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## Indoor Air Quality Monitoring System for Homes Using Solid Fuels: A Universal Design Approach Integrating Sensor Network with Human Computer Interaction

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# INDOOR AIR QUALITY MONITORING SYSTEM FOR HOMES USING SOLID FUELS: A UNIVERSAL DESIGN APPROACH INTEGRATING SENSOR NETWORK WITH HUMAN COMPUTER INTERACTION

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A Project in The Department of Computer Science, Faculty of Technology, Art and Design Oslo Metropolitan University (OsloMet), In Collaboration with Mozambique-Norway Accessibility Partnership (MAP).

This project involves the Universal Design of a System that integrates Sensor Network with Human Computer Interaction for Detection of Pollutants from Burning Solid Fuel While Monitoring Indoor Air Quality.

The Project Was Carried Out In Partial Fulfilment of a Master of Science Degree Programme in Universal Design of ICT.

## Abstract

The Universal Design (UD) approach to develop technology to combat the effects of Indoor air pollution (IAP), as a result of burning solid fuels or biomass in this project, required a wide range detection of pollutants, Inclusive design and Accessibility. These important aspects and system features are well espoused and implement in the design of the system (prototype named COZiN) in a tantalizing effort to solve a global problem affecting people in homes that use such fuels for sustenance. A substantial literature study examines the many different approaches dealing with indoor air pollution with-respect-to research, development and technology. The project aims to design an indoor air quality monitoring system, a network of sensor nodes that collaboratively check the indoor air quality (IAQ) and notify users by means of a tri-colour coded warning if there is a risk of pollution or a change in the air quality. Of the many system features discussed, the most important are the Auditory, Tactile and Visual feedback notifications. The integration of Human Computer Interaction (HCI), a special feature (concept) specifically designed to prevent child exposure to IAP for increase accessibility, are a few innovative aspects of the system. After sufficiently describing the project while carefully stating the problem, research questions and the aim and objectives of the project make clear the tedium inherent. Quantitative data generated from laboratory experiments and measurements, qualitative data from World Health Organisation (WHO) and data from user analyses, testing and interviews carried out in Mozambique, converge in a mixed research Method seeking solutions. The system prototype was developed and tested by potential users. The results of the field study indicated potential users were interested and there is a need for such a system, while the laboratory testing proved the concept of UD and HCI render the system accessible. Personas are used to show the accessibility and usability of the system among users with a disability. To successfully carry out the project to a reasonable conclusion and timely completion, the research development would follow a plan detailed on Gantt chart that shows the steps from design, development and prototyping to the final documentation.


**Keywords:** Cozin, Biomass, Universal Design, Solid fuel, HCI, Indoor Air Quality, Household-Pollution, Indoor-Pollution, Innovation, Wireless Sensor Networks, Persona, Accessibility, Inclusive Design.

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## List of Abbreviations

| | |
|---|---|
| COHb | Carboxyhaemoglobin |
| DALYs | Disability-Adjusted Life-Years |
| EDA | Electronics Design Automation |
| IAP | Indoor Air Pollution innovation |
| IAQ | Indoor Air Quality |
| ICT | Information and Communications Technology |
| IDE | Integrated Development Environment |
| HAP | Household Air Pollution |
| HCI | Human Computer Interaction |
| LED | Light Emitting Diode |
| LPG | Liquefied Petroleum Gas |
| MAP | Mozambique-Norway Accessibility Partnership |
| MCU | Micro Controller Unit |
| NDHS | Nigeria Demographic and Health Surveys |
| NHAPS | National Human Activity Pattern Survey |
| PCB | Printed Circuit Board |
| PM | Particulate Matter |
| PPM | Particle per Million |
| RF | Radio Frequency |
| TQR | The Qualitative Report |
| UD | Universal Design |
| UDI | Universal Design of Instruction |
| UDL | Universal Design for learning |
| UID | Universal Instructional Design |
| VSD | Value Sensitive Design approach |
| WHO | World Health Organization |
| WSNs | Wireless Sensor Networks |

