Developing a Wearable Sensor Network for Air Pollution Monitoring on Construction Sites

Bachelor of Science Thesis - Creative Technology

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Abstract

Air pollution is one of the leading environmental health risks, contributing to a variety of health issues such as asthma and cardiovascular diseases. The construction sector significantly contributes to air pollution in urban areas, necessitating urgent measures to address the health impacts on local residents and construction workers. However, the complexity of the construction site environment poses challenges in identifying the specific activities that contribute most to pollution and their impact on construction workers. Existing technologies deployed for this purpose utilise static sensor networks, relying on algorithms to infer from collected data. Wearables, in shape of sensors worn by construction site workers, show potential in removing the need for algorithmic inferences, but have not yet been applied in the context of construction sites.

The objective of this research is to create a prototype of a wearable sensor network capable of air pollution sensing and localisation. Through iterative design and testing, a prototype was developed utilising the Arduino® platform. User evaluation with 5 participants determined the best placement of the sensor on the upper back, as well as indicated potential for real-life implementation. However, further research is needed in front-end dashboard implementation, and especially in enhancing the localisation techniques.

The project could pave the way for better understanding of construction-related air pollution, contribution to its mitigation, ultimately improving the health and safety of construction workers and neighbourhoods around construction activities.

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To all, thank you.

"Environmental pollution is an incurable disease.
It can only be prevented."

– Barry Commoner

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Chapter 1: Introduction

This chapter provides a brief overview of the research project, focusing on providing justification for the relevance of the project, presenting a gap in existing research in construction site air pollution solutions research that it aims to address. Afterwards, it states the guiding research questions that the project will explore, before finally presenting an outline of the report.

1.1. Context and Relevance

Exposure to air pollution has been linked to a wide range of cardiovascular and respiratory complications, globally making it one of the leading health hazards, contributing up to 7 million premature deaths yearly [1]. Sources of air pollution vary by region and context, and include energy generation, vehicles, power generation, and construction. In all of these, urgent action is necessary to minimise the amount of pollutants entering the air, causing harm to the local environment, residents, and workers. Construction pollutants, specifically, were found to be correlated with health concerns such as asthma, chronic obstructive pulmonary disease, and other cardiovascular and pulmonary complications [2]. Moreover, for some pollutants construction was found to be a contributor of up to 80% in urban areas [3].

In the case of construction, however, addressing air pollution remains a challenging task, in part due to lack of insight into its direct causes and influences. Construction equipment, materials used, handling of those materials, and external forces such as weather all impact the composition, release and dispersion of polluting particles into the air. Furthermore, construction generally consists of a large number of actively involved stakeholders and contractors, each simultaneously working on one aspect of the site, often without much overview of other ongoing activities [4]. Because of this inherent complexity, it can be difficult to understand what the main drivers of air pollution on the level of one construction site are, or even further, at the individual level of employees and activities. Understanding these relationships is key to tackling the issue.

For this effort, sensor networks have been used to measure and analyse the spread of pollutants around construction sites. This method has been proven to be an effective way of providing insight into the spatial and temporal distribution of pollutants. [5] Nevertheless, most of the existing literature places the sensors in a static location, usually on the edge or outside the area of the site, relying on computational algorithms to infer from the collected data. However, this presents technological challenges in validating the predicted pollutant distribution, as the sparse allocation of the sensors lacks the needed granularity [6]. This problem can potentially be mitigated with the usage of wearable technologies, in which case the sensors are placed on the site workers. The potential of wearable technology comes not only in the sensors being placed on the area of the construction site itself, but also in the fact that the system would intrinsically physically follow the construction activity, providing flexibility and adaptability to the constantly changing environment of the site.

However, wearable devices must be made to fit the end user to ensure that they are compliant to their needs and culture [7]. The Design Thinking (DT) method shows promise in addressing this need due to the required high degree of user involvement, especially in the evaluation stage [8].

This report describes the design and development of a network of wearable sensors for on-site construction workers to track temporal and spatial distribution of air pollutants on a construction site using the Design Thinking methodology. Furthermore, the focus will be on doing so in an effort to gain more insight into worker and neighbourhood potential health hazards caused by air pollutants arising from construction activities.

1.2. Research Questions

The object of this research is to produce a functional prototype of a wearable sensor network for construction workers to accurately monitor the spatial and temporal distribution of potentially hazardous air pollutants in and around construction sites. Subsequently, it is addressed how the system, and the data collected through its usage, could potentially be used to improve site management practices for worker safety. This goal is what forms the research question (RQ):

RQ: How can a wearable sensor network be designed for accurate real-time spatial and temporal monitoring of key air pollutants in construction sites, ensuring reliability and usability, to address worker and neighbourhood health?

To granularize the question further, it was split into a set of sub-questions (SQs), each aimed at more specifically examining an aspect of the main RQ.

SQ1: What air pollutants of construction sites are hazardous to the health of on-site workers and the surrounding neighbourhood population and in what concentration ranges?

SQ1.1: What are the common air pollutants at construction sites and in what concentration ranges?

SQ1.2: What air pollutants of construction sites have known impacts on the health of on-site workers and the surrounding neighbourhood population?

SQ2: How can networks of wearable sensors be used for real-time monitoring of air pollutant distribution?

SQ2.1: What approaches can be used to improve spatial and temporal sensing coverage?

SQ2.2: What are existing approaches of sensing networks being used to measure air pollution at construction sites?

SQ2.3: What are existing examples of wearable sensing networking being used to measure air pollution?

1.3. Report Structure

Chapter 2: Background Research presents the background knowledge and state-of-the-art in the field, laying the foundation for problem definition and ideation.

Chapter 3: Methods and Techniques delves into the techniques and methodologies used throughout the project. Starting with Design Thinking as a general guide for the project process, and continuing by outlining specific techniques used in every step of the process.

Chapter 4: Ideation elaborates on the techniques used in arriving to the idea behind the final system.

Chapter 5: Specification builds on the idea laid out in the chapter before and specifies the details of the final system.

Chapter 6: Realisation describes the process of turning the product idea proposed in the previous two chapters into a physical working product, focusing on the iterative process and prototyping.

Chapter 7: Evaluation outlines the final evaluation step of the product, as well as its outcome.

Chapter 8: Discussion and Future Work elaborates on the outcome presented in the previous chapter, addressing any shortfalls, and proposing future work to build on top of the insights gained with this project.

Chapter 2: Background Research

This chapter outlines how a structured literature review was conducted to help answer background knowledge related research questions. The methodology behind this research is described in Section 2.1, after which the review is split into two distinct sections: Subsection 2.2 reviews the current issues behind construction-work caused air pollution, focusing on worker and neighbourhood health and finding the pollutant most fit to be tracked; Subsection 2.3 explores existing technologies in the field of construction pollutant tracking, focusing on the use of distributed sensing networks and wearables.

2.1. Structured literature review

To answer the first two research sub-questions, related to background knowledge, two structured literature reviews were conducted. The first review comprised of collecting information about the types of pollutants arising from construction sites, and the associated hazards posed to the human health. The goal of this review was to choose which pollutant raises the highest concern, and therefore presents the most dire need for a solution. Therefore, the outcome of the review determines what pollutant will be measured by the final design. The second review has to do with examining the existing solutions in the field of air pollutant tracking and sensor networks.

Shown in Figure 1 is the visualisation of the literature review process. Initially, a round of unstructured research in the topic of air pollution monitoring was conducted. The goal of the unstructured review was to familiarize with the topic in order to be able to construct relevant search queried. However, some sources deemed valuable were already at this step added to the final research matrix. Following the unstructured review, two queries were designed, each to answer one of the research sub-questions. To ensure relevancy of the papers, a filter was applied to limit the papers at the year of publication no older than 2000. The resulting papers were then reviewed based on their titles and abstracts, after which they were added to the research matrix. All the sources in the research matrix where then reviewed, and the matrix completed with the most valuable and relevant findings. The outcome of this process can be found in Appendix A: Research Matrix.

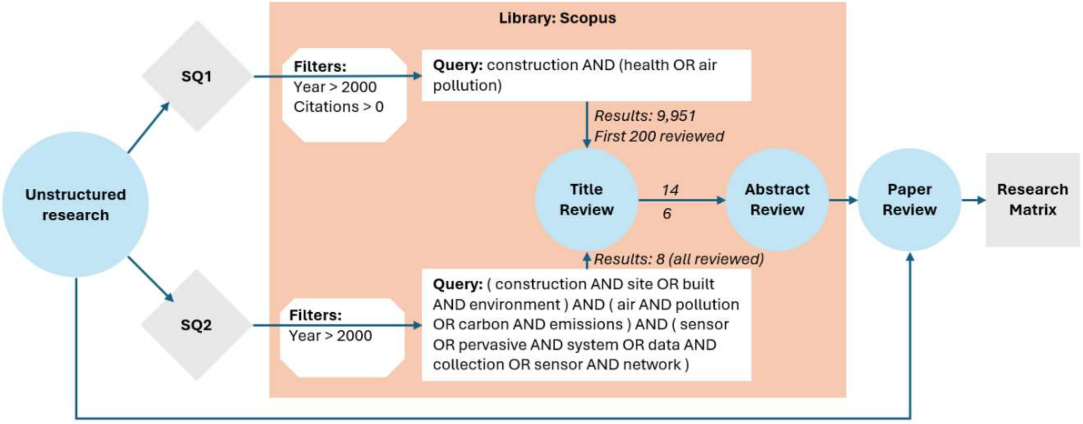

Figure 1: Visualisation of the literature research process

2.2. Air Pollution & Construction Sites

There is a wide range of pollutants associated with construction work. Their composition largely depends on the activities present at the site. Determining which of these pollutants' concentrations reach hazardous levels is key in determining what pollutant to focus on when designing a system aimed at human health. Zhuravleva et als. [9] outlines a number of pollutants and their source activities. NO_2, NO, C, SO_2, CO, CO_2, Ozone and Kerosene, for example, arise from operation of construction equipment, such as excavators and cranes; welding produces iron oxides and manganese compounds; NO2, NO, SO2, carbon oxides, and poisonous gas formaldehyde arise from welding. Since each construction activity is expected to produce a different combination of pollutants, this chapter contains two subsections dedicated to two activities with leading contributions to pollution: transportation and operation of heavy machinery. Finally, the third subsection discusses air pollution of construction in a wider context, analysing sources that would not have fit into the first two subsections.

Pollutants from Transportation

Sarkar et als. [3] makes a point for Particulate Matter (PM) particles in the form of construction dust as of highest concern due to various reasons. Firstly, it recognises construction dust as having the biggest burden on the health of exposed construction workers. Secondly, it raises the problem of wide distribution of the particles. Due to construction material arriving to the site, equipment arriving and leaving, and waste being disposed of by trucks, dust is the pollutant that spreads the farthest around and away from the site. This strongly suggest that PM particles should be considered as the key pollutant. However, the paper is specific to the context of the city of Kolkata, so more reviews need to be done in differing context to show the universality of the finding in other locations and contexts.

Motiar [10] finds that transportation of materials and equipment has the highest impact on the greenhouse gas emissions of a construction site. The nature of those emissions is analysed by Rahiman et als. [11] which presents a comprehensive analysis of emissions of the entire life cycle of a built environment. Crucially, it finds that CO2 comprises 97% of all greenhouse gas (GHG) emissions contributing to anthropogenic climate change. However, not a significant portion of GHGs occur on the construction site. Consequently, we find that they fall out of the scope of consideration for this research. Furthermore, [10] also concludes that dust-based pollution has the most adverse effects on the construction site workers.

Pollutants from heavy machinery operation

Desouza et als. [12], Chuanda et als. [13] and Boyle [14] examine the dangers of pollution from heavy construction machinery, such as excavators and cranes, towards a variety of pollutants. [13] compares the emissions of ozone and PM-based pollution in a life-cycle analysis. However, only emissions happening on the site, when the machine is being used, apply to this research, and not the machine's off-site construction nor transportation. With that distinction, PM particle pollution is found to have a higher impact on human health than ozone. [12] confirms PM pollution as the most hazardous for human health when compared to gaseous components. According to both papers, exposure to PM air pollution has been linked to cardiovascular diseases, cerebrovascular diseases, respiratory infections, asthma and other chronic lung diseases, respiratory organ sclerosis, lung cancer, and more. [14] reviews how using diesel as the most common fuel for powering construction machinery impacts air pollution, finding that the concentrations nitrogen oxides (NOx) and PM particles are heavily impacted by diesel emissions. The three sources all tackle a case study on a different continent ([12] Europe, [13] Asia, and [14] North America), providing proof for a certain level of universality to the described problem.

Wider context

While most reviewed works directly address health information, Tolga and Celk [15] review public opinion. The participants in the study were residents in a neighbourhood with active construction work. The participants were asked to report on the most important nuisances related to the nearby site in the form of a survey. The study found that daily nuisances scored highest, such as noise, while air pollution generally ranked lower, hence implying a certain level of ignorance from the public about health concerns of air pollution. However, construction dust scored high due to aesthetic reasons, such as covering cars and windows with dust.

