productivity and human cognition, which are subcategories of health. The aim is to translate air quality parameters into terms relevant to direct affect on productivity and cognition. This niche was chosen to maintain a manageable project scope and target a new market segment, as most competitors concentrate on general health. A product integrating both health and productivity aspects could be more comprehensive but would also be more complex and very likely more expensive.

Focus on Monitoring

The product is intended solely to monitor air quality, not to improve it. This choice simplifies the product, making it less complex and expensive, while still meeting a market need. Customers can achieve value in knowledge of air quality without necessarily improving it, which is beneficial since monitoring alone demands fewer resources. The data collected can motivate users to make improvements further on and invest more resources. Only measuring and not improving is also seen as a reasonable approach when looking at similar successful products such as an indoor thermometer. So although this thesis will not develop air purifiers or filters, recommendations for such improvements may be suggested to work alongside the air quality monitor.

Air Quality Parameters

With the product development engineering methods as the core of the project, the supporting research about AQ will be limited to six parameters which seem to have the biggest impacts. Light and sound, which can otherwise have major impacts on productivity, are not considered since the focus is solely on air quality.

Product Design & UX

The product's mechanical and electrical components will be addressed in this report while the final user experience design both regarding form and medium of communication is left for future work. Designs are created but as examples without specific research or methodological processes.

Manufacturing, Supply Chain & Commercialization

While the manufacturing & supply chain possibilities are taken into consideration during the development to evaluate how they can affect the economics of the product, the specifics of the manufacturing as well as how the supply chain will look are not detailed in this report. Similarly, no concrete commercialization plan or break-even analysis is created.

1.3 Report Layout

This report is structured in a progressive timeline format, reflecting the chronological order in which the project was conducted. Each chapter represents a main phase of the project, completed sequentially before progressing to the next. There is no methodology chapter since this is included in each chapter on its own for a more cohesive reading experience.

At the start of each chapter there is a short introduction to how the previous work is connected to this chapters task, how it turned out and what the goal of that phase is. Similarly there is an introduction under each section. Lastly there is a discussion chapter including reflections on different major aspects of the project and after that a shorter conclusion connecting back to the initial thought of the abstract.

2

Background Research

For developing the product, theoretical research is required to understand what parameters the product should evaluate and in what range the values should be. As well as what an appropriate response is if one of the parameters goes outside the normal safe range.

There are an abundance of parameters in the indoor air that affect the human ability to perform. Many of the parameters are inter-dependant and therefore in a complex relationship. *"Due to the complexity and interconnectedness of parameters, IAQ is a very complicated entity to measure"* [5]. To create a simple product that the user can understand easily, a few main parameters have been identified. These six parameters are explained in their respective subsection and have been identified as the most impactful and the most realistic to measure, they can be seen below shortlisted:

- Temperature
- Humidity
- Carbon Dioxide - CO_2
- Particulate matter 2.5 µm - PM2.5
- Particulate matter 10 µm - PM10
- Volatile Organic Compounds - VOC

2.1 Temperature

Temperature is a major air quality parameter that affects productivity. *"It represents the longest studied and a very important parameter of IEQ. Only when people feel thermally comfortable, can they produce in full capacity"* [5]. Thermal comfort can be seen as an umbrella term for all parameters affecting performance connected to temperature. This includes [6]:

- Dry bulb air temperature
- Mean radiant temperature
- Relative humidity of the air
- Air velocity
- Human metabolism
- Clothing level

Out of these six parameters, only two are relevant to include in the intended air quality monitor, namely dry bulb air temperature and relative humidity of the air because of project limitations. These will hereafter be referred to as just temperature and humidity. Studies have also shown that people of different sex, body mass and age have different thermal comfort levels [5]. How these personal factors have an impact will not be analyzed in the report's scope.

Combining the research done by Mujan et al. stating that optimal working temperature ranges from 21 - 25°C [5] and Seppänen, O. and Fisk, W.J. who shows that 20 - 23°C [7] are preferable, a suitable range for productivity to aim for will in this project be used as between 21 - 23°C. Worth to note here is that this range differs some for different areas in the world [5] and that the rate of impact from temperature on productivity follows a bell curve that can be seen in Figure 2.1. It is also described that if the upper limit of 25°C is exceeded, productivity decreases by 2% for each degree, which in the long run can generate major impacts on the overall performance.

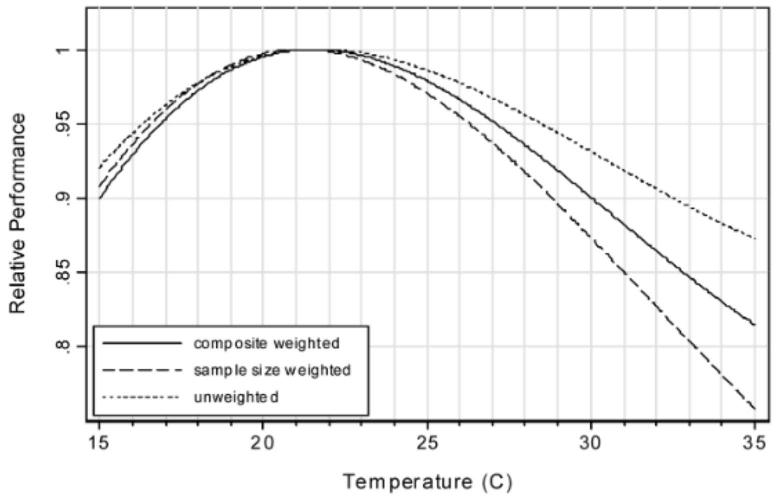


Figure 2.1: Relative performance vs. temperature. 20 - 23°C can be identified as the greatest performance temperature with approximately 21.5°C being optimal for the average person. This graph is derived from other data gathered by Seppänen, O. and Fisk, W.J. and can be furter studied in their report [7].

2.2 Humidity

Air humidity has a big impact on people mainly since it changes the way temperature is perceived, but it also indirectly affects humans with its effect on for example viruses, bacteria and mold [8]. Humidity can be seen both in absolute humidity referring to the actual amount of water vapor in the air, measured in grams per cubic meter (g/m^3), and relative humidity which is the amount of water vapor in the air in relation to how much the air can hold in total [9]. The humidity level is usually noted as relative humidity, referring to how many % of water the air is holding in comparison to the total amount it is capable of. 50% humidity means it could hold twice as much water before fully saturated. Since it is a relative term and warm air can hold more amount of water, the relative humidity can decrease if it gets warmer even though the actual amount of water vapor is the same.

In general, the recommended relative air humidity level has some sources mentioning the span of 30-50% while others and often more recent numbers are between roughly 40-60% [10]. The major direct effect of relative humidity is how cold or warm people feel. When increasing humidity in already warm temperatures people feel hotter since water has a higher heat transfer capability and it limits the body's internal regulation through sweat, it works less efficiently since it is harder for the sweat to evaporate into the air [11]. As seen in Figure 2.1 performance drops around 2% for each degree over 25°C and with higher humidity the increase in temperature is felt at a higher degree. 30 degrees with 40% humidity is felt like 30 degrees while if it is 80% humidity it is felt as 37 degrees [12]. The direct correlation between humidity and immediate productivity is less prominent than temperature while self-reported workload has been seen with a higher correlation to humidity [13]. Ghanbariazarneir then raises the hypothesis that the higher self-reported workload is more mentally draining and could in the long run affect productivity. To reduce the risk of an increased sense of workload which could affect productivity it could then be beneficial to strive for a 40-60% humidity.

2.3 Carbon Dioxide

Carbon dioxide or CO_2 as it is commonly written is an important chemical even though it typically only persists in 250-400 ppm of the air outdoors and 400-1000 ppm indoors in normal conditions. In badly ventilated rooms it often ranges from between 1000-2000 ppm [14]. The CO_2 in the atmosphere comes from many different sources like burning wood or using fossil fuel but also comes from humans or animals breathing when using cellular respiration to create energy. This means that people can affect the CO_2 levels in a room, especially in smaller spaces with limited ventilation, so when people are indoors the CO_2 levels go up rapidly simply by breathing[15]. The major effect that can occur was documented with empirical data gathered by PhD students at IITD, where they studied the CO_2 levels with four people in a car without ventilation as the levels went from 2168 ppm to over 7000 ppm in half an hour [16].

When the CO_2 levels increase it can affect cognitive ability. In conditions of 950 ppm CO_2 researchers saw a 15% decline in a set of cognitive function tests in comparison to the normal level at 600 ppm CO_2 [1]. The same test also collected data when the concentration of CO_2 was 1450 ppm and showed the results of a 50% decline in cognitive function score, which is a value that as stated previously often occurs in poorly ventilated rooms. Further details regarding how different performance aspects were correlated to the different CO_2 levels can be seen below in Figure 2.2.

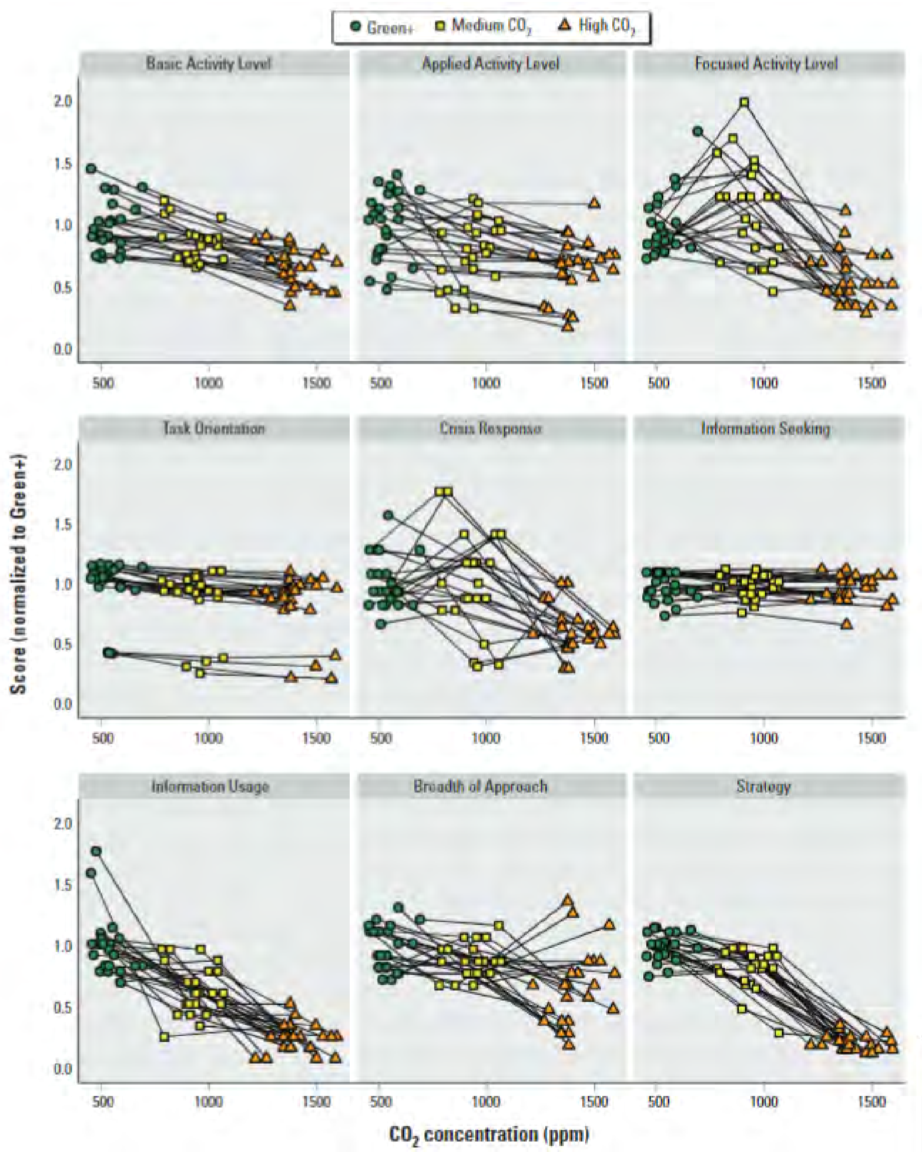


Figure 2.2: Cognitive function scores in relation to three different levels of CO_2. The score is normalized to 1 for the average user in the low CO_2 level. The tests were conducted using the Strategic Management Simulation (SMS) software tool, regarding 9 different cognitive categories [**CognitiveFunction_VS_CO2_VOCs_e**].

2.4 Particulate Matter

Particulate matter or PM as it is commonly called measures how many particles there are in the air, looking not only at one kind of particle but at all particles under a certain size [17]. It is divided into different size categories where PM2.5 and PM10 are commonly used, PM2.5 measures all particles under the size of 2.5 micrometers and PM10 measures all particles under 10 micrometers. The particles can come from natural sources like gravel roads, fields, and fires but also from construction sites and similar human production. A major part of the particles do not directly come from the sources but are created in complex chemical reactions in the atmosphere of different chemicals that have been produced by industries and automotive [17].

There is a growing amount of research showing the negative impact on labor productivity from air pollution and specifically particulate matter[18]. Laurent et al. states in their conclusion that "*we found that higher indoor PM2.5 levels were significantly associated with decreased performance in Stroop response time, interference time, and throughput, and lower ADD throughput*" [19]. These are all different methods of estimating cognitive function which in turn has a direct impact on productivity. It has been found that a numerical decline of 1% in performance for every 10 μg/m^3 of PM2.5 [20].

Particulate matter is also an important factor considering that the WHO states that 5.5 billion people are living in places where the PM2.5 levels are above the recommended safety level [18]. PM2.5 levels under 12 μg/m^3 are regarded as safe, while if it is above 35 μg/m^3 for longer periods it is a health concern and affects people's breathing, and levels above 50 μg/m^3 causes serious health alterations [21].

2.5 Volatile Organic Compounds

Volatile Organic Compounds or VOCs is an umbrella term for many different particles and chemicals, like for example benzene, ethylene glycol or formaldehyde. They are organic compounds created mostly by humans and come predominantly from factories and combustion of fuels. Indoor sources persists of human activities such as cooking, smoking etc, but also come from the building and furniture itself [5], [22].

"The problem with VOC measurement is that they have a high diversity in their physical and chemical characteristics and developing standardized procedures for their sampling and analysis has proven to be difficult" [5]. Allen et al. include as many as 27 different VOCs in their study about cognitive function in connection to CO_2, VOCs and ventilation [1]. The full list of all the parameters measured during this study for each simulated scenario can be seen in Appendix A. They however also show profound increases in cognitive function when VOCs are decreased from normal conventional levels to more optimal levels as seen in Figure 2.3. The more suitable levels of VOCs were simulated in two scenarios called Green and Green+ which reflects the VOC air quality for buildings classified as Green or Green+. The VOC levels were constantly under 50 μg/m^3 on the Green and Green+ days and approximately 506 – 666 μg/m^3 on the Conventional days. *"On average, cognitive scores were 61% higher on the Green building day and 101% higher on the two Green+ building days than on the Conventional building day ($p < 0.0001$)"* [1]. The great impact on productivity imparts that VOCs definitely should be included for an air quality monitor. Although what parameters of VOCs should be measured and the complexity of this process will decide on what is feasible to include.

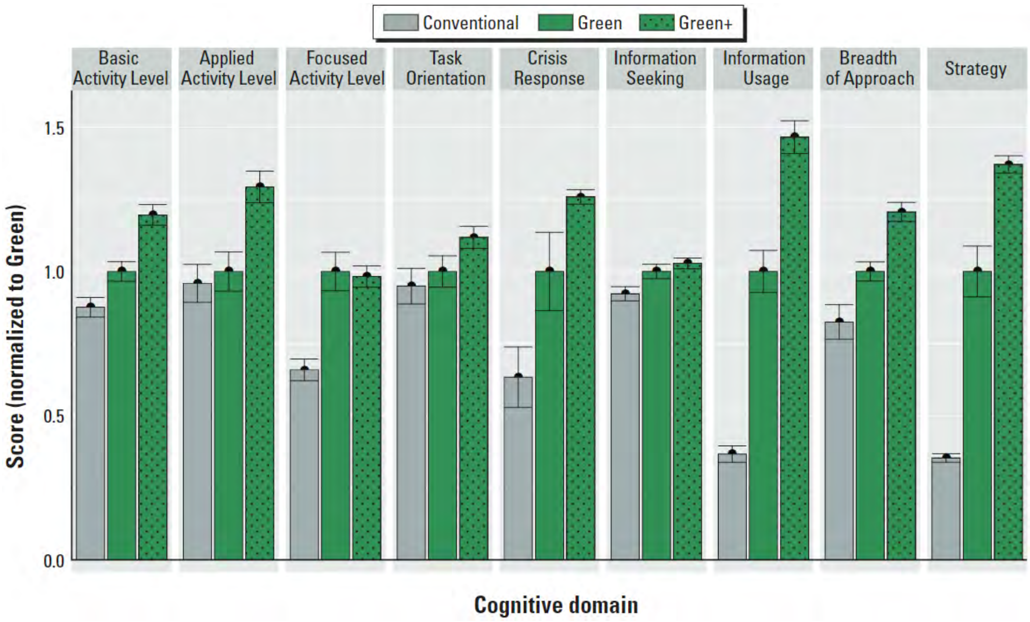


Figure 2.3: Average cognitive function scores and standard error bars for three different testing situations (Conventional, Green and Green+), where score is normalized to 1 for the average user. The tests were conducted using the Strategic Management Simulation (SMS) software tool, regarding nine different cognitive categories [1].

3
Market Analysis

This chapter handles the initial market analysis done before starting to develop the product. First investigating the current market and how it would impact the sale and use of the air quality monitor, and then diving deeper into what technical aspects and what components might be of special interest for the development. The goal is to gather a better understanding of whether the product would succeed in the market as well as identifying major obstacles and opportunities.

3.1 Competitor and Market Analysis

The competitor and market analysis has a pivotal role in the development of an air quality monitor, understanding the market landscape as well as the different competitors is important to make a realistic and comprehensive evaluation of the business opportunity.

The goal of this section is to first evaluate if the development of an air quality monitor can be competitive in the market. Then to get a quick overview of where this opportunity lays, a SWOT and PESTLE analysis is made. The standard of the market is found in analysing different competitors as well as analyzing the different solutions for measuring AQI parameters. This information is later used for setting realistic requirements and desires for the product. As well as knowing in what areas to prioritise what aspects, to get as much value out as possible from the development resources spent.

3.1.1 Real-Win-Worth

The first method used during the project was a real-win-worth analysis, since it forces the developers to investigate and see if a business idea actually has potential and should be further developed. If there is a **Real** demand and if the customer can and will buy the product. **Win** regards to if the product will out-compete competitors and find a place in the market. If the product is **Worth** to develop takes costs and commitment into account. The answered Real-Win-Worth analysis can be seen in Appendix A.2.

The two main negative aspects identified are *if the the product will be worth the price*, and *if the product will be better than the competitors*. The price is however highly dependent on the scale of production. Many competitors that sell similar electronic products for a low price gives an indication that low cost is achievable if a big enough scale is produced. This in combination with higher living standards in the future validates the development of this product, although the risks are taken into consideration during the development.

If the product will outperform its competitors is difficult to answer. Because many different things can increase productivity and be qualified as competitors, for example having a lamp with adjustable lighting settings or simply taking a walk, it is difficult to see if people would still purchase the air quality monitor. The lamp would have a more direct competition where both are physical products that the user can buy and use while working. Taking a walk is a more indirect competitor since the use is different, but if the end goal is to be more productive during the day, the walk can be an easier and cheaper alternative people prefer. A positive fact is that an air quality monitor is synergistic with these other competitors of productivity even if still using competitors. So from this point of view and with predictions that productivity will be even more valued in the future makes it relevant for further development.

3.1.2 SWOT

The SWOT analysis was made early during this project to get a quick understanding of the monitors position in the market before continuing the project. To understand what areas needs to be considered and acted upon, with the outcome seen in Figure 3.1 showing the **S**trengths, **W**eaknesses, **O**pportunities and **T**hreats for the project. The main benefit was to get a broader understanding of what opportunities and threats there are for the product and business idea and what areas needs to be inspected more closely during the project. The main takeaways are that productivity is highly valued [23] and is a strong driver and motivator for the product in general. Although it is uncertain if the need for the product is big enough, so this is one of the first things that needs to be investigated. Is the need for a small and uncertain increase of productivity worth the price that the product will cost? Is the connection between productivity and air quality well known enough to create a sustainable customer base? But few competitors together with a possibly substantial customer base makes it worth to explore the idea further.

Strengths	**Weaknesses**
• Product Development skills • Broad understanding of engineering • International contacts • High flexibility and low risk	• Limited experience in entrepeneurship • Small budget • Limited time for project • Connection between productivity and air quality is difficult to study and understand
Opportunities	**Threats**
• Productivity very relevant and higly valued • Not really any competitors in exactly this field • Relevant contacts in the field • Very broad target customer base • Can see future possible sub-categories of the product targeting more markets	• Uncertainties regarding need for product • Difficult to get competitive price • Possible difficulties to understand user needs • Difficult to introduce new product into new market

Figure 3.1: SWOT analysis regarding both the product and business.

3.1.3 PESTLE

The PESTLE analysis is similar to the SWOT analysis in the sense that it establishes a structured understanding for the product or project regarding the subjects from the abbreviation: **P**olitical, **E**conomical, **S**ocial, **T**echnological, **L**egal, and **E**nvironmental aspects. It can be seen in Figure 3.2 and focuses on external factors that can impact the project or business and are worth taking into account when researching and developing the product. The disadvantages realised again regarded the uncertainty of the price, but also the technological complexity of the product. As an interactive consumer product, legal requirements might be necessary to satisfy for the use of the product. This could potentially constrain development significantly, especially if the product claims to increase productivity. Otherwise, most aspects found were positive. Political agendas mostly align with the product's, same for social norms. A market demand is found and should only be expanding with the growing middle class. The product monitors the air quality which is a great benefit for the environment. Lastly there are opportunities regarding economical production in for example India with the use of less complicated and outsourced technology.

Political	Economical
• In line with many political agendas • Can potentially get subsidised • Public sector can be seen as a customer • In public sectors interest to support start-ups	• Can possibly yield great return on personal investment • Uncertainty regarding price, can potentially become expensive as a one time investment • Affordable manufacturing in India • Trending to invest in environmental products
Social	**Technological**
• Productivity is generally seen as valuable • Trending to maximise productivity • Many people interested in ones own environment • Potentially useful for greenwashing • Shift towards more remote workspaces increase demand for portable environmental monitors • Global growing middle class and rising living standards	• No new technology needs to be developmed • Relatively simple technology can be used • Technology dependant • Relatively complex product and supply line • Possible connection into IoT systems for monitoring and awareness of complex air quality systems
Legal	**Environmental**
• May require many certificates for use • May require many certificates for manufacturing • Might conflict with existing patents • Can be used for standard testing and validation	• Relevant to care about the environment • Enables easier monitoring of environment • Environmentally friendly in terms of improvement of awareness • Manufacturing impacts the environment negatively

Figure 3.2: PESTLE analysis regarding both the product and business. Green dots describe positive aspects, black means neutral and red shows negative aspects.

3.1.4 Competitor Analysis & Benchmarking

A benchmarking analysis has been done to get a more comprehensive understanding of the market and what components are used in similar products. In total 10 competitors have been analysed ranging from high end to low end products with somewhat different use scenarios. All of the products only monitor the air and do not improve it, however some are able to connect to wider systems for automated monitoring and improvement of the air. The full benchmarking analysis can be seen in Appendix C, but a summary is shown in Table 3.1 with following descriptions of each competitor. Following are also a competitor analysis for each of the 10 competitors.

No.	Competitor	CO_2	PM 2.5	PM 10	VOC	Humidity	Temperature
1	Kaiterra Sensedge	•	•		•	•	•
2	Kaiterra Sensedge Mini	•	•	•	•	•	•
3	Atmotube PLUS				•	•	•
4	Atmotube PRO		•	•	•	•	•
5	Atmocube	•	•	•	•	•	•
6	Sensibo Air PRO	•			•	•	•
7	Air Quality Guardian	•				•	•
8	Airthings Wave Plus	•			•	•	•
9	Airthings View Plus	•	•		•	•	•
10	Cikonielf Air Quality Monitor	•				•	•

Table 3.1: Table showing with a dot (•) which products monitors what parameters.

(a) Kaiterra Sensedge [24]

(b) Kaiterra Sensedge Mini [25]

(c) 3. Sensibo Air PRO [26]

1. Kaiterra Sensedge

Kaiterra Sensedge is by far the most expensive air quality product in this analysis with a price of 12500 SEK. However it delivers with a sleek and large interface with clear data and instructions. It measures every interesting parameter except PM 10. Overall the product focuses on large scale high end businesses which are mostly office based. Quality and customer service are key competitive factors.

2. Kaiterra Sensedge Mini

The Kaiterra Sensedge Mini is from the same brand as the previously mentioned product, this means that many of the same services and values are put into this product. The Mini version is smaller and actually also measures the lacking PM 10 covering all parameters. It is also less costly with a price of 7500 SEK and have a smaller size. Because it focuses on only measuring, it does not have any user interface leaving the user to use either the Sensedge original or use of an app or website. Only the cost of this product makes it less competitive on the market, but overall a very solid product.

3. Sensibo Air PRO

Sensibo Air PRO is made with connection to another air purifying device in mind. It competes through great communication with the user, including a voice recognition feature. But it only senses a few of the sought after parameters, with its CO_2 done by calculation using other parameters sensed, leaving a close, but not real monitoring of the actual CO_2.

(a) Atmotube PLUS [27]

(b) Atmotube PRO [28]

(c) Atmocube [29]

4. Atmotube PLUS

The Atmotube PLUS is definitely the smallest product out of the ten. It has a size similar to a cigarette lighter with a suitable clip for a key chain. This of course has an impact on the amount of sensors and battery it can have. Measuring only VOCs more than the easy to measure humidity and temperature does make this product much less competitive in the air quality sense. But the size and extreme portability in combination with the low price still makes it relevant for many situations.

5. Atmotube PRO

This product, as the name hints, has a similar use case as the Atmotube PLUS, but is more comprehensive overall. It measures all parameters except CO_2, but because of this comes in a larger size with a higher price. It is still marketed as a portable air quality monitor that has a clip for easier carry. Same for this product, the interface is through connection to an app.

6. Atmocube

Atmocube is the second product that actually senses all parameters that are included in this project. It needs to be connected to another device for reading the data, but also has a number of buttons for setting the product. It is relatively small but has a price more on the expensive side of 6500 SEK. Because of the broad sensing array, combined with its interface and size and not too expensive price, the Atmocube is identified as the best product for a similar use as the project is looking for.