## 1. Introduction

The ability to sense and detect gaseous emissions from burning solid fuels is essential for homes that rely on such fuels for cooking. There exist many different conventional methods and technology invented for the purpose of detecting hazardous gases emitted from fuels used for indoor heating or cooking. However, a universally designed gas sensor warning system integrating carbon dioxide ($CO_2$) and carbon monoxide ($CO$) sensor network and Human Computer Interaction (HCI) would be a better and more innovative approach to detect gaseous emissions. The idea is to incorporate universal design (UD) and HCI into the design of a network of sensor nodes to check indoor air quality (IAQ) by detecting pollutants in the air and provide a visual, auditory and possibly tactile alert or warning signals to any user or users exposed to indoor or household air pollution[1].

Solid fuels as the name suggests are bio-energy sources that are essentially in solid form or nature; these include, wood, dung, crop waste and all forms of coal, also known as biomass. (Laird, 2008). The concentrations of pollutants differ with the type of solid fuel as can be seen in Figure 1.1, where it is indicated that the burning of dung, crops and wood produces emission of about 10 grams(g)/meal of Particulate matter (PM) and $CO$. Compare to other alternative source of fuel, such as Kerosene and gas. The gaseous emissions from the combustion or burning of solid fuels for cooking purposes are a growing health hazard. This therefore requires a means by which such emissions would be detected, especially in indoor situations where biomass is burnt for cooking.

The burning of solid fuels or Biomass very is rampant and accounts for destruction the earth's ecosystems, deforestation and increase in $CO_2$ in the atmosphere. There are other harmful gases caused by bush fires, burning solid fuel and or biomass, these include $CO$ and oxides of nitrogen ($NO_x$). (Kaiser et al., 2012). Thus, to emphasize constantly the potency and deathly effects of these gases on human health and not just the environment is imperative. *Table 2.2*, titled (Health-damaging pollutants as products of incomplete combustion of solid

[1][Note that the terms Indoor Air Quality (IAQ), Household Air Pollution (HAP) and Indoor Air Pollution (IAP), may be used interchangeably to refer to pollution generated due to indoor activities throughout the text.]

fuels) shows some of the gasses and their possible effects on humans (Pérez-Padilla, Schilmann, & Riojas-Rodriguez, 2010). This, therefore, makes it more important to detect their presence and warn anyone risking exposure, especially in homes and indoor situations where the risks are greater.