Khamraev [16] offers a comprehensive review of PM particle pollution from the construction industry. It finds that 70-80% of PM particle pollution in urban environments arises from construction. This furthers the findings of research presented in the previous paragraphs, pointing at PM particles are the pollutant in need of most addressing.

Conclusion of Background Research

The objective of this research was to identify what air pollutant typically arising from construction site activities has associated with complications for human health. This objective was achieved through a comprehensive review of relevant literature, finding a near consensus among the reviewed sources. Across sources ([3], [10], [11], [12], [14], [15]) particulate matter pollution in the form of construction dust is most widely accepted as the pollutant raising most concern for its implications on human health, as well as a very common pollutant of construction activities. Furthermore, it is a pollutant that arises from almost any type of construction activity, making it the most widely applicable one.

This review was limited by only considering direct impacts of pollutants to human health. The reviewed sources did not consider the impact of a pollutant on the environment. However, from affecting the local built environment, to the local and global ecosystem, there are many ways that pollutants can have an indirect influence on human wellbeing, [17] which is not being acknowledged by any of the reviewed research. The lack of academic sources that address the intersection of environmental and human health impacts underscores the need for further research in this area.

2.3. State of the art

This subsection of the report will describe existing methodologies and research in the relevant fields. There was no research found that directly combines the goal of measuring air pollution, the technology of wireless sensor networks, and wearable technologies together as one whole. The section of the report was split into two subsections. Firstly, the examples of using the Sensor Networks to track air pollution in the context of construction sites. Secondly, existing research into wireless network wearable technologies being used for air pollution monitoring in any context will be presented, as using it in the context of a construction site specifically remains practically unexplored.

Wireless Networks

For the purposes of this research, a subtheme within the wireless networks field will be explored, namely, the Internet of Things (IoT). IoT is a concept describing a wireless network of devices sharing data over the Internet [18]. The potential of the technology is to distribute an array of sensors across an area, such as a construction site, with each individual sensor collecting data that domes together wirelessly in a separate location utilising internet technology.

One such example is presented by Chandrasekaranet als. [5], where an IoT system was used to create 3D models that displayed gas distribution data in real time. A variety of gas sensors were used to detect

CO_2, NO_2, SO_2, and CO and display it in the interactive 3D model. The system was proven to be more efficient than manual methods. Using a similar method, Bousiotiset als. [19] created density maps that showed distribution of pollutants using low-cost sensors.

Loo et als. [20] utilises IoT technology to create large datasets for AI modelling. The IoT connected sensors measure the levels of various pollutants in order to make models about how different construction techniques impact CO_2 and other pollutant emissions. It successfully finds that in-situ building produces an increase in emissions when compared to Modular integrated Construction.

To ensure optimal performance of the system, Gangwar [18] states that key features of a system are uniform spread and widespread of the sensors across the measured area.

Wearables

Wearables are a technological category consisting of devices that can be worn on the users body, such as an accessory, a piece of clothing, or an implant [21]. Such devices can be used individually, augmenting the user's abilities or providing useful information in isolation, or they can be connected into a larger network. Such networks of wearable sensors have been used for distributed, flexible data collection. Using a network of wearable sensors for air pollution monitoring is a well-researched niche, with available commercial solutions. However, no example was found of a wearable sensor network being utilized in the specific context of a construction site.

Zhang et als. [6] uses a wearable sensors connected using a Bluetooth®-based networking system to measure air pollution across seven stations of the London underground. The system connects to the user's phone to track GPS and stores data on a mobile app. The information is used to study the spatial and temporal distribution of particles. The system extrapolates the data to make an assessment of what health impact the air pollution has had on the user.

Similarly to [6], the ATMO Tube Pro® [22] uses the user's smartphone to connect the sensor data into a larger system, while the sensor device itself communicates only with the phone through a Bluetooth® connection. The sensor measures a wide range of pollutants, such as PM, temperature, and volatile organic compounds. The data collected is directly accessible to the user through the mobile app, through which it also contributes to a global database, together with user location measured by the phone. While achieving the goal, the system comes at a high price, making it unavailable for most consumers, and for purposes in which a large number of sensors is needed under one control. The TZOA sensor [23] manages to achieve similar results as the ATMO®, but at the fraction of the size and price. However, the sensor is no longer available commercially.

Dam et als. [24] uses the Arduino® platform to develop a low-cost wearable device to measure a wide range of environmental parameters, such as ozone, PM concentration and humidity. However, unlike other examples, the system is intended to be used for an individual, and is not connected to a larger network or database. Tian [25] explores the space further by augmenting a low cost wrist-worn sensor with an accompanying mobile app, similarly to [6] and [22]. However, due to a relatively bulky design, the product failed to meet the criteria for wearability.

Chapter 3: Methods and Techniques

This chapter will describe some of the methodologies followed by the project. Mainly, in section 3.1 Design Thinking process, the main guiding principles of the project will be described. Further on, the chapter will describe methods used to realise a product, and lastly, the evaluation methods used to evaluate the developed prototype.

3.1. Design Thinking process

The design thinking (DT) process is a design method that describes an iterative process of identifying problems, coming up with solutions, and improving them through a series of prototypes [8]. By involving stakeholders throughout the process, it ensures that the final design serves the users in a meaningful way, and responds to their concerns and needs. The structure of DT consists of five stages: Empathizing, Defining, Ideating, Prototyping, and Testing. While the five stages are discretely described, they are not meant to be a straightforward linear process, but a guide for steps that are constantly and iteratively to be revisited, generally guiding the process towards a desired solution.

Figure 2: The Design Thinking framework visualisation

Empathizing composes the first stage of DT. In this step, the designer is meant to reach out to as many potential stakeholders as possible and connect to recognise what problems they are facing. This step ensures that the design is from the beginning tackling an issue they recognise, and is responding to concerns that the stakeholders might have. While the stakeholders are in this case usually and generally the final intended users of the design, it is best to include anyone else that could be impacted by it without using it. The techniques that can be utilised in this step range from interviews for more unstructured data that allows for more exploration, to surveys as a more structured alternative. Usually a combination of techniques is used.

In the defining step, the designer analyses the data collected during empathising and combines it with background research to define a problem that the design will try to solve. The problem definition needs to meaningfully describe the user needs, while also providing a realistic scope for the project. As a defined problem gets more specific, it might require some return to the previous stage to ask for more specific input from stakeholders or experts.

Ideation is the phase of generating ideas. The outcome of this step will determine the first outline of the shape for the final design. For successful ideation, a number of techniques are at disposal to the designer, meant to help expand the range of possibilities and focus on the most liked ideas.

The concept(s) chosen at the end of ideation will be realised in a prototype. In the prototyping stage, ideas are turned from concept to its physical representation. In the first iterations, it takes the form of a lo-fi prototype of limited to no functionality. Features get implemented throughout the iterative process, moving the prototype to a hi-fi one, where functionality and design are getting to their final form. With every iteration, it is crucial that the prototype is tested and evaluated in a way that informs the design of future iterations.

In the so called 'final' step of the iterative cycle, the prototype is taken to the Testing phase. At this stage, the prototype is brought to the final users, and critically evaluated on how well it achieves the desired goal. Through surveys, focus groups, interviews, and other methods, the users give their input and influence the future designs. From here, the product re-enters the design cycle to incorporate the design of the users, and the process repeats itself until a satisfying conclusion.

By using an iterative process that ensures focus in placed on the end user, the Design Thinking method shows high potential in ensuring wearability and end user satisfaction, which are key for successful implementation. As DT will be used as the guide for the general project flow, this is reflected in the structure of this report, the chapters of which follow the DT process stages. The influence of DT on the project should become apparent in the existence of multiple prototypes, user evaluations, and the iterative cycle.

3.2. Realisation Methods

The Arduino® environment

The Arduino® environment makes it easy to interface with a variety of off-the-shelf sensors, utilise existing solutions such as programming libraries, and offers extensive online documentation and support. Due to these attributes, it has high potential in the prototyping cycle, as it can be implemented quickly and easily, and most issues should be addressed in the documentation. Hence, the project will be built utilizing the Arduino® environment. This will largely be detailed in Chapter 6: Realisation.

FDM 3d printing

Fused Deposition Modelling (FDM), is an additive manufacturing technique where an object is built by depositing material, typically thermoplastic polymer, layer by layer in a predetermined path. The material is heated and extruded through a nozzle, and upon extrusion fuses with the material below it, creating a rigid structure [26]. The technique is commonly used for rapid prototyping, as it allows for quick production of relatively detailed 3d structures.

To create the models that will be printed, a 3d modelling software Fusion 360® will be used throughout the project. This choice is made based on the capabilities of the software and the of the researcher familiarity with it.

To produce the 3d model, the BambuLabXL1® 3d printer is used due to its high speed, precision, and availability to the researcher. Transforming the 3d model into the path that the printer will follow to deposing the material will be the slicer programme the Bambu Studio®, chosen due to its compatibility with the BambuLabX1® printer.

3d printing with embedded textile

In addition to regular FDM 3d printing technique, the project utilised a specialised technique of 3d printing with embedded textile [27]. The technique allows for inclusion of 3d models on textiles by incorporating a textile layer in between layers of plastic. In practice, this means stopping the 3d printing device during the printing process and placing a textile mesh over the printing area before resuming the printing. As new layers deposit, they merge with the layers below through the mesh, creating a strong bond between the printed parts and the textile. The technique was utilised for wearability of certain components, as it allowed for highly reliable connection between the printed parts and construction safety clothing.

3.3. Ideation Methods

Research-Driven Ideation

There are many available ideation techniques that help guide one to a consider creative ideas to solve a problem [8]. Due to the highly technical and specific nature of the project, instead of immediate pursuit of creative brainstorming, research-driven ideation was pursued in this project. In essence, it comprises of reviewing relevant literature with the focus on academic gaps that provide fertile ground for ideation. For example, such gaps can be identified when a certain technology shows high potential, but has not been used in a certain context, or when two technologies could seemingly be combined to improve their effectiveness, but no examples of such a development could be found. The identified gaps created the space of exploration, providing creative constraints for idea generation.

Feasibility-Effectiveness Matrix

To select which of the generated ideas will be pursued in the project, the ideas will be rated on the Feasibility-Effectiveness Matrix. The matrix (also named 'Impact-Feasibility Matrix' in some literature) is a useful tool for evaluating ideas based on perceived potential to solve the required problem, and the likelihood that it will be completed within the scope of the project [28].

The tool does not rely on rigorous empirical data, but on perceptions of the researcher, which should be informed by the background knowledge and experience. The technique consists of placing ideas on a a 2D plane where their vertical position determines how effectively the idea would help address the problem, and their horizontal position how feasible is it to implement the idea in the context of the project.

3.4. Specification Methods

MoSCoW Rating

The MoSCoW rating method provides a way of creating hierarchy of importance within requirements of the project [29]. It is useful when considering what aspects of the system need to be developed and to what level of completeness, therefore providing a guide for where to dedicate time and resources when the scope of the project does not allow for production of a fully functional product.

In essence, the MoSCoW rating method assigns 4 levels of importance to a requirement:

RATING	EXPLANATION
M	**Must have** - Essential requirement at the foundation of the system
S	**Should have** - Requirements of a high priority;
C	**Could have** - Desirable requirements that could be included if scope allows
W	**Will not have** - Requirements that stakeholders would want, but that will not be implemented at this stage.

Table 1: MoSCoW scale ratings

The rating will be applied to any requirement based on how relevant the requirement is to answering any of the research questions, how important it is for a critical evaluation by the end-user, and how feasible it is to fulfil within the scope of the project.

3.5. Evaluation Methods

SUS and WEAR scales

The System Usability Scale (SUS) is one of the standard and most efficient techniques of gathering data about usability of systems. It consists of 10 questions which the participants answer on a Likert Scale, ranking their answer on a range from 1 to 5 based on how much they agree with the statement they are reading [30] [31]. SUS itself relies on the user directly interacting with the system, which is why the scale was not utilized fully in the case of this project. Instead, it helped inform the adapted version of a scale that was used in the evaluation stage (further elaborated in Chapter 7: Evaluation).

The WEAR scale provides a method of user evaluation focusing on usability and adoption of wearable devices [7]. The scale focuses on measuring the likelihood of a wearable device gaining wide adoption based on its cultural and contextual attributes. Similarly to SUS, the scale was not fully adopted in the evaluation stage, but helped inform the final developed questionnaire (further elaborated in Chapter 7: Evaluation).

Chapter 4: Ideation

This section will describe the ideation phase of the project, the process of arriving to the idea of the final product designed by the project.

4.1. Research-driven ideation

Due to limited familiarity with the construction site context and technologies employed in it, the first step of the ideation phase was to find and build atop of existing developments. Utilising the state-of-the-art research presented in Section 2.3, research-driven ideation focuses not only on the existing knowledge, but specifically in finding gaps between the existing works. Gaps were identified by looking at existing technologies that were not applied to the context of construction site; existing technologies in the context of construction sites, but that might not have been successful due to a design feature; and cases where two technologies showed opportunities for synergy that was not yet explored. These were seen as opportunities for exploration, and hence informed the ideation process going forward.