(a) Air Quality Guardian [30]

(b) Airthings Wave Plus [31]

(c) Airthings View Plus [32]

(d) Cikonielf Air Quality Monitor [33]

7. Airthings Wave Plus

This sensor measures most parameters but leaving particulate matter. It needs to be connected to another device for seeing the data, but has some intuitive simple led displays. This monitor is although the only sensor that monitors the amount of radon in the air. Because of this it makes it a more niche product which has a smaller market, but more competitive there.

8. Airthings View Plus

The Airthings View Plus is actually not similar to the previous monitor, even if from the same brand. This monitor focuses more on displaying the real time data measured. It almost cover the full spectrum of parameters, but still is able to have a competitive price. Overall a good product.

9. Air Quality Guardian

The Air Quality Guardian is mainly marketed towards health focused users. It only measures CO_2 apart from the common humidity and temperature. However the CO_2 seems to be thorough which makes it competitive in just that area. It has a good interface screen which makes it suitable to use as a health monitor.

10. Cikonielf Air Quality Monitor

This little monitor is the the least costly of all of the products. It measures only CO_2 and humidity and temperature. This is the only product not being able to connect to another device for reading the data online. It because of this has a quite good user interface and screen on the product itself. It competes through its simpleness and the price.

Benchmarking conclusion

Since the project's task is to develop an air quality monitoring product that increases productivity, the competitors analysed all focus on monitoring air quality. Other competitors focusing on productivity could also have been relevant to analyse like lamps or noise-canceling headphones that are used to increase productivity. However, this connection is more vague and the physical products differs in a major way that is outside of the scope. Comparing air quality monitors to noise-canceling headphones is more connected to finding the user needs rather than gaining knowledge on how to develop an air quality monitor. Finding user needs is of course important, but the latter is more of a focus during this phase. Similarly indirect competitors like having a snack or taking a nap, might be the first step people take before buying a product to increase their productivity, but the intangible alternatives are too different to reveal beneficial information.

One important note is that none of the products focus or mentions how air quality affects productivity specifically which leaves a hole in the market while it could also be an indication that the market segment is not that big. However, most competitors have the possibility to consider including productivity because they monitor the correct parameters to draw a conclusion about the effects of air quality on people's performance.

It is also important to note that the competitor analysis and benchmarking is conducted against existing products, not future products that the developed product will actually compete against. Also the analysis gives a valuable understanding of the market and generates ideas, but also creates a bias towards existing products that is attempted to be disregarded.

3.1.5 Market validation

For a product to be sold there needs to be a market where there are customers willing to pay for it. The market can give a perspective on how much a product or idea is worth pursuing. It can also give information on what market segment would be worth targeting the most if there are multiple available. For evaluating the size of the market, rough estimations have to be done, to increase the trustworthiness certain empirical data was gathered from a questionnaire created for this project which can be seen in Section 4.2.2. In the early stage of the development of this air quality monitor the main goal was to understand if a viable market exists or not. The actual market size does not matter as much, which is why rough estimations and limited empirical data are used and further data is not collected at this stage. At a later stage when a prototype is created, there could be additional user studies to gather data on the likelihood of people buying the product and the price they would be willing to pay for a more precise market estimation. This would however be further work that is not performed in this thesis.

For making the first estimation to find out if there is a viable market is to identify who the customers would be, how many of those would purchase the product, and lastly how much they would be willing to pay for it. Potential customers are people or organizations who want to show that they have good air quality or to understand it better to be able to improve upon it and in turn, become more productive. This product could be sold all around the world, possibly with some smaller design changes to fit the country's standards. Initially, India, where the thesis is being conducted, will be evaluated at the start for a quick estimation. Other countries and market segments would most probably also be suitable so this estimation does not mean that the segments estimated will be the targeted markets for the end product, but are simply the easiest to evaluate and to collect data from initially. Two major identified customers that are used for this analysis are:

- Students
- Office space personnel

In India, a bit over 40 million students are studying in higher education [34]. Additionally, there are around 50 million white-collar jobs [35]. This fact in combination with the data collected from the questionnaire seen in the Appendix H shows that people are interested in both air quality and productivity. We also see that around 74% students were interested in buying a product that could measure air quality while 67% office workers felt the same way. With the additional question about what they would be willing to pay for such a product an average is produced of how much they would pay. The major limitation at this stage is the uncertainty of manufacturing cost.

Market segment	Students	Office workers
Amount of people	40 M	50 M
Percentage that hears about the product	5%	1%
Precentage of intrested people that actually goes through with purchase	10%	10%
Average price intrested people have stated they are willing to pay	660 SEK	900 SEK
Market value	98 MSEK	30 MSEK

Table 3.2: Market size estimations, indicating initial market of at almost 130 MSEK.

These are rough estimations of what could be possible, and with a product not yet created, the price of it as well as what customers would be willing to pay might not align and could result in a too-costly product. The "percentage that says they might buy it" and "the average prices" are taken from empirical data from the questionnaire that can be seen in Appendix H. The empirical data might not necessarily be reliable either, since answering the questionnaire and what would occur in the real scenario could differ vastly. The "Percentage that hears about it" is a rough estimation with students discussing productivity more and being more interested in an air quality monitor. To deal with this uncertainty and have a margin of error the "percentage of potential buyers that actually purchase it" was added estimating 10 % of the interested people would actually go through with the purchase, which was in a similar range as ChatGPT also found reasonable [36]. The conclusion of the calculations with all the parameters multiplied is that the market could still be almost 130 million SEK which would motivate further development of the product.

3.2 Product and Technology Analysis

In a similar sense to the market and competitor analysis, the product and technology analysis is helpful for understanding the technical requirements for the product. What kinds of sensors there are available and what their advantages or disadvantages are is identified here. A more technical perspective of the market is also gained through the patent analysis. The analysis is used to have some base to stand on when choosing components as well as gathering inspiration for different ways of designing the product.

3.2.1 Technology Assessment

A technology assessment was done to get a quick understanding of the possible sensors available on the market together with their prices, accuracy's, sizes and other parameters. Sensors were therefore identified for all relevant parameters to measure, together with their data and sources. These can be seen in Figure 3.6 or in the full technology assessment matrix in Appendix D.

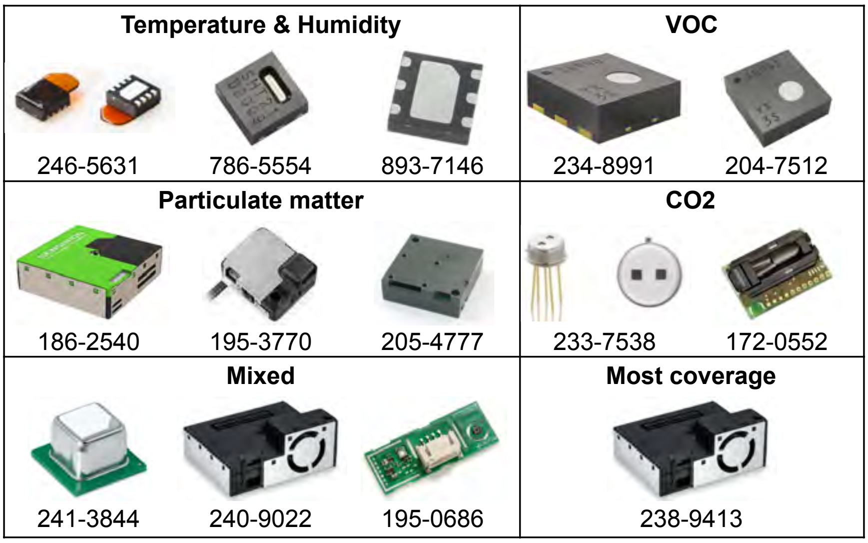


Figure 3.6: All sensors identified to be relevant for measuring the required parameters together with their article numbers. Their respective parameters can be seen in Appendix D.

A conclusion here is that some sensors have a much higher price than others. To measure CO_2 for example is significantly more costly, but in this case includes both humidity and temperature sensing. Humidity and temperature on the other hand are much less costly and are also commonly sold integrated together in one sensor. All sensors are easily available on the market and usually have a lower bulk price which was one of the main objectives of this assessment to conclude.

Technical requirements are also found for the separate sensors; particulate matter sensors require exposure to the air outside of the product or exposure to airflow of the air outside of the product [37]. The humidity and temperature sensors are not as sensitive but require good coupling to ambient air for the measurements to be accurate, wanting good air exposure while still aiming to avoid sensor noise in measurements from air turbulence [38]. One requirement for the VOC sensors identified is that they can not at any time be exposed to humidity over 90%. Exposure to bright light should also be avoided for many of the sensors [39], [40]. This is an aspect that will be taken into consideration in the product layout design.

There are many sensors on the market that measure multiple parameters. These are especially interesting because of the lower price compared to purchasing each sensor individually, and also because of the more simple development and assembly. Although no sensor is found to measure all of the sought after parameters. A combination of two mixed sensors would satisfy all parameters, like a combination of 241-3844 [41] and 240-9022 [42]. However, many parameters are then overlapping, which would not be necessary, but would also increase reliability and robustness of the monitoring.

Note that battery, fan, display or other electrical components are not included in this technology assessment since the needs for these are unknown at this stage. It is also concluded that these components are simpler, have a much larger component variety, and have less design requirements. It is therefore not seen as a risk of not finding a suitable component and will be researched when the specific needs are discovered.

3.2.2 Certifications & IP Assessment

For an every-day-use product like this air quality monitor to be durable and withstand the use environment with exposure to dust and water, fulfilment of the commonly used IP standard is a good way to ensure reliability. The IP standard is written with two numbers where the first one represents the size of particles it is protected against, and the second number indicates how much water it is protected from. It can for example be written as IP53, meaning that the product is "dust-protected" and "protected against spraying water" where the whole specification list can be seen in Appendix E. The numbers for dust protection range from 0 to 6 while the water goes from 0 to 9. The higher the number the better protected it is, but higher numbers also have a strong positive causality to higher cost.

In general, the IP standard plays an important role since it is used to determine how protected the product is, in what environment it should be used and how careful the user should be. But contradictory to the standard where higher is almost always better, in this case the sensors inside of the product also require some exposure to the outside elements to work as seen in Section 3.2.1. The IP standard is given to a product as a whole, but certain sensors needing constant airflow and being exposed directly to the air to capture the dust particles, while also being protected from sunlight and water creates a complicated design problem.

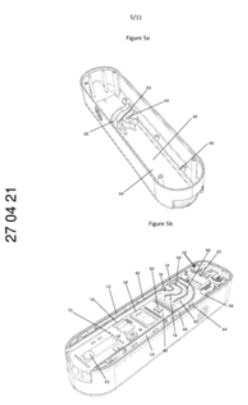
The project goal is to have a minimum viable product that can be used to determine further if there is an interest in such a product. Therefore the prototype does not need to satisfy any certain certifications either, but rather it is concluded that it would be further work for future projects if the prototype is verified to create value.

3.2.3 Patent Analysis

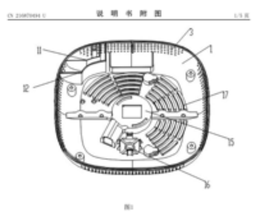
The patent analysis and landscape search can be useful in many ways while developing a new product. Making sure that there is no patent infringement, identifying opportunities for innovation, and understand the competitive landscape are main areas of interest. In this stage of the project, a clear layout of components or design of the product in general had not been decided and because of this, the patent analysis was conducted to get a glimpse of the size of the market and to gather inspiration for upcoming concept generation phases more than investigating specific detailed patents.

The website Espacenet [43] was used for the patent search. Espacenet is a renowned service for patent searches with many tools for simplifying searches, such as classifications or categories and advanced search options for identifying relevant patents easily. Contents about the patents were stated through the advanced search tools, starting with *"air quality monitor?" AND "devic*" AND "produc*"*. This simply means to only receive patents that include all of these phrases with question marks (?) representing any or no symbol and asterisk (*) meaning any string of symbols. This phrasing was done to achieve a more inclusive search.

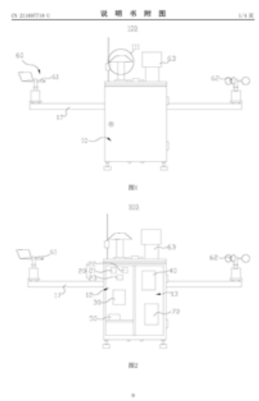
With the given constraints 961 results were found, which were too many to analyze under time constraints. To narrow down further to a more moderate amount, the terms *"indoor?"*, *"user?"* and *"consumer?"* were added condensing down to 273 and then finally to 95 results [44]. These results were screened to quickly see if any were evidently relevant for this project. Design of casing, layout and choice of components were main focus areas. With this in mind, 8 promising patents were identified and they range from mounting to casing design to air flow. The insight from the patents will be used in later phases as inspiration for the concept development, purchasing of components and the design of the casing. Also the argumentation behind the design of the patents has given perspectives on how other parties see the demand and market for these kinds of products. Why the patents are relevant is briefly described below and the patents can be seen in Figure 3.7.



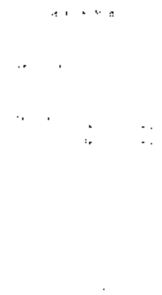
(a) GB2589693A [45]



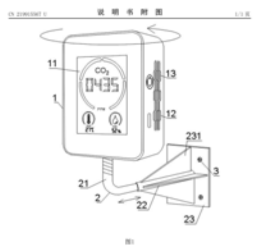
(b) CN216870494U [46]



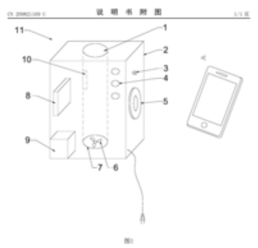
(c) CN211697719U [47]



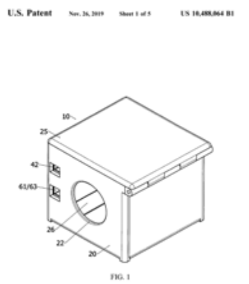
(d) CN106768005A [48]



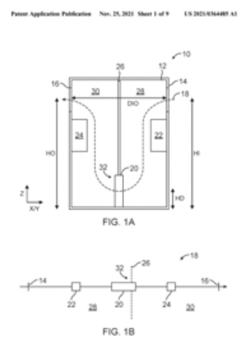
(e) CN219915567U [49]



(f) CN209821169U [50]



(g) US10488064B1 [51]



(h) US2021364485A1 [52]

Figure 3.7: Eight promising patents identified from Espacenet patent search [44].

- **3.7a** is interesting because of the compact layout of components and a intricate design for the air flow.
- **3.7b** because of its design of the air inlet and injection molded design.
- **3.7c** although more scientific, gives a good explanation of components used.
- **3.7d** is the closest patent to an every day portable consumer product which is interesting by itself.
- **3.7e** has an interesting mounting and display for indoors use.
- **3.7f** is a monitor for factory settings with large displays for employees.
- **3.7g** is portable and aimed for "first responders" or emergency situations.
- **3.7h** has an interesting layout of components to direct airflow for more accurate measurements etc.

4

User Studies

A customer is the person or organisation who purchases the product, while the user is the one who would finally use the product. To gain valuable insights into understanding the user and customer, different types of methods are used which all have slightly different deliverables with a balance of gathering both qualitative and quantitative data. Examples could be questionnaires, interviews, or observations. Questionnaires and interviews can be used to both actively ask for specific information through closed questions, but also use more open questions to gather insights into underlying needs and values. Observations can be used even more generally by just noticing how users handle the product.

4.1 Requirement List

With the market analysis done in the previous phase, the next step was to create an initial requirement list that then could be updated and confirmed with the questionnaires and interviews to reduce biases and attain a better understanding of the users. The requirement list is used to see what things are required and what things might be desired, meaning things that are favorable but not necessary, and are what the developers will strive to achieve. Since this was initially done before communicating thoroughly with users it meant a bit of uncertainty. To deal with this, the interviews and questionnaires stated below were used to gather empirical data from actual stakeholders to verify the requirements and desires stated by the developers in the matrix. A cutout of the initial list can be seen below in Table 4.1 for clarification of the layout. The full first iteration of the requirement list can be seen in Appendix F. The list consists of seven columns that specify the criteria description and then all the relevant data are noted down individually in each row.

The criterion	Target value	Requirement or Desire	Importance	Why it is a criterion	Evaluation	Stakeholder
1.1 Long lasting battery	250 hours	D	4	Easy to use	Calculations	User
1.2 Measure CO2	± 5%	R		Core value	Calculations	Developers

Table 4.1: Table showing a cut out of the requirement list for the first two criteria.

The criteria are stated as open and independent as possible for later conceptualisation of solutions to the problem. For example, noting "clear communication to the user" as a criterion instead of "clear display" leaves more design space and does not bias the development at all as much for later development. In the first iteration, the needs were estimated by the developers, using the background research and different market analyses to summarise the gathered information into the requirement list. The measuring requirements came from the research to estimate productivity, the product's shape and price from the different market analyses, and recyclability or ethical aspects came from the SWOT and PESTLE for example.

4.2 Questionnaire Development

To understand the market, user, and customer values, two questionnaires were created using Google Forms and sent out to a variety of people to gather quantitative data. It was sent to people through channels such as public air quality Facebook groups, Chalmers Masters students, and potential customers at universities. This provides input but can be a limitation of not reaching a varied enough group or reaching the people that are expected to be the most likely customers.

4.2.1 Framework for the Questionnaires

The questionnaires consist of mostly closed questions to gather quantitative data, and ideally can get enough replies to be statistically significant results. There are also a few open questions, intending to receive some feedback about unknown unknowns for the researchers, such as needs from certain customer groups that researchers do not have a great insight in. To gain as much valuable information as possible from the respondents while still making it as easy as possible for them to reply, some guidelines were followed which are noted in the list below. These guidelines mostly come from the book Product Design and Development chapter five [53] and The UX Book: Process and Guidelines for Ensuring a Quality User Experience chapter eight [54].

- Use neutral questions to avoid creating bias through leading questions that make the respondents reply in a certain way.
- Avoid field-specific jargon or over-technical terms to not confuse respondents.
- Avoid multiple barrel questions that overwhelm the respondent.
- Use optional questions so people do not have to answer if they do not feel like it to avoid them not answering the questionnaire entirely.
- Avoid double negatives.
- Ensure multiple choice questions cover all possibilities, including "other: " to let respondents add if something is missed.
- Use limited alternatives on multiple choice questions so the respondent does not over-analyze and get stuck.

First, preliminary questionnaires were created with relevant questions and were sent out to a pilot group. This was done to see if respondents understood the questions correctly and if they had feedback regarding how they interpreted the questionnaire. After this, the questionnaires were updated with the relevant feedback from the pilot group and then sent out to reach as many respondents as possible.

4.2.2 Creation of the Market Questionnaire

This first questionnaire focused on understanding people's thoughts about productivity, air quality, their relationships, and how interested people are in acting on the situation. Demographics are also gathered for the possibility to analyse trends between for example age or gender and how they perceive air quality. The data is used to identify if there is a market for the product and possibly receive information regarding user needs. It gathers information about for example if people care about indoor and outdoor AQ, which aspects they consider the most, and how often they try to improve their local AQ. Similarly regarding productivity, if it is something they try to optimise and in that case, if they are interested in it mostly during working hours or also for leisure. This provides indications of which direction to focus the product in and what message needs to be sent through the product to be lucrative for the customer. This is also used to make rough market size estimations with empirical data, seeing how many percent of the sample group would be interested in buying a product that solves the needs the product from the thesis will target. The full response summary can be seen in Appendix H and its data was used mostly in improving the requirement list in Section 4.4. The answers for example indicated that there is an interest for air quality monitoring, that people regularly do something to increase their productivity, and that users can notice when the AQ gets worse, for example in their work environment.

4.2.3 Creation of the User Needs Questionnaire

When creating a product the developers aim to satisfy all the needs and desires of the users as much as possible. These requirements are estimated by the developers but empirical data regarding what needs are most important for the users can be gathered. The estimated requirement list was verified and a deeper user understanding was generated through a questionnaire before the concept development phase would start. Certain requirements had been identified by the developers but with the aim to reduce biases and reduce the risk of missed needs, this questionnaire was created. It asked the respondents to rate how important different needs where on a scale from 1-7 in combination with open questions asking if there is any additional need they feel could be considered. Except from the needs identified by the developers from the start, it also included needs that had been heard from other potential customers both in formal interviews and during informal discussions about the potential product. All the responses can be seen in Appendix I.

4.3 Interviews

Interviews were used to focus more on collecting qualitative data to complement the quantitative data from the questionnaires. This combination of using both methods can cover misunderstandings and gaps in the previous questionnaire questions while also being able to gather data from a larger group, confirming the conclusions from the limited amount of interviews.

Interviews can be conducted in a variety of different ways, from structured to unstructured, single or group, etc. Having slightly different use cases and different preparations, but a general theme is the diminishing amount of new information gained from the interviews. Where the first interview of about one hour can conclude about 30% of the total user needs and at around 7-8 interviews 80% of the customer's needs are revealed as seen in the book Product Design and Development chapter five [53]. After a while, the information of user needs becomes saturated and the same user needs are identified repeatedly, at this point it might not be worth the effort to conduct more interviews.

An additional objective focused on in the interviews was to identify latent needs, meaning needs that the customer might have but are not aware of or are not expressing explicitly. This can be targeted by using highly open questions and then probing unclear responses with follow-up questions. As well as asking scenario questions, how this would make the interviewee feel, and from that, conclude something that could be improved and how that would be implemented. Additionally, another method can be to ask about pressure points and what the interviewee has issues with. The interviewee might not be aware of their own needs, but they know what they feel is a problem or get irritated about.

4.4 Refined Requirement List

Once the questionnaires and interviews had been evaluated, the requirement list was updated with additional desires as well as the empirical data of how users weigh different desires. This second iteration also includes an updated estimation of importance by developers, ranking from 1-7 instead of 1-5 for increased specification in the difference between needs. In addition, it also includes the data gathered from the questionnaires about the respondents average ranking of the different needs from 1-7. The refined requirement list can be seen in Appendix G.

Certain desires were also added in a similar way as the example in Section 4.1 using "clear display". Feedback from the interviews was also broadened likewise with the statement "I never want my device to suddenly shut off due to low battery" being documented as the need "Indication of low battery". It was observed during the interviews that people seemed to want data regarding sleep and well-being more than productivity. The justification for the product to focus on productivity more is because that the competition in this field is less and therefore the market might not be saturated. However, the actual desire for it needed to be confirmed so with the questionnaire, it is found that on a scale from 1-7, productivity got an importance score of 4.9 while sleep got 5.4 and well-being 5.2. This shows that even if people are more interested in the other factors, there is still a need for productivity also.

The questions regarding prices asked in what range people would be interested in paying instead of ranking the importance of price from 1-7. This is beneficial for getting data on the absolute amount of money people would be interested in purchasing this product for. However the conversion from the prince range question to an importance scale from 1-7 was needed. This led to an estimation being done by a conversion from the price willing to pay to how important low price was weighted. This is based on the first questionnaire because of the higher number of respondents. Finally this is used to evaluate the desire of "selling price".

$$Selling\ price\ importance = \left(\frac{\sum_{i=1}^{n} Price_i \times Respondants_i}{\sum_{i=1}^{n} Respondants_i} \right) \times \frac{7}{3500} \approx 4.8 \tag{4.1}$$

An additional comment about the values is the uncertainty in the result, for a certain statistical significance there is a certain amount of responses required as seen in equation 4.2. By rearranging Equation 4.2, and having precision as the only unknown factor, the Equation 4.3 can be derived. Using this equation with the factors in the list below that come from the user need questionnaire results in a precision of approximately 0.5. This means that an importance of 4.9 on the scale from 1-7 actually can be from 4.4 to 5.4 in importance. This is the case for how important it is to gather information about productivity for example.

- Sample size of user questionnaire: N = 25
- Variance since Likert scale 1-7: Variance = 2.5
- Confidence level 0.9: Z = 1.6

$$N = Z^2 * Variance/Precision^2 \tag{4.2}$$

$$Precision = \sqrt{\frac{Z^2 * Variance}{N}} = 0.506 \approx 0.5 \tag{4.3}$$

5
Concept Development

After theoretical research, marked validation, and then user studies, the next phase is starting to develop the air quality monitor. The first steps are to generate initial solution ideas, then to combine these into concepts and lastly to systematically choose one of the best-performing concepts and finalising the detailing. All was done while considering the previous research and work to reach an optimal solution concept.

5.1 Product Specification

Having identified the values important to stakeholders and especially what the users value, the development process is initiated. There is a wide design space of products that could satisfy the requirement of the stakeholders, but it is at this stage unclear which would do it the best and how it would look like. To reduce the risk of missing potentially good features, the aim is to systematically explore as much of the design space as possible within the time limitations.

5.1.1 Identification of Sub-functions

The main function of the intended product is to measure air quality and communicate the information to the user, which can then be used to improve their productivity and well-being. To accomplish this there are plenty of sub-functions that all need to be fulfilled and work together to reach the end goal.

To simplify the problem of measuring air quality and informing users, a common method of problem decomposition was used to divide the problem into sub-problems. This gives a clearer view of all parts that need to be solved and work together as an integrated product [53]. The decomposition is made to a level where different specific solutions can be arrived at for all the new sub-functions. Meanwhile, a further division would create sub-functions that both can have the same solutions as each other, or create sub-functions that do not have an impact on the product type, meaning they can be detailed at a later stage. Dividing simple problems into even simpler ones at this stage would not create enough value and disrupt the flow of the development process. For example, the function "Gather data about AQ" could be divided down further into gather data about each specific AQ parameter, but since it does not fundamentally alter the product's nature the more suitable way is to elaborate on these specifics at a later stage in the development process. The detailing level chosen arrived at the following sub-functions:

- Gather data about AQ
- Store data
- Medium to Convey information
- Type of information
- Turn on/off
- Change settings/user interacts with product
- Easy to transport
- Product placement

- Hold product intact
- Provide power
- Store power

5.1.2 Generation of Sub-solutions

After the problem decomposition and identification of the sub-functions, the next phase is finding sub-solutions to each of them. To find these sub-solutions, the initial step involved a brainstorming session conducted independently by the developers. It was performed to not influence each others' design space from the start to gather a wide array of possibilities. The following step was a common brainstorming session to see if inspiration could be drawn from other developers' original ideas, creating combinations of ideas from the different developers.