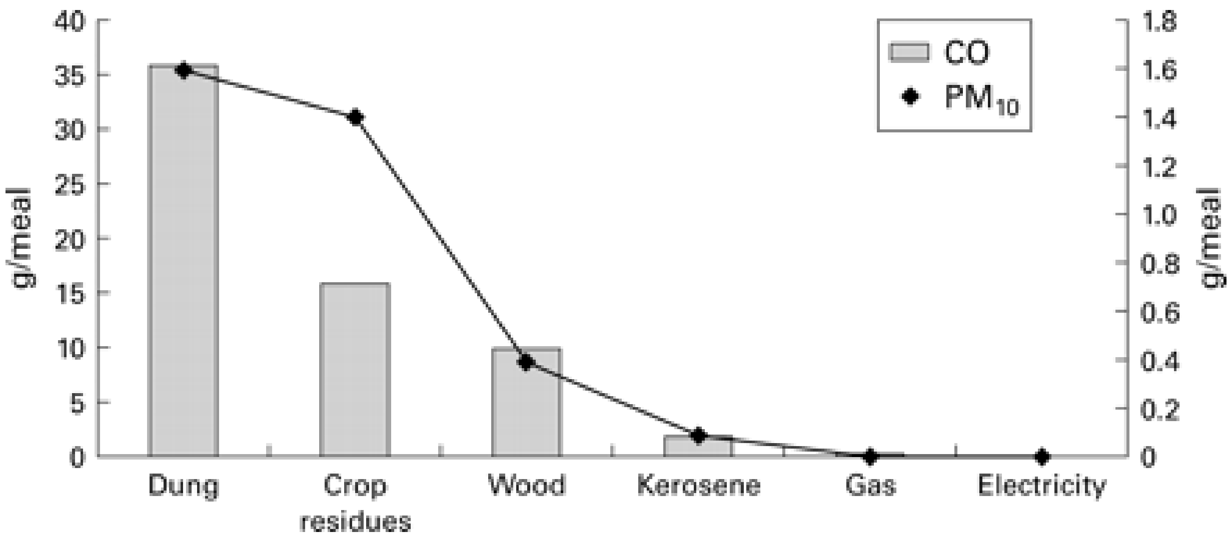



*Figure 1.1: Pollutants by source and level in Most Developing countries* (Smith, Samet, Romieu, & Bruce, 2000)

Note. Copied from: Indoor air pollution in developing countries and acute lower respiratory infections in children) (Smith et al., 2000)

As will be subsequently outlined under the project plan (section 3), the introduction of the topic of the study, the literature study or review, the aims and objectives together with the detailed research questions, constitute the first phase of the project-research thesis. However, in this second phase of the master's thesis, the focus will be on the research methods employed to answer the research questions and meet the objectives. According to Fetters, Curry, and Creswell (2013) "Mixed methods research offers powerful tools for investigating complex processes and systems in health and health care." Since this research is an attempt to solve a global health problem directly related to the use of solid fuels, a mixed research method is also used. (Fetters et al., 2013)

This approach would examine some publications and claims from the World Health Organization (WHO), with the development of an ICT system (called COZIN) universally designed to resolve the problem. The exercised ethics of mixed methods research can be exemplified through design study that in essence would utilize the method illustrated as exploratory sequential, explanatory sequential, and convergent. (Fetters et al., 2013; World Health Organization, 2015) On their web site under the Factsheet: Ambient (outdoor) air quality in the subsection Household Air Pollution and Health and heading: 'Indoor air pollution (IAP) and household energy: the forgotten 3 billion,' WHO Regional Office for Africa (2017) states, "Around 3 billion people still cook and heat their homes using solid fuels (i.e. wood, crop wastes, charcoal, coal and dung) in open fires and leaky stoves ..." (WHO Regional Office for Africa, 2017)

The Quantitative data supporting the WHO claims (since it is already well-established statistical data), it is used here as the bases upon which a statistical hypothesis is developed. Thus, the research hypothesizes that IAP is a global problem and that research and development of a universally designed system is an Accessible preventive measure as proposed. This basically acknowledges the WHO assertions that Indoor air pollution is a global health issue and suggests the development of a system that could potentially solve the problem. In addition, the system must be Accessible and conform to the principles of Universal Design. The researcher will have to determine from the users if the system meets the design objectives and to what extent.

The development and testing of the detection system against indoor air pollution also would generate a lot of quantitative laboratory data from the different measurements and the sensor readings. The key point here is to see if the system presents a possible and viable solution to the established problem and if it also addresses the hypothesis. These quantitative data are then combined with qualitative data obtained from the user testing interviews as a mixed method approach exploiting and exploring quantitative and qualitative data at different stages of the research to achieve convergence on the solution to the problem.

## 1.1 Project Description

This project is about developing an indoor air quality (IAQ ) sensor warning system for homes using solid fuels for cooking, by UD application and Integration of Sensor Network with HCI. Studies are focusing on the kitchens or cooking area because the hazards of burning solid fuels mostly occur in these zones. The system could be described as, a Sense-Detect-Warn system designed for simplicity (UD principle 3, Appendix A, Figure A.2), ease of use, understanding and maintenance, hence the necessity of incorporating the concepts of UD and HCI with emphasis on accessibility and usability. (Imrie, 2012)

The goal of the project is to design an IAQ sensor and warning system for homes where solid fuels are used mostly for heating and cooking also where there is a risk posed by hazardous emission to human health. In accordance with the aims of this project, the gas sensor or detection system must be universally designed, that is, it should be built following the universal design principles and integrate HCI capabilities. UD is defined as, " the design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design." (Steinfeld & Maisel, 2012)