After finding the opportunities for creative exploration, the space was filled with ideas through rapid idea generation. This stage consisted of one ideation session without boundaries of what is feasible, realistic, or effective. Instead, the goal is to create a large quantity of varying creative ideas.

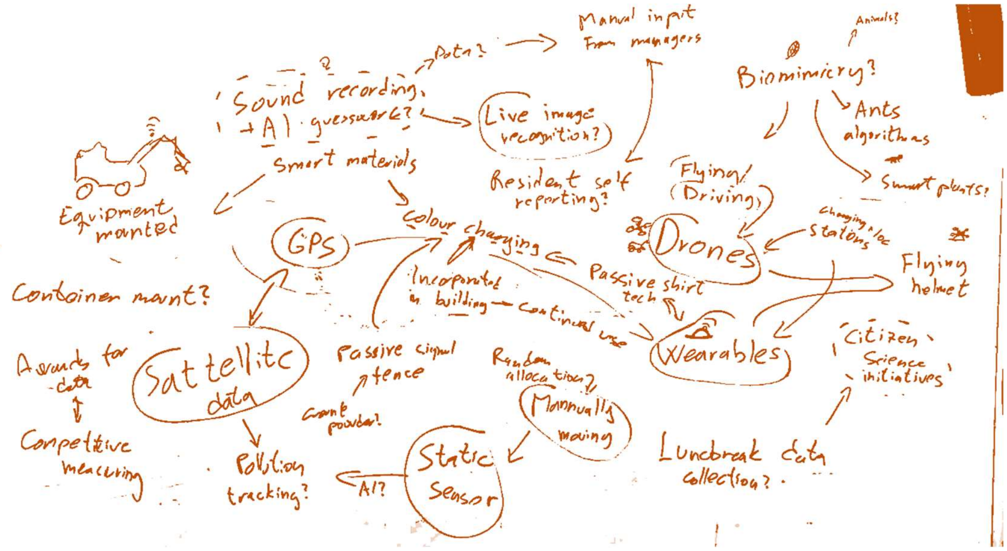

Figure 3: Idea generation brainstorming session

Afterwards, the ideas are filtered to only keep those which realistically fit the project scope and purpose. Specifically, this step evaluated whether the ideas fit within the space defined by research-driven ideation to ensure a balance between relying on existing technologies and exploring a unique research niche. Finally, the ideas are evaluated on a feasibility-effectiveness matrix.

4.2. Feasibility – Effectiveness matrix

As outlined in Section 3.2, to help organise the generated ideas, they were evaluated based on their potential effectiveness and feasibility. Both metrices are based on a vague, subjective perception and are in no way empirical or scientific. However, their perceived position was informed by the conducted background research. In cases of indecisiveness and uncertainty, whiskers were added to ideas, representing the range of uncertainty.

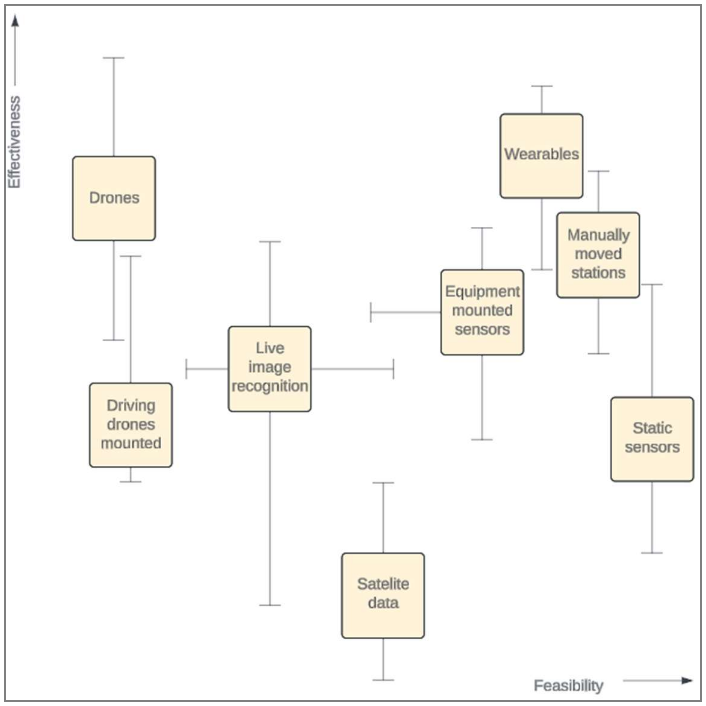

Figure 4: Generated ideas placed on a Feasibility - Effectiveness matrix

4.3. Idea development

The idea rated most highly on the two axis in the Feasibility – Effectiveness matrix was further developed through sketching ideation. Attention was paid to existing literature about suitable wearable placement [32], leading to three choices of wearable placement to be developed into prototypes: The upper back placement, mounted on a protective vest; the waist placement, mounted on a belt; and the back head placement, mounted on a construction helmet.

Additionally, a preliminary system graph was sketched out, beginning the process of specification, which will be continued in the next chapter.

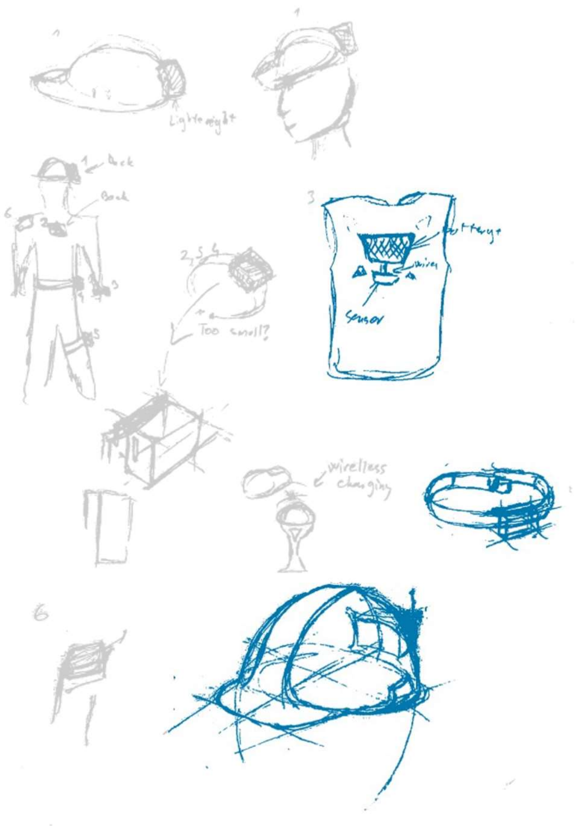

Figure 5: Ideation sketches for sensor design & placement

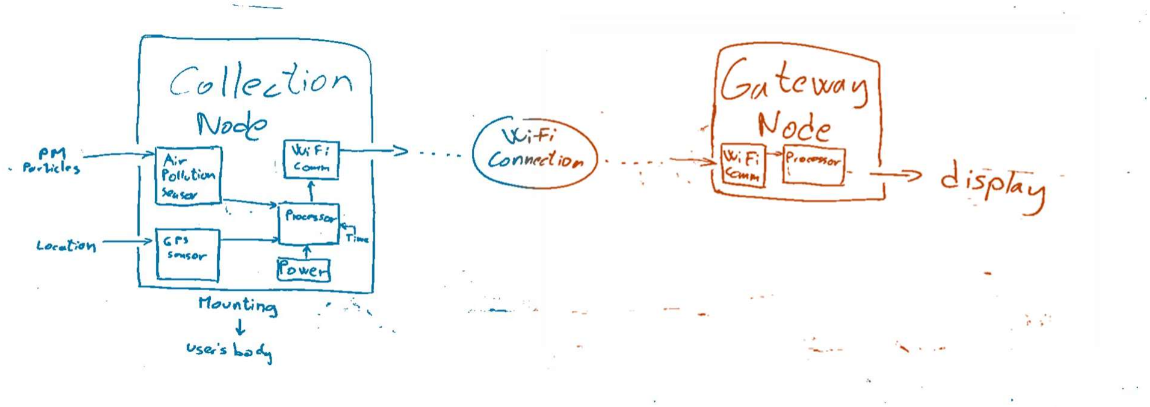

Figure 6: Ideation sketches for preliminary system graph

Chapter 5: Specification

This chapter will outline the features necessary for the system that will be developed as the outcome of the project to be considered satisfactory. First, the user requirements will describe the needs of the end-user in 5.1. In 5.3, user requirements are developed into functional requirements, which provide more detail into technical considerations of the system.

5.1. User requirements

User requirements, also known as preliminary or non-functional requirements [33], describe the needs of the final end-user for the functionality of the system. In other words, they are a set of features and attributes that the design needs to have in order to be suitable for the end-user's use and context. These features have been defined according to the framework presented in [34]. In accordance with the framework, the requirements have been split into categories: Wearability, Interactivity, Security, Effectiveness, Real-Time Processing, Communication, Power Supply, Scalability. For each category, a number of requirements were defined, each with an indicator, a measure that will determined how well the requirement was fulfilled by the final design. The indicator might be a user test, a fact that a feature is part of the design, a physical measure, or other, which will be described in Chapter 7: Evaluation. All Categories, Requirements, and their respective Indicators have been presented in Table 2.

While all of the listed requirements should be present in a final, product-level, version of the system, not all are feasible in the scope of this project. For the purposes of evaluating which requirement should be pursued, a rating was placed on all the requirements according to the MoSCoW requirement rating method [29].

CATEGORY	REQUIREMENT	INDICATOR	RATING
1. WEARABILITY	1.1 The design is **lightweight** and has a **small size**.	Upon testing a prototype of the system, the users find the design's weight and size sufficient for use.	M
	1.2 The design is **comfortable**.	Upon testing a prototype of the system, the users find the design comfortable.	M

CATEGORY	REQUIREMENT	INDICATOR	RATING
	1.3 The design does not hinder the ability to perform work.	Upon testing a prototype of the system, the users find the design would not hinder their ability to perform their work.	S
	1.4 The design is **adjustable**.	Upon testing a prototype of the system, the users find that they can easily fit the design to their body.	C
	1.5 The design does not severely affect the user's appearance.	Upon seeing a prototype of the system, the users find the design's appearance is fitting to their cultural and in-use needs.	C
2. INTERACTIVITY	2.1 The system can be used **hands-free**.	The user does not need to directly interact with the system for it to function.	S
3. SECURITY	3.1 The user's status and personal data are **protected**.	The users status and personal data are securely stored and transmitted, and forbidden to be disclosed to anyone but the wearer and supervising personnel.	C
4. EFFECTIVENESS	4.1 The measured data achieves high **accuracy**.	The measured data accurately represents the real world.	S
	4.2 The measured data achieves **precision**.	The measured data is consistent across repeated readings.	C
5. REAL-TIME PROCESSING	5.1 The system collects and transmits the data in **real-time**.	The system collects and transmits data continuously, as it is being used.	M
6. COMMUNICATION	6.1 The system nodes communicate **wirelessly**.	The data collection nodes do not need to be wired to a central node to transfer data.	M

CATEGORY	REQUIREMENT	INDICATOR	RATING
7. POWER SUPPLY	7.1 The power supply is **rechargeable**.	The collection nodes of the system can be charged.	C
	7.2 The power supply has a **capacity** that is satisfactory to the use-case.	The power supply stores enough energy to make the system last for one work day of a construction worker (8 hours).	W
8. SCALABILITY	8.1 The system can be easily **scaled** and reconfigured for applicability.	The system can be scaled up to any construction site context, and to work with any number of collection nodes.	W

Table 2: List of user requirements and their respective indicators, split across categories. In the Requirements column, most relevant keywords have been made bold.

5.2. System Graph

To specify what functional components are needed to realise the functionality of the product, a system graph was created, as can be found in Figure 7: System Graph. The system recognises two separate devices, called nodes: The Collection node, which presents the wearable part of the system, collecting the data; and the Gateway Node, which receives the data from all collection nodes and sends it to a displaying device.

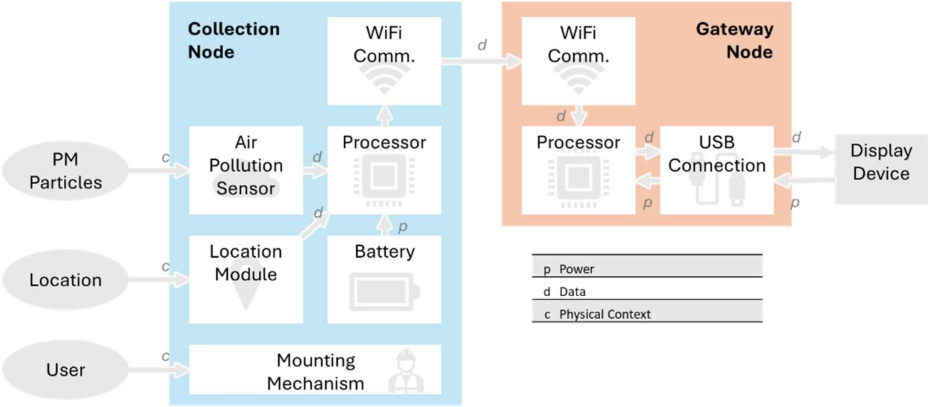

Figure 7: System Graph

5.3. Functional requirements

Functional requirements detail the technical needs the system needs to exhibit in order to meet the user requirements in the context of the proposed idea. Specifically, it breaks down each component of the system to define what components need to be procured in the realisation stage.