For further solutions, especially for the more complex functions, external research was done. The research looked at the competitors, and how similar sub-tasks are solved in other products. Even though the main function between products may differ they can still have similar sub-functions that work very similarly for both products. For example, "turning product off/on" can be seen in a very high variety of products and many different options can be seen and used as inspiration or suggestions. The concluded sub-solutions can be seen in Appendix J.

The sub-solutions that were added to the matrix were ones that alter the customer's use of the product. This means that underlying choices of components that were not shown to the user were kept for later decisions to keep the process moving forward. For example, the decision between screen or speaker changes the way the product is used, while what kind of speaker does not. For this reason, the different sensors and batteries that had been found were excluded from the matrix leaving this decision to be taken further down the process when more data is available.

5.2 Concept Generation

Moving from identified functions and sub-solutions, the next phase is to combine these into different holistic concepts. The combination process follows structured methods to minimise bias and to ensure more effective progress without many mistakes. The goal is to end up with a group of general concept candidates for later evaluation.

5.2.1 Elimination Matrix

The first step in the concept development phase is to eliminate all previously generated sub-solutions that are not feasible or suitable to develop. This is done to avoid spending too much time developing a concept using sub-solutions that might not actually be suitable in some way.

To eliminate the sub-solutions systematically, an elimination matrix is used. This challenges each sub-solution to meet different requirements, and the moment a solution does not fulfill one of them, it is eliminated. An example can be seen in the elimination matrix (Appendix K) where using "Scent / fragrance" as a "Medium to convey information" fulfills the need as a "Solution alternative", "Fulfills the mission statement" and "Fulfills the requirement matrix". On the other hand, it is not "Compatible / realisable" and does because of this get eliminated and is then marked with a minus (-). If a solution passes all requirements, it is finally marked with a plus (+).

During the conducting of the matrix, some sub-solutions were marked with a question mark (?) or exclamation mark (!) which meant that the subject needed to be researched further to be able to reach a clear conclusion.

This was done on a limited time basis and then decided if the solution would pass or fail that requirement. The end goal is to have a clear answer if the solution is eliminated or not, so this is therefore the final result that can be seen in the elimination matrix in Appendix K.

After conducting the elimination matrix, 22 of the 48 sub-solutions were eliminated. This means that almost half of the generated solutions were eliminated and in turn means that many less combinations for the possible full concepts can be made.

5.2.2 Morphological Matrix

To go from the individual sub-solutions to full concepts using a methodical approach, a morphological matrix was created. This method combines many variations of sub-solutions to possibly end up with many many more full concept variations. It works by choosing one sub-solution per row and combining this with a sub-solution of the next row until a sub-solution from each row is combined into a final concept.

There are a couple of ways the concepts can be created using the morphological matrix. The approach chosen in this project regards making a limited amount of concepts, but with themes in mind. This is suitable because it is very time efficient and usually results in concepts that are realisable. It also makes sure to end up with diverse concepts for a more dynamic evaluation later. Example themes used were "Budget friendly", "Luxurious" and "Environmentally friendly". The downside of this approach is that more bias from the developers is put into the concepts. There are themes that the developers are not aware of and those concepts are then never created. So because of this, as broad and diverse themes as possible were chosen. The final morphological matrix with all possible sub-solutions can be seen in Appendix L.

5.2.3 Initial Concepts

11 different concepts were created using different themes. These were combined out of the sub-solutions with the themes in mind to imagine how the product for that theme would look like. For example does the "Budget friendly" theme not have a screen because of its higher cost, while the "Easy to use" concept has a touch screen because of the simpler interaction between the user and the product. All 11 concept themes can be seen in the list below.

- Budget friendly
- Lowest price
- Luxurious
- IKEA influenced
- Environmentally friendly
- Professional / Most accurate
- Portable
- Easy to use
- Minimalistic
- Community product
- Family version

The themes are meant to cover multiple different areas of the design space while still being relevant and without going into too much detail since the concepts in this stage are still quite abstract. None of the concepts have the same combinations of sub-solutions, but a few are quite similar to each other. The detailed description of what combinations the different concepts are made out of can be seen in Appendix M.

5.3 Concept Evaluation

After creation of multiple initial concepts for the air quality monitor, some methods were used to specify what area of the design space that should be developed further. With the time limitation, all concepts can not be developed fully detailed, so the least promising concepts are therefore removed successively as more detailing is done. The methods help with this complex task and aims to reduce the biases from the developers as well as having a structured and documented way of evaluating.

The concept evaluation process is iterative and goes through multiple detailing stages paired with continued evaluation. The goal of the phase is to end up with one single concept or a product family to continue the development of.

5.3.1 Concept Screening

The first step in narrowing down the concepts was to create and evaluate all 11 concepts using Pugh matrices [53]. The process is called screening because the goal is to filter out the least promising concepts in a quick and efficient way. This is done by evaluating all concepts by if they are better or worse at satisfying a desire than a chosen reference concept, where the relative rating is quicker than grading all of them on a scale.

All the concepts by definition must satisfy all of the requirements from the requirement list. How they satisfy the desires can vary though and are therefore the parameters to be evaluated against. Most of the desires from the requirement list (Appendix F) are used, with some exceptions like "Water resistant", "Ethical suppliers" or "Easy to replace parts" not being used. These were excluded because of their low importance, or difficulty in evaluating these desires at this stage. Statements about what concepts can for example have "Ethical suppliers" are unclear at this stage which means that this desire does not give any meaningful information at this stage of the screening. It would be time consuming to try to find differences which probably would even have a low degree of certainty. For the remaining 31 desires, all concepts are given a +1 if the concept is better than the reference, -1 if it is worse and 0 if it is the same or similar. When all desires are evaluated for each concept, the sum is calculated and given as a final score. The desires does in this evaluation all have the same weight for simplicity and quick evaluation, but it also increases the risk of low importance desires diluting the response on the high importance desires.

Pugh Matrix 1

The first concept screening matrix, also called a Pugh matrix used the "budget friendly" concept as the reference. This was mainly because it was considered to be the most average and well understood concept, which are two main aspects to consider when choosing a reference concept [53]. A well understood concept helps when comparing other concepts against it.

The full matrix can be found in Appendix N but a summary of the results can be seen in Figure 5.1. The "Budget friendly" version of course gets a score of 0 by being the reference, and "Lowest price" gets a score of 0 as well by being better in regards to 5 desires and worse in 5. Only "Environmentally friendly" got a better score with a score of +2. The "environmentally friendly" concept seems to win by being very similar to the "budget friendly" one, but having some advantages mainly regarding sustainability. Otherwise more simple and low-cost concepts did well with the exception of "Luxurious" that landed on 4th place with a score of -1.

	Budget friendly	Lowest price	Luxurious	IKEA influenced	Environmentally friendly	Professional / Most accurate	Portable	Easy to use	Minimalistic	Community product / room measure	Family version
Σ +	0	5	9	5	6	9	6	8	7	8	5
Σ -	0	5	10	11	4	11	9	13	12	10	11
Σ o	23	13	4	7	13	3	8	2	4	5	7
Total	0	0	-1	-6	2	-2	-3	-5	-5	-2	-6
Rank	3	3	4	11	1	6	7	8	9	6	11

Figure 5.1: Score of Pugh matrix 1.

Pugh Matrix 2

Because of the relative scoring in the Pugh, the final results might differ based on which reference concept is used. For example, two similar concepts can get the same score against a third different reference, while there still are differences between the two concepts with one being less promising than the other. This is true for "Budget friendly" and "Lowest price". They get the same score against the "Budget friendly" reference in the first Pugh, but a different score against the "Easy to use" reference in the second Pugh. To compare each concept to all other concepts all of them except one would be used as reference, but due to diminishing returns on each one and the time it would take it is not suitable. Because of time constraints for this project, two iterations is chosen as sufficient for this early screening phase to get an overview. Additional rounds would have been made if some concept was cut out while still being a promising concept in one of the rounds. Like if a concept would have got a very high score in first round and very low in second round. The results however show that the less scoring ones that were removed had a lower score in both of the rounds.

"Easy to use" is chosen as a reference because of the biggest difference to the previous reference (it had the least zeroes in the score). The whole matrix can be seen in Appendix O but the results can be seen in Figure 5.2.

This time the "Budget friendly" and "Environmentally friendly" concepts again get a high score. But also the "Community", "Minimalistic" and "Portable" concepts get a good score mostly because of their good communication properties which were highly correlated to the inclusion of a screen.

	Easy to use	Lowest price	Luxurious	IKEA influenced	Environment ally friendly	Professional / Most accurate	Portable	Budget friendly	Minimalistic	Community product / room measure	Family version
Σ +	0	9	7	8	12	5	8	13	9	9	6
Σ -	0	10	10	8	10	10	6	8	6	6	9
Σ o	0	4	6	7	1	8	9	2	8	8	8
Total	0	-1	-3	0	2	-5	2	5	3	3	-3
Rank	5	6	8	5	3	9	3	1	4	4	8

Figure 5.2: Score of Pugh matrix 2.

Concept Elimination

To find the best concepts from the two Pugh matrices, the average scores for each concept are simply calculated and then ranked. This can be seen in Figure 5.3 where the top 5 concepts are chosen to be further developed and compared in the following Kesselring matrix. These concepts are marked in green in the heading, and the eliminated concepts are marked in red.

	Easy to use	Lowest price	Luxurious	IKEA influenced	Environment ally friendly	Professional / Most accurate	Portable	Budget friendly	Minimalistic	Community product / room measure	Family version
Score Pugh 1	-5	0	-1	-6	2	-2	-3	0	-5	-2	-6
Score Pugh 2	0	-1	-3	0	2	-5	2	5	3	3	-3
Average Score	-2.5	-0.5	-2	-3	2	-3.5	-0.5	2.5	-1	0.5	-4.5
Rank	8	5	7	9	2	10	5	1	6	3	11

Figure 5.3: Average score from Pugh 1 and 2. Rank is shown with the top 5 concepts seen in green, and the 6 eliminated in red.

5.3.2 Concept Selection

To have a more detailed and grounded base for which concept to develop, a Kesselring matrix is done. This is similar to the Pugh matrix, but uses scoring instead of relative evaluation against a reference concept. From this, different scores will emerge with the ability for sensitivity analysis to evaluate if the results are considered significant.

Updating of Concepts and Desires

Before going ahead with the shortlisted 5 concepts, it was decided to develop two more combinations from some of the previously best performing concepts. This was done because some overlap in advantages could be seen between the concepts which could mean that hybrids might perform even better.
A combination between the "Community" and "Portable" concepts was developed, basically into a small but still easily understandable product with a screen, conveniently named "Game boy". The second combination was called "Fancy" because of the combination between the "Budget friendly" and "Luxurious" concepts. It keeps the great communication properties of the luxurious concept, but still tries to be relatively budget friendly.
All five concepts plus the two new combinations each got a sketch for the developers to more easily picture how the different concepts would be used and look. Therefore they are more detailed compared to their previous description of just being a code from the morphological matrix. The concept sketches can be seen in Figure 5.4.

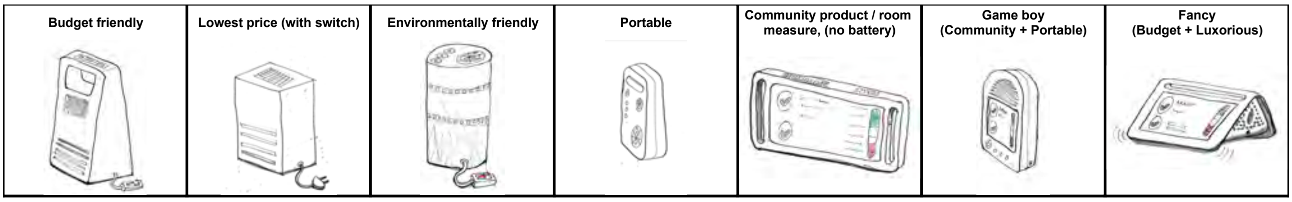


Figure 5.4: Sketches of the seven concepts evaluated in the Kesselring matrix. Shape and sizes can vary but the most important aspects like what communication tool they use as well as how to change settings can be seen.

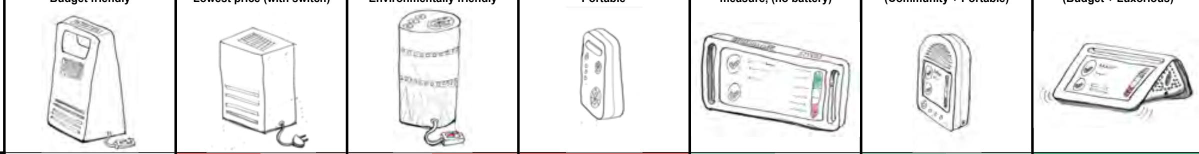
Final Score

The grading for the Kesslering was decided to be done in absolute terms. This means that the concepts were not graded relatively based on each other, but on how well they actually satisfy the different desires. Because of this, for example, all of the concepts not having a battery received a 1, and all that had a battery received 7 in score for the "1.1 Long lasting battery" desire. This could lead to more difficult differentiation between those concepts in the end because of the identical scoring, but also ensures that the winning concepts are the true winners without risk of confusion.

Another update from the Pugh matrices is that the Kesselring uses weighted desires, so that the important desires are valued higher and have a bigger impact in the design process than the lower. These weights were derived directly from the requirement list by calculating the average of the weight decided by the developers, and the weight gained from the user research.

Some things to note from this was that the general categories of cost, environmental sustainability and measuring data had a high importance for this evaluation. A note is that the weights themselves did not differ that much from each other, with the large majority of the desires having a weight between around 4 and 6 on a scale of 1-7. This results in the different desires actually not having that much of a difference in importance between each other. However, these are the concrete results from the grading of the developers and the user research which is declared as a robust enough basis for evaluation.

The final results of the Kesselring selection matrix can be seen in Appendix P and as a short cutout version in Figure 5.5. The "Fancy" concept had the highest score, this was surprising because it was the most expensive concept, and cost is usually a very important factor in product development, and had also been the results from interviews and questionnaires done for this project. The cost of the product made up around 12% of the total weight in the selection matrix which is lower than a previous understanding of average weight put on cost in these scenarios. A weight of around 30-40% is commonly used for cost in similar selection matrices [55], [56], [57], [36]. However Ulrich at al. [53] also show examples of them using cost at around 10%, and that a theoretical increased weight on cost up to 20% done in the sensitivity analysis still makes the "Fancy" concept achieve the highest score. Due to these considerations, the decision was to continue developing the "Fancy", keeping in mind the risk that higher prices might limit the market size the product can target.



	Budget friendly		Lowest price (with switch)		Environmentally friendly		Portable		Community product / room measure, (no battery)		Game boy (Community + Portable)		Fancy (Budget + Luxorious)	
Σ	3.70	0.53	3.57	0.52	3.65	0.51	3.57	0.51	3.91	0.54	3.96	0.55	4.13	0.59
Rank	4		5		6		7		3		2		1	

Figure 5.5: Final results from the Kesselring matrix. the "Fancy" concept can be seen as the winner marked by both the rank and greenest color. The sum symbol firstly shows what the weighted score is in total on a scale of 1-7, while the second represents the score in relation to the highest possible score.

Sensitivity Analysis

A brief sensitivity analysis was performed on the Kesselring matrix to improve confidence in the results and decisions achieved from the concept evaluation phase.

The first consideration has already been mentioned in the previous section, namely to increase the weight of only the cost and price criterion because of the generally high importance put on this. A doubling of the already high weight of cost + price from $5.9+7=12.9$ to $11.8+14=25.8$ results in a weight changing from $\sim 12\%$ to $\sim 20\%$. Doing this puts "Fancy" on par with "Budget friendly" and "Lowest price" which is expected. With "Fancy" having a very similar score even after this adjustment, shows the decision to continue with this concept is a viable and resonable option.

Continuing in a similar way with increasing the impact of low and high scores, another analysis was done where all of the weights were multiplied by themselves a number of times. This was done for ˆ1 (which is the original weight), ˆ2, ˆ3 and ˆ5.This results in a larger range of weights, resulting in the higher weights being increased even more in proportion to the lower ones. Leading to an increase in the percentage difference between low high importance desires. This also includes the high score of cost which has a higher and higher impact the more the weights are multiplied by themselves which can be seen in Figure 5.6. It should be noted that of course, all parameters are more extreme. It can be seen that up to the power of 3, "Fancy" still ranks the highest, but increasing the power to 5 makes "Lowest price" the highest ranking concept which should be considered. Cost has an impact of around 28% when the weights are raised to the power of 5 and is the main reason for why "Lowest price" ranks the highest in that situation. The power of 5 is however considered as very extreme and is mainly there to illustrate the difference on impact. It can again be seen that if cost has a weight of around 20%, "Fancy" still wins which is considered as enough of a margin.

Lastly, a final sensitivity analysis was made to prevent the potential dilution of the important criteria against the not so important ones. For example, even if cost has the highest weight, including many more criteria in the matrix dilutes the weight overall of cost and then lessens its impact. Eliminating the less important criteria down to ten remaining most important ones to give another view of which concepts score the best. This new

Power of the weights	Manufacturing cost + Selling price weight in procent %	Budget friendly		Lowest price (with switch)		Environmentally friendly		Portable		Community product / room measure, (no battery)		Game boy (Community + Portable)		Fancy (Budget + Luxorious)	
^1	11.7007	3.70	0.53	3.57	0.52	3.65	0.51	3.57	0.51	3.91	0.54	3.96	0.55	4.13	0.59
^2	15.1459	3.70	0.53	3.57	0.54	3.65	0.50	3.57	0.51	3.91	0.52	3.96	0.55	4.13	0.58
^3	19.0275	3.70	0.54	3.57	0.55	3.65	0.49	3.57	0.51	3.91	0.50	3.96	0.55	4.13	0.58
^5	27.9073	3.70	0.55	3.57	0.59	3.65	0.45	3.57	0.52	3.91	0.45	3.96	0.55	4.13	0.56

Figure 5.6: Final results from the Kesselring matrix. the "Fancy" concept can be seen as the winner marked by both the rank and greenest color.

analysis can be seen in Appendix Q and shows that "Fancy" still wins, and actually with a larger margin to the cost conscious concepts than before. Showing that it has clear benefits in the most important desires.

Finally after these sensitivity analyses, "Fancy" can be considered as a robust winning concept with a lot of margin and should be the one concept that the project continues to develop.

5.4 Concept Detailing

Before moving straight on to prototyping, the chosen concept needs some further detailing to streamline the process. Theoretic planning of the prototype regarding what components to use as well as assembly are things needed to be decided fully upon. Design of the casing and the user interface are also aspects looked into.

It must be noted that much of the detailing is purely for a prototyping purpose. This means that some aspects are chosen as an example solution and not necessarily the optimal solution for this kind of product if sold in the market. This is clarified in the future works Section 9.2.

5.4.1 Electrical Detailing

A significant reason to develop the prototype is to get a better understanding of what components need to be included and how the electronic framework of these would look like. The components chosen for the prototype can be seen below in Figure 5.7 and will be described in the following sections:

Sensors

During the technology assessment, no sensor monitoring all sought after air quality parameters was found, so because of this at least two different sensors had to work together to manage the complete monitoring. The sensors chosen for the prototype were the **Sensirion SCD41** [59] and the **Sensirion SEN54** [58]. These were chosen because of their coverage of all parameters together while at the same time overlapping on measuring temperature and humidity which results in reliability and extra validation. The SCD41 measures CO_2, temperature and humidity while the SEN54 measures PM1.0, PM2.5, PM4, PM10, VOCs, temperature and humidity. Both sensors are also from the same renowned company Sensirion which supports each sensor with thorough instructions and advice on how to integrate the sensors in a product. Lastly the sensors from Sensirion was used during experiments done by the PhD group at IITD [16], [38] and could be trusted because of this.

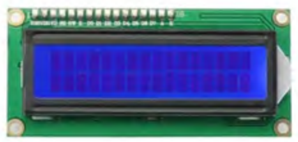
Computer

For computing and handling the monitoring, a small portable computer device needed to be used. The **Arduino Uno Rev3** [60] was a suitable alternative because of its low price and simplicity. Existence of extensive user

(a) Sensirion SEN54 [58]

(b) Sensirion SCD41 [59]

(c) Arduino UNO Rev3 [60]



(d) 16x2 LCD display with I^{2}C interface [61]

(e) Coin Vibration Motors [62]

(f) Battery Charging Module ESP32 [63]

(g) 18650 2200mAh batteries [64]

Figure 5.7: All main electrical components included in the monitor.

guides and online literature exists on the internet and its straightforward use were the main reasons for choosing this board. It also contains many different pins which makes it have many different use cases and multiple other devices can be used at the same time. It is also very easy to upload new code to the Arduino, which is useful in this prototyping and testing phase. However, it is not the most compact board on the market so another one would certainly be used in a more commercialised and further developed product.

Screen

The "Fancy" concept included a large touch-screen for communication and interaction medium with the users. A 5-inch display was therefore chosen for the concept detailing because of its suitable size paired with the layout of the four batteries. For the physical electronic prototype on the other hand, a very simple **16x2 LCD display** [61] was used. This was used because of similar reasons for why the Arduino was chosen with it being simple to use and for a low cost.

Vibrator Motor

For creating the vibration feedback from the product, a small **coin vibrator motor** [62] was used. These are very small, 10mm in diameter, and are easy to connect.

Energy Source

The last major component handles how to supply all the other components with power. The calculated energy consumption by all components was summarised to a maximum be around 3 Watts. Their individual energy consumption can be seen in the following list:

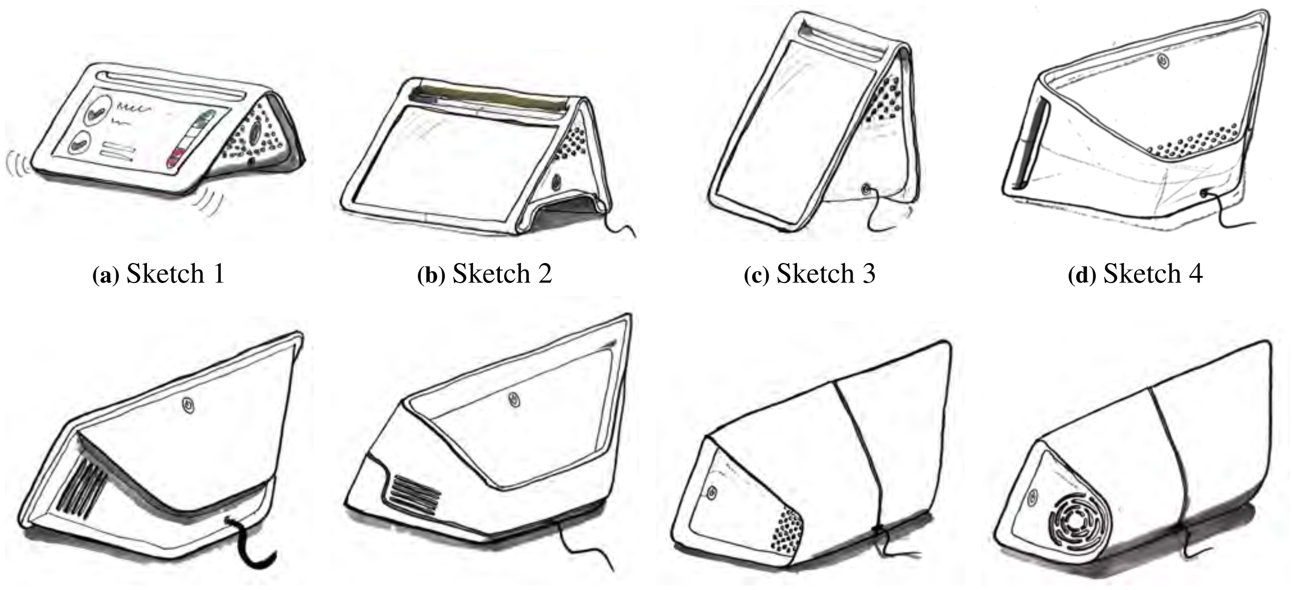
- SEN54: $110mA \cdot 5.5V \approx 0.6W$
- SCD41: $205mA \cdot 3.3V \approx 0.7W$

- UNO Rev3: $50mA \cdot 12V \approx 0.6W$
- LCD display: $20mA \cdot 3V \approx 0.1W$
- Vibrators: $66mA \cdot 6V \approx 0.4W$

With a desired battery life of around 12 hours for the monitor, 3 Watt per hour equals to 36 Wh of energy capacity needed. With the choice of using the type **18650 Lithium-ion batteries** [64] because of their versatility and energy capacity compared to their volume, who each have a capacity of 8.14 Wh ($2200mA \cdot 3.7V$) of energy, four batteries would need to be used for the entire product to last for 12 hours. To mount the batteries and enable charging and discharging simultaneously, a **battery charging module** was needed [63]. The module chosen has an integrated ESP32 micro-controller which ensures safety through protection from overcharging and over-discharging. Finally the charging module also includes a USB-C charging port for convenient charging.

5.4.2 Case Detailing

Even if the comprehensive design of the casing is outside of the scope, a somewhat consciously considered design was desired for communication of the product to potential users and external parties. The first step to choosing the casing design was to make some relatively different sketches as examples. Inspiration was taken from competitors such as the Air Quality Guardian [30] and especially the Kaiterra Sensedge [24] with its large screen and sleek design. Some patents, like the CN219915567U [49] was also used as a reference. It was decided that the large screen would take up the majority of the front space of the product, which then left the back side for more intricate design. Some sketches of considered designs can be seen in Figure 5.8.



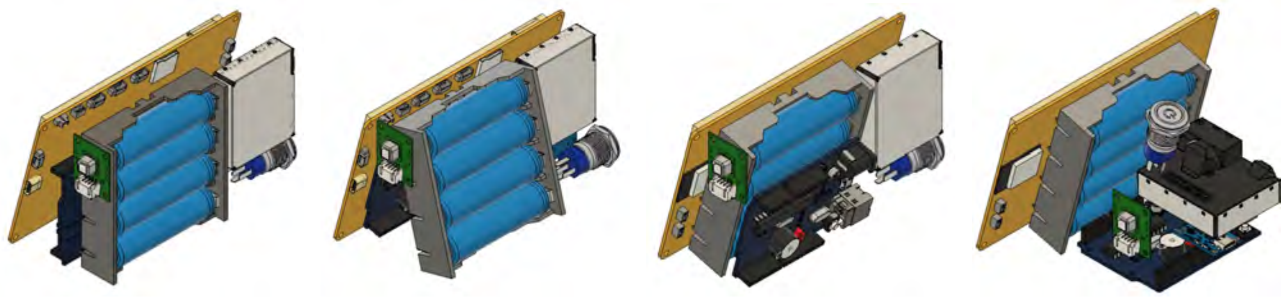
(a) Sketch 1 **(b)** Sketch 2 **(c)** Sketch 3 **(d)** Sketch 4

(e) Sketch 5 **(f)** Sketch 6 **(g)** Sketch 7 **(h)** Sketch 8

Figure 5.8: Different sketches as inspiration for designing the monitor. 8 different versions can be seen.