This project also involves carrying out a systematic studying of homes where solid fuels are used, the emission from the use of such fuels, the health effects and how best to prevent the health hazards. It should be noted that the system's design focus is on detection and warning users of the presence of dangerous emissions from the solid fuels. To detect any gaseous pollutant, its characteristics and properties must be known first, then a system can be built to specification. With the required and available technological knowledge, the system would have to accurately detect the pollutants. For example, $CO$ is a colourless and odourless gas, almost the same mass and density as air and could be present indoors and outdoors and would explode when concentrated at 12.5% to 74.5%. If concentrated to about 75%, it will burn in the presence of air and fire, thus could be used as fuel. (J. Yang, Zhou, Lv, Wei, & Song, 2015).

## 1.2 Problem Statement

There are several problems associated with cooking with solid fuels that are mostly health related. Among these health issues, respiratory diseases are responsible for the high worldwide morbidity and mortality, (Akunne, Louis, Sanon, & Sauerborn, 2006). Also, the World Health Organization (WHO) Asserts that the burning of biomass has often been considered a major indoor air pollution contributor throughout the whole world. In many Energy deficient developing countries, biomass is burnt massively in open fires and stoves producing smoke, which causes, pneumonia, bronchitis and other chronic obstructive pulmonary diseases. (Akunne et al., 2006)

The aim of this project is to universally design a system to monitor the air quality in homes where mainly solid fuels are used as a primary energy source. The problems and or difficulties involved in this project can be placed into three main categories that also indicate the approach for possible solutions. The integration of HCI and UD principles (Appendix A, Figure A.1 - Figure A.4 ) necessitates that the users be involved in every step of the design. Therefore, the problems would be addressed by their categories in three project research and development phases that constitute the following:

I. Research: Research is carried out in two phases prior to the design and development of the detection system and afterwards during the user testing of the system. During the first phase, existing statistics from WHO, literature and other documentation about the burning solid fuels and IAQ were studied. The information retrieval or data collection (for example, by means of interviews) from people who use solid fuels for cooking was not easy to come by because it significantly covers gaseous emissions, health issues, user habits, traditions and ethics. The second phase comes after the development of the detection system and will focus mainly on collecting information and data from the users to determine if the system works effectively as designed.

II. Development: Working to develop a system to save human lives by itself constitutes a problem and more so because of the nature of this project. User-data collected during the research phase one (as already discussed in ‘i’) was used to design a sensor network system to detect and alert or warn people risking exposure to the gaseous emissions. At this stage, the gases to be detected and the type and nature of the alert system are determined.

III. Innovation: The innovation would involve how to incorporate aspects of UD and HCI, to ensure accessibility and usability features are effected into a sense-and-alert system. One way to achieve this is through a wireless gas sensor network with an interface optimized for HCI.

Looking through all three categories of problems just outlined, it can be deduced that, the problems are on one hand involving socioeconomic status, health, traditions and ethics and on the other hand, technological innovation, accessibility, usability and inclusiveness. The best solutions to tackle these problems would be addressed subsequently in the following sections as the project report progresses.

## 1.3 Research questions

The research questions have been designed to cover research and development of the system, system functionality, user experience, usability and accessibility. All these system features related to the project have been addressed in three research questions classified in the following categories:

i. Research System Design and Development
ii. System functionality and Efficacy
iii. Usability Accessibility and User Experience

**1.3.1 Research system design and development question.** The first research question falls under research, development and design of the system. The question is designed to tackle the process of data collection from already existing credible and well-espoused sources of data and statistics on the subject. How did the information and or data influence or impact the development of the system? What parameters were chosen, which ones were discarded and why? This question also addresses how the design of the system was made to function with the user-data, information from the stated researches, sources and whether it also functions as required.

**Research Question 1**: Could the system be used to effectively detect gaseous emissions, indoor air pollutants and alert users, considering that all WHO and field user sources of data used in the development of the system are accurate?