COMPONENT	REQUIREMENT	SPECIFICATION	RATING
ALL COMPONENTS	Supply voltage	max 5.5V (USB port supply)	M
	Size	max 5cm × 5cm × 3cm	M
	Weight	max 15g	M
AIR POLLUTION SENSING	PM Particle sensing	Ability to measure PM sizes of 1 µm to 10µm	M
GEOLOCATION SENSING	Geo-location system support	Multi-modal	S
	Accuracy	Within 5m	S
WIFI® COMMUNICATION	Range	500m	W

Table 3: List of functional requirements of system components

Chapter 6: Realisation

This chapter will describe the process of bringing the idea and outline of the project to reality. Starting with section 6.1 Functionality & detailing the technical aspects of the project, and section 6.2 Wearability & Casing describing the process of fitting the technology to the end user through physical prototypes.

6.1. Functionality & Electronics

This section will describe the technical aspects of the constructed prototype, and the process of arriving at the final design. The system itself consists of two separate parts: The Collection Node and the Gateway Node. The Collection Node is responsible for collecting data about the environment through a variety of sensors, and wirelessly sending the data to the Gateway Node. The Gateway Node gathers the data of all Collection Nodes, and stores it or displays to the user. The system was built on the open-source Arduino® software and hardware platform.

Collection Node

As described above, the collection node is responsible for collecting data and sending it wirelessly to the Gateway node. It other words, the Collection Node is the 'wearable' part of the system. The functionality of the Collection Node consists of the central computing and communication section, which is connected to two sensors at the periphery, namely the location module and the air pollution sensor, and finally, the power supply. All of which are described in more detail further in this section.

All of the components were at first assembled on a breadboard, allowing for easy testing of individual components and setups. Each separate part of the system was made on its own, without the other parts connected, before putting them all together as shown in the circuit diagram below.

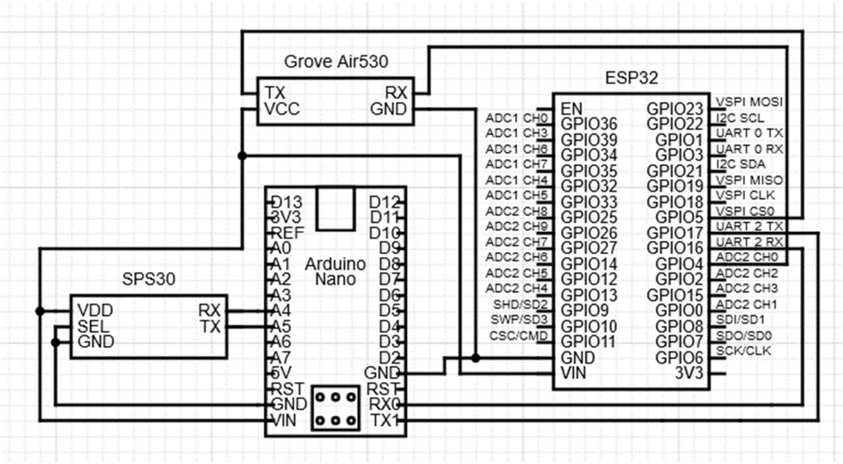

Figure 8: Circuit diagram of the collection node electronics.

Collection Node: Central Computing & Communication

Central Computing and Communication at the core of the system is responsible for gathering the data sent by all the individual sensors and re-formatting the data in a way that is easy to transmit, before transmitting the data to the Gateway Node. A microcontroller board, a programmable device used to control a larger system [35] [36], had to be used at the core of the collection node.

For the purposes of this project, the ESP32-WROOM-DE (going forward: ESP32) microcontroller was used in this role. It was chosen due to its compatibility with the Arduino® programming environment, making it easy to interface with a variety of off-the-shelf sensors, utilise existing solutions such as programming libraries, and extensive online documentation and support. Furthermore, the ESP32, as opposed to most other Arduino® boards, features on-board WiFi® communication capabilities, which streamlines the system setup by subtracting the need for an additional module tasked solely with wireless communication.

Figure 9: The ESP32-WROOM-DE board (Source: [37])

WiFi® Communication

Once the central microcontroller board has received both Air Pollutant data and geolocation data, it combines it with internal time data in a data package, before sending it to the gateway node. A data package in this case is a specially constructed variable type that recognises the three distinct parts of the message (namely, the geolocation data, the air pollution data, and the time data). The exact same variable type needs to be constructed on both the collection and gateway node in order for messages to be able to be sent and received correctly.

Collection Node: Air Pollution Sensing

To collect data on Air Pollution, specifically, on PM-particulate matter concentration, an adequate sensor needed to be installed. The choice of sensor has to be made based on a set of attributes stemming from the requirements described in the previous chapter. Namely, the accuracy and precision of the sensor and it’s size and weight. Additionally, the sensor should be as low-cost as possible for the purposes of the prototype. Sensirion SPS30 laser-based ‘dust’ sensor was found to be matching the requirements of small size and weight [38], with low power consumption options providing opportunities for smaller required batteries, further contributing to the lightness of the system.

Figure 10: Sensirion SPS30 laser-based PM particle concentration sensor (Source: [39])

However, an issue was encountered when communicating between the Sensirion SPS30 sensor and the central ESP32 microcontroller. The difference in communication requirements rendered direct connection of the sensor to the microcontroller impossible. To circumvent the problem, another microcontroller, the Arduino Nano® was added to the circuit to interface between the sensor and the ESP32, as shown in the circuit diagram above. The code used for the purpose of interfacing the elements of the system consists of parsing the information recorded by the sensor and passing it on through wired serial communication to the ESP32.

Collection Node: Location Sensing

To record the location of collected pollution data, a sensor had to be installed to handle location positioning. Similarly to the Air Pollution sensor, the location module needed to balance accuracy and precision with weight, size and price. At first the NEO-8M® GPS module was chosen for the role. However, the NEO-8M® was proven inadequate due to taking too much time when booting up, and impossible to use indoors or next to built structures. The problem was identified in the sensor's limitation to using only one positioning system, GPS, and therefore being exposed to a limited amount of satellite data. Hence, an additional requirement was made, namely, for the system to be Multi-Modal, utilising a variety of positioning systems alongside GPS equivalents, such as GALILEO, GLONASS, and BeiDou.

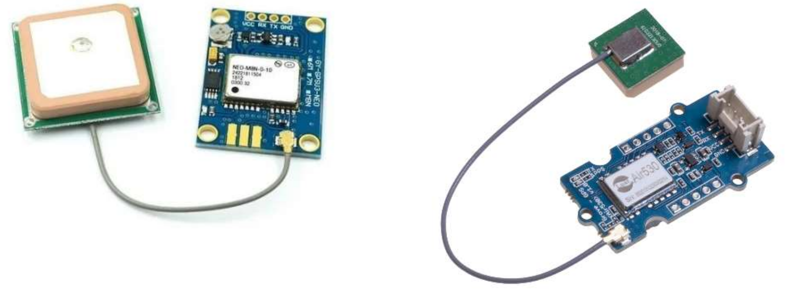

Figure 11: Location modules: left – NEO-8M (Source: [40]); right - Grove Air530 (Source: [41])

The addition of the multi-modality requirement informed the choice of sensor going forward, which is how the choice was made for the Grove GPS (Air530) module..

Collection Node: Power

To power all the electronics in the collection node, a 5V power supply supply was required. The supply needed to be easily rechargeable without being disconnected from the system, as well as have the key requirements of being lightweight and small size. A compact 5V polymer lithium battery was chosen as the ideal power source for the system considering the requirements. However, due to shipping complications, it was never successfully utilized in the project.

Instead, a pivot was made for a temporary power source. The Anker® Power-Core battery does not exhibit the necessary small size nor light weight, making it a less than optimal choice, but was instead chosen due to its accessibility to the researcher. This has resulted in non-ideal compromises in design, which will be further discussed in the Casing - Casing Cover subsubsection.

Figure 12: Power sources: left – initial choiceplymer lithium battery (Source: [42]); right - Anker® Power-Core (Source: [43])

Gateway Node

As previously described, the gateway node's primary purpose is to wirelessly receive data sent by the collection node and parse it through to the displaying device. The node needs to serve as a WiFi® transmitter for the collection nodes to connect to in order to be able to send the data. The node itself needs to be connected to a computer that will display the received data.

Microcontroller

The gateway node consists of an ESP32-WROOM-DE microcontroller board with an on board WiFi® module, mimicking the collection node core component. The microcontroller supplies the WiFi® connection to all the collection nodes, which in turn target its MAC address with all the collected data. Upon receiving the data, the ESP re-formats it into a String variable, before sending it via USB cable as a serial message packet to the connected computer. The string variable is formatted as "[DATA TYPE] : [DATA MESSAGE]" where DATA TYPE determines what type of data the system is receiving ("GPS", "Time" or "Air"), followed by the delimiter ":", marking the beginning of the DATA MESSAGE. The DATA MESSAGE might be sufficient on its own, or, in case of air pollution data, needs to be further unpackaged into individual PM particle ranges.

<table>
<tr><th>TYPE</th><th></th><th>DATA MESSAGE</th></tr>
<tr><td>“GPS”</td><td>“:”</td><td>Geolocation data expressed in NMEA Code (the <i>National Marine Electronics Association</i> code standardly used to denote geo location data) [44]</td></tr>
<tr><td>“Time”</td><td></td><td>Time expressed as <i>hh:mm:ss</i></td></tr>
<tr><td>“Air”</td><td></td><td>Further broken down into individual PM sizes, separated by a tab “\t” character. Then, the data is separated from the PM size indicator through the “:” delimiter. The data is expressed in a single float number, being the concentration of pollutants.
<table>
<tr><td colspan="2">PM1.0:[data]</td><td>“\t”</td><td colspan="2">PM2.5: [data]</td><td>“\t”</td><td colspan="2">PM4.0: [data]</td><td>“\t”</td><td colspan="2">PM10.0: [data]</td><td>“\t”</td></tr>
<tr><td>“PM1.0”</td><td>“:”</td><td>[data]</td><td>“PM2.5”</td><td>“:”</td><td>[data]</td><td>“PM4.0”</td><td>“:”</td><td>[data]</td><td>“PM10.0”</td><td>“:”</td><td>[data]</td></tr>
</table></td></tr>
</table>

Table 4: Data formatting in the Gateway node

Displaying device (computer)

The computer receiving the data is tasked with displaying it in a data dashboard. For this purpose, it runs a code written in the Python programming language. The code parses the received data, recognising the required delimiters and data type indicators to store it in a dictionary type database. The dictionary comprises all of the data in one place.

The dictionary is used to update the graphics of the dashboard, as shown in Figure 13. The dashboard consists of two frames: a pollution line graph and a pollution measurements map. The pollution line graph displays the recorded pollution in a line-graph where time is displayed on the x axis and pollution on the y axis. Each PM particle size is displayed in a different colour, as explained in a legend in the corner. The pollution measurements map displays a world map and places a scatterplot over it. The scatterplot was made in such a way that it places a dot on the map for each latitude-longitude pair, and the colour of the dot is determined by the total pollution (the sum of all PM particle sizes' concentrations). Both graphs were made utilising the matplotlib python library [45], and are being live generated with the incoming data being stored in the dictionary. The graphs are updated 5 times a second, and with each frame update the code checks for an incoming data packet. However, the noise of the incoming location data impeded the capability of the system to show that data live, as will be elaborated upon in the discussion.

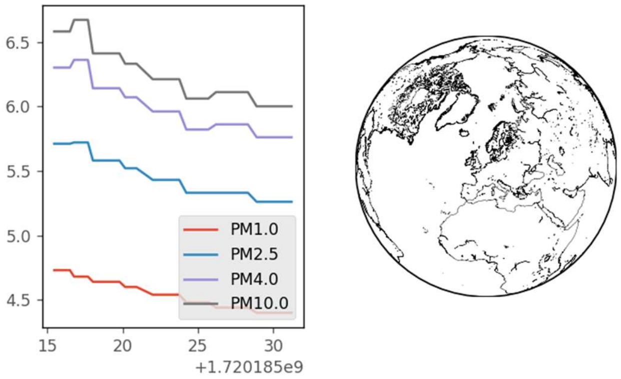

Figure 13: The live data dashboard

6.2. Wearability & Casing

To make the device wearable, a casing needed to be designed that will house all the electronical elements and be easily mounted onto the protective gear for wearability. Additionally, a special mount needed to be designed to attach the casing to the three pieces of construction equipment (helmet, vest, belt). The design of each of the individual parts is detailed further in the subsection.