It can be seen that most of the sketches does not contain a handle for the product. Even if the "Fancy" concept included a handle, it was here decided that the small size and relatively low weight of the product would not benefit from a handle as much as previously thought. Because the handle is a relatively small factor differentiating the concepts from each other, it was accepted to ideate on designs that were lacking the handle. The advantage of not having a handle is a smaller, more compact, and possibly more sleek aesthetic.

To make a more grounded decision of what design to choose, the layout of the components played an essential role to what was most feasible. All components were therefore downloaded from the website GrabCAD [65], inserted into the CAD program Autodesk Fusion [66] and then arranged in different configurations. Each arrangement had a sketch design in mind and also took extra space for wires and mounting into consideration. All configurations can be seen from the back side in Figure 5.9. In these configurations, the 5-inch display can also be seen in yellow from the back side.



(a) Layout 1 **(b)** Layout 2 **(c)** Layout 3 **(d)** Layout 4

Figure 5.9: Four different compact layouts of electrical components arranged in Autodesk Fusion.

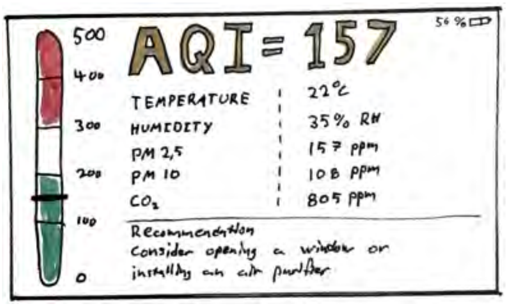
The most promising sketch design paired with the component layout was sketch 5 (5.8e) with layout 4 (5.9d). This design showed to potentially have a clear and clean view from the front side, with the downside of having a longer back. However this was a fair trade and decided to be the final design for this example prototype. This design was also seen to be relatively easy to prototype and still leave potential for industrial injection molding manufacturing if mass-produced. The choice was however mostly based on personal preferences and could by small changes result in another aesthetic design.

5.4.3 UI Detailing

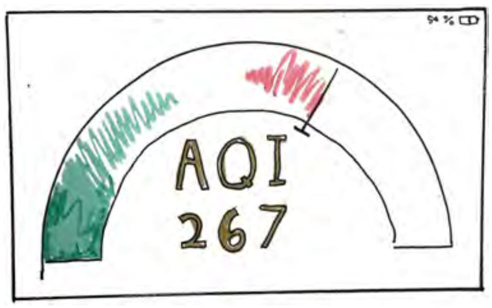
The user interface for the product is the area spent the least amount of resources and time on in this project. This is essentially used to give the user and other stakeholders an idea of how the final product would look like. The three major impacts of the UI for the product are that the product is seen to be used on a table or desk, that it has a 5-inch display, and lastly that it will have the screen laying down (landscape view) instead of standing up (portrait view).

The touch-screen is planned to be used for easy interaction and for the user to customise the display of the monitor as well as choose what data to access. It could for example display a comprehensive and diverse amount of measured parameters as seen in Figure 5.10a, or a more simple but clearer description of the AQI that can be seen from further away as seen in Figure 5.10b. These two sketches are used as guidelines and to give the developers a common understanding of how the product would look like for further development.

The user interface and user experience of the product is mostly left for future work but a basic version is developed in this project for easier communication.



(a) Example of UI sketch 1 showing all measured parameters.



(b) Example of UI sketch 2 displaying a very clear status of AQI.

Figure 5.10: Two example UIs for the product interface.

6

Prototyping & Testing

This chapter details the process of prototyping the minimum viable product and outlines the final outcome. The process is highly iterative because of continuous testing and improvement. Finally, the prototype gives valuable insights for example into how the product could be shaped and which processes could be used for manufacturing. Creating the prototype allows testing of all components and interactions between them, increasing their reliability. Furthermore, it provides a reference for developers to discuss as the product is tangible but also has intangible aspects which developers get a better understanding about. This together with component testing and assembly is important feedback for further development.

The prototype contains aspects from a couple of different engineering fields and is therefore divided into each of them to simplify the process. The first prototype constructed was constructed to verify the functionality of the components. To ensure this, additional software was required and was therefore integrated. The casing was designed around the components and lastly, the UI was based on user feedback and market inspiration.

6.1 Electronics

The initial testing was done for the electronic components decided upon in the Electrical detailing Section 5.4.1. The main reason was to ensure that all components work individually and in the way expected by the developers and to verify this early because of logistics of ordering new components.

The most important electronical componentes were the two particulate matter and CO_2 sensors that were ordered from Sensirion. The testing was guided and supported by well defined user manuals provided by Sensirions website [67]. Connecting these to the Arduino individually turned out to be a simple task and did not come with many complications. This was the main objective and showed that the sensors work individually as required. However, connecting both sensors to the Arduino using the I^2C interface required more thorough research to ensure that none of the sensors would get damaged or compromised. In the end, the wiring became relatively compact and manageable. The circuit for the sensors as well as all other components can be seen in Figure 6.1.

To analyse how the sensors behaved over time a test was conducted in India during master thesis presentations in a smaller room filled with around 30 people over a duration of four hours. The room had a size of about 40 sqm with one wall being windows, and the opposite wall having one door; all windows and the door being closed at the beginning of the testing period. Four working ACs were set to 22°C, two ceiling fans were on but no HVAC system was active. Data was gathered every ten minutes and documented to finally form a diagram of the AQ over time.

The results can be seen in Figure 6.2 where all parameters are logged for the four hours. The main reason for this test was to make sure that all sensors behave as expected during longer duration's of time, which proved to be successful with only one error for the VOC measurements which could probably be managed for a more optimised product. Some major events were logged during the testing which can be traced back from the data:

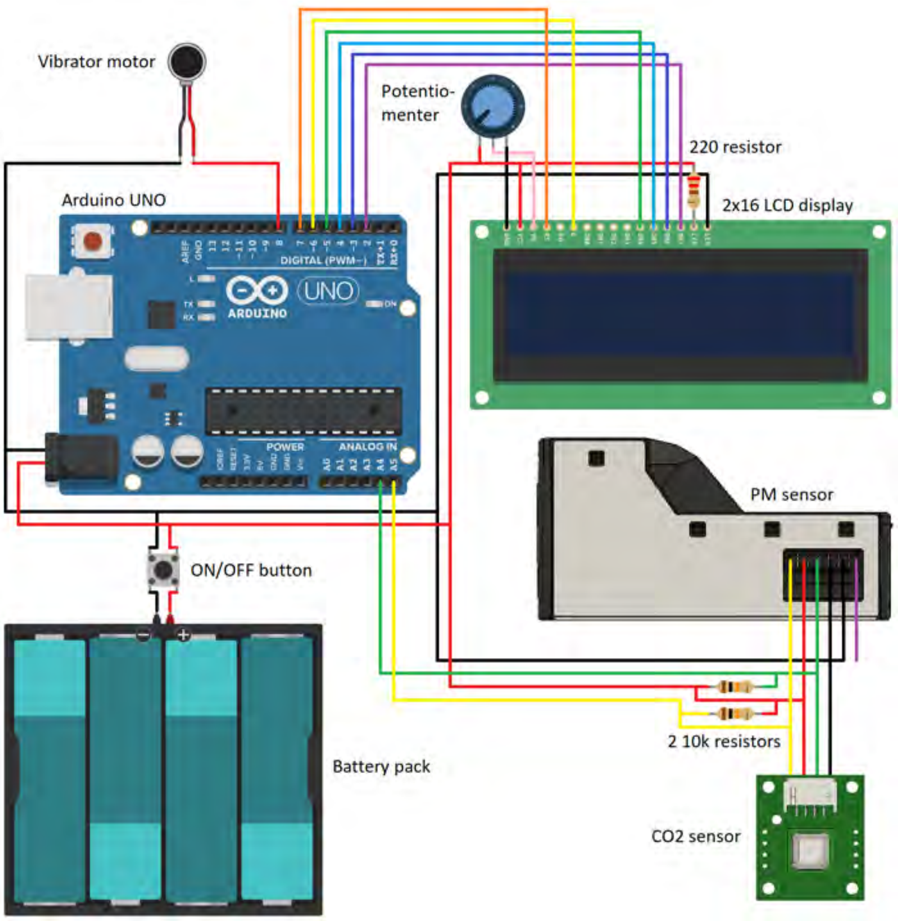


Figure 6.1: The complete schematic electrical circuit for the prototype. All red wires are positive 5V DC and all black ones are ground. All component names can be seen.

1. At 16:10 both the door and windows were both opened for a short period or around 5 minutes. This change made it so that the CO_2 levels dropped a noticeable amount from 1742 to 1333 ppm with an amount of about 400 ppm. Having the windows and door opened for a longer time would most probably decrease the levels much more.

2. At 16:20 the windows were closed again, but the door was kept open before finally being closed at 17:40. Stable CO_2 levels can be seen during this period, which must mean that the output of CO_2 from the people inside matched the escape of CO_2 from the door to the outside.

3. Lastly after the door and windows again were closed, a steady rise of CO_2 can be seen reaching extreme levels that peaked at 2293 ppm before finally the windows and door were opened again, drastically reducing the CO_2 to the outside at 19:10.

4. The error in the VOC measuring can also be seen here at 18:20. This can be due to many diferent things, but most probably an unstable physical connection between the sensor and the Arduino.

5. Most of the other parameters stayed at a stable level during the testing period. This is probably due to minimal changes between the inside and outside qualities for the air regarding these parameters.

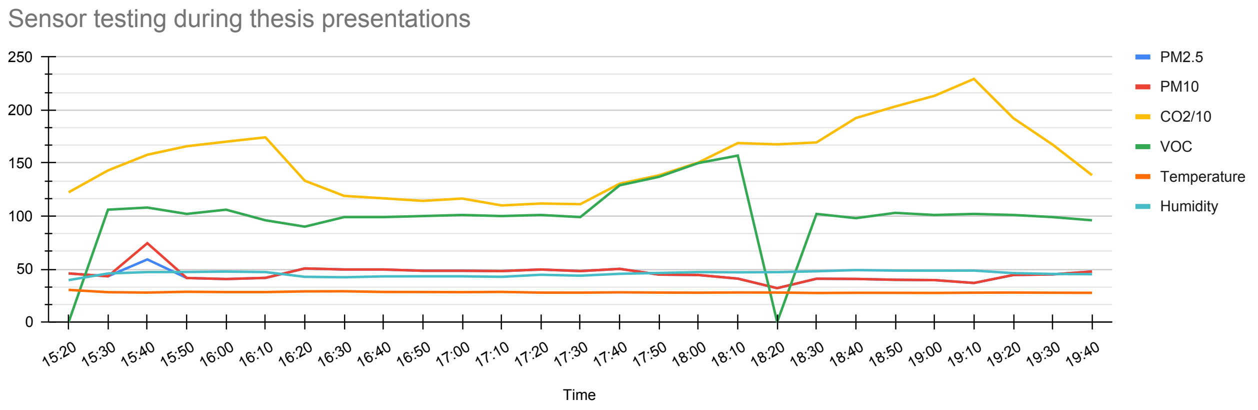


Figure 6.2: AQ data measured by sensors documented over a period of four hours. Timestamps can be seen for each measurement with intervals of 10 minutes.

The screen used for the prototype was the 2x16 LCD display mentioned before. This is a standard component under the Arduino franchise and was therefore also relatively straight-forward to connect. The wiring could have been different for faster or more robust communication between the Arduino and the display, but this version requires the least amount of wiring and was because of this chosen. The display was initially tested with a straight connection to the Arduino but this resulted in a very dark screen with difficulty to identify the symbols on it. A potentiometer was therefore necessary for the option to tune the brightness of the LCD for best visual communication. This resulted in a perfect balance to see the data clearly.

A couple of different battery layouts were tested before the final one was decided. The main problems was that the battery pack would need to be both charged and drained at the same time, that this would be done in a safe and controlled way, and that a stable 5 V output would be provided to the other components. First a simple setup with four 18650 Li-on batteries connected in serial was tested paired with a separate USB-C charging module. This worked but did not offer a stable and safe output from the batteries to the components since the output just was connected to the positive and negative side of the battery.

The battery pack described in the concept detailing Section 5.4 was the final one chosen for the product. It included the ESP32 module which ensured stable charging and discharging which was a key feature. However for the prototype this module had no option to connect an external USB-C charging module, which left the module needed to be charged by opening up the prototype and charging it directly on the battery pack. The previous testing of the working external charging module although shows that this is something easily included in the future.

The output from the battery went through a self-locking push button to act as an on/off-button to manually turn the product on and off. Lastly, the small vibration motor required less electricity and could therefore simply be connected directly to the Arduino's output as seen in Figure 6.1.

6.2 Software

The first step was testing all of the components individually, needing only a basic run operation. The code was written specifically for the Arduino programming language since it was the Arduino Uno microcontroller that was the master over the other devices.

The initial code for the sensors was sourced from Sensirions own webpage linking to GitHub which provided driver code, setup for the device, and doing the measurements [68], [69]. While the coin-vibrator was tested simply with one of the pins on the Arduino, using a pin as an output with alternations from high and low each second. The screen was then tested using the LCD.print function which can be used by including the Liquid-Crystal.h library.

With the electronics tested individually, they needed to work together for the finished product. This was done through a process of merging the different already existing codes. First all the libraries from the individual codes were included as well as the setup for each of the devices. With testing of the codes simply after each other, it was seen that the measurements took different amounts of time which led to the sensors not printing the same amount of times. Therefore the loop code, which runs repeatedly as long as the Arduino has power, the different sensors were programmed so that all measurements occurred, and then once that was achieved all measurements were printed at the same time. With a limited display for the prototyping and testing, abbreviations were used, on the first-row temperature is shown as T, humidity as H, carbon dioxide as C, and VOC with V. The second row PM2.5 as pm, PM10 as PM and the current measurement as M where the code example can be seen in Figure 6.3.

```
LCD.setCursor(0, 0);
LCD.print("T" + String(round(TempSCD)) + " H" + String(round(HumSCD)) + " C" +String(round(co2)) + " V" + String(round(vocIndex)));
LCD.setCursor(0, 1);
LCD.print("pm" + String(round(PM2p5)) + " PM" + String(round(PM10p0)) + " M" + String(measure) );
```

Figure 6.3: The code where all parameters are printed at the same time on the LCD using the upper and lower row.

The communication between the devices uses I^2C meaning the single Arduino can control multiple different other devices on the same two pins besides the power instead of communicating to each device from different pins [70]. This is because of the use of addresses and each device having its own, so the message is only acknowledged by the device with the same address as the sender forwards. The full code Arduino code for the prototype can be seen in Appendix G.

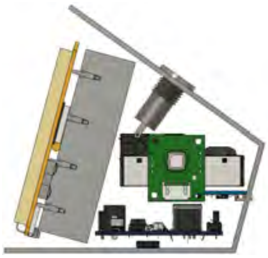
6.3 Casing

After the shape and layout of the components had already been tested and decided in the previous chapter, the final prototyping step was to create a detailed CAD model for 3D printing. This essentially means to use Sketch 5 from Figure 5.8 as a guideline, while realistically fitting all components inside paired with mounting.

The first draft of the shape combined with component placements can be seen in Figure 6.4. The sensors had to be mounted horizontally to the ground to minimise buildup of particles and other debris inside of them which was instructed by Sensirions guidelines [67]. The two sensors are also mounted on different sides of the product. This is done to minimise the possibility that the air that one sensor has measured affects the air that the other sensor will measure [38]. It also increases reliability since both sensors are measuring temperature and humidity. These parameters could differ between the sides of the product and if in a major way send a notification to the user, for example, if one side measures 20°C while the other side measures 30°C the product is placed next to the outlet of warm air from a laptop. No sensor is mounted on the back wall of the product since this wall is seen to have a high risk of being placed against another wall, restricting airflow.

Initially the product was aimed to be designed so it could be injection molded easily to use the advantages of the inexpensive and quick manufacturing on a large scale of this process. It should also be noted that injection moldable designs usually align well with 3D printing because of the same direction of manufacturing. So for this, inspiration from other injection molded products and competitors was used as well as the patents GB2589693A 3.7a and CN216870494U 3.7b which can also be seen in Figure 3.7.

(a) Front corner view.



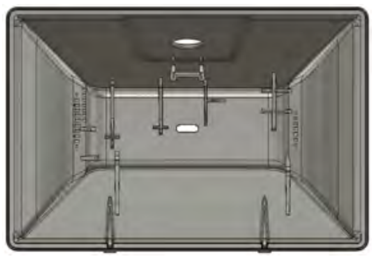
(b) Side view.

(c) Back corner view.

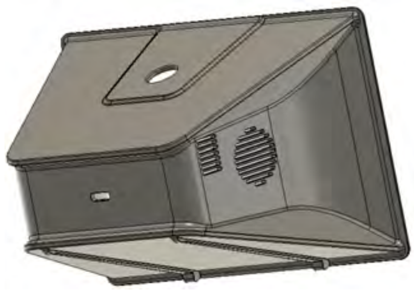
Figure 6.4: Three different views of the first CAD shape draft.

The final injection molded design can be seen in Figure 6.5. This is however the first iteration and some mistakes were realised after printing the case and testing with mounting of the electrical components. The first unfortunate fact, although completely possible, is that the air flow holes on the sides of the casing as well as the hole for the button all need to use side pull-outs when injecting molding which increases complexity. The other mistake is the direction of molding or orientation of the components which results in an unstable physical mounting.

(a) Front corner view of back part.



(b) Front view of back part in the direction of the injection molding.



(c) Back corner view of back part.

(d) Front corner view of front part.

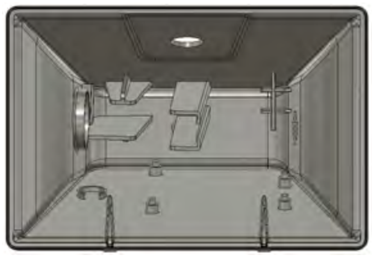
(e) Back view of front part in the direction of the injection molding.

(f) Back corner view of front part.

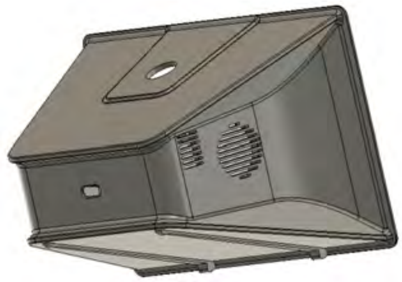
Figure 6.5: Different views of the injection moldable CAD model.

Even if an injection molded version of the casing would most definitely be possible, it was decided based on the downsides of the first iteration of the casing, that a new version should be developed. This new version ignored the aim to be injection molded, and only focused on optimal assembly and mounting of all the components. The new version also includes a mounting frame for the LCD screen as well as an opening for a simple display template to be inserted in front of the LCD for demonstration purposes. This model was made more for communicative purposes of the idea rather than to be the planned future product. The final CAD design can be seen in Figure 6.6.

(a) Front corner view of back part.

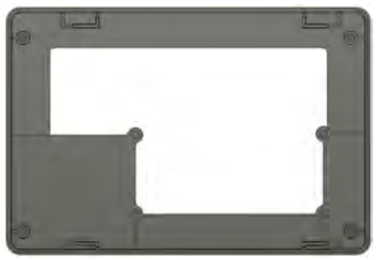


(b) Front view of back part.



(c) Back corner view of back part.

(d) Front corner view of front part.



(e) Back view of front part.

(f) Back corner view of front part.

Figure 6.6: Different views of the second iteration of the CAD model.

The final physical 3D printed case can be seen in Figure 6.7. It includes all details for mounting the components and shows a uniform thickness of 2 mm walls. The fit of all components is good except for the mounting of the battery pack. After testing, it was clear that the downloaded CAD model of the battery pack was not the same as the real one. This resulted in it not fitting in the product perfectly, since it was to too big. Figures of this physical case including all physical components can be seen later in the product results Section 7.2. Moreover can a more technical rendering of an exploded view and an assembled model with contours for the covers be seen in Appendix S.

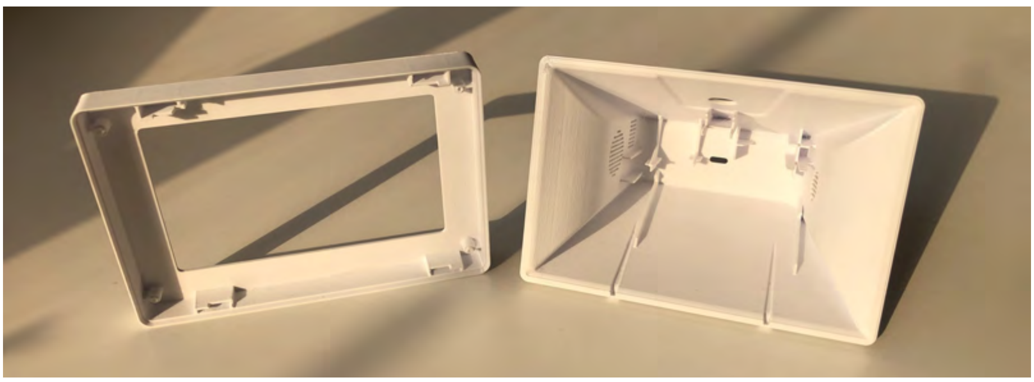


Figure 6.7: Final 3D printed casing for optimal mounting of components.

6.4 User Interface

A couple of versions of the final user interface for the product has been created for clearer communication with the users and to achieve a more developed feel of the prototype. The interface designed is based on the sketches done in the UI detailing Section 5.4.3 with main objectives of giving the user different options of what information to display and for what purpose.

No thorough research was put into designing the most optimal UI since this is outside of the scope and will be left for future work. Nevertheless some inspiration was gained from AI generated images and other inspiration sources. Some images can be seen in Figure 6.8 from which mainly the font, layout and graphical visualisation of the data was used as inspiration.

(a) AI UI example 1.

(b) AI UI example 2.

(c) AI UI example 3.

(d) AI UI example 4.

(e) AI UI example 5.

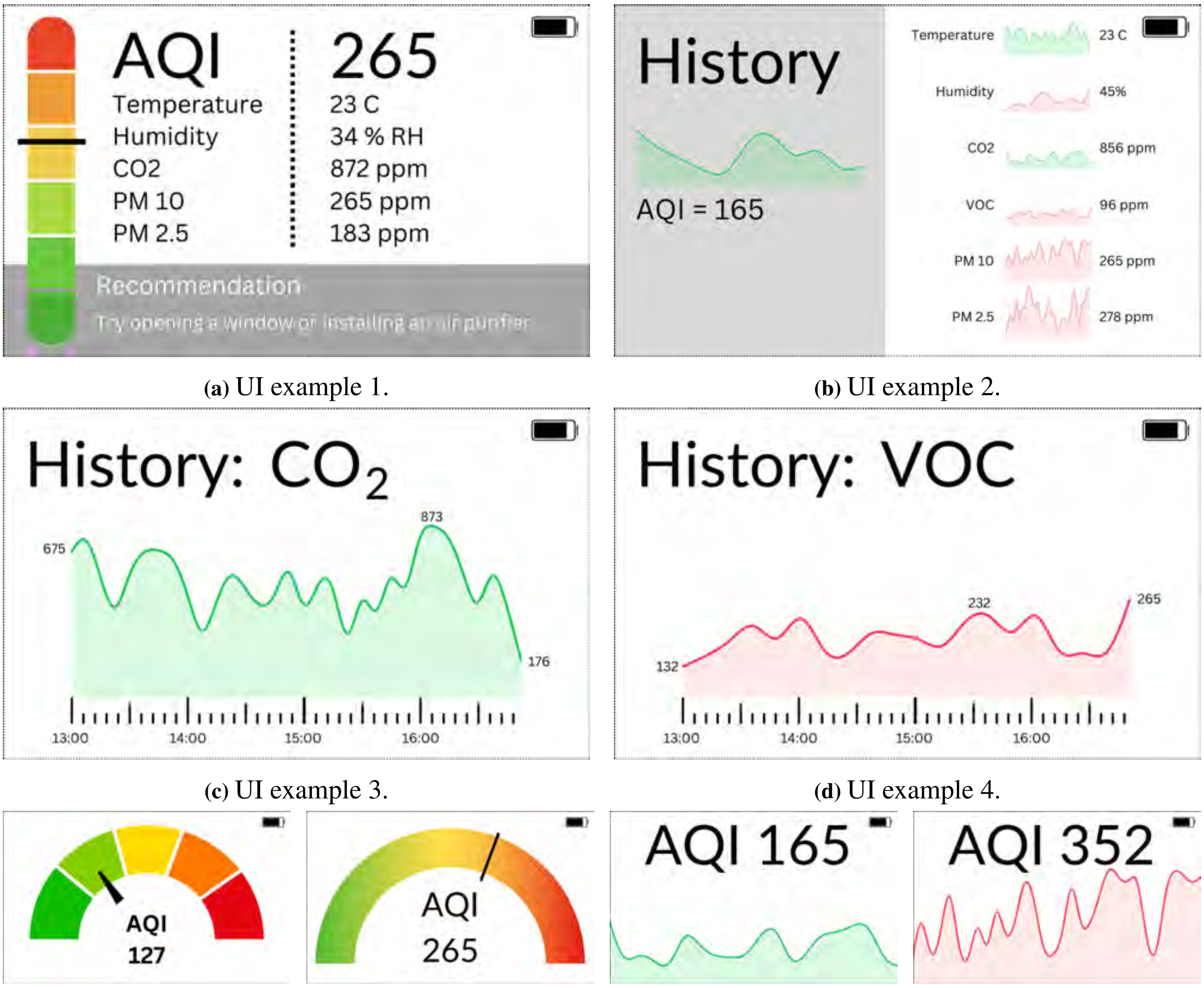
(f) AI UI example 6.

(g) AI UI example 7.

(h) AI UI example 8.

Figure 6.8: Different examples of UI for the product generated with the Designer generative AI tool of Microsoft Bing [71].

From this inspiration together with a minimalistic clear view, some example UIs were developed. These range from displaying all possible information that the sensors measure, to very simple clear displays showing only the AQI or productivity status. All can be seen in Figure 6.9. The history of the AQ is sought to be visualised so the user can draw conclusions if a method of improving the AQ has worked or not. This is a key tool for creating understanding for the user and for them to verify different AQ scenarios over time.