**1.3.2 System functionality and efficacy question.** The second question concerns the system's functions and efficacy in comparison with other similar systems currently available to the targeted users. What aspects of the system make it stand apart, what makes it more efficient and useful to the user, and does the user get desirable feedback?

**Research Question 2**: How does the system compare to the current state of the art of similar systems, in terms of detection, accuracy, range and feedback?

**1.3.3 Usability accessibility and user experience question.** The third and last research question involves the accessibility and usability of the system and user experience. Is the system accessible, what aspects of the system makes is usable, and what is the impact on user experience? Are there any specific system design features that make the system achieve usability and accessibility from the user's viewpoint?

**Research Question 3**: What aspects of the system make it Usable and Accessible with-respect-to the impact on user experience?

**1.3.4 Motivation.** Given that morbidity and mortality rates as indicated by data from the WHO (especially for women and children), due to IAP from the burning of solid fuels notably for cooking, heating and for other domestic uses are considerably high, nothing could be more motivating than the prospects of saving lives.

i. The main motivation is having the opportunity to design and build a system that would save human lives; adults, children and infants inclusive.
ii. The second motivation is to see that the design of the system achieves UD aspect of attaining a level of accessibility and usability for a wide range of users irrespective of their socio-economic status and or their disabilities.
iii. The final motivation involves innovation. Pushing the limits of the technology of Indoor pollution detection and the prospect of developing a system that could potentially be a future solution to indoor pollution detection.

The current state-of-the-art in the detection of indoor pollution has some limitations and there is the motivation to see to what extent the design flaws and accessibility gaps can be closed for better usability and user experience.

**1.3.5 Aim and objectives.** Following up from the points discussed in previous sections, Indoor air pollution as a result of burning solid fuel constitutes a serious global health problem. The major objectives that have been put forward as a systematic path to a feasible solution to the outlined problem are in our main objectives delineated as follows:

i. Research and identify the gaseous pollutants to be detected that are known to be hazardous to human health, resulting from the burning solid fuels.
ii. Design a usable and accessible IAQ-sensor system with a wide range of gas detection that includes $CO$ and PMs like Smoke.
iii. Linking of the detection system to a mobile Phone via Bluetooth and dedicated mobile application and provide visual, tactile and auditory feedback to the user.
iv. Building and test a prototype(s), consisting of 3 sensor-nodes (2 wearable, 1 fixed) linked together in a network via Bluetooth.

***1.3.5.1 Objective 1.*** The first objective is to collect and study already existing statistics from the World Health Organisation and other sources of data and literature on the call topic to get a better understanding of the problem. The WHO web site proved to be a very rich source of data on which the entire qualitative study could be based. The information on the gathered impact on health would be very useful for the improvement of the health outcomes for people exposed to emissions from the burning of solid fuels.

***1.3.5.2 Objective 2.*** The main goal of this project deals with the detection of major gaseous pollutants from burning solid fuels, and from Figure 1.1, it can be seen that using solid fuels or biomass for cooking emits a lot of CO gas of about 10g/meal to 35g/meal depending on the type. However, in addition to CO gas, there is also the production of $CO_2$, PM and or smoke, therefore it would be necessary to design system with a wide range of detection capabilities. Accordingly, the second objective deals with the study for the characteristics of the sensors and gaseous pollutants to be detected are incorporated into the system's design. The various thresholds for the IAQ-sensors relative to the gaseous pollutant levels are also determined and set for proper detection.

***1.3.5.3 Objective 3.*** For the purpose of having multiple feedback and HCI capabilities, the IAQ sensors for detection are linked in a sensor network via Bluetooth connections to a mobile phone platform. Therefore objective 3 makes sure that sensor information is displayed visually, and feedback in an auditory manner and used the mobile phone vibration for tactile feedback for increase usability and accessibility.

***1.3.5.4 Objective 4.*** The fourth and final objective is mostly prototyping on the Arduino-ATmega328 platform. Then the later stages of prototyping might involve design and development of Printed Circuit Board (PCB), customized for the system and testing the system. First carrying out tests in the laboratory then later user testing in the field, where the system's capabilities would be challenged. This step must be achieved before the system is ready for the first phase of user testing.