> *For clarification: this section only refers to the wearable aspect of the system, hence only concerns the collection node (mentions of 'all electronics' refer to all the electronics of the collection node).*

The required parts were designed as a digital 3d model using the 3d modelling software Fusion 360®. The parts were printed on a BambuLab X1® 3d printer, and the material was BambuLab Marble Red PLA® plastic.

Casing

Figure 14: The casing

The casing was designed to precisely fit the protoboard containing all the electronics. This includes placing an opening for the air quality sensor to ensure unconstructed airflow. Additionally, for the purposes of the prototype, another opening was made on the case for the ease of access to the USB ports of the two microcontrollers (the ESP32® and the Arduino Nano®). This was done in such a way so that the system can still be connected to a computer for purposes of debugging or code changes and would not be featured in a theoretical final design.

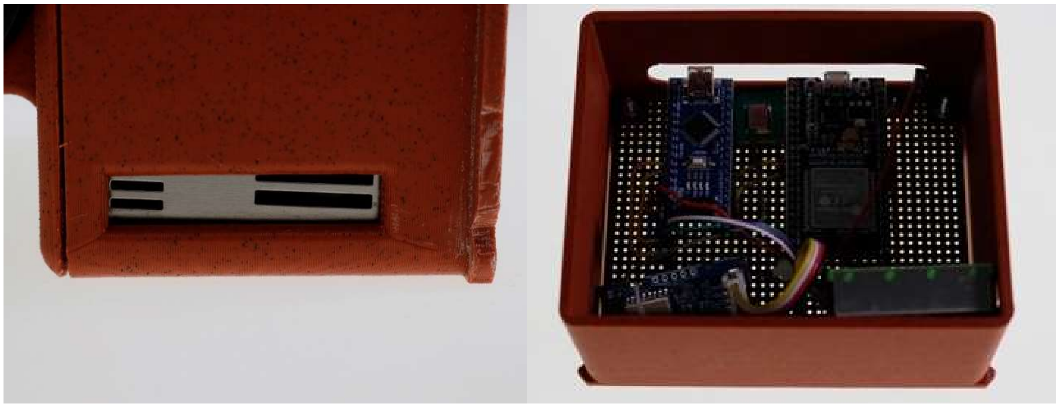

Figure 15: Openings on the casing for the air pollution airflow (left) and USB access (right)

The protoboard was secured to the casing through 3 bolts placed through pre-made holes in the model. This ensured that the electronics stay in place, minimizing the risk of a lost wire or component damage during testing and development.

Casing Cover

While the casing cover was intended to be flat, minimising design size, due to the change in battery type (as described in subsection *Collection Node: Power*), a special cover needed to be designed to hold the external power supply in place. Hence, the design saw an addition of circular 'clip-on' holders that ensure stable friction-fit of the battery, as shown in Figure 16.

Figure 16: Casing cover for the external battery holder

Figure 17: Casing with the cover and battery

Mounting for wearability

The casing needed to be attachable to each of the three pieces of construction gear. The mounting design for this purposes needed to be made in such a way that the attaching and removal of the casing is as easy and quick as possible in order to be able to switch between gear pieces during the user evaluation.

To this end, a mount was designed with features to enable easy removal, while securing the casing safely in place. The mount system consists of a rectangular frame that snugly fits around the bottom of the casing, and contains a notched protrusion. A railing is added to the design of the casing that fits inside of the frame, and contains a small hole in the position of the frame notch (as shown in Figure 18). The casing is slid through the frame until a the notch and hole click together and secure it in place.

This system (going forward: Basic Mount) is the key part of the design of the Helmet, Belt, and Vest mounts described below.

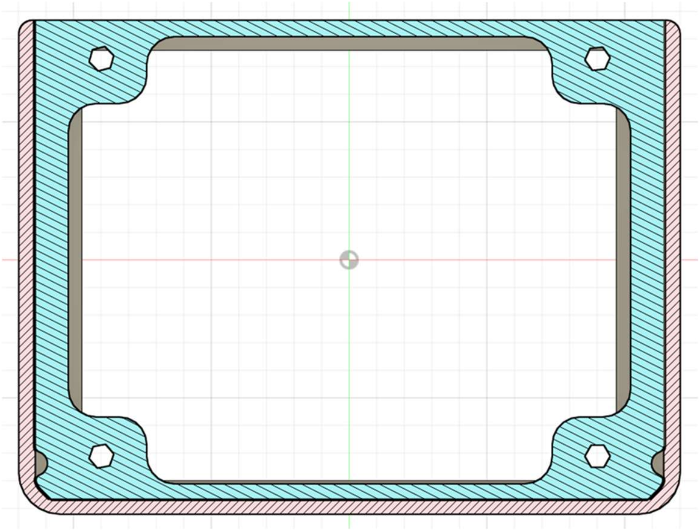

Figure 18: Casing mount mechanism 3d model

Vest Mount

The vest mount consists of the basic mount design, combined with 4 surrounding panels to help it stay fixed when attached to textile. The surrounding panels are not directly connected to the mount in the 3d model. Rather, they are connected through the usage of the 3d printing with Embedded Textiles technique [27]. The outcome of the technique is shown in the figure below.

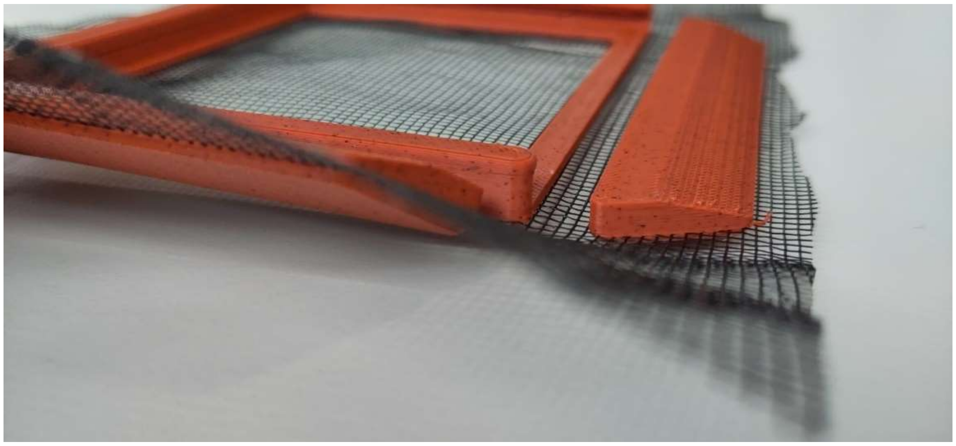

Figure 19: Outcome of 3d printing with the embedded mesh

The mesh with the embedded 3d parts was manually sawn on the back of the vest with thread to complete the process.

Figure 20: The completed vest mount

Helmet Mount

The helmet mount design extends the basic mount design with a curved surface to fit the curvature of the helmet. This was done by overlaying an image of the helmet in Fusion 360®, and tracing the curvature manually, resulting in an approximate fit. After printing, the piece was attached to the helmet using lightweight epoxy glue and epoxy putty.

Figure 21: The completed helmet mount

Belt Mount

The belt mount features a simple design that allows the basic mount to hang from a standard sized belt using a simple hook, as shown below.

Figure 22: The completed belt mount

Chapter 7: Evaluation

This section describes the process and outcome of the evaluation of the prototypes developed in the realisation stage of the project. It will describe the specific goals of the evaluation stage in the context of the project, describe the design of the study, and conclude by presenting the findings of the study. In the final section, an evaluation will be given to the technical aspects of the developed design.

7.1. Study Objectives

The outcome of the prototyping stage was the development of three distinct designs for the system, differing by the placement location of the collection node on the user's body (Head-mounted, Back-mounted, Waist-mounted). The primary goal of the evaluation study was therefore to find the most suitable placement of the three options, as well as gain insight into their benefits and downfalls. Moreover, the goal was to evaluate how well the prototypes answer the main Research Question. These formed three distinct evaluation questions (further EQs):

EQ1: What are the benefits and downfalls of each of the developed designs?

EQ2: Which of the three designs is most preferable?

EQ3: Does the project satisfy the set user requirements?

The first two EQs focus on informing and improving the design, hence making them part of a 'formative evaluation' [8]. Generally, formative evaluation is conducted earlier in the design process in order to be able to identify key aspects of the design which have the potential for improvement before the final evaluation. However, due to external factors, this was not possible in the scope of the project. Instead, the formative evaluation will be used to inform the project discussion, especially in regards to future research (as presented in Section 8.2: Future Work).

7.2. Study Design

To answer the set EQs, the study was conducted among attendees of the University of Twente (going forward: participant/participants). The study consisted of two distinct parts, each recording data in a different format, and for a different purpose. Due to the open-ended nature of EQ1, it was answered through the format of a semi-structured interview and written feedback. EQ2 was tackled in form of a ranked-choice scale across multiple questions. Finally, EQ3 utilized a set of Likert scale questions to evaluate the prototypes according to the set user requirements.

Following the guideline proposed by the Nielsen & Norman Group [46], stating that after 4-5 participants, the value of a usability test increasingly falls to a level where each additional participant provides a fraction of input not worth the invested resources, the study consisted of 5 participants.

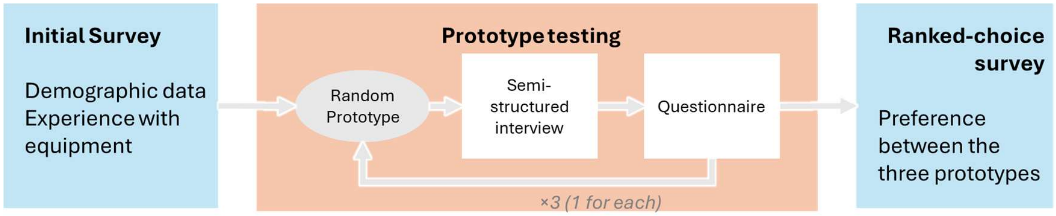

Figure 23: Study design flowchart

Study Introduction

After the initial briefing about the goals and structure of the user test, and the signing of a consent form, the participant was asked to fill in the anonymous demographic information survey. The goal of the acquired information is to ensure that any design features that could accidentally discriminate against members of any age group, gender identity, or sex. Additionally, a question is asked about the participant's past experience with using construction protection gear. This question is intended to highlight responses with higher experience level, as those are expected to match the final users to higher degree.

After the demographic data is filled in, the participant is asked to inform the researcher about their progress before continuing to the prototype testing stage. This is done to prevent confusion about the coming stage, which involves trying the physical prototype on. The full list of questions and their respective answer options, and instructions to the participant can be found in Appendix B: User Evaluation Form.

Prototype testing stage

At the start of the prototype testing stage, the participant is instructed to put on one of the three prototypes (Head-mounted 'Helmet', Back-mounted 'Vest', Waist-mounted 'Belt'). After the testing of one prototype and answering the related questions, the participant would move onto the next one, until all three have been tried. The order in which the prototypes were tested was randomised to eliminate potential biases, hence making the study a randomised 'true' experiment [47]. The randomisation was conducted utilizing an online randomizer Random.org [48].

After completing the final questionnaire, the participant submits their answer, and is thanked for their contribution with a gift.

Semi-structured interview

While the participant is trying on the prototype, the researcher will be asking them questions in a semi-structured interview format. The questions focus on user experience while wearing the design, and were designed to be open-ended to incentivise the participants to give full answers. This gives the participants an opportunity to express their opinion in a setting less constrained than a survey. The researcher will use this time to test how the user opinion changes as changes are made to the system, such as removing the power supply (which, due to the unwanted adjustment, now adds to a sizable portion of the system's weight).

All data during the interview is recorded in shape of written digital notes.

User satisfaction survey

After trying out a prototype, the user is asked to fill in the survey to rate the wearability and comfortability of the system. All of the prototypes were rated on the same set of questions to allow for direct comparison.

The questionnaire was inspired by the System Usability Scale questionnaire [31], and the WEAR scale [7], but modified to suit the needs of the specific system and context. The questions were split in two sections: questions 1 through 6 relate to the wearability of the system, while 7 through 10 relate to comfort. Each question is a statement to which the participant responds based on how much they agree with it on a scale: Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree.

Q	STATEMENT
1	The design is **lightweight**.
2	The design is **small in size**.
3	The design does not hinder my **ability to perform** *(construction)* **work**.
4	The design is **adjustable** to fit my body.
5	The design does **not** severly impact my appearance.
6	The design feels **safe to use**.
7	I would **not** feel **strained** in any way after wearing the design for a prolongued period of time (8h).
8	The system is **unobtrusive**.
9	The design is fitting to my **cultural need**. (i.e. I feel comfortable in using the system without facing cultural reprecautions)
10	In general, I would say the design is **comfortable** to wear.