(a) UI example 1. (b) UI example 2. (c) UI example 3. (d) UI example 4. (e) UI example 5. (f) UI example 6. (g) UI example 7. (h) UI example 8.

Figure 6.9: Different examples of UI for the product created in Canva [72]. These were used for demonstration purposes of the product.

7
Results

This chapter provides information about the specific results and outcomes reached by the development process. Having Section 7.1 answering the RQ:s stated in the scope which have been the focus for the project. Section 7.2 shows a broader picture of the final MVP product and its components in detail.

7.1 Research Question Discoveries

The research questions in the thesis were kept in consideration during the whole process and this section describes what the results are for each of them. With the first one being the main goal of the project and the two others supporting the first one.

RQ1: What is the optimal minimum viable product design of an air quality monitor for increased productivity?

The product is found to have different possible use cases which created trade-offs; however the most suitable concept found is **a smaller portable product with easy communication and limited information aimed at private users**. The most lucrative customer base is found to be every day consumers who do not have a thorough understanding of AQ or the parameters affecting human cognition. The amount of parameters monitored are therefore kept to a small amount for easier understanding and simpler monitoring while still being the most impactful on productivity and the opportunity for users to dive deeper into the field if wanted. The parameters measured are:

- Temperature
- Humidity
- Carbon Dioxide - CO_2
- Particulate matter 2.5 µm - PM2.5
- Particulate matter 10 µm - PM10
- Volatile Organic Compounds - VOC

The information is gathered through two sensors and is later presented on a large 5-inch display with clear information for the end user. There are options to specify what information the user desires to see including current values and their effect on productivity, historical data as well as recommendations for how to easily improve the AQ leading to increased productivity.

These components are configured to fit in a smaller plastic molded case to be portable even with the relatively large display. For the product to be portable it is equipped with a battery with capacity to power the product for a full day of use. It can then easily be charged with a USB-C cable which is commonly used and easily accessible. Further, a vibrating mechanism is included as a communication medium to draw attention which is used to remind users to consider the AQ, when levels reach certain limits or when the battery is low.

RQ2: How interested are the main customers and users of monitoring air quality as a way to increase productivity?

This RQ supports the first one by investigating where there is a market and how large it seems to be, with the results indicating unexplored markets with primary students and office workers as customers. The data from the questionnaire in Appendix H shows that **74% of students and 67% of office workers who replied could consider buying an air quality monitor** like the one developed during this project.

The main difference between customer and user is assumed to be when office workers and students show interest, if it is most suitable to sell directly to them or the responsible personnel. Meaning that the university or school and the companies would see value in providing their students respectively employees with such a device. Feedback gained from interviews indicate that a less costly portable product could be suitable to sell to the individuals, and with a suggestion to sell a more extensive but less portable product to organizations.

RQ3: Is there an impact from air quality on productivity? If so, what are the major parameters that have an impact?

The overall effect that AQ has on productivity is found to be quite significant with most parameters having a negative impact when the parameters reach higher limits. One of the most commonly known parameters is temperature which people can feel the difference in rather clearly, and it is derived from Figure 2.1, that **for every degree above 25°C productivity decreases by 2%**. Humidity is then closely linked to temperature since it changes the perceived temperature where for example 30 degrees with 40% humidity feels true to 30 degrees while if the humidity is increased to 80% it is perceived as 37 degrees [12]. Further, humidity outside of the range 40%-60% of can also affect productivity in the longer run with its correlation to viruses and bacteria spreading, but no evident correlations are found with a direct link to productivity [9].

A strong effect is seen with examples **for CO_2, of cognitive function showing a 15% decrease in test scores at a concentration of 950 ppm compared to 600 ppm** [1]. In higher concentrations **with CO_2 at around 1450 ppm, the same report shows a 50% decrease in these cognitive function tests**. Further CO_2 is especially relevant since it is a pollutant we humans produce ourselves and inside a smaller closed space it can quickly increase. A group of PhD students at IITD found that in a closed non-ventilated with four people in the car the CO_2 levels went from 2168 ppm to over 7000 ppm in half an hour [16].

There is a growing amount of research showing the negative impact on labor productivity from air pollution and specifically particulate matter [18]. **Particulate matter for specifically PM2.5 it is seen to have an effect where there is a 1% performance drop for every 10 µg/m^3 of PM2.5** [20]. Further similar to CO_2 it is important since it affects many people, with WHO stating that 5.5 billion people are living in places where the PM2.5 levels are above the recommended safety level [18].

7.2 Product Results

The **minimum viable product is a portable consumer product used for monitoring the air quality for increased productivity**. It works by creating awareness to the user for them to act upon the situation and improving it or by changing location. Minor changes like opening a window, changing the temperature or switching location can have major impacts on how productive the user is. This section will further describe what the actual MVP represents and the groundwork can be seen in the concept detailing Section 5.4.

The **product has a width of 145 mm, a height of 100 mm and a depth of 120 mm**. It has a similar size to a table clock and shape like an older computer monitor. The display is a 5-inch touch screen with a width of 110 mm and a hight of 66 mm, not far from a modern smartphone. It displays the AQ data gathered from the sensors paired with the status as well as how this data actually impacts productivity. Battery status and other preferences are also planned to be included. A small vibrator motor is also included for communication but can be turned off if desired. The display and screen of the final MVP model can be seen in Figure 7.1.

(a) Final MVP rendering viewed from front.

(b) Final MVP rendering viewed from back.

Figure 7.1: Renderings of final MVP from different angles.

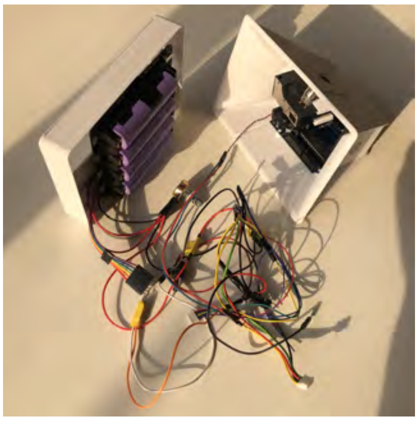
Two main sensors that manage to cover all interesting parameters are included in the product which provides the user with real-time, accurate measurements of CO_2, VOC, PM2.5 and PM10 as well as temperature and humidity readings. The sensors are mounted on each of the sides of the product to achieve robustness and more accurate readings. Minimal maintenance is also needed which is done entirely by the sensors themselves through specific maintenance software schedules which leaves the user to not need to think about this.

For powering the product a **battery pack of around 32 Wh** is used which means that it can be fully on during **a whole day of usage** without needing to be recharged. **Charging is done easily through a USB-C outlet** and a button for turning the product on and off is mounted on the top of the product.

For the physical prototype created during this project a smaller but much simpler and budget-friendly LCD display is used instead of the 5-inch display planned to be used for the MVP. This displays all the data from the monitors in a raw but similar fashion to how it would be displayed for the commercialised product. It does however mean that there are no options for easy customisation for the user but different layouts of the information can be pre-programmed. Finally everything is controlled with an Arduino Uno processor which is easy to iterate and test on.

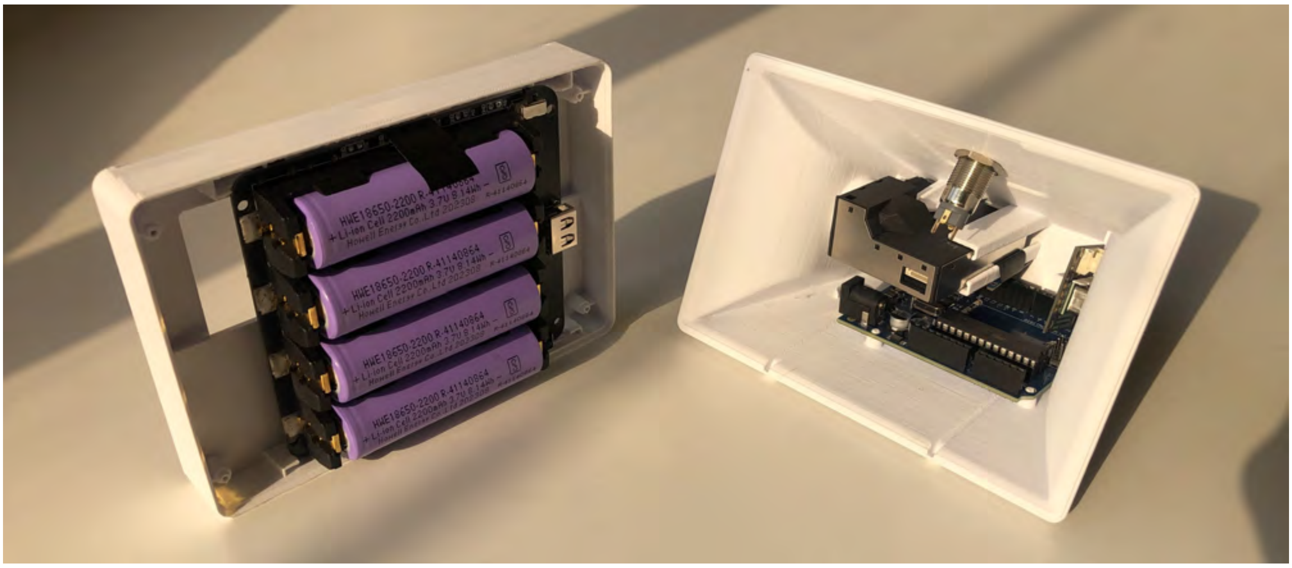
The final physical prototype including all components and wiring for the monitor to work can be seen in Figure 7.2. The 5-inch display is not included and not either paper slips for prototyping the UI.

(a) Final physical prototype viewed from front.



(b) Final physical prototype including all cables.

(c) Final physical prototype viewed from back.



(d) Final physical prototype viewed from back excluding wires.

Figure 7.2: Final physical prototype seen from different angles. Outer and inner casing can be seen with included components inside. All wires used can also be seen, although in a less organised fashion.

8 Discussion

Most steps in this project has followed the general methods of product development. Although there are often different ways to conduct each step and careful consideration to which methods and tools that should be used is important. Since the product development process varies a lot between projects, justifications of what methods should be used is important for the sought after results as well as creating understanding and transparency for other parties who might be interested in the process. Some of the main topics of consideration will be discussed here.

8.1 Productivity VS Health

The first topic for discussion appeared just in the beginning of this project, namely what the project proposal should include. It was clear that the purpose was to develop an air quality monitor into an MVP, but for what intent was difficult to conclude. Through some initial quick market analysis as well as consideration of the project as a master thesis with limited resources, it was decided to develop a product that would focus only on the effect on human cognition and productivity. Almost all products in the market at the time focused on the impact of the air on health, and its effect on human cognition, which was identified as a hole in the market and therefore as an opportunity. Another primary reason for solely prioritizing productivity for this project was simply the limited time and resources available for developing a prototype; including health aspects in the product would probably have been a positive aspect but it would increase the engineering time needed for development. Including health into the scope would also most certainly make the project much more research-oriented than developing a consumer product. It is however worth to note that very short-term health impacts like nausea or drowsiness are still considered because of their impact on the current productivity of the user. After some more thorough market and user research it was concluded that focusing on only productivity was feasible both in terms of user needs and economical aspects. However, a larger need for health focused products instead of focus on productivity was found, and implementation of this kind of new novel product into the market were considered as two notable disadvantages for this project.

8.2 Subjective VS Objective Methods

As in every product development project, subjective impacts are impossible to completely eliminate. Subjective and biased views are often considered as negative for a project since these perspectives are not necessarily the ones that are the same as what the user wants. Therefore many tools and methods exist to try to eliminate as much bias as possible, and are because of this implemented in this project. However, often using these tools requires much more time than just subjectively choosing and is therefore sometimes considered as not worth the benefit. A good example can be the unrealistic endeavor of evaluating every possible solution generated through a morphological matrix, even though this would give the best results, ensuring the whole design space is evaluated. More realistic concepts were therefore generated by the team in this project to save time, but also meant that more subjective thoughts were put into the concepts and some parts of the design space could have even more promising concepts.

In general, systematic methods has been used to maximal extent under the limits dictated by the Gantt schedule regarding time usage. But because of this, the reader of this report should be consious and know that all biased aspects of this project has not been able to be eliminate.

8.3 Use of AI in the Project

With the new modern powerful tools of AI being available they are used to simplify the work greatly with inspiration and finding deviations in the grammar. Of course however the AI tools have its boundaries and can or should not be used for everything. The approach used in this thesis has been to use AI tools for menial tasks, to gather quick and simple information when for example writing, or to generate inspiration for the project. More specifically the generative AI tools used have been ChatGPT [36] and the Microsoft Bing Designer tool [71].

Finding synonyms, translating, or organising text in alphabetical order are all example of things that have been done through AI during this project and are seen to be of minimal risk. However using AI for generating images or examples as inspiration has been done and could come with a larger risk. First this is plainly letting another relatively unknown source to influence the project, and secondly it also comes at a risk of accidentally using copy-righted information. But because the advantages of using AI in certain situations are seen outweighs the risks it is still used. The method used has been to first come up with as many original ideas as possible by the developers before using AI to see if it can give any other possibilities. This was for example used when brainstorming concepts, identifying all functions for the product or even writing this section about AI. There have been identified occasions where some ideas would have been missed if not for the use of AI. This together with the convenient way AI can solve simple problems are the justifications to why it has been used in this project.

While AI has been used it has had a minimal impact and only been used as inspiration and not been allowed to make any decisions during the project. Also since this project does not include any secrecy of other parties apart from what the developers want to share, there has been no risk of sharing disclosed information.

8.4 Reflections on Final Concept

Even if the final concept identified showed to be the optimal MVP one using the product development methods, the developers had some critiquing thoughts on the results. The first reflection is that the winning concept is on the more expensive side of the spectrum. Price is often the most important factor for a product, especially for a consumer product. Therefore it is unsure if the price had a too small weight during the concept evaluation in Section 5.3.2. The cost weight might have been diluted by many other less important desires. However the concept survived through the sensitivity analysis with enough margin which shows that the final concept most likely is correctly graded. Also with this said, looking at the broad range of prices of the competitors, there seems to be a market segment for the price of the product developed during this project.

Another somewhat surprising fact is that the final product is not very portable. The original imagined product was a small very portable monitor with a small screen for conveying the information compared to the final solution which employs a large screen and a not very compact size. This result mostly comes from desires for the product to have a clear communication and for it to be used more for displaying the data rather than to be more portable. The combination of the needs resulted in a product which has a bit of an awkward size of not being small enough to be very portable, but not having a large or sleek enough design for it to have very clear communication or a more luxurious design. However the final solution is a trade-off of both these parameters and therefore also is a "one size fits all" product which is desired.

8.5 Design of User Experience

The user experience of a product is very important for it to be successful, it does not matter how well the monitor can measure the air or what conclusions it can give if those can not be conveyed to the user in the correct way. This is one reason why the product focuses on possibilities for good interaction between the product and the user through a large clear touch-screen and vibration motors. However, this project spends less time on developing a good UX and UI because of limited resources. The first aim was to develop a working MVP with research put into what AQ parameters to measure and how. A UI example was however developed as can be seen in the UI Section 6.4, but mainly to show for the user, stakeholders or for marketing the product. No research or specific methods were used for the creation of the UI which means that the results should be considered as examples and not the optimal design. But for taking the project further in the future, and especially conveying the idea to stakeholders for commercialisation, a clear visualisation of the product is seen to be of high value and is another reason for why some weight is put on this already during this project.

8.6 Ethical Considerations

Since the product developed during this thesis is a consumer product meant to create awareness for the user, it is also exposed to many risks of ethical consideration. The first consideration is to imagine how the product will actually be accepted by the society and how it would be used. The idea is that it should be used as a simple air quality monitor for the regular user to benefit from the understanding of how the air we breathe can affect how productive we are. But this positive view can also be seen as being exploited for greenwashing purposes. This means that companies or other parties could use the product to convey that they are aware of the environment and are protective of their employees to receiving a positive social view. While in reality they might only use this as a marketing strategy and could be measuring only where they know it is good and avoid worse off areas or as a medium to cover up other much worse impacts on the environment. More information about greenwashing and its impacts can be read on the United Nations website about the subject [73].

Another aspect connecting to the discussion section about developing a more refined product is that the product will most likely not reach the people in most need. Even if the product would have been developed to be as inexpensive as possible, with half the cost of the sensors being around 500 SEK [67], it would still most probably not satisfy the budget of the people who could use the productivity boost the most and are in the areas with the worst AQ. This is however only true if seeing purely from a private customer point of view. In reality the product could easily be subsidised by for example governments to achieve a more lucrative price for the end user. But then this would need to be done and could fall under a welfare program which would bring its own ethical considerations. It should be noted that there are multiple areas where the effect of the monitor could have great impacts even in the more developed world, as for example in large cities or just poorly ventilated areas, which is one reason for why the poduct was developed.

Information gathered from the user research also showed that the mere awareness can act as a source of stress, leading to a negative view of the product. Being reminded at all times to be productive and to make the most of ones time and resources can definitely create an anxious environment. It could because of this maybe be of consideration to keep the product only in a work environment even if the use could be beneficial in more leisure oriented activities. This is an area less explored and would require thorough user research and testing to verify how the situation actually becomes around the product.

Lastly, because this is a product that informs the user about the air quality around them, and how this affects their productivity, it is important that no misunderstandings or wrong use of the product is done. Wrong interpretation of the data could have grave impacts on peoples health both physically and psychologically. Awareness about a bad air quality situation, with no solutions of improvement, could possibly have worse psychological impacts rather than innocently not knowing about the poor situation at all. In a similar sense can the data be misunderstood to have a bad influence on someones health, which in reality might not be the case, especially if the data is paired with other sources.

9
Conclusion

After a comprehensive development process, reaching from early background research all the way to a final working prototype, some main conclusions can be made to the questions asked early in the project and findings in the relevant fields. Since this project aimed to develop a minimum viable product, some areas are left for improvements and more iterations which are also described at the end of this chapter.

9.1 Findings

To conclude the interest in air quality as well as productivity both seem to be rising in correlation with the developing world. The relationship between these two different subjects does not however appear to have become well established yet. An air quality monitor seemed to be especially interesting because very few products exist today in the field of improving productivity by considering air quality.

Air quality is a complex area to study and understand since there are multiple parameters affecting each other creating an intricate environment. People are found to consider air circulation, dust particles, temperature and CO_2 regarding AQ, but lesser known are PM, VOC:s and humidity. With some parameters that are commonly understood by the user creates an easy start in using the product and other parameters can create the possibility for a more comprehensive understanding of AQ and a deeper dive into the field. This could mean that a potential product that can evaluate the general AQ using all these parameters can teach users more in-depth relations between the parameters and how they affect performance without overlooking any important factors.

Air quality is seen to have a major impact on human health and is therefore also interlinked to productivity both directly and indirectly. These effects happen both outdoors and indoors and does not necessary mean one is always better than the other. However the outdoors usually offer limited options to mitigate the effects of the AQ since it is on such a large scale, and is mainly why this project has focused on developing an indoor product where changes are more feasible. A common way to improve the IAQ is also opening a window and getting air circulation with outdoor air. A conclusion is that an air quality monitor would benefit a user by informing them about the local AQ and providing suggestions on how to improve the situation or to change location switching indoor to outdoor, vice-versa or going to another area. Paired with this is to describe the connection the local AQ has on the individuals productivity or performance, and to show a historical trend so the user easily can connect events that has affected the AQ and therefore also the productivity; trying to utilise a learning by doing process for the user to see the results affected by their own actions.

A product as mentioned in Section 7.2 has been created and is a proof of the possibility to combine all sought after functions into one consumer product. It has been found that potential users prioritise clear and easily understood information in combination with some portability. The technology exists and utilised in a large enough scale can reach an attractive price for many regular consumers. With some refinements described in the coming future works Section 9.2, an air quality monitor for increased productivity is seen as a both feasible and viable product to introduce to today's or the near futures market.

9.2 Future Work

This thesis involved the development of an MVP prototype and an evaluation of the potential for the identified product, which has been identified. But many further steps has been identified for improving the product and introducing it to the market in a successful way. Some of the initial and most important steps that were not performed during this thesis, but would be necessary for taking the project further are described in this section.

Product Specifications

Specifically connected to the product is the MVP which was created and can be used to obtain more feedback for improvement of the product further. Conducting more user studies using the prototype for observations and other testing would reveal new areas of improvements, but certain aspects are already identified but the developers that can be initial subjects of improvements.

The MVP prototype had loose wires connecting all of the different devices, useful for quick iterations, but not robust enough in avoiding them to disconnect, or minimising space or assembly time. To solve these problems, a printed circuit board which enables very compact wiring could be used. This is also closely related to installing a more optimised and smaller microprocessor instead of the current Arduino Uno.Another component change would be to identify a compact suitable rechargeable lithium-ion battery instead of using the current four 18650 batteries placed in a battery charging module as seen in Section 5.4.1. This would reduce the space needed and make it possible for a smaller, sleeker and more portable product. An estimation is that a highly optimised product could take up only half the space of the current one.

Another planned component change is for the display, using a 5-inch touchscreen, for easier communication to the user as well as a way for them to interact with the product. With further feedback from customers this choice of display could also be updated for an even larger display for use in public spaces like in a hotel lobby or office landscape. It could also be updated with a smaller display for a more portable personal product similar to a smartphone. A final comment regarding the actual product is to develop the UI interface, making the product more visually appealing, not only for effective communication but also in an engaging way to optimise the user experience.

Commercialisation

Besides working on the specific product, the introduction of the product into the market would also require a commercialization strategy. Having a planned process of going from selling a product to crating a profit would include a large set of actions and a few are mentioned here.

A first step could be to make a cost-benefit analysis, with the thesis as a base to see if the future development is warranted and if it would ultimately generate profit. This could also then include identifying the break-even point to know how long it would take until seeing a return from the initial profit.

For selling the product, a comprehensive supply chain would be needed. From suppliers manufacturing and delivering components, to assembly and the creation of the product, and lastly transport to suitable sellers. Importance would be put on trying to reduce supplier cost as much as possibly with agreements on bulk-purchases, where with larger quantities it brings the possibility to have a larger influence on reducing price per component with the sellers still turning a profit.

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A

Appendix

This appendix includes all important documents used during the project process but that are too large to be shown directly in the text. It covers all areas from the initial background research to the final MVP. All of the documents are referred to at least once in the text.

A List of VOCs covered in study by Joseph G. Allen et al.

Analyte	Background	Day 1 Green+	Day 2 Med. CO_2	Day 3 High CO_2	Day 4 Green	Day 5 Conventional	Day 6 Green+
	Condition						
VOCs							
1,2,4-Trimethylbenzene	0.3	0.2	ND	0.1	ND	0.5	0.1
2-Butanone	2.5	0.7	0.7	0.8	1.1	1.1	0.6
2-Propanol	1.0	1.2	1.1	3.1	1.2	312.5	8.2
Acetone	12.0	14.7	9.6	8.7	20.0	20.0	8.6
Benzene	0.5	0.8	0.5	0.9	0.7	0.5	0.5
Carbon disulfide	0.6	0.2	ND	ND	ND	ND	0.1
Carbon tetrachloride	ND	0.2	0.4	ND	0.2	ND	ND
Chloroform	ND	0.1	ND	ND	ND	0.1	ND
Chloromethane	1.3	1.7	1.5	1.4	1.9	1.5	1.4
Cyclohexane	0.2	0.3	0.4	0.5	0.1	0.4	0.3
Dichlorodifluoromethane	2.5	2.6	2.9	2.7	2.9	2.4	2.5
Ethyl acetate	ND	ND	ND	ND	1.0	2.0	ND
Ethylbenzene	0.3	0.4	ND	0.3	0.2	0.1	0.1
Freon 113	0.3	0.7	0.8	0.8	0.8	0.2	0.4
Heptane	ND	0.3	ND	0.3	ND	257.5	6.9
Hexane	0.4	0.7	0.5	0.7	0.4	0.8	1.3
m,p-Xylene	0.8	1.5	0.4	1.0	1.0	0.7	0.7
Methylene chloride	0.5	0.3	0.6	0.5	0.3	0.4	0.4
o-Xylene	0.3	0.4	ND	0.4	0.1	0.3	0.1
Styrene	0.1	ND	ND	ND	ND	ND	0.1
Tetrachloroethene	3.7	0.9	ND	ND	0.9	0.6	0.2
Tetrahydrofuran	ND	ND	ND	ND	0.2	0.1	0.2
Toluene	2.4	2.1	1.4	1.9	2.2	1.9	2.9
trans-1,2-Dichloroethene	19.0	8.8	12.6	6.2	10.3	21.8	8.7
Trichloroethene	ND	ND	ND	ND	ND	ND	0.2
Trichlorofluoromethane	1.3	1.2	1.6	1.4	1.5	1.1	1.2
Grand total	50.0	40.1	35.0	31.4	46.9	626.4	45.6
Aldehydes							
2,5-Dimethylbenzaldehyde	ND	ND	ND	ND	ND	ND	ND
Acetaldehyde	1.0	3.7	3.2	3.1	5.4	7.3	2.1
Benzaldehyde	ND	ND	ND	ND	ND	1.5	ND
Crotonaldehyde	ND	ND	ND	ND	ND	ND	ND
Formaldehyde	2.4	5.9	5.5	5.4	8.9	11.7	4.4
Hexanaldehyde	ND	0.8	0.8	ND	1.9	2.4	ND
Isovaleraldehyde	ND	ND	ND	ND	ND	ND	ND
m,p-Tolualdehyde	ND	ND	ND	ND	ND	ND	ND
n-Butyraldehyde	1.1	2.7	1.4	2.3	2.8	2.4	2.0
o-Tolualdehyde	ND	ND	ND	ND	ND	ND	ND
Propionaldehyde	ND	0.7	1.2	ND	1.4	1.6	0.6
Valeraldehyde	ND	ND	ND	ND	ND	ND	ND
Glutaraldehyde	ND	0.5	ND	ND	0.4	ND	ND
o-Phthalaldehyde	ND	65.1	57.7	70.0	41.6	38.4	76.8
Grand total	4.6	79.4	69.8	80.9	62.4	65.3	85.8

Abbreviations: ND, non-detect; VOC, volatile organic compound.

Figure A.1: Speciated VOC concentrations (μg/m^3) on each study day (Conventional, Green and Green+), averaged across rooms [1].