## 2. Literature Study

Over the years ever since human beings started cooking indoors with solid fuels or Biomass, indoor air pollution has been a serious problem. However, in recent years, some efforts have been made through public awareness, scientific research, and technology to address the potential health hazards and other environmental concerns. Much of the research done by the World Health Organization (WHO) clearly indicates the health problems associated with emissions from both outdoor and indoor cooking are acute. On their website, WHO (2016) states the following summarized points in Factsheet number 313, updated September 2016:

I. The health risks associated with pollution cannot be overemphasized and have been determined to be the root cause of many deadly diseases such as stroke, lung cancer, various types of respiratory and heart disease. Countries could significantly reduce or avoid these diseases simply by reducing the levels of pollutants in the air people breathe.

II. "In 2014, 92% of the world population was living in places where the WHO air quality guidelines levels were not met. " (World Health Organization, 2015, 2016)

III. The health of some 3 billion people is also at risk due to indoor pollution from the use of biomass fuels and coal for cooking in some homes, plus the risks from outdoor pollution add to the predicament. (World Health Organization, 2016)

Other estimates attribute 1.6 million premature mortality and less than 38.5 million Disability-Adjusted Life-Years (DALYs ) events to solid fuel emissions, which led to 4% of the global health problems in 2000. (Po, FitzGerald, & Carlsten, 2011)

The effect of breathing polluted air is an old problem to human beings ever since the prehistoric times, the age of discovery and usage of fire for domestic purposes. This was evident in the five hundred thousand years old hominid remains discovered in China. Once fire became indispensable for scaring of beasts, heating and cooking, all the fire associated pollutants followed the humans into their primitive homes. Hence indoor pollution was born from the emission due to the burning of wood, crop remains, and dung and dirt, which is a habit that persists to date in the rural areas many countries throughout the world and in some developing countries. (Pérez-Padilla et al., 2010)

The development of a system of sensor network for detecting or monitoring hazardous gaseous pollutants to improve indoor air quality is not new. There exist many such systems designed for gas detection, however, most of the existing or commercially available systems are rather expensive. Despite the high cost of these indoor air quality monitoring systems, some inexpensive systems notably, a microcontroller-based wireless sensor network system that also employs the use of low-cost transceiver modules such as NRF24L01, XBee or HC-12 combined with gas detection sensors, have occasionally been developed. (Abraham & Li, 2014)

### 2.1 Impact of Using Solid Fuel

The appetite to use and rely on solid fuel by a huge part of the world's population is mostly driven by a deficiency in alternative energy sources. It is estimated that the worldwide household energy sources can be distributed in the following manner: 2.4 billion out of the 3 billion people using solid fuel, use biomass (wood, charcoal, animal dung, crop wastes) while the rest use coal to meet their domestic energy needs. The percentage in countries and regions estimate 77% in sub-Saharan Africa, 74% in South-East Asia, 74% in the Western Pacific Region, 36% in the Eastern Mediterranean Region and 16% in Latin America and the Caribbean and in Central and Eastern Europe. These percentages are however not as high in most of the industrialized world, where the use of such fuel is about 5% or less. (Pérez-Padilla et al., 2010)

## 2.2 Health Effects

According to the World Health Organization (WHO), there are about 2.0 million deaths worldwide due to pollution from the use of solid fuels or biomass for cooking and heating, making indoor gas pollution the leading cause of deaths superseding malaria. Since the way of life in poorer communities necessitates that men tend to be out fending for their families, it is there for the women and children who suffer the most from these pollutants. (Martin, Glass, Balbus, & Collins, 2011)

*Table 2.1: Health-damaging pollutants as products of incomplete combustion of solid fuels* (Pérez-Padilla et al., 2010)

| Smoke phases | Characteristics | Mechanism and associated health effects |
|---|---|---|
| Gaseous | Carbon monoxide ($CO$) | Binds to haemoglobin interfering with transport of oxygen. Headache, nausea, dizziness, Low birth weight, increase in perinatal deaths. Fetotoxicant, have been associated with poor foetal growth |
| | Sulphur dioxide ($SO_2$), mainly from coal | Irritant, affecting the mucosa of eyes, nose, throat, and respiratory tract Increased bronchial reactivity, bronchoconstriction |