Table 5: List of questionnaire questions

Ranked-choice survey

After testing all the prototypes, the participant concludes by answering three ranked-choice questions, ordering the prototypes on preference based on comfort, perceived safety, and unobtrusiveness. The goal of these questions is to validate the data gathered throughout the prototype testing stage by allowing the participants to state a preference after they have knowledge of all three prototypes.

7.3. Study results

The outcome of the study will be presented in the following subsections. The outcome of each aspect of the study (interview, questionnaire, ranked-choice survey) will be presented separately, with the final subsection providing an overall conclusion.

Interview results

The data collected as notes consisted of comments participants made on any design, as well as observations made by the researcher. The notes were analysed using coding techniques, and can in such form be found in Appendix C: Evaluation Interview Results.

The interview findings show a clear preference for the back-mounted (vest) prototype. The participants expressed their liking of how little they could feel the prototype being worn, stating that they could see themselves forgetting that they were wearing it with time. Furthermore, while moving about, the participants did not experience any restrictions in motion, even when purposefully trying to find them.

The head-mounted (helmet) prototype suffered the highest criticisms, mostly concerning the disbalance it creates in the weight distribution of the head. Multiple participants have felt the need to hold the helmet in place with their hand as they moved about, and highlighted experiencing a feeling of a ‘light headache’.

The waist-mounted (belt) prototype received mixed reviews. While it was overall deemed quite comfortable, interestingly, most participants instinctively placed the prototype on their side, and not the back, as intended. When prompted about why, they expressed that the placing the sensor on the back in the waist area felt unsafe. However, when placed on the side, some expressed feeling like it impeded the range of motion of the hand, making it more obtrusive than the vest.

Questionnaire results

To analyse the results of the questionnaire, the collected data was transformed into a format that allowed for empirical analysis. The answers, which were textual, were turned into values from 1 to 5 (from 1 - Strongly Disagree to 5 - Strongly Agree). This allowed for averaging of the data for every question. The average score of each prototype per every question can be found in Appendix D: Evaluation Questionnaire Results.

Overall, the helmet prototype highly underperforms compared to the other two, having the lowest average score in every question. The belt and vest scores consistently score similarly, mostly without a significant difference, apart from questions 6 and 10 (*"The design feels safe to use"*; *"In general, I would say the design is comfortable to wear"*), where the vest performed better.

Ranked-choice survey results

When asked to rank the prototypes according to how comfortable, unobtrusive, and safe they felt, once again a clear consensus was formed about the helmet prototype, it almost consistently being placed in third place. Most common first choice was the vest, apart from comfort, where the belt showed a slight advantage.

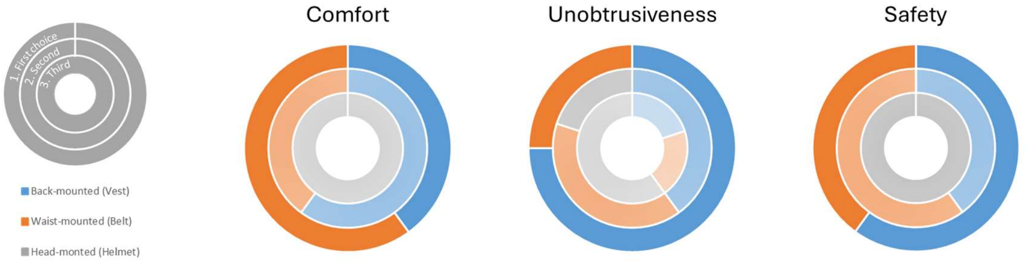

Figure 24: Ranked-choice survey results

Summary & Conclusion

In summary, the study showed an overall preference for the back-mounted (vest) prototype, due to high degree of perceived safety, and the design not obstructing the users range of motion or ability to work. While the waist-mounted (belt) prototype performed similarly, concerns in obtrusiveness were apparent, especially during the interview stage. Finally, the head-mounted (helmet) prototype had the worst results overall, in each category and phase of evaluation.

7.4. Technical Evaluation

On the technical side of the project, various aspects of the design feature mixed results. The air pollution sensing showcases a high degree of reliability, providing quite consistent measurements that match expected reality. However, the accuracy can not be confirmed, as it could not be tested in a controlled setting, or compared to a known value. The only drawback recognised for the air pollution sensor is found in the initial period after the sensor is turned on, when it can take up to a minute for it to start reading consistent and realistic data.

Contrary to the air pollution sensor, the geolocation capabilities were severely lacking. While the accuracy of the sensor was satisfactory, the reliability is too low for application in a construction site setting. During testing, while the sensor was placed statically, the measurements read by the sensor reached up to 150m in difference, which does not provide the necessary granularity. Furthermore, the data collected by the sensor featured a high degree of noise, making is unusable in a live setting.

Figure 25 showcases the data collected in 3 minutes of running the system. In the map, the dots represent the only valid location datapoints, while the lines between them represent data that was manually extrapolated in between the measured data points. The heatmap was made using the measured air pollution data and the extrapolated location data.

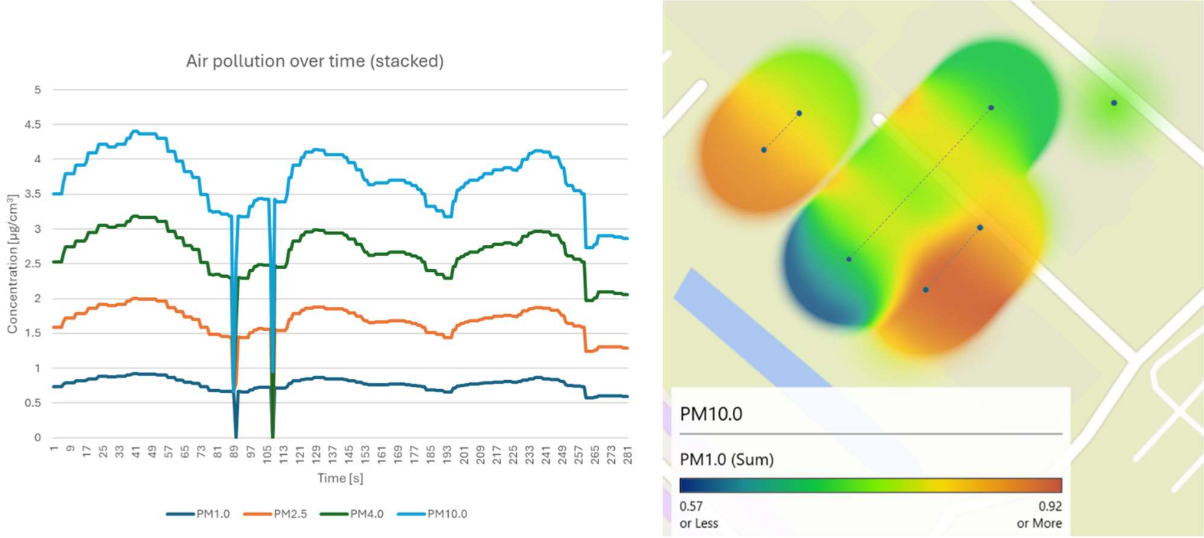

Figure 25: The data dashboard with extrapolated location data

COMPONENT	EVALUATION
AIR POLLUTION SENSING	+ Measures the necessary PM particles and distinguishes their size - Takes some time to start giving proper measurements
GEOLOCATION SENSING	- Unsatisfactory Precision + Satisfactory Accuracy - Unsatisfactory Reliability
WIFI® COMMUNICATION	+ Very Satisfatory Reliability - Low Range (not necessary in scope of the projet)

Table 6: Technical Evaluation outcome

Chapter 8: Discussion and Future Work

This chapter will discuss the conducted research, evaluating how well it answers the set research questions, and how well the outcome prototype meets the functional and non-functional requirements.

8.1. Review of Research Goals

The goal of this research was to produce a functional prototype of a wearable sensor network for accurate spatial and temporal distribution of potentially hazardous air pollutants in the construction site environment for worker and neighbourhood safety. Hence, the aim was summarised as an attempt to answer the following research question:

RQ: How can a wearable sensor network be designed for accurate real-time spatial and temporal monitoring of key air pollutants in construction sites, ensuring reliability and usability, to address worker and neighbourhood health?

To answer the question, the research employed design thinking as a methodology for developing a prototype on the Arduino® platform. Through the iterative process, a wearable system was created that features air pollutant measuring, geolocation, and real-time wireless communication, as well as a digital dashboard for displaying the collected data. Three wearable prototypes were developed and evaluated in a user satisfaction study. The successfulness each of these aspects of the project are discussed further in this section.

Review of technical elements

The technical elements were found to be successful in fulfilling their respective requirements in the overall system. Despite this, some aspects would not be deemed satisfactory if the same system was further developed to a product ready level.

The air pollution measuring shows a high degree of precision, as the readings show consistency and a lack of noise, while still noticeably changing as the sensor enters different environments. However, whether the specific value readings of the sensor are correct is left uncertain, as there was no baseline the sensor could be compared to or calibrated by. Future work could focus on testing the sensor by placing it in an environment of known PM concentration for purposes of calibration. Furthermore, in such a scenario, one could also examine how sensor placement on the wearer’s body impacts the accuracy and precision of the measurements.

The reliability of the geolocation module was deemed too low for use in a practical setting. In a system ready for real-life implementation, it is unlikely that geolocation alone could be used to reliably track position of the measurement. Instead, the system could rely on other, small-scale specific, localisation techniques such as Wi-Fi® based localization or Bluetooth® Beacons which are based on using multiple locally set up static points, such as a router or a Bluetooth device, and calculating the location of the wearable relative to those. Low performance of geolocation was expected, but the other techniques fell out of scope for the project.

Using WiFi® communication to send data between the collection and gateway node has been deemed a success, with no noticeable loss of data or introduction of noise. Additionally, the ESP32 microcontroller board has the potential to be scaled up with antenna improvements to increase the communication range.

In summary, while all technical aspects show relative success in the scope of the project, large improvements can be made in the localisation module. Furthermore, air pollution measuring should be evaluated in a laboratory setting in pursuit of accuracy.

Review of methodology & realisation techniques

As aforementioned in the previous subsection, not all methodologies could be utilized to their full potential due to limitations of the study. Design Thinking, for example, which focuses on letting the design process be guided by the needs of the end user, was impeded by the lack of availability of the end users, namely, construction workers. With that caveat, other facets of the method were proven useful in providing a guide for the project to follow, such as the iterative prototyping loop, user evaluations, and the general project structure and flow.

Techniques utilised in the realisation stage have shown a high degree of success. 3d printing, for instance, was a key component of the iterative prototyping cycle, allowing for a wide range of designs to be made, each informed by the previous ones. 3d printing with embedded textiles specifically shows high potential as a technique to be utilised in the design of wearable devices. While it comes secondary to this project's goal, and therefore could not be explored in depth, the success of the technique points to an area of prospective research that should be explored.

Review of the evaluation procedure

The evaluation of the three produced prototypes found a high degree of consensus among the participants. A preference was seen in the sensor mounted on the protective vest of on the user's back. The other two prototypes were found to have drawbacks, such as the head-mounted piece giving some participants a feeling of a light headache, and the waist-mounted piece raising concerns about obstructing work. However, due to them being occupied by other aspects of the larger project, it was impossible to engage the real end users (construction workers) in the evaluation stage. The study hence faced critical limitations due to these situational elements.

Firstly, among the participants there was an overall low degree of experience with wearing construction equipment. While this should not prevent them from experiencing comfort (and lack there of) when trying out the prototypes, it does hinder their ability to critically examine the impact of a design on the work environment. This problem is further exacerbated by low demographic diversity of the participants. Going forward, the research should ensure participation by members of the specific end user demographic (the construction worker).

On the other hand, the study design itself was proven to be quite successful, providing highly valuable feedback. The hybrid format combining semi-structured ad-hoc interviews and pre-planned structured surveys provided a close to optimal ratio between exploratory research collecting creative input from participants with and empirical research collecting easily comparable data. This was highlighted by some of the participants themselves, who un-prompted stated that they found the study enjoyable and felt like it allowed them to be more critical and provide more valuable information.

Summary

In summary, the project’s overall goal of developing a wearable sensor network for measuring air pollution at construction sites was completed through the construction of a functioning high-fi prototype. The design thinking process, through iterative prototyping, has proven to be a valuable tool in the development process. Especially worth noting are 3d printing, and 3d printing with embedded textile as realisation methods for wearables. While the developed prototype does contain all the relevant aspects of the system, due to complications arising during the development process, trade-offs needed to be made, affecting its wearability. Geo-positioning using satellite data has proven to be a non-optimal method due to high unreliability.

8.2. Future Work

The user evaluation study has shown that improvements should be made in wearability of the system, especially when it comes to the weight of the sensor. However, further development of the project would require addressing the limitations of the study. Gathering higher quality data in form of expert interviews, and testing the system with participants that more closely represent the final users, is key to informing the ongoing process and ensuring that developments are made in a fashion that ensures that the system is implementable and will be adopted by the users. Additionally, this research could include not only the construction workers themselves, but also other relevant stakeholders such as site managers and health & safety department workers.