B Real-Win-Worth Analysis

			YES/NO	Confidence	Comment
REAL	**Is there a real market and a real product?**	**Splitting up of question**	-		
	Is there a need? (What is the need? How is the need presently satisfied?)	Need for productivity?	YES	90%	Yes but most probably quite latent. For example is peoples productivity is low and they dont do anything about it even if they can, the need is either latent or nonexistent. The question is more if teh need is important enough, but that comes more under "Will the customer buy?".
		Need for monitoring?	YES	50%	Same as above. Also this depends if the user can do anything about the situation, if not, there is not really a need for the monitoring. Also awareness of air quality may be detremental in the sense of too much emphasys of being productive.
	Can the average customer buy? (size of the market, customer decision-making process)	Indian individual?	NO	70%	Not enough resources
		Swedish individual?	YES	90%	
		Indian business?	YES	70%	May have very restricted resources
		Swedish business?	YES	90%	Depending on the final price, but most likely
		Indian school?	YES	40%	Probably have very restricted resources
		Swedish school?	YES	70%	Probably have very restricted resources
	Will the customer buy? (precieved risks and benefits, excpectations on price and availability)	Prioritising of productivity?	YES	20%	Yes some people most likely will. But this can be a quite niche market. People who would prioritise small improvements with an seemlingly easy fix.
		Understanding connection between productivity and air quality?	YES	30%	Most people will probably understand the connection between air quality and productivity, at least when seeing the product and its marketing. Not difficult to connect productivity to air quality.
		Is the product worth the price?	NO	50%	For the product to be worth it we expect that it would have to cost less than 300kr. And we expect that it would cost more than that.
		Can the product be targeted to businesses?	YES	100%	Definately, it can easily be seen as either a monitor just to get to know and understand the air quality, but also as a individual product that a company buys for individual employees. Also can be used as greenwashing...
	Is there a viable concept for a product already? How likely are we to be able to develop a viable concept?	Are there no other consumer products focusing on air quality?	NO	100%	There are other similar products on the market, but not any found connecting air quality to productivity
		Are there no other consumer products focusing on productivity connecting to air quality?	YES	80%	We havnt found any doing this, but there is a chanse there are some.
		Are there no other small portable battery driven products doing this?	YES	90%	Same as above but now it has to be battery driven also which decreases the chanse of others existing.
	Is the product acceptable within the social, legal and environmental norms?		YES	100%	
	Is the product feasable? Can it be made? Is the technology available? Does it satisfy the needs?		YES	90%	Could be certain factors that do affect productivity that there are not sensors for
	Will our product satisfy the market? Is there a relative advantage to other products?		YES	90%	State of the art PD methods, developing product in the are it could be used,
	Can it be produced at low cost?		YES	80%	With the intended product only needing already available components, and require relatively simple components, in combination with mass production, this product should be able to develop in a low enough cost.
WIN	**Can we win? Can our service or product competitive? Can we succeed as a company?**		-		
	Do we have a competetive advantage? Is it sustainable? (Performance, patents, barriers to entry, substitution, price)	Performance?	YES	70%	Most likely the product will be performing well enough since we will work with quality and PD techniques. Although improvement will always be possible.
		Patents?	NO	100%	We don't have any patents, how big setback this would be in others having patent is unclear
		Barriers to entry?	YES	40%	Understanding of productivity in connection to air quality might be difficult to communicate. Creating an efficient production and supply chain takes some time, it would be quite a entry barrier to get that going as a start-up or small company without any production connections
		Novelty?	YES	70%	Nothing really similar exists on the market, that is a specifc product for increasing awareness that can be used to increase productivity, but there is alternatives of air quality monitors on the market
		Substitution?	NO	20%	There are alternative ways for users to get awareness of the air quality and connect this to productivity, but is is quite difficult and time consuming.
		Price?	NO	30%	Product will probably not be cheap enough to be competing to indirect air quality competitors
	Is the timing right?		YES	80%	Not clear if the timing is right yet, but seems like both air quality and productivity has and is increasing focus in society
	Does it fit our brand?		YES	100%	Start-up
	Will we beat our competitors? (How much will they improve? Price trajectories, entrants)	Competitors regarding health	NO	100%	Our product is not focusing on health directly, so therefore nothing that a user seeking for health would prioritise
		Competitors regarding productivity?	NO	80%	Our product is probably not the first thing people would think of if wanting to improve productivity. Lighting, sound, or food and excercise are all things they will probably think of before.
		Competitors regarding productivity in connection with air quality?	YES	80%	No other real competitors identified doing exactly what we are doing, as the air quality monitor for increased productivity
	Do we have superior resources? (engineering, finance, marketing, production; fit with core competencies)		NO	80%	Just a master's thesis. Although we are educated in the PD field and have some powerful contacts.
	Do we have the management that can win? (experience? fit with culture? commitment to this opportunity?)		NO	50%	Just a master's thesis. Although we are educated in the PD field and have some powerful contacts.
	Do we know the market as well as or better than our competitors? (customer behaviour? channels?)		YES	30%	In exactly our field we are probably superior. But regarding all subjects individually: air quality, health and productivity we are not the best in any
WORTH	**Is it worth doing? Is the return adequate and the risk acceptable?**		-		
	Will it make money?		YES	70%	But if it is money worth the time and original investment will be more worth investing in other possibility is not clear
	Do we have the resources and the cash to do this?		YES	90%	Fot the master's thesis we have cash for the prototype most probably
	Are the risks acceptable to us? (What could go wrong? technical risks vs. market risk)		YES	100%	As a master's thesis this is very low risk because a failure is still accepted
	Does it fit our strategy? (fit our growth excpectation, impact on brand, embedded options)		YES	100%	Start-up

Figure A.2: Real-Win-Worth analysis for the product.

C Benchmarking Matrix

Product name	Picture	Link	Price (SEK)	Expected lifesp	Dimensions (mm)	Power	Battery	Connectivity	Sensor specs	CO2	PM 2.5	PM 10	VOC	Humidity	Temperature	Other sensors
Kaiterra Sensedge		https://www.kaite	12500		L 184	DC	5200mAh	Wifi 2.4 GHz	*Sensor type*	Non-dispersive infrared	Light scattering (350 nm)		Metal Oxide Semiconductor Sensor (MOS)	Digital	Digital	
					W 146	5 V		Ethernet	*Measuring range*	400 - 2000 ppm	1 - 1000 µg/m3		125 - 600 ppb	0 - 99%RH	-20 - 100 °C	
					H 48	1.8 A		Others	*Sensor output resolution*	1 ppm	1 µg/m3		1 ppb	1% RH	1 °C	
						USB A			*Accuracy*	± 3% ±50 ppm	± 10% (< 30 µg/m3: ± 3 µg/m3)		± 15%	± 5% RH	± 1 °C	
									Lifetime							
Kaiterra Sensedge Mini		https://www.kaite	7500	5 - 7	L 155	100 - 240 V AC		Wifi 2.4 GHz	*Sensor type*	Non-dispersive infrared (ND	Light scattering	Light scattering	Multi-pixel metal oxide sensor (MOx)	Digital sensor	Digital sensor	
					W 129	USB C		Others	*Measuring range*	400 - 2000 ppm (extended 1	0 - 1000 µg/m3	0-1000 µg/m3	0 - 60000 ppb	0 - 99%RH	-20 - 100 °C	
					H 34				*Sensor output resolution*	1 ppm	1 µg/m3	1 µg/m3	1 ppb	1%RH	0.01 °C	
									Accuracy	±3 % m.v. ±50 ppm	± 10% (30 - 1000 µg/m3)		±15 % ±8 ppb	± 5%RH	± 1 °C	
									Lifetime (years)	15+	1.3 - 2	1.3 - 2		10	10	
Atmotube PLUS		https://atmotube.	1500		H 66	USB C	500 mAh 7 days	Bluetooth 5.0	*Sensor type*				Sensirion SGPC3	Bosch BME280	Bosch BME280	Pressure
					Dia 22				*Measuring range*				0 - 1000 ppm	0 - 100% RH	-40 - 85 °C	
									Sensor output resolution				0 - 60 ppm (0.2 % of meas. value)	0.008% RH	0.01 °C	
									Accuracy				15% of meas. value	± 3% RH	± 1 °C	
									Lifetime (years)							
Atmotube PRO		https://atmotube.	2150		H 86	USB C	2000 mAh Up to 10 days	Bluetooth 5.0	*Sensor type*		Sensirion SPS30	Sensirion SPS30	Sensirion SGPC3	Bosch BME280	Bosch BME280	PM1
					W 50				*Measuring range*		0 - 1000 µg/m3	0 - 1000 µg/m3	0 - 1000 ppm	0 - 100% RH	-40 - 85 °C	PM4
					Depth 22				*Sensor output resolution*				0 - 60 ppm (0.2 % of meas. value)	0.008% RH	0.01 °C	Pressure
									Accuracy				15% of meas. value	± 3% RH	± 1 °C	
									Lifetime (years)		10+	10+				
Atmocube		https://atmotube. https://seetheair.	6500		W 128	50/60Hz		Wifi	*Sensor type*	Sensirion SCD41	Sensirion SPS30	Sensirion SPS30	Sensirion SGP41	Sensirion SHTC3	Sensirion STS35	PM1
					H 128	5 V		Bluetooth 4.1	*Measuring range*	0 - 5000 ppm	0 - 1000 µg/m3	0 - 1000 µg/m3	1 - 500 VOC index points	0 - 100% RH	-40 - 125 °C	PM4
					D 38	2 A		Ethernet	*Sensor output resolution*					0.01% RH		NOx
						USB A		Others	*Accuracy*	± (40 ppm + 5% of reading)			15% of meas. value	± 2% RH	± 0.2 °C	Many more
									Lifetime (years)		10+	10+				
Sensibo Air PRO		https://sensibo.c	2300		L 65	5 V		Wifi	*Sensor type*	CO2 equivalent (using VOC			Should have			
					W 65	1 A		Bluetooth	*Measuring range*					5 - 95% RH	0 - 55 °C	
					H 17	Micro USB		Voice assist	*Sensor output resolution*							
								Others	*Accuracy*					± 5% RH	± 0.5 °C	
									Lifetime (years)							
Air Quality Guardian		https://analoxgro	2650		W 190	5 V	Lithium battery 8 hours operational		*Sensor type*							
					H 90	1.6 A			*Measuring range*	0 - 5000 ppm				5 - 95% RH	0 - 50 °C	
					D 35	USB (?)			*Sensor output resolution*							
									Accuracy	± 40 ppm (± 5 - 7%)				± 5% RH	± 1 °C	
									Lifetime (years)							
Airthings Wave Plus		https://www.airthi https://www.clasc	2290		Dia 120	2 AA batteries	16-18 months	Bluetooth 4.2 or later	*Sensor type*	NDIR Sensor (Non-Dispersi						Radon
					Depth 36				*Measuring range*	400 - 5000 ppm			250 - 2000 ppb			Pressure
									Sensor output resolution							
									Accuracy	Optimal ±30ppm ±3%				± 1% RH	± 0.1 °C	
									Lifetime (years)							
Airthings View Plus		https://www.airthi	3380		W 170	6 AA batteries	Optimal 2 year		*Sensor type*	NDIR Sensor (Non-Dispersi	Laser scattering based optical pa		Metal-oxide based gas sensor			
					H 90	USB (?)			*Measuring range*	400 - 5000 ppm	0 - 500 µg/m3		0 - 10000 ppb			
					D 33				*Sensor output resolution*							
									Accuracy	Optimal ±30ppm ±3%	15 - 20 %			± 3% RH	± 0.5 °C	
									Lifetime (years)							
Cikonielf Air Quality Monitor		https://www.ama	1220		Dia 81	USB (?)	2400mAh	No connectivity	*Sensor type*							
					Depth 32				*Measuring range*	400 - 5000 ppm				1 - 99% RH	-10 - 70 °C	
									Sensor output resolution							
									Accuracy					± 2% RH	± 1 °C	
									Lifetime (years)							
					Volume dm3		Of the ones having battery			Range	Range	Range	Range			
Average			4199		0.509		3050 mAh			Low: 342, High: 3857 Acc: 3.83%	Low: 0, High 900 Acc: 13.3%	Low: 0, High 1000	0 - 345 Acc: ±15%	0 - 100% Acc: ±3.4%	Low: 13.75 °C, High: 83.75 °C Acc: ±0.63 °C	
Median			2475		0.306		2200 mAh			400 - 5000	1000	1000	0 - 10	Acc: ±3%		
Lowest			1220		0.026		500 mAh			400 - 2000 Acc: 3%	500 Acc: 10%	1000	0 - 0.6	Acc: ±1%	0 - 50 °C Acc: ±0.1°C	
Highest			12500		1.359		5200 mAh			0 - 5000 Acc: 7%	1000 Acc: 20%	1000	0 - 1000	Acc: ±5%	-40 - 125 °C Acc: ±1°C	

Figure A.3: Benchmarking analysis.

D Technology Assesment Matrix

Sensor	Link	Article number	Voltage	B	L	H	Volume (mm3)	Weight (g)	Interface type	Compat-ability	Multi-tasking sensors	Qt.	Price (SEK)	Price per Qt.	Comment
Temperature & Humidity	[74]	246-5631	2.15 - 5.5	25	25	9	5625	-	I2C	Digital output, 8 pins	2	2	83	41.5	Low humidity hysteresis at 25°C, ± 0.8%RH.
	[75]	786-5554	2.1 - 3.6	3	3	1.1	10	0.025	Serial - I2C	Digital output, 6 pins	2	1	110	110	±0.3 °C, ±2%RH.
	[76]	893-7146	1.5 - 3.6	3	3	0.9	8	0.025	Serial - I2C	Digital output, 6 pins	2	1	38.5	38.5	±2%RH accuracy.
Particulate matter	[37]	186-2540	4.5 - 5.5	41	41	12	20172	26.3	UART7 & I2C	5 pins	2	1	620	620	Both PM 2.5 and 10. (+ 0.5 ,1 & 4 PM) Requires exposure to air outside of product. Same one as the pHds use in India.
	[77]	195-3770	5	62	52	23	74152	45	UART & Modbus (RS485)	6 pins	4	1	866	866	Both PM 2.5 and 10. (+ PM 1) Temperature & RH Great user guide
	[78]	205-4777	5	37	37	12	16428	13	3	5 pins	2	1	339	339	Both PM 2.5 and 10. (+ PM 1)
VOC	[40]	204-7512	3.3	2.44	2.44	0.85	5	-	I2C	6 pins	1	1	122	122	Maximum humidity exposure of 90%. Avoid exposure to bright light.
	[39]	234-8991	1.7 - 3.5	2.44	2.44	0.85	5	-	I2C	6 pins	1	1	112	112	VOC ±15 VOC Index points or % (the larger). Device to device variation NOx ±50 NOx Index points or %. Maximum humidity exposure of 90%. Avoid exposure to bright light.
CO2	[79]	233-7538	-	8.3	8.3	13.5	930	-	-	5 pins	1	1	830	830	Very low temperature coefficient of responsivity of -0.04%/°C.
	[80]	172-0552	3.3 - 5.5	35	23	7	5635	3.4	UART & I2C	7 pins	3	1	862	862	CO2: 400 - 10000PPM Temperature & RH
Mixed	[41]	241-3844	2.4 - 5.5	10.1	10.1	6.5	663	0.6	I2C	Digital, 6 pins	3	1	677	677	CO2: High accuracy: ± 75 ppm @ 400 ppm – 1’000 ppm. Large output range: 0 ppm – 40’000 ppm. RH measuring range of 0 - 100% with ±9%RH accuracy. Temperature measuring range of -10 - 60°C with ± 0.8°C accuracy.
	[42]	240-9022	5	22.3	52.3	43.3	50500	36.4	I2C	6 pins	5	1	468	468	RH measuring range of 20 - 80%. Temperature measuring range of 10 - 40°C. Both PM 2.5 and 10. (+ 0.5 ,1 & 4 PM) VOCs. (+ NOx)
	[81]	238-9413	5	22.3	52.3	43.3	50500	36.4	I2C	6 pins	5	1	302	302	RH measuring range of 20 - 80%. Temperature measuring range of 10 - 40°C. Both PM 2.5 and 10. (+ 0.5 ,1 & 4 PM) VOCs.
	[82]	195-0686	5	39	15	6.5	3803	-	IC2	Digital, 4 pins	3.5	1	288	288	CO2 equivalent. VOCs. RH measuring range of 25 - 75% with ±5%RH accuracy. Temperature measuring range of 5 - 55°C with ± 1°C accuracy.

Table A.1: Full technology assesment matrix including all analysed sensors with their relevant data for the development project. Their article number, link, price and comments etc. can be seen regarding all of the components.

E IP Standards

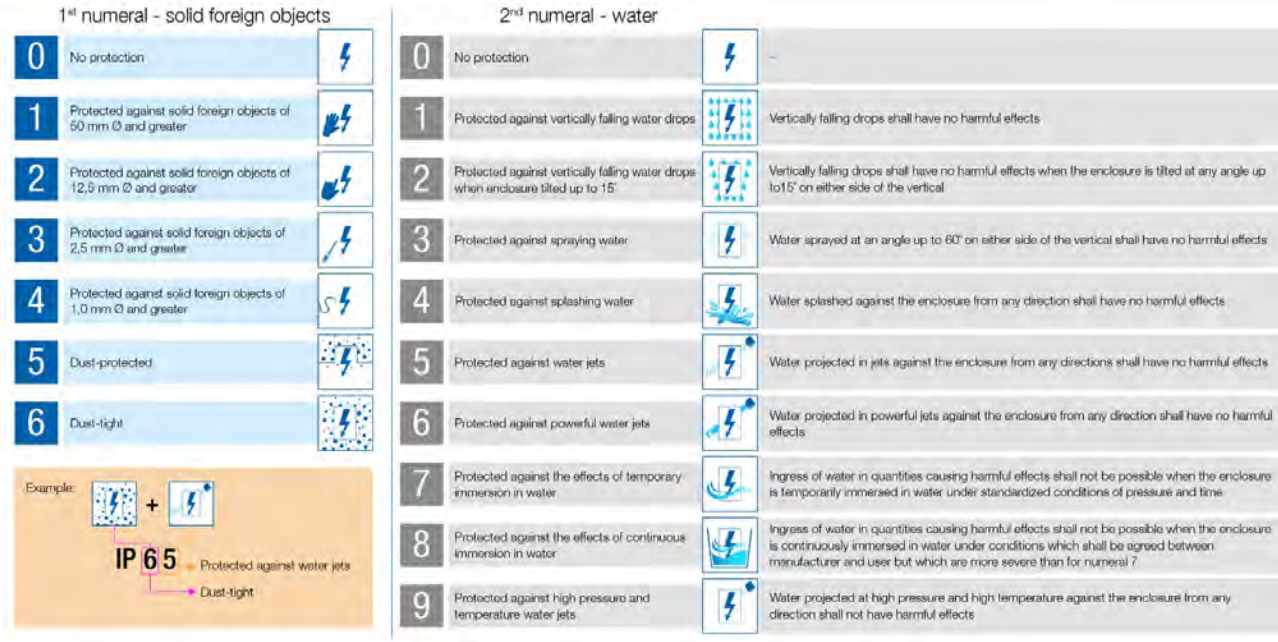


Figure A.4: How the IP standard works and its different values [83].

F Requirement List

Air quality monitor for increased productivity			2024-02-12	Requirement specification		
Requirement (Criterion)	**Target value**	**Requirement/Desire**	**Importance**	**Justification**	**Evaluation/Verfication**	**Reference (Demander)**
	Hours, seconds, g, % that use it right etc	**D/R**	**5=Very high 1=Very low**	**Increases sales, good for enviroment, etc**	**Questionnare, interview, testing, calculations, estimation, observation**	**Goverment, user, customer manufacturer, investor, Developers (us)**
1.Technical						
1.1 Long lasting battery	250 hours	D	4	Easy to use	Calculations	User
1.2 Measure CO2		R		Core value	Calculations	Developers
1.3 Measure temperature	±1C	R		Core value	Calculations	Developers
1.4 Measure humidity	± 2%	R		Core value	Calculations	Developers
1.5 Measure PM2.5		R		Core value	Calculations	Developers
1.6 Measure PM10		R		Core value	Calculations	Developers
1.7 Measure VOC		R		Core value	Calculations	Developers
1.8 Easy to charge	Does not require	D	5	Easy to use	Testing	User
1.9 Long product life	10 years with reg	D	2	Enviromentally fr	Calculations, estimation	User
1.10 Low maintenance	None	D	3	Easy to use	Testing, estimation	User
2. Portable						
2.1 Size length	12cm	D	3	Easy to use	Calculations	User, Developers
2.2 Size width	8cm	D	3	Easy to use	Calculations	User, Developers
2.3 Size height	20cm	D	3	Easy to use	Calculations	User, Developers
2.4 Weight	500g	D	3	Easy to use	Calculations	User, Developers
2.5 Operatable without pow	built in battery/de	R		Easy to use	Calculations	User, Developers
2.6 Easy to hold with hand	Ergonomic handl	D	2	Easy to use	Testing, observation	Developers
2.7 Stand steadily on flat su	Does not tip over	R		Easy to use	Testing	Developers
3. Intuitive						
3.1 Effective communicatio	>90% understand	D	4	Easy to use	interview, observation	Developers
3.2 Intuitive battery position	>90% can charge	D	4	Easy to use	interview, observation	Developers
3.3 Set up time	Avrage setup <30	D	4	Easy to use	Testing	Developers
3.4 Easy to use in the dark	Can be used any	D	2	Easy to use	interview, testing	Developers
3.5 Indication of low battery	Warns the user s	D	2	Easy to use	Calculation, testing	Developers
4. Durable						
4.1 Water resistant	IP63	D	2	Customer value,	Testing, calculation	Developers
4.2 External forces resistar	Can be dropped	D	3	Customer value,	Testing, calculation	Developers
4.3 Dust resistant	IP63	D	4	Customer value,	Testing, calculation	Developers
4.4 Temperature range	0* to 40*C	R		Customer value,	Testing, calculation	Developers
5. Economy						
5.1 Manufacturing cost	<500 SEK	D	3	To gain profit	Calculate, estimate	Investor, us
5.2 Selling price	<1000 SEK	D	3	To gain profit	Calculate, estimate	Customer
6. Miscellaneous						
6.1 Ergonomic product		D	3	Easy to use	Testing, observation	User
6.2 Environmentally friendly		D	3	Evironmentally frie	Testing, calculations	User
6.3 Recyclability	>50%	D	2	Evironmentally frie	Testing, calculations	User
6.4 Certification	Can be sold in gl	R		Legal need	Have the required certificat	Goverment
6.5 Exclusive aesthetics	>75% thinks it	D	4	increase sales	Questionnare	Developer, user
6.6 Mitigate any harm	No sharp edges No toxic material No high tempera	R		Prevent harm	Testing	User
6.7 Easy to recycle	Easy Separation	D	2	Evironmentally frie	Testing	Developer, User, Government, investor
6.8 Ethical suppliers	Official suppliers	D	4	Evironmentally frie	Research	Developer, User, Government, investor
6.9 Easy to replace parts	Can change batt	D	1	Environmentally	Testing	Developer
6.10 Adaptable use	Can change inter	D	3	Customer value	Testing	Developer

Figure A.5: First iteration of the requirements from different stakeholders.

G Refined Requirement List

Air quality monitor for increased productivity				2024-03-12	Requirement specification		
Requirement (Criterion)	Target value	Requirement/ Desire	Estimated Importance	User studied Importance	Justification	Evaluation (Verfication)	Reference (Demander)
	Hours, seconds, g, %that use it right etc	D/R	7= Very high 1= Very low	7= Very high 1= Very low	Increases sales, good for enviroment, etc	Questionnare, interview, testing, calculations, estimation, observation	Government, user, customer, investor, Developers
1.Technical							
1.1 Long lasting battery	250 hours	D	6	6.1	Easy to use	Calculations	User
1.2 Measure CO2	± 5%	R			Core value	Calculations	Developers
1.3 Measure temperature	± 1C	R			Core value	Calculations	Developers
1.4 Measure humidity	± 5%	R			Core value	Calculations	Developers
1.5 Measure PM2.5		R			Core value	Calculations	Developers
1.6 Measure PM10		R			Core value	Calculations	Developers
1.7 Measure VOC		R			Core value	Calculations	Developers
1.8 Easy to charge	Does not require special charger, USB-C port	D	6	5.7	Easy to use	Testing	User
1.9 Long product life	10 years with regular use	D	3	6.2	Enviromentally friendly, good investment	Calculations, estimation	User
1.10 Low maintenance	None	D	5	6.4	Easy to use	Testing, estimation	User
1.12 Measure PM2.5	± 15%	D	4	6.0	Core value	Calculations	Developers
1.13 Measure PM10	± 15%	D	4	6.0	Core value	Calculations	Developers
1.14 Measure VOC	± 15%	D	4	6.0	Core value	Calculations	Developers
2. Portable							
2.1 Size length	20cm	D	4	4.8	Easy to use	Calculations	User, Developers
2.2 Size width	10cm	D	4	4.8	Easy to use	Calculations	User, Developers
2.3 Size height	30cm	D	4	4.8	Easy to use	Calculations	User, Developers
2.4 Weight	500g	D	4	4.6	Easy to use	Calculations	User, Developers
2.5 Operatable without powercable	built in battery/desposable batteries	R			Easy to use	Calculations	User, Developers
2.6 Easy to hold with hand	Ergonomic handle	D	3	6.1	Easy to use	Testing, observation	Developers
2.7 Stand steadily on flat surface	Does not tip over, on surface with 20% angle	R			Easy to use	Testing	Developers
2.8 Can be positioned in different ways	Can be positioned in more than 1 way and function properly	D	2	N/A	easy to use	Interview	User
2.9 Portable	>90 thinks it is possible to bring	D	5	4.4			
3. Intuitive							
3.1 Effective communication to user	>90% understand what information is conveyed	D	6	6.1	Easy to use	interview, observation	Developers
3.2 Intuitive battery positioning	>90% can charge it without manual	D	6	4.7	Easy to use	interview, observation	Developers
3.3 Set up time	Average setup <30 seconds	D	5	N/A	Easy to use	Testing	Developers
3.4 Easy to use in the dark	Can be used any time during the day	D	2	4.6	Easy to use	interview, testing	Developers

Figure A.6: Second iteration of the requirements from different stakeholders, page 1.