Furthermore, by including such stakeholders as managers and health & safety department workers, developments could be made on the front-end display side of the project, developing an insightful dashboard that showcases the temporal and spatial distribution of pollutants, as well as individual worker's exposure levels. Such a development is necessary to ensure that the data collected can be used to pursue worker and neighbourhood safety.

On the technical side of the project, in most need of further work and research is the localisation aspect of the wearable device. Satellite positioning has shown to be too limited in so far due to low reliability and interference with the built environment. Techniques such as WiFi® or Bluetooth® beaconing could provide fruitful areas for future research in addressing the issue.

The background research of this project showed that PM-based pollution is the pollutant requiring most urgent action, however, other types of harmful pollutants remain, such as sulfidic pollutants and carbon dioxide. Future implementations of the system should strive to include the variety of pollutants measured to bring forth more comprehensive insights into the issue.

Chapter 9: Conclusion

This chapter will concisely recap the findings of the report and provide the societal implications that future work could have.

Construction activities contribute up to 80% of Particulate Matter pollution in urban areas. Being correlated with a range of health complications as wide as ranging from asthma to heart strokes and aneurisms, and with the number of victims as large as 7 million yearly, it is of utmost importance to address this problem. Conversely, in an environment as complex as a construction site, it can be difficult to draw direct correlations between activities and pollutants, hence making it difficult to discern what actions are worth pursuing in the interest of minimising harmful pollution.

Through the use of specialised sensors and wireless communication, and following the Design Thinking methodology, this project presents a solution in shape of a wearable device tasked with recording temporal and spatial distribution of PM-based pollution in the context of construction sites. While the created prototypes show positive results and potential for further development, more research is needed into better localisation methods and meaningful front-end interaction.

Environmental pollution, according to ecologist Barry Commoner, is a problem without a remedy. It needs to be tackled preventatively, stopping pollution from arising in the first place [49]. The implementation of a system such as the one presented in this report has the potential to lift the veil of complexity that prevents meaningful action, contributing to the end of construction caused air pollution, lessening it's impacts on health and wellbeing.

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Appendix A: Research Matrix

REF	TAGS	STAGE	SHORT SUMMARY	SOURCE	SEARCH QUERY	RELEVANCE
[9]	Air Quality, Machine-caused	BR: 1 - Problem research	"The results of calculations of maximum allowable emissions make it possible to assess the level of impact on the atmospheric air. If the emission values are exceeded, monitoring of compliance with environmental pollution is introduced in order to take corrective measures to improve the environmental situation"	Scopus	air AND pollution AND construction	Medium
[20]	Air Quality, IoT, ML / AI	BR: 1 - Problem research	Uses agent-based models (ABM) to simulate multi-threaded and multi-objective construction activities through collecting detailed project data of two case studies (one using the modular integrated construction (MiC) method and the other one using the cast-in-situ method) in Hong Kong.	Scopus	air AND pollution AND construction	Medium
[3]	Air Quality, Worker's health	BR: 1 - Problem research	"When compared with the average Kolkata city residents, the health burden of the exposed construction workers is found to be alarmingly higher"	Scopus	air AND pollution AND construction	High
[12]	Air Quality, Machine-caused	BR: 1 - Problem research	Air pollution ("34% of the total PM10 and 7% of the total NOX – the largest and 5th largest sources, respectively") in London coming from construction machines. The study compares different types of engines' contribution	Scopus	Reference	Medium

REF	TAGS	STAGE	SHORT SUMMARY	SOURCE	SEARCH QUERY	RELEVANCE
[5]	Air Quality, GIS, IoT, Water Quality	BR: 1 - Problem research	Focuses on environmental impact analysis of air and water quality for selected construction and demolition waste dump yards for Chennai metropolitan city in India for two recycling units with 15 legal dumping yards. The Internet of Things (IoT) and Geographic Information System (GIS) is used to monitor and analyze environmental effect due to C&D waste dump yard.	Scopus	Reference	High
[13]	Air Quality	BR: 1 - Problem research	Largely irrelevant, but provided a great starting point for finding other papers.	Scopus	air AND pollution AND construction	Low
[19]	Air Quality, IoT	BR: 1 - Problem research	This paper provides an important breakthrough towards the wider and more comprehensive use of source apportionment via low-cost techniques. Low-cost sensor measurements, along with the statistical methods of Positive Matrix Factorization (PMF) and k-means clustering, were able to successfully pinpoint and quantify the main sources of pollution in three regulatory important sites (a construction site, a quarry and a roadside).	Scopus	Reference	
[14]	Air Quality, Local impact	BR: 1 - Problem research	Paper examines most common nuisances of construction sites, as reported by residents. Dirt in the air is one of the highest categories.	Scopus	Ecosia	Medium
[11]	Global Emissions, IoT, ML / AI	BR: 2 - State of the art research			Provided by supervisor	High

REF	TAGS	STAGE	SHORT SUMMARY	SOURCE	SEARCH QUERY	RELEVANCE
[18]	IoT	BR: 2 - State of the art research	Compiles research in Air pollution monitoring	Scopus	Provided by supervisor	High
[16]	Air Quality, Local impact, Worker's health	BR: 1 - Problem research	70-80% of the overall PM comes from construction	Scopus	construction AND (health OR air pollution)	High

Appendix B: User Evaluation Form

This appendix contains the list of questions in the User Evaluation Form. User input options are marked by an empty circle, and elaborated by the smaller font text in italics. As shown in the box below.

Different styles meaning:

Section title

- ○ User choice option

(explanation of user choice)

Wearable Sensor Network for Air Pollution Monitoring on Construction Sites - User Evaluation

Study background:
The goal of this study is to evaluate the outcome of a project, the goal of which is to design and develop of a network of wearable sensors for on-site construction workers to track temporal and spatial distribution of air pollutants on a construction site.

Project motivation:
Exposure to air pollution has been linked to a wide range of cardiovascular and respiratory complications, globally making it one of the leading health hazards, contributing up to 7 million premature deaths yearly. Sources of air pollution vary by region and context, and include energy generation, vehicles, power generation, and construction. In all of these, urgent action is necessary to minimise the amount of pollutants entering the air, causing harm to the local population.

Data:
The data will be collected anonymously, there will be no links between the identity of the participant and the collected data. All collected data will be deleted by the end of the research project.

Contact information:
If you have any questions regarding the research, the wider research project, or your participation, please contact the researcher:

- Fran Karlović [HIDDEN]@student.utwente.nl

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee Information & Computer Science:

- ethicscommittee-CIS@utwente.nl

Demographic information	
1.	What age group do you belong to? *(The purpose of this question is to ensure that the design is not discriminatory against members of any age group)* ○ 18-24 ○ 25-34 ○ 35-44 ○ 45-54 ○ 55+ *(choose 1, not required)*
2.	Please specify your sex. *(The purpose of this question is to ensure that the design is not discriminatory against members of any sex)* ○ Woman ○ Man ○ Intersex ○ Prefer not to say *(choose 1, not required)*
3.	How much experience do you have with wearing construction work protective equipment *(such as construction helmets, vests, boots...)?* ○ 1 - I have never used it ○ 2 - I have used it once before ○ 3 - I use it rarely ○ 4 - I use it occasionally ○ 5 - I use it regularly *(choose 1, not required)*
	STOP HERE For the following questions, you will be asked to put on a prototype of the system. After a couple of moments of wearing it, continue with the questions below. The questions will all be about the comfort, wearability, and look of the prototype. This procedure will be repeated three times, one for every prototype version, which differ in placement (Head, Back, and Waist) While you are trying on the prototype, the researcher might ask some verbal questions and take notes in shape of a semi-structured interview. As always, you are welcome to not answer

<table>
<tr><td></td><td>any question, ask for something not to be written down, decide to skip any section, or leave the interview.

Feel free to ask any questions to the researcher before proceeding.

Inform the researcher that you have reached this step.

Confirm before going forward.
○ I confirm I have read the text above and asked the researcher for any clarifications.
<i>(checkmark, required)</i></td></tr>
<tr><td colspan="2">Prototype test 1</td></tr>
<tr><td>5.</td><td>Select the current prototype placement.
Select your answer
○ Head-mounted (Helmet)
○ Waist-mounted (Belt)
○ Back-mounted (Vest)
<i>(select 1, dropdown, required)</i></td></tr>
<tr><td>6.</td><td>Select how much you agree with the statement about the wearability of the system.

<table>
<tr><th></th><th>Strongly Disagree</th><th>Somewhat Disagree</th><th>Neutral</th><th>Somewhat Agree</th><th>Strongly Agree</th></tr>
<tr><td>The design is lightweight.</td><td>○</td><td>○</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>The design is small in size.</td><td>○</td><td>○</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>The design does not hinder my ability to perform <i>(construction)</i> work.</td><td>○</td><td>○</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>The design is adjustable to fit my body.</td><td>○</td><td>○</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>The design is does not severly impact my appearance</td><td>○</td><td>○</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>The design feels safe to use.</td><td>○</td><td>○</td><td>○</td><td>○</td><td>○</td></tr>
</table>
<i>(choose 1 in each row, not required)</i></td></tr>
<tr><td>7.</td><td>Select how much you agree with the statement about the comfortability of the system.</td></tr>
</table>

<table>
<tr><td></td><td>

<table>
<tr><th></th><th>Strongly Disagree</th><th>Somewhat Disagree</th><th>Neutral</th><th>Somewhat Agree</th><th>Strongly Agree</th></tr>
<tr><td>I would not feel strained in any way after wearing the design for a prolongued period of time (8h).</td><td>○</td><td>○</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>The system is unobtrusive.</td><td>○</td><td>○</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>The design is fitting to my cultural need. (i.e. I feel comfortable in using the system without facing cultural reprecautions)</td><td>○</td><td>○</td><td>○</td><td>○</td><td>○</td></tr>
<tr><td>In general, I would say the design is comfortable to wear.</td><td>○</td><td>○</td><td>○</td><td>○</td><td>○</td></tr>
</table>
<i>(choose 1 in each row, not required)</i>
</td></tr>
<tr><td>8.</td><td>Do you have any additional remarks, proposals, or feedback about this prototype you would like to give? Feel free to provide it here.
<i>(text input, not required)</i></td></tr>
<tr><td>9.
-
16.</td><td><i>Prototype test 2 & Prototype test 3 sections (questions 9. – 12. & 13. – 16.) follow the same procedure as Prototype 1 (questions 5. – 8.). They have been ommitted from the report to preserve page space and avoid redundancy.</i></td></tr>
<tr><td>17.</td><td>Please rank the prototypes based on how comfortable they are to wear.
○ Head-mounted (Helmet)
○ Waist-mounted (Belt)
○ Back-mounted (Vest)
<i>(rank choices, not required)</i></td></tr>
<tr><td>18.</td><td>Please rank the prototypes based on how safe they feel to use.
○ Head-mounted (Helmet)
○ Waist-mounted (Belt)
○ Back-mounted (Vest)
<i>(rank choices, not required)</i></td></tr>
<tr><td>19.</td><td>Please rank the prototypes based on how unobtrusive they are.
○ Head-mounted (Helmet)
○ Waist-mounted (Belt)
○ Back-mounted (Vest)
<i>(rank choices, not required)</i></td></tr>
</table>

20.	Do you have any additional remarks, proposals, or feedback you would like to give? Feel free to provide it here. *(text input, not required)*
	Thank you for participating in the study! Your feedback and contributions are highly appreciated :) Please Submit your answers below before leaving. *(final submit button)*

Appendix C: Evaluation Interview Results

Coding highlights meaning:

Comment on weight & size

Comment on safety

Comment on obstructivity and affecting movement

Workplace related comments

Comments on placement & size

	HEAD-MOUNTED (HELMET)
1	- horrible, my head feels supper heavy - too heavy - very noticable difference to when the sensor is removed - doesn't feel very unsafe - looking up especially difficult - makes the hat tighter then usually to compensate for the added weight - doesn't feel obtrusive, you would forget that it is there - the added battery makes it way too heavy
2	- participant feels the need to hold it in place - feels heavy, especially in the back - doesn't feel stable - wouldn't want to have it for long, especially while working - placing it on top of the helmet would help the balance, but still it is too heavy in movement
3	- it's very heavy - upon removing the prototype, a big difference was noticed - feels unsafe, more chances to hit something going into crammed places - you forget it's there at some point - could get used to it - feels the shifting weight when the head moves - looks silly - the colour is nice
4	- too heavy - drags the helmet and head back - doesn't like it - could not wear it for a work day - smaller could work - not ideal in the culture & context - could impact safety, especially if the helmet is not adjusted correctly - makes the helmet less safe - wants to like it, but it is too big - could work if the design was smaller and less heavy

HEAD-MOUNTED (HELMET)