3.5 Indication of low battery	Warns the user so they have time to charge/change batteries	D	3	5.4	Easy to use	Calculation, testing	Developers
3.6 Can see the raw AQ data	The numerical data	D	6	5.6	Customer value	observation	User
3.7 Can see reccomendations on how to improve AQ	At least 1 suggestion for improved AQ for each parameter	D	5	5.4	Customer value	observation	User
4. Durable							
4.1 Water resistant	IP63	D	2	5.5	Customer value, environmentally friendly	Testing, calculation	Developers
4.2 External forces resistance	Can be dropped 10 cm withouth breaking	D	4	5.5	Customer value, environmentally friendly	Testing, calculation	Developers
4.3 Dust resistant	IP63	D	6	5.5	Customer value, environmentally friendly	Testing, calculation	Developers
4.4 Temperature range	0° to 40°C	R			Customer value, environmentally friendly	Testing, calculation	Developers
5. Economy							
5.1 Manufacturing cost	<500 SEK	D	7	N/A	To gain profit	Calculate, estimate	Investor, us
5.2 Selling price	<1000 SEK	D	7	4.8	To gain profit	Calculate, estimate	Customer
6. Miscellaneous	**Target value**	**Requirement/ Desire**			**Justification**	**Evaluation/Verification**	**Reference (Demander)**
6.1 Ergonomic product	>75% think so	D	4	4.4	Easy to use	Testing, observation	User
6.2 Environmentally friendly		D	4	5.8	Evironmentally friendly	Testing, calculations	User
6.3 Recyclability	>50%	D	3	5.4	Evironmentally friendly	Testing, calculations	User
6.4 Certification	Can be sold in global market	R			Legal need	Have the required certifications	Goverment
6.5 Exclusive aesthetics	>75% think so	D	5	5.4	increase sales	Questionnare	Developer, user
6.6 Prevent any harm	No sharp edges No toxic materials No high temperatures	R			Prevent harm	Testing	User
6.7 Easy to recycle	Easy Separation between components, DFD	D	3	5.4	Evironmentally friendly	Testing	Developer, User, Government, investor
6.8 Ethical suppliers	Official suppliers	D	5	5.8	Evironmentally friendly, legal need	Research	Developer, User, Government, investor
6.9 Easy to replace parts	Can change battery or sensor	D	1	N/A	Environmentally friendly,	Testing	Developer
6.10 Adaptable use	Can change intervals	D	4	5.2	Customer value	Testing	Developer
6.11 Not disturbing the user	<10% think it is disturbing them from working or disturbing them when relaxing	D	4	5.2	Customer value	observation	User
6.12 Warnings about particles not measuerd in AQI like pollen or poisenos gases		D	1	N/A	Customer value	Testing	User

Figure A.7: Second iteration of the requirements from different stakeholders, page 2.

H Market Questionnaire

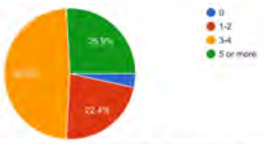
Air quality & Productivity

58 responses

Publish analytics

How many times per week do you think about how productive you are in your work environment?

58 responses

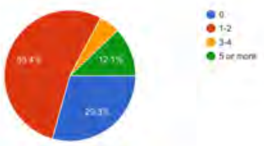


How many times per week do you think about how productive you are in your spare time?

58 responses

How many times per week do you care about other peoples productivity?

58 responses



What do you feel are the 3 biggest impactors on your productivity?

53 responses

Sleep, energy, motivation

My energy-level, distractions, motivation

Environment, time pressure, too many things at the same time

Motivation, Diet, mental clarity

Sleep, Noise, Temperature

Distractions, whether you know what to do, whether you care about what you're doing

Sleep, good nutrition, air quality and conducive work atmosphere

Motivation, Health

Lighting, fresh air, sleep

Silence, comfort, pomodoro

Atmosphere, Distractions, Balancing with other activities

Sleep, motivation and structure

Office designed for working without beeing disturbed of your college work, quiet low noice level, widow make it possibly to see outside environment

Distractions such as noise and movement of others, interest in topic(motivation), goals or rewards

If I worked out yesterday, slept well and if the room is quiet

Interruptions, Sleep, Lightning

Sound, other people

Noise, light, comfort

Sleep, coffee quality, clear goals

Noise, oxygen level, feeling that I'm doing something meaningful

Amount of work, chance to prioritize and overall stress factor

Motivation, energy, and time pressure

Sleep, locus of control, training

Sleep, vision, goal

Discipline, Environment, Health

environment, sound, water

Work environment, deadlines, who in working with

Light, air quality and temperature

Sleep, distractions, enjoyment

If I'm Making a list of my tasks or not, how clean my work environment is, how tired I am

Well rested. Well fed. The closer the deadline the more productive :)

Cellphone usage, environment, room temperature

Lightning, energy, focus

Being well rested, having a good work environment, and working towards a goal

Energy, air, lighting

Tiredness, Interuptions and Deadlines

Gaming & gooning

Physical tiredness, mental tiredness, sleepiness

Sleep, feeling well, happiness

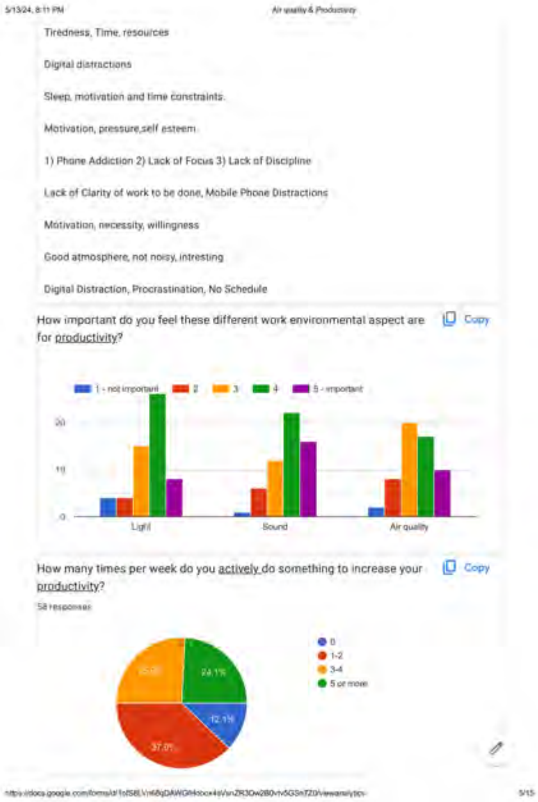
Motivation, Mood, Sleep.

Environment, Amount of work, Amount of time left

Sleep training social life

Loss of motivation, Monotonous lifestyle, Lack of focus, Lack of enthusiastic collaborators.

1. Utilizing the hours, 2. Focus, 3. Environment


5/13/24, 8:11 PM Air quality & Productivity

Tiredness, Time, resources

Digital distractions

Sleep, motivation and time constraints.

Motivation, pressure,self esteem

1) Phone Addiction 2) Lack of Focus 3) Lack of Discipline

Lack of Clarity of work to be done, Mobile Phone Distractions

Motivation, necessity, willingness

Good atmosphere, not noisy, intresting

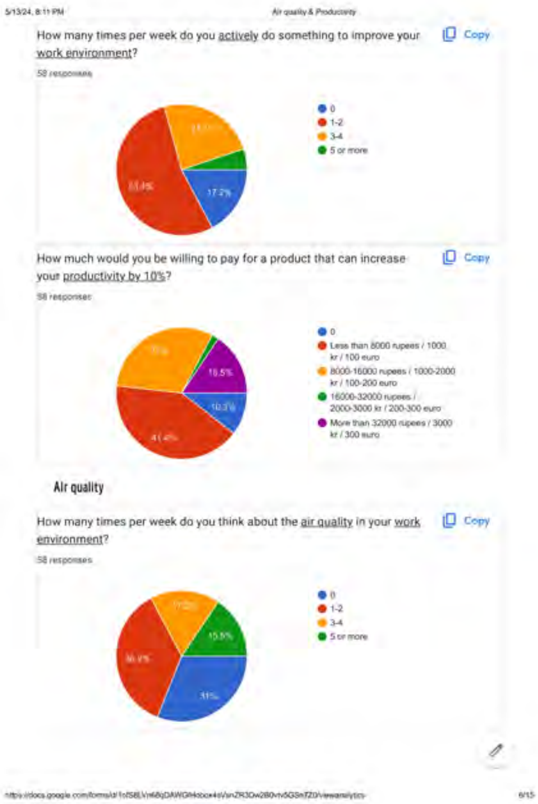
Digital Distraction, Procrastination, No Schedule

How important do you feel these different work environmental aspect are for productivity?

How many times per week do you actively do something to increase your productivity?

58 responses

https://docs.google.com/forms/d/1ofS8LVn6BqDAWGH4obox4sVsnZR3Ow2B0vtv5GSnTZ0/viewanalytics 5/15


5/13/24, 8:11 PM Air quality & Productivity

How many times per week do you actively do something to improve your work environment?

58 responses

How much would you be willing to pay for a product that can increase your productivity by 10%?

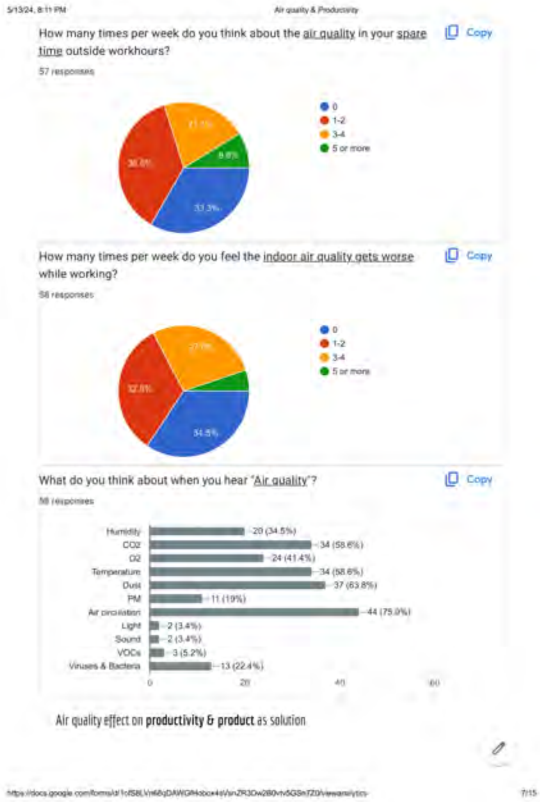
58 responses

Air quality

How many times per week do you think about the air quality in your work environment?

58 responses

https://docs.google.com/forms/d/1ofS8LVn6BqDAWGH4obox4sVsnZR3Ow2B0vtv5GSnTZ0/viewanalytics 6/15


5/13/24, 8:11 PM Air quality & Productivity

How many times per week do you think about the air quality in your spare time outside workhours?

57 responses

How many times per week do you feel the indoor air quality gets worse while working?

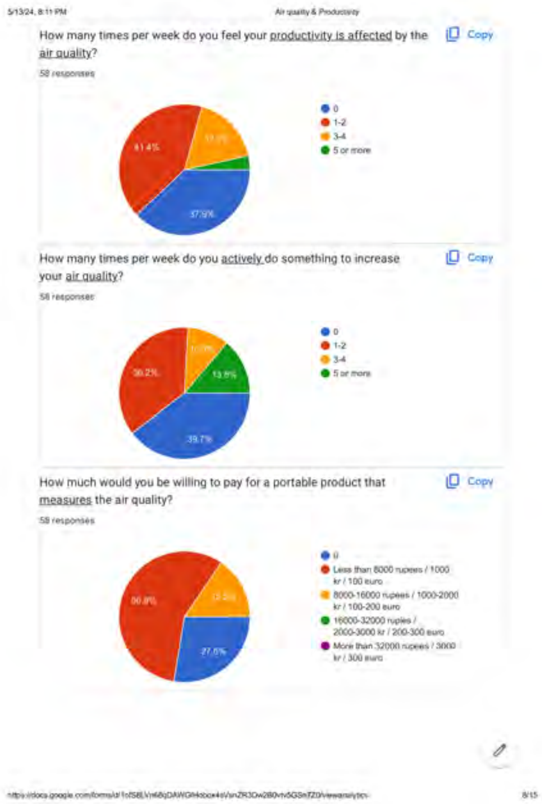
58 responses

What do you think about when you hear "Air quality"?

58 responses

Air quality effect on **productivity & product** as solution

https://docs.google.com/forms/d/1ofS8LVn6BqDAWGH4obox4sVsnZR3Ow2B0vtv5GSnTZ0/viewanalytics 7/15


5/13/24, 8:11 PM Air quality & Productivity

How many times per week do you feel your productivity is affected by the air quality?

58 responses

How many times per week do you actively do something to increase your air quality?

58 responses

How much would you be willing to pay for a portable product that measures the air quality?

58 responses

https://docs.google.com/forms/d/1ofS8LVn6BqDAWGH4obox4sVsnZR3Ow2B0vtv5GSnTZ0/viewanalytics 8/15

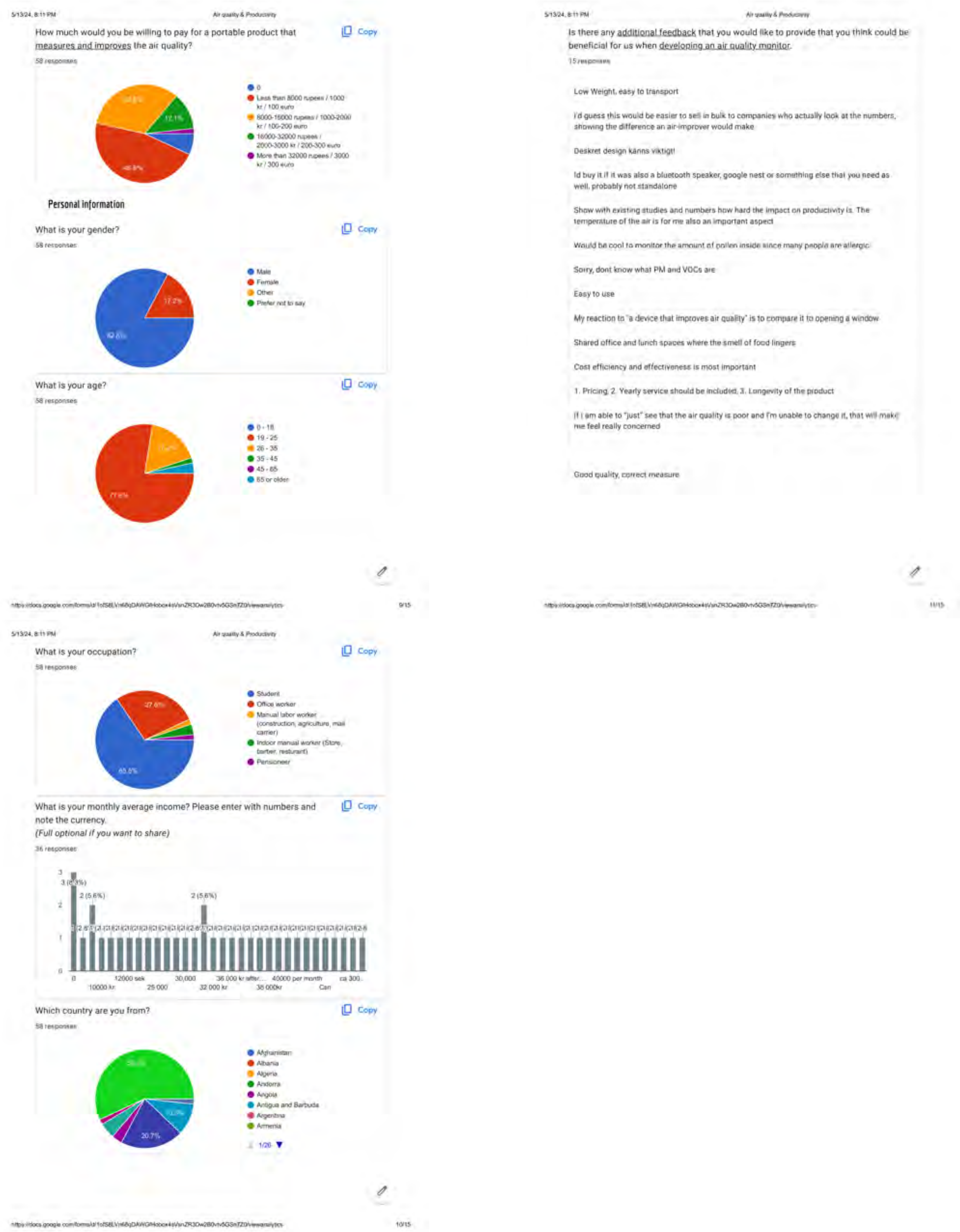
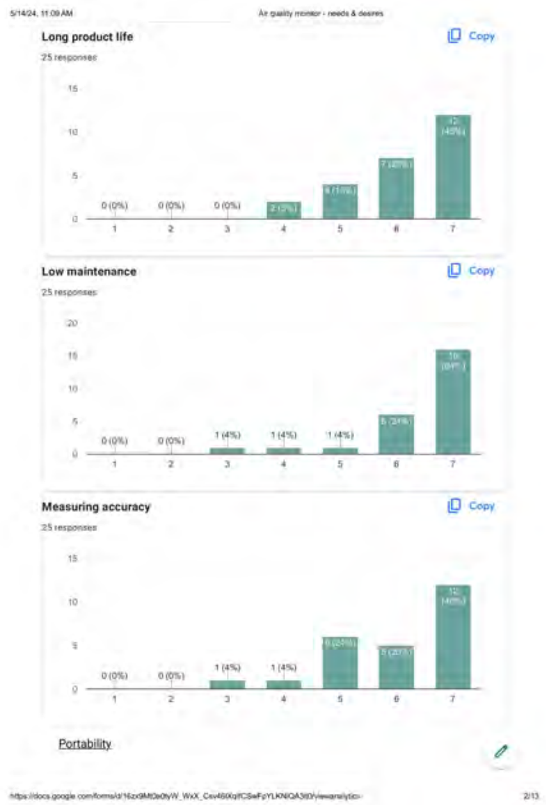
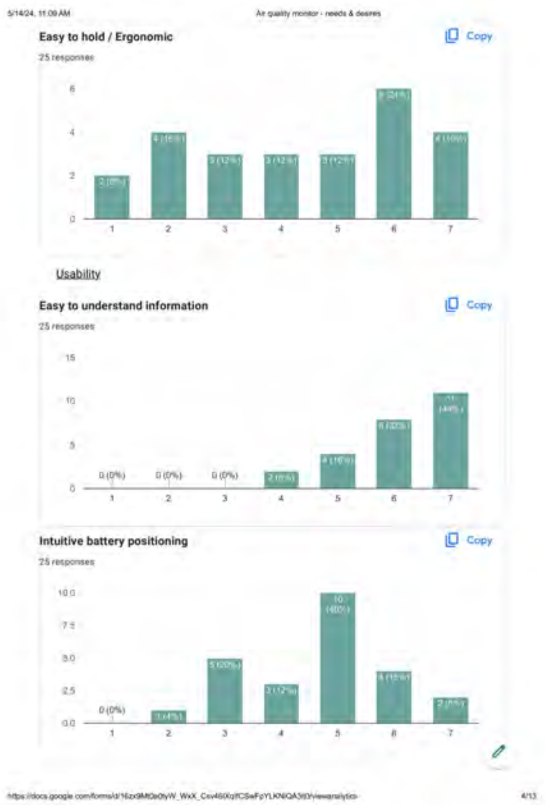


Figure A.10: Responses of the market questionnaire. Questions can also be seen.

I User Needs Questionnaire






5/14/24, 11:09 AM
Air quality monitor - needs & desires
Battery status
25 responses
Copy
Easy to use in the dark
25 responses
Copy
Getting exact data about air quality
25 responses
Copy
5/13


5/14/24, 11:09 AM
Air quality monitor - needs & desires
Aesthetically pleasing
25 responses
Copy
Ethical production
25 responses
Copy
Easy to repair
25 responses
Copy
7/13


5/14/24, 11:09 AM
Air quality monitor - needs & desires
Getting recommendations to improve air quality
25 responses
Copy
Miscellaneous
Environmentally friendly
25 responses
Copy
Possibility to recycle
25 responses
Copy
6/13

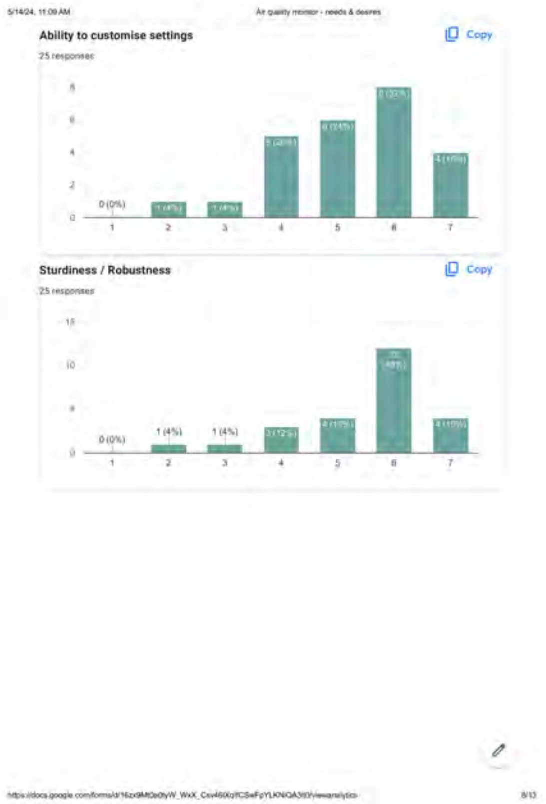

5/14/24, 11:09 AM
Air quality monitor - needs & desires
Ability to customise settings
25 responses
Copy
Sturdiness / Robustness
25 responses
Copy
8/13

Figure A.13: Responses of the user questionnaire. Questions can also be seen.

J Sub-solutions

		SubFunctions	A	B	C	D	E	F	G	H	I	J
	Gather data											
1		**Gather data about AQ**	Measure using sensors	Internet API								
2		**Store data**	Locally on hard drive	Cloud								
	UI											
3		**Medium to Covey information**	Sound/Speaker	Bluetooth / wifi to app	Screen	Scent / fragrance	Tactile / vibrations	Vibrations with screen	Vibrations with app	Light / LED / spotlight with app	Light / LED / spotlight with speaker	Light / LED / spotlight
4		**Type of information**	Raw data	Scale - good to bad	Recommendation of what to do	Productivity status						
5		**Turn on/off**	Swtich (like lights in apt)	Button like on computre, same for on/off	Bluetooth/wifi to app	Automaticlly on with power avilable	Voice					
6		**Change settings/user interacts with product**	Touchscreen	Buttons	Bluetooth/wifi to app	Voice	Remote	Joystick	None			
	Portability											
7		**Easy to transport**	Handle	Small size	Hook/clip	Wheels	Stationary	None				
8		**Product placement**	Stand on flat surface	Hang on hook	Mount on ceiling	Wearable / necklace						
9		**Hold product intact**	Chassi	Frame								
	Power											
10		**Provide power**	Electrical charger	Electrical motor	Solar	Wind	Dynamo	Piezoelectric				
11		**Store power**	Battery	Flywheel	Gravity	None						

Figure A.14: The different sub-solutions to each of the sub-functions.

K Elimination Matrix

Elimination matrix for the sub-solutions

Decision:
(+) Continue
(-) Remove
(?) More info needed
(!) Check with specification

Criteria fulfilment:
(+) Yes
(-) No
(?) More information needed
(!) Check with specification

Function	Ranking	Solution alternative	Fulfils the mission statement / project scope	Fulfils demands (requirement specification)	Compatible / realisable	Reasonable cost	Safe	Time consuming	Enough information	Comment	Decision
Gather data	Measure with sensors	+	+	+	+	+	+	+	+		+
	Use internet API	+	-							We state our product will measure it	-
Store data	Locally on hard drive	+	+	+	+	+	+	+	+		+
	Cloud	+	+	+	+	+	+	-		Could have potential, but not sure if feasible to research with time constraint for building MVP	+
Medium to Covey information	Sound/Speaker	+	+	+	+	+	+	+	+		+
	Bluetooth / wifi to app	+	+	+	+	+	+	-		Could have potential, but not sure if feasible to research with time constraint for building MVP	-
	Screen	+	+	+	+	+	+	+	+		+
	Light / LED / spotlight	+	+	+	+	+	+	+	+		+
	Scent / fragrance	+	+	+	-					Too complex and complicated	-
	Tactile / vibrations	-								Can't tranfer enough information on it's own. But could be used in combination with other subsolutions.	-
	Vibrations with screen	+	+	+	+	+	+	+	+		+
	Vibrations with app	+	+	+	+	+	+	-		Could have potential, but not sure if feasible to research with time constraint for building MVP	-
Type of information	Raw data	+	+	+	+	+	+	+	+		+
	Scale good to bad	+	+	+	+	+	+	+	+	Will probably work in combination with any other	+
	Recommendation of what to do	+	+	+	+	+	+	+	+		+
	Productivity status	+	+	+	+	+	+	+	+		+
Turn on/off	Swtich (like lights in apt)	+	+	+	+	+	+	+	+		+
	Button like on computre	+	+	+	+	+	+	+	+		+
	Bluetooth/wifi to app	+	+	+	+	+	+	-		Could have potential, but not sure if feasible to research with time constraint for building MVP	-
	Automaticlly on with power avilable	+	-							Has to be portable - Requirement 2.5 "Operatable withouth power cable"	-
	Voice	+	+	+	+	+	+	-			-
Change settings/user interacts with product	Touchscreen	+	+	+	+	+	+	+	+		+
	Buttons	+	+	+	+	+	+	+	+		+
	Bluetooth/wifi to app	+	+	+	+	+	+	-		Could have potential, but not sure if feasible to research with time constraint for building MVP	-
	Voice	+	+	+	+	+	+	-			-
	Remote	+	+	+	+	+	+	+	+		+
	Joystick	+	+	+	+	+	+	+	+		+
Easy to transport	Handle	+	+	+	+	+	+	+	+		+
	Small size	+	+	+	+	+	+	+	+		+
	Hook/clip	+	+	+	+	+	+	+	+		+
	Wheels	+	+	+	-					Not resonable	-
	None / stationary	+	-							Has to be portable	-
Product placement	Stand on flat surface	+	+	+	+	+	+	+	+		+
	Hang on hook	+	+	+	+	+	+	+	+		+
	Mount on ceiling	+	+	+	+	+	+	+	+		+
	Wearable / necklace	+	+	+	+	+	+	-		Know too little regarding wearable devices with health requirements etc. Also complicates adoption of sensors a lot.	-
Hold product intact	Chassi	+	+	+	+	+	+	+	+		+
	Frame	+	+	+	+	+	-			Not safe with exposed components	-
Provide power	Electrical charger	+	+	+	+	+	+	+	+		+
	Electrical motor	+	+	+	-					Not efficient enough	-
	Solar	+	-							Has to work indoors	-
	Wind	+	-							Has to work indoors	-
	Dynamo	+	+	+	-					Too complicated	-
	Piezoelectric	+	+	+	-					Too complicated	-
Store power	Battery	+	+	+	+	+	+	+	+		+
	Flywheel	+	+	+	-					Too large in scale	-
	Gravity	+	+	+	-					Too unreliable and not feasable for portability	-
	None	+	+	-						Does not fulfill the requirement matrix	-

Figure A.15: Elimination matrix with all sub-solutions. Each sub-solution can be identified if being eliminated or not, and for what reason. If the sub-solution has got eliminated, a small description is added for what the reason was.