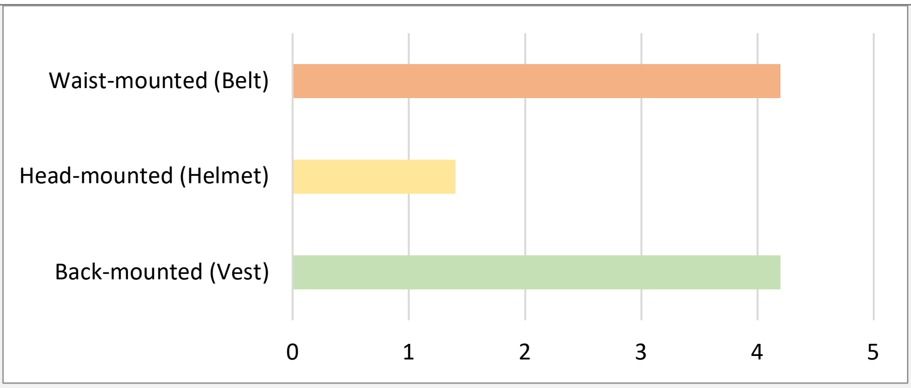
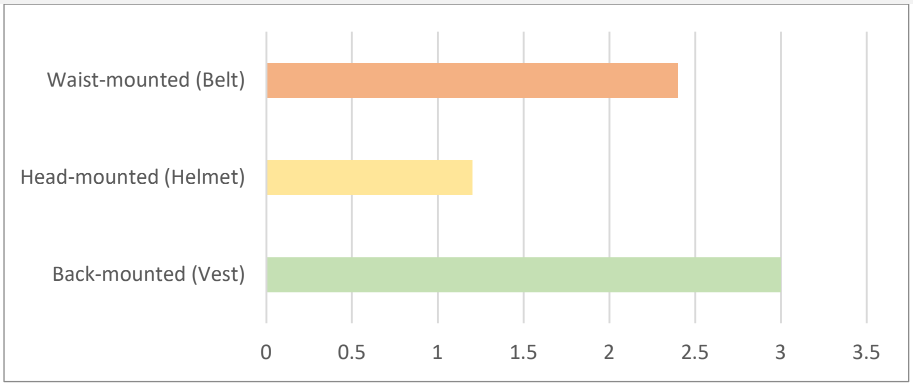
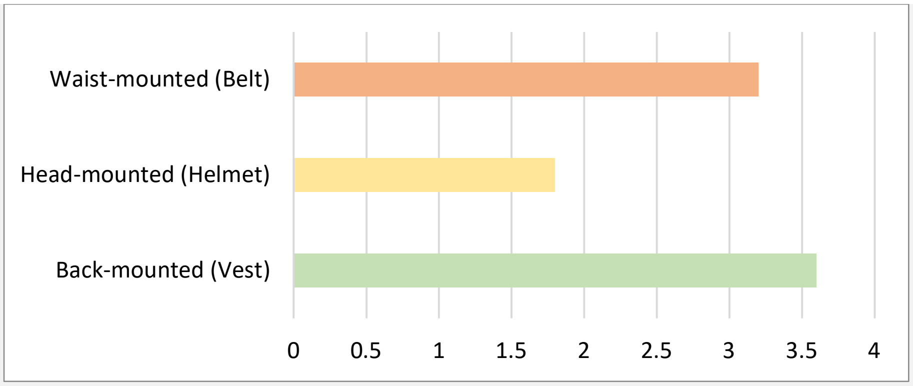
5	- too heavy - feels like a light headache - goes off in a lean forwards, constricting movement - doesn't feel safe - feels weird, wouldn't fit the culture - Go-Pro weight could work, but in general wouldn't go for the head - could fall of most easily

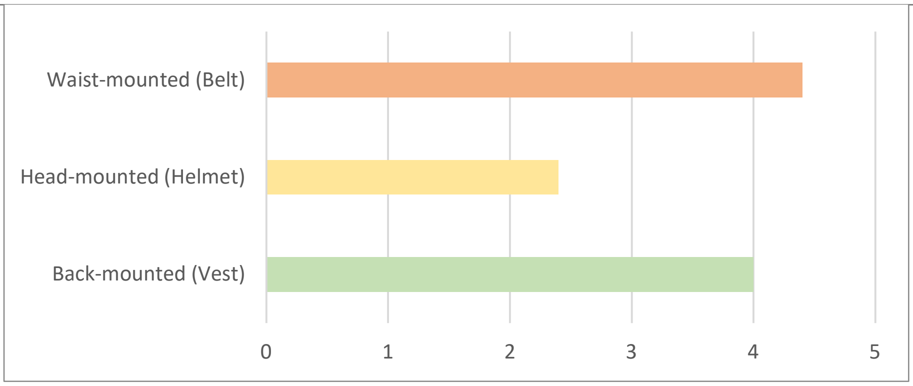
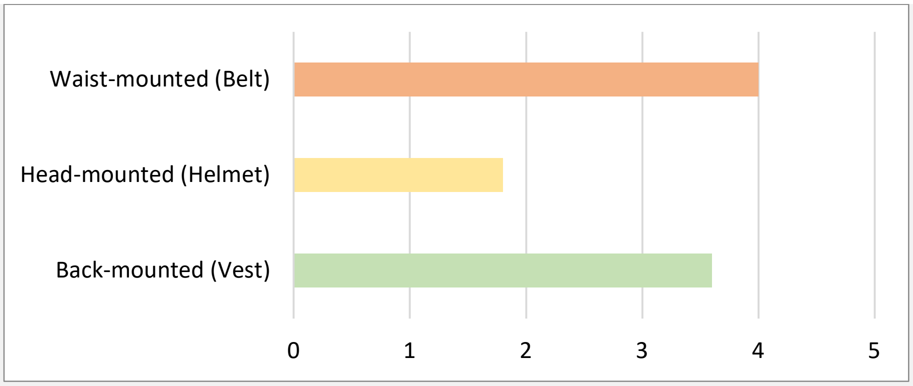
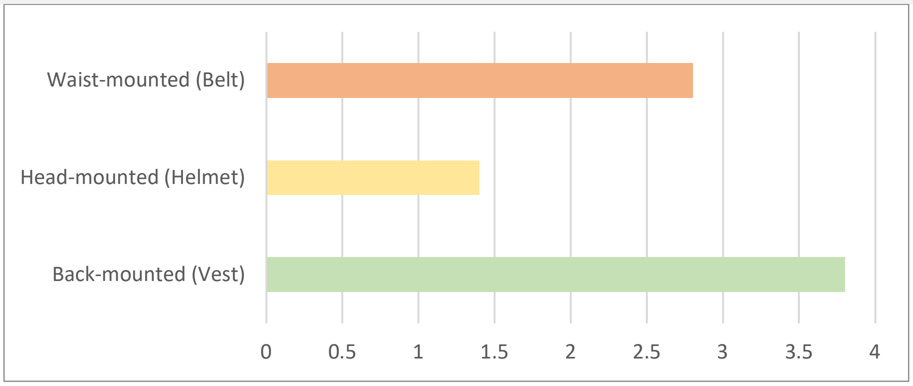
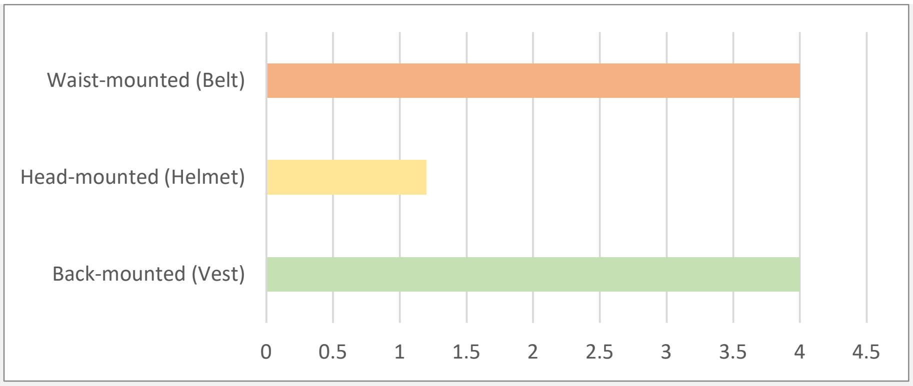
WAIST-MOUNTED (BELT)

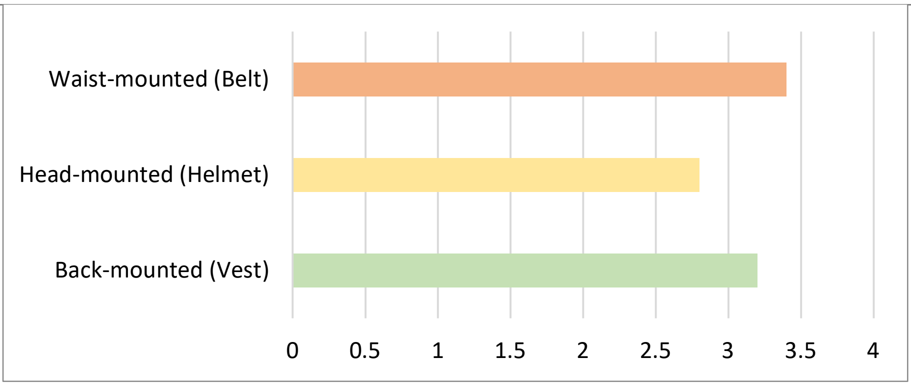
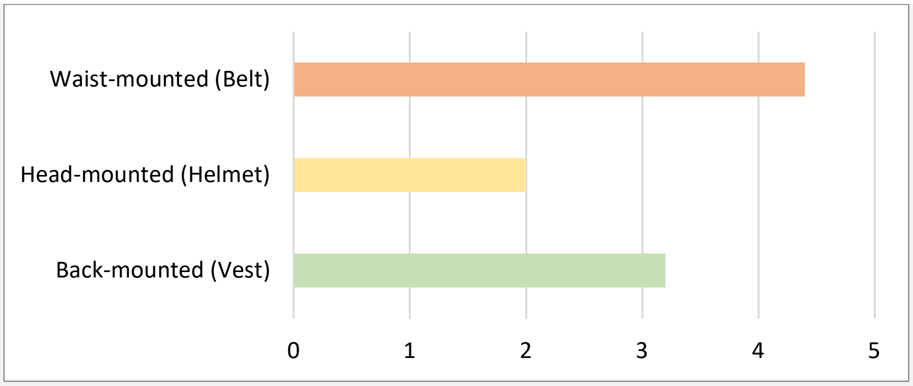
1	-a bit less sturdy - in the way of my hands - if I grab something from behind, it will hit it - doesn't feel secure and is too much in the way - if there was cables around they might trip it - the battery should be on the bottom - it should be on the side, if it is on the back you can't sit correctly - should be longer and smaller (more like a belt) - nice in the middle as it is more even
2	- preferred on the back side, apart from if something is being carried on the back - picking up things is not a problem - feels safe - you don't really feel it - I could forget about it if I wear it for a while
3	- instinct to put it on the side - too much in the way if it is on the side - upon moving to the back - a bit more noticable - sturdy - if a toolbelt is often worn, works well, but might take too much space - less safe than the vest - not very taxing - not visibly obvious, people will dismiss it
4	- more inclined to wear this - fits nicely with existing toolbelts, but might not be enough space - could be more lightweight, but better than the back one - integrates more in the design - safety-wise, it could get snatched on something - not more obtrusive then existing things on the belt
5	- prefers side-back placement - doesn't work on the side, as it gets in the way - back placement constricts back bending movement - doesn't disappear in the background, you need to think about it - it's cool, fits with the toolbox - no culture shock to wear it - wouldn't go with this one - potentially could damage the belt of the user - potentially discriminatory towards people who wouldn't wear belts

	BACK-MOUNTED (VEST)
1	- Seems quite sturdy. Doesn't block any motion. - Could not use it if I had to work on the floor. - It would be better if it was larger in area but flatter overall. - The edition of a battery makes it quite a bit heavier. Doesn't feel great with the battery on. If the battery was closer to the body, would be better.
2	- nice, better than the head one - feel more of the weight compared to the belt one - feels safe to wear - the participant seems relieved - feel something pulling the vest back, but wouldn't mind wearing for 8 hours
3	- not very heavy, surpirsingly light - the participant easily does a range of motions - enjoy the placement, good location on the body - don't really feel it - not annoying - even when using back muscles, you can't feel it - might forget it's there -> which could be a safety problem! - thinks it would work on a construction site - 8/10, blends with the vest
4	- can feel a box - it is not heavy - it is pulling the vest - doesn't feel like it impacts the safety - it could impact the look of the worker - very visible and weird - it would be less weird if it was on the front - smaller size would work on the back (size of a nametag) - behaviour change would be difficult with this size of the sensor
5	- in the beginning, the weight can be felt, but it disappears after a couple of minutes - it can disappear in the background - it doesn't fall down - it's pretty comfortable - doesn't think it impacts safety - doesn't recognise societal problems with the sensor ("people would approve it")

Appendix D: Evaluation Questionnaire Results

Q	**RESULT**
1	
2	
3	

Q	RESULT
4	
5	
6	
7	

Q	RESULT
8	
9	
10