L Morphological Matrix

Main funciton category	Function	A	B	C	D	E	F	G	H	I	J
Gather data											
	Gather data about AQ	Measure using sensors	Internet API								
	Store data	Locally on hard drive	Cloud								
UI											
	Medium to Covey information	Sound/Speaker	Screen	Vibrations with screen	Light / LED / spotlight with speaker	Light / LED / spotlight	Vibrations with app	Light / LED / spotlight with app	Bluetooth / wifi to app	Scent / fragrance	Tactile / vibrations
	Type of information	Raw data	Scale - good to bad	Recommendation of what to do	Productivity status						
	Turn on/off	Swtich (like lights in apt)	Button like on computre, same for on/off	Automaticlly on with power avilable	Bluetooth/wifi to app	Voice					
	Change settings/user interacts with product	Touchscreen	Buttons	Remote	Joystick	None	Bluetooth/wifi to app	Voice			
Portability											
	Easy to transport	Handle	Small size	None	Hook/clip	Wheels	Stationary				
	Product placement	Stand on flat surface	Hang on hook	Mount on ceiling	Wearable / necklace						
	Hold product intact	Chassi	Frame								
Power											
	Provide power	Electrical charger	Electrical motor	Solar	Wind	Dynamo	Piezoelectric				
	Store power	Battery	None	Flywheel	Gravity						

Figure A.16: Morphological matrix with all sub-solutions. Eliminated sub-solutions can be seen in red and are not part of the concept generation when combining sub-solutions with each other.

M Initial Concepts

Functions		Gather data about AQ	Store data	Medium to Covey information	Type of information	Turn on/off	Change settings/user interacts with product	Easy to transport	Product placement	Hold product intact	Provide power	Store power
	Concept theme	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1	Budget friendly	A	A	A	ABCD	A	B	A	A	A	A	D
2	Lowest price	A	A	A	A	D	G	F	A	A	A	D
3	Luxurious	A	A	AF	ABCD	B	AE	AB	AB	A	A	A
4	IKEA influenced	A	A	I	BC	B	F	F	B	A	A	A
5	Environmentally friendly	A	A	A	ABC	A	B	F	A	A	A	D
6	Professional / Most accurate	A	A	C	A	A	A	A	AB	A	A	A
7	Portable	A	A	A	ABCD	B	B	AB	A	A	A	A
8	Easy to use	A	A	F	B	A	B	B	AB	A	A	A
9	Minimalistic	A	A	J	B	B	G	B	A	A	A	A
10	Community product	A	A	AC	ABCD	D	E	A	AB	A	A	A
11	Family version	A	A	C	ABCD	B	A	A	A	A	A	A

Figure A.17: Initial concepts with their combination of sub-solutions. This table has to be paired with the Morphological matrix found in Appendix L to understand what the combinations are. An A in the third row of "Medium to convey information" means to use "Sound/Speaker" as the sub-solution for example. A combination of letters means that those all are used as sub-solutions for that function as a product can have many different mediums for communication for example.

N Pugh Matrix 1

Air quality monitor Created:2024-03-20 Updated:	Pugh Matrix 1										
Desire \ Concept	**Budget friendly**	**Lowest price**	**Luxurious**	**IKEA influenced**	**Environmentally friendly**	**Professional / Most accurate**	**Portable**	**Easy to use**	**Minimalistic**	**Community product / room measure**	**Family version**
1.1 Long lasting battery	REFERANCE	0	1	1	0	1	1	1	1	1	1
1.8 Easy to charge		0	0	0	0	0	0	1	0	-1	0
1.9 Long product life		-1	1	0	1	-1	0	0	1	1	-1
1.12-1.14 Measure		0	-1	0	0	1	-1	-1	-1	1	0
2.1-2.3 Size		0	1	0	0	0	1	1	1	0	0
2.4 Weight		0	-1	-1	0	-1	-1	-1	-1	-1	-1
2.6 Easy to hold with hand		-1	0	-1	-1	0	1	-1	-1	0	0
2.8 Can be positioned in different ways		0	1	1	0	1	0	1	0	1	0
3.1 Effective communication to user		0	1	1	0	1	0	1	-1	1	1
3.3 Set up time		1	-1	-1	0	-1	-1	1	1	-1	-1
3.4 Easy to use in the dark		1	1	-1	0	1	0	1	1	0	-1
3.5 Indication of low battery		0	-1	-1	0	-1	-1	-1	-1	-1	-1
3.6 Can see the raw AQ data		0	0	-1	0	1	0	-1	-1	0	0
3.7 Can see reccomendations on how to improve AQ		-1	0	0	1	-1	0	-1	-1	0	0
4.2 External forces resistance		0	-1	-1	0	-1	1	-1	1	-1	-1
5.1 Manufacturing cost		1	-1	-1	-1	-1	-1	-1	-1	-1	-1
5.2 Selling price		1	-1	-1	-1	-1	-1	-1	-1	-1	-1
6.1 Ergonomic product		0	1	1	-1	1	1	1	1	1	1
6.2 Environmentally friendly		0	-1	-1	1	-1	-1	-1	-1	-1	-1
6.3 Recyclability		1	-1	-1	1	-1	-1	-1	-1	-1	-1
6.5 Exclusive aesthetics		-1	1	1	1	1	1	-1	0	1	1
6.7 Easy to recycle		0	-1	0	1	-1	-1	-1	0	-1	-1
6.10 Adaptable / customisable use		-1	1	0	0	1	0	0	-1	1	1
$\Sigma +$	0	5	9	5	6	9	6	8	7	8	5
$\Sigma -$	0	5	10	11	4	11	9	13	12	10	11
$\Sigma \circ$	23	13	4	7	13	3	8	2	4	5	7
Total	0	0	-1	-6	2	-2	-3	-5	-5	-2	-6
Rank	3	3	4	11	1	6	7	8	9	6	11

Figure A.18: Pugh matrix 1 including score.

O Pugh Matrix 2

Air quality monitor Created:2024-03-22 Updated:	Pugh Matrix 2										
Desire \ Concept	**Easy to use**	**Lowest price**	**Luxurious**	**IKEA influenced**	**Environmentally friendly**	**Professional / Most accurate**	**Portable**	**Budget friendly**	**Minimalistic**	**Community product / room measure**	**Family version**
1.1 Long lasting battery	REFERANCE	-1	1	0	-1	0	0	-1	1	1	0
1.8 Easy to charge		-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
1.9 Long product life		-1	1	-1	1	-1	1	0	1	1	-1
1.12-1.14 Measure		0	0	1	1	1	0	1	0	1	1
2.1-2.3 Size		-1	0	-1	-1	-1	1	-1	1	-1	-1
2.4 Weight		1	0	0	1	-1	0	1	1	-1	0
2.6 Easy to hold with hand		-1	1	0	-1	1	1	1	0	1	1
2.8 Can be positioned in different ways		-1	0	1	-1	0	-1	-1	-1	1	-1
3.1 Effective communication to user		-1	-1	-1	-1	-1	-1	-1	-1	0	-1
3.3 Set up time		0	-1	-1	-1	-1	-1	-1	0	-1	-1
3.4 Easy to use in the dark		-1	-1	-1	-1	-1	-1	-1	-1	-1	-1
3.5 Indication of low battery		1	0	-1	1	0	-1	1	-1	0	0
3.6 Can see the raw AQ data		1	1	0	1	1	1	1	0	1	1
3.7 Can see reccomendations on how to improve AQ		0	1	1	1	0	1	1	0	1	1
4.2 External forces resistance		1	0	1	1	0	1	1	1	0	0
5.1 Manufacturing cost		1	-1	1	0	-1	0	1	1	0	0
5.2 Selling price		1	-1	1	-1	-1	0	1	1	-1	-1
6.1 Ergonomic product		-1	-1	-1	-1	-1	0	-1	-1	0	-1
6.2 Environmentally friendly		1	-1	0	1	0	0	1	0	0	0
6.3 Recyclability		1	-1	0	1	0	0	1	0	0	0
6.5 Exclusive aesthetics		0	1	1	1	0	0	1	1	1	1
6.7 Easy to recycle		1	-1	1	1	1	1	1	1	0	0
6.10 Adaptable / customisable use		-1	1	0	1	1	1	0	0	1	1
Σ+	0	9	7	8	12	5	8	13	9	9	6
Σ−	0	10	10	8	10	10	6	8	6	6	9
Σo	0	4	6	7	1	8	9	2	8	8	8
Total	0	-1	-3	0	2	-5	2	5	3	3	-3
Rank	5	6	8	5	3	9	3	1	4	4	8

Figure A.19: Pugh matrix 2 including score.

P Kesselring Matrix

Air quality monitor Created:2024-04-01		Kesselring Matrix													
Updated: 2024-04-04		**Budget friendly**		**Lowest price (with switch)**		**Environmentally friendly**		**Portable**		**Community product / room measure, (no battery)**		**Game boy (Community + Portable)**		**Fancy (Budget + Luxorious)**	
Sketch															
Description		- Speaker - ABCD - Switch - Buttons - Handle - Stand on surface - No battery		- Speaker - A - Switch - No interaction - Stand on surface - No battery		- Speaker - ABC - Switch - Buttons - No battery		- Speaker - ABCD - Button - Buttons - Handle - Stand on surface - Battery		- Speaker & Screen - ABCD - Automatically on - Remote - Stand and hang on wall		- Screen - ABCD - Button - Buttons - Stand and hang on wall - Battery		- Screen & Vibrations - ABCD - Button - Touch - Handle - Stand on surface - Battery	
Comment		+ Benefit with a switch to draw less energy and not disturb user with sound • Button for each type of information, pressing button again skips to next subinfo in that field, Raw data --> AQI --> CO2		+ Cheapest possible + Simple use • Tells the user when turning on, or every 30 min		• Similar to budget, but with additional cost to have environmentally friendly materials and suppliers and construction for reliability • Made to look green/show enviromental focus		+ Benefit with small size and handle for ergonomic use, maybe the size of a 50cl bottle • Button for each type of information, pressing button again skips to next subinfo in that field, Raw data --> AQI --> CO2 • Intended for portable use, to bring with the user and use quickly		+ Large clear display + Attention through speaker + Hangable on the wall • Can be moved easily for a new local monitoring scenario		+ Benefit with small size, maybe the size of a 50cl bottle + Clear communication with screen • Buttons for changing settings on screen • Intended for portable use, to bring with the user and use quickly		+ Clear and sleak communication with large screen + Reminders using vibrations for discrete notifications (but can be turned off) + Easy to change settings or customise with touch screen + Hande for easy movement - Large in size and heavy because of screen, design and battery - Expensive because of luxoriois components and design	
Desire	**Weight**	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
1.1 Long lasting battery	6.05	1	6.1	1	6.05	1	6.05	7	42.35	1	6.05	7	42.35	7	42.35
1.8 Easy to charge	5.85	4	23.4	4	23.4	4	23.4	3	17.55	3	17.55	3	17.55	3	17.55
1.9 Long product life	4.6	3	13.8	2	9.2	4	18.4	3	13.8	6	27.6	2	9.2	5	23
1.12-1.14 Measure	5	3	15.0	2	10	4	20	2	10	6	30	2	10	5	25
2.1-2.3 Size	4.4	3	13.2	3	13.2	4	17.6	5	22	5	22	5	22	5	22
2.4 Weight	4.3	5	21.5	4	17.2	4	17.2	6	25.8	1	4.3	5	21.5	2	8.6
2.6 Easy to hold with hand	4.55	4	18.2	2	9.1	2	9.1	5	22.75	3	13.65	4	18.2	4	18.2
2.8 Can be positioned in different ways	2	3	6.0	2	4	2	4	4	8	5	10	6	12	4	8
3.1 Effective communication to user	6.05	2	12.1	3	18.15	2	12.1	2	12.1	6	36.3	4	24.2	6	36.3
3.3 Set up time	5	4	20.0	7	35	4	20	3	15	1	5	2	10	3	15
3.4 Easy to use in the dark	3.3	2	6.6	3	9.9	2	6.6	2	6.6	6	19.8	6	19.8	7	23.1
3.5 Indication of low battery / Low risk of product losing power	4.2	7	29.4	7	29.4	7	29.4	1	4.2	7	29.4	4	16.8	4	16.8
3.6 Can see the raw AQ data	5.8	3	17.4	4	23.2	3	17.4	3	17.4	5	29	5	29	5	29
3.7 Can see reccomendations on how to improve AQ	5.2	3	15.6	1	5.2	3	15.6	3	15.6	5	26	5	26	5	26
4.2 External forces resistance	3.75	4	15.0	4	15	4	15	6	22.5	2	7.5	5	18.75	3	11.25
5.1 Manufacturing cost	7	6	42.0	7	49	3	21	4	28	1	7	3	21	2	14
5.2 Selling price	5.9	6	35.4	7	41.3	2	11.8	4	23.6	1	5.9	3	17.7	1	5.9
6.1 Ergonomic product	4.2	3	12.6	2	8.4	2	8.4	4	16.8	6	25.2	5	21	6	25.2
6.2 Environmentally friendly	4.9	5	24.5	5	24.5	7	34.3	3	14.7	3	14.7	2	9.8	1	4.9
6.3 Recyclability	4.2	5	21.0	5	21	6	25.2	3	12.6	3	12.6	2	8.4	2	8.4
6.5 Exclusive aesthetics	5.2	2	10.4	1	5.2	5	26	3	15.6	5	26	4	20.8	7	36.4
6.7 Easy to recycle	4.2	5	21.0	5	21	7	29.4	4	16.8	3	12.6	1	4.2	1	4.2
6.10 Adaptable / customisable use	4.6	2	9.2	1	4.6	2	9.2	2	9.2	6	27.6	6	27.6	7	32.2
	Total maximum score	Average score	Procentage score of maximum	Average score	Procentage score of maximum	Average score	Procentage score of maximum	Average score	Procentage score of maximum	Average score	Procentage score of maximum	Average score	Procentage score of maximum	Average score	Procentage score of maximum
Σ	771.8	3.70	0.53	3.57	0.52	3.65	0.51	3.57	0.51	3.91	0.54	3.96	0.55	4.13	0.59
Rank		4		5		6		7		3		2		1	

Figure A.20: Kesselring matrix including sketches, description and comments for easier understanding of the different concepts. The final score can also be seen at the bottom of the matrix where "Fancy" can be identified as the winner.

Q Kesselring Sensitivity Matrix

Air quality monitor Created:2024-04-01		Kesselring Sensitivity													
Updated:		Budget friendly		Lowest price (with switch)		Environmentally friendly		Portable		Community product / room measure, (no battery)		Game boy (Community + Portable)		Fancy (Budget + Luxorious)	
	Weight														
Desire		Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score	Rating	Weighted score
1.1 Long lasting battery	6.05	1	6.1	1	6.05	1	6.05	7	42.35	1	6.05	7	42.35	7	42.35
1.12-1.14 Measure	5	3	15.0	2	10	4	20	2	10	6	30	2	10	5	25
2.1-2.3 Size	4.4	3	13.2	3	13.2	4	17.6	5	22	5	22	5	22	5	22
2.4 Weight	4.3	5	21.5	4	17.2	4	17.2	6	25.8	1	4.3	5	21.5	2	8.6
3.1 Effective communication to user	6.05	2	12.1	3	18.15	2	12.1	2	12.1	6	36.3	4	24.2	6	36.3
4.2 External forces resistance	3.75	4	15.0	4	15	4	15	6	22.5	2	7.5	5	18.75	3	11.25
5.2 Selling price	5.9	6	35.4	7	41.3	2	11.8	4	23.6	1	5.9	3	17.7	1	5.9
6.1 Ergonomic product	4.2	3	12.6	2	8.4	2	8.4	4	16.8	6	25.2	5	21	6	25.2
6.2 Environmentally friendly	4.9	5	24.5	5	24.5	7	34.3	3	14.7	3	14.7	2	9.8	1	4.9
6.5 Exclusive aesthetics	5.2	2	10.4	1	5.2	5	26	3	15.6	5	26	4	20.8	7	36.4
	Total maximum score	Average score	Procentage score of maximum	Average score	Procentage score of maximum	Average score	Procentage score of maximum	Average score	Procentage score of maximum	Average score	Procentage score of maximum	Average score	Procentage score of maximum	Average score	Procentage score of maximum
Σ	348.25	3.4	0.48	3.2	0.457	3.5	0.48	4.2	0.59	3.60	0.51	4.2	0.60	4.3	0.626
Rank															

Figure A.21: Sensitivity matrix showing the 10 most important criteria. This results in a more extreme result, but still showing the "Fancy" concept as a clear winner.

R Arduino Code for the Complete Product

```
#include <Arduino.h>
#include <SensirionI2CSen5x.h>
#include <SensirionI2CScd4x.h>
#include <Wire.h>

SensirionI2CSen5x sen5x;
SensirionI2CScd4x scd4x;

void printUint16Hex(uint16_t value) {
    Serial.print(value < 4096 ? "0" : "");
    Serial.print(value < 256 ? "0" : "");
    Serial.print(value < 16 ? "0" : "");
    Serial.print(value, HEX);
}

void printSerialNumber(uint16_t serial0, uint16_t serial1, uint16_t
   serial2) {
    Serial.print("Serial: ");
    printUint16Hex(serial0);
    printUint16Hex(serial1);
    printUint16Hex(serial2);
    Serial.println();
}

#include <LiquidCrystal.h>

LiquidCrystal LCD(7,6,5,4,3,2);

void setup() {

  LCD.begin(16,2); // amount of rows (16) and columns (2) on the display
    Serial.begin(115200);
    while (!Serial) {
        delay(100);
    }

    Wire.begin();

    sen5x.begin(Wire);
    scd4x.begin(Wire);

    uint16_t error;
    char errorMessage[256];
    error = sen5x.deviceReset();
    if (error) {
        Serial.print("Error trying to execute deviceReset(): ");
        Serial.println(errorMessage);
```

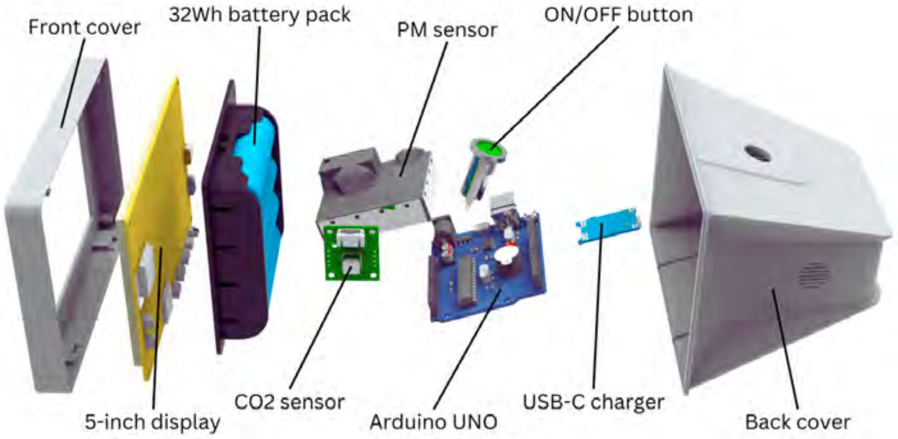
```
    }

    uint16_t serial0, serial1, serial2;
    error = scd4x.getSerialNumber(serial0, serial1, serial2);
    if (error) {
        Serial.print("Error trying to execute getSerialNumber(): ");
        Serial.println(errorMessage);
    } else {
        printSerialNumber(serial0, serial1, serial2);
    }

    error = sen5x.startMeasurement();
    if (error) {
        Serial.print("Error trying to execute startMeasurement(): ");
        Serial.println(errorMessage);
    }

    error = scd4x.startPeriodicMeasurement();
    if (error) {
        Serial.print("Error trying to execute startPeriodicMeasurement(): ");
        Serial.println(errorMessage);
    }

    Serial.println("End of SetuUp: waiting for first measurement... (5 sec)");

}

int measure = 0;
//// Here the loops starts ----------------------------------------------------------------------


void loop() {

 if (measure < 1000){
  delay(4500);
  Serial.println(" ");
  measure = measure+1;
  Serial.print("Currently doing measure number: ");
  Serial.println(measure);

  delay(500);

    float massConcentrationPm1p0, massConcentrationPm2p5, massConcentrationPm4p0, massConcentrationPm10p0;
    float ambientHumidity, ambientTemperature, vocIndex, noxIndex;
```

```

    uint16_t error;
    char errorMessage[256];

    error = sen5x.readMeasuredValues(massConcentrationPm1p0,
        massConcentrationPm2p5, massConcentrationPm4p0,
                                             massConcentrationPm10p0,
                                                ambientHumidity,
                                                ambientTemperature, vocIndex,
                                             noxIndex);

    if (error) {
        Serial.print("Error trying to execute readMeasuredValues(): ");
        Serial.println(errorMessage);
    } else {
        //Serial.print("Pm1: ");
        //Serial.print(massConcentrationPm1p0);
        //Serial.print("\t");
        Serial.print("PM2.5: ");
        Serial.print(massConcentrationPm2p5);
        Serial.print("\t");
        //Serial.print("PM4: ");
        //Serial.print(massConcentrationPm4p0);
        //Serial.print("\t");
        Serial.print("PM10: ");
        Serial.print(massConcentrationPm10p0);
        Serial.print("\t");
        /*
        Serial.print("AmbientHumidity:");
        if (isnan(ambientHumidity)) {
            Serial.print("n/a");
        } else {
            Serial.print(ambientHumidity);
        }
        Serial.print("\t");
        Serial.print("AmbientTemperature:");
        if (isnan(ambientTemperature)) {
            Serial.print("n/a");
        } else {
            Serial.print(ambientTemperature);
        }
        Serial.print("\t");
        Serial.print("VocIndex:");
        if (isnan(vocIndex)) {
            Serial.print("n/a");
        } else {
            Serial.print(vocIndex);
        }
        Serial.print("\t");
```

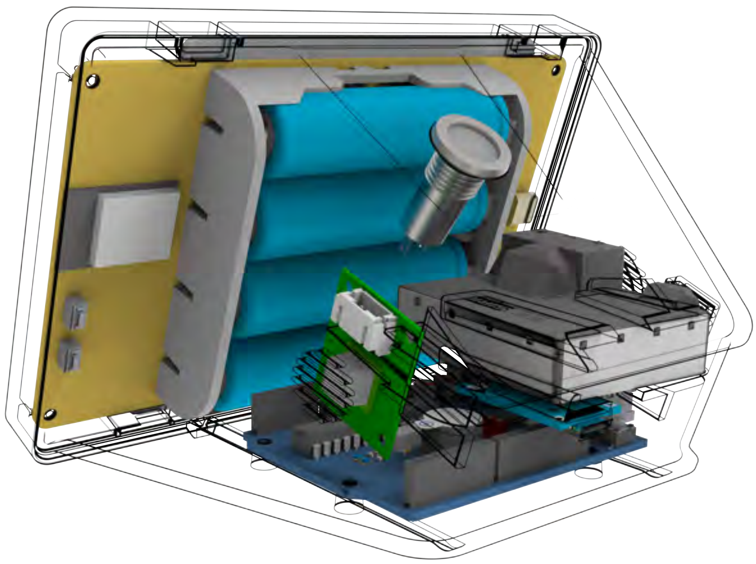
```
        Serial.print("NoxIndex:");
        if (isnan(noxIndex)) {
            Serial.println("n/a");
        } else {
            Serial.println(noxIndex);
        }
        */
    }

    uint16_t co2 = 0;
    float temperature = 0.0f;
    float humidity = 0.0f;
    bool isDataReady = false;

    error = scd4x.getDataReadyFlag(isDataReady);
    if (error) {
        Serial.print("Error␣trying␣to␣execute␣getDataReadyFlag():␣");
        Serial.println(errorMessage);
        return;
    }
    if (!isDataReady) {
        return;
    }
    error = scd4x.readMeasurement(co2, temperature, humidity);

    if (error) {
        Serial.print("Error␣trying␣to␣execute␣readMeasurement():␣");
        Serial.println(errorMessage);
    } else if (co2 == 0) {
        Serial.println("Invalid␣sample␣detected,␣skipping.");
    } else {
        Serial.print("Co2:");
        Serial.print(co2);

        Serial.print("\t");
        Serial.print("VocIndex:");
        if (isnan(vocIndex)) {
            Serial.println("n/a");
        } else {
            Serial.println(vocIndex);
        }

       // Serial.print("\t");
        Serial.print("Temp_SCD:␣");
        Serial.print(temperature);
        //Serial.print("\t");
        Serial.print("␣␣␣Humidity_SCD:␣");
        Serial.println(humidity);

```

```
//Print to the LCD screen does not work down here

//// From here
Serial.print("Temp_SEN:␣");
        if (isnan(ambientTemperature)) {
            Serial.print("n/a");
        } else {
            Serial.print(ambientTemperature);
        }
        Serial.print("␣␣␣Humidity_SEN:␣");
        if (isnan(ambientHumidity)) {
            Serial.print("n/a");
        } else {
            Serial.println(ambientHumidity);
        }

float tempdiff, humiditydiff;
tempdiff = temperature - ambientTemperature;
humiditydiff = humidity - ambientHumidity;

 Serial.print("tempDiff:␣" + String(tempdiff));
 Serial.println("␣␣␣humidityDiff:␣" + String(humiditydiff));

LCD.setCursor(0, 0);
LCD.print("T" + String(round(ambientTemperature)) + "␣H" + String(round(humidity)) + "␣C" +String(round(co2)) + "␣V" + String(round(vocIndex)));
LCD.setCursor(0, 1);
LCD.print("pm" + String(round(massConcentrationPm2p5)) + "␣PM" + String(round(massConcentrationPm10p0)) + "␣M" + String(measure) );

//// To here
    }
 }

 else{
  Serial.println("The␣Code␣is␣now␣done,␣it␣has␣measured␣100␣times,␣this␣will␣be␣printed␣every␣10␣min");
  delay(600000);
 }
}
```

S Renderings of Exploded View and Contour Casing



(a) Exploded view including names for all components.



(b) Product rendered with contours of the casing.

Figure A.22: Two technical views of the product including all components.

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