Note. Reprinted from: Respiratory Health Effects of Indoor Air Pollution (*Pérez-Padilla et al., 2010*)

The National Human Activity Pattern Survey (NHAPS) indicates that, in the United States, and Canada people spend 87% of their time indoors and 6% in their vehicles on the average. In developing countries, however, the average for women is 70% in Kenya and 75% in Mexico for example. Despite the lesser percentage of time spent indoors for rural compared to urban areas, the high concentrations of pollutants in the rural areas produces a higher exposure to pollutants. (Pérez-Padilla et al., 2010)

Many studies have shown that the effect of burning solid fuel is far more serious on children than adults as Table 2.2 clearly indicates, there is strong evidence that acute infections of the lower respiratory tract, chronic obstructive pulmonary disease present a relative risk of 2.3 among children between the ages 0 to 4 years old. In Nigeria for example, the Nigeria Demographic and Health Surveys (NDHS) shows that 69% of Nigerians by households relying on solid fuels for their cooking did not change much over the years from 2003 to 2013. The statistics also indicate the many children die below the age of 5 years due to the constant exposure to smoke from burning wood. Among the 95,000 Nigerians dying every year from disease and other consequences directly related to the use of solid fuels for cooking, childhood mortality is high and there is a clear indication that these deaths are related to the household use solid fuels. (Ezeh, Agho, Dibley, Hall, & Page, 2014).

*Table 2.2: Health impacts of indoor air pollution on population.* (Rehfuess, 2006)

| **Health outcome** | **Evidence** | **Population** | **Relative risk** | **Relative risk (95% confidence interval)** | **Evidence Status** |
|---|---|---|---|---|---|
| **Acute infections of the lower respiratory tract** | Strong | Children 0-4 years | 2.3 | 1.9-2.7 | Sufficient |
| **Chronic obstructive pulmonary disease** | Strong | Women ≥ 30 years | 3.2 | 2.3-4.8 | Sufficient |
| | Moderate I | Men ≥ 30 years | 1.8 | 1.0-3.2 | Sufficient |
| **Lung cancer (coal)** | Strong | Women ≥ 30 years | 1.9 | 1.1-3.5 | Sufficient |
| | Moderate I | Men ≥ 30 years | 1.5 | 1.0-2.5 | Sufficient |
| **Lung cancer (biomass)** | Moderate II | Women ≥ 30 years | 1.5 | 1.0-2.1 | Insufficient |
| **Asthma** | Moderate II | Children 5-14 years | 1.6 | 1.0-2.5 | Insufficient |
| **Tuberculosis** | Moderate II | Adults ≥ 15 years | 1.5 | 1.0-2.4 | Insufficient |

Note. Table 2.2; Reprinted from "Household energy, indoor air pollution and health," Rehfuess (2006) Fuel For Life: Household Energy and Health p. 10- (Max Roser & Hannah Ritchie, 2014)

As per Table 2.2, the evidence of health outcomes from Indoor Air Pollution (IAP) has a far greater impact on women and children compared to men. The table also provides supporting data to the fact that women and children are the most affected by pollution from cooking with solid fuels. Possibly because women spend more time in the kitchens or cooking areas and are usually carrying or caring for babies at the same time, they are preparing a meal for the family.

When combined with data from exposure, in many cases, health outcomes would indicate a direct link between cooking or heating stoves with indoor pollution health effects. This was evident also from studies carries out amongst women in Mozambique where the indoor pollution from cooking with wood and other solid fuels show very high levels of pollution. Typical exposure to particulate matter while cooking with wood doubled compared to cooking with charcoal, 6 times compared to LPG in addition to the fact that users of wood suffer serious respiratory health symptoms when compared to users of other fuel types. (Gall, Carter, Matt Earnest, & Stephens, 2013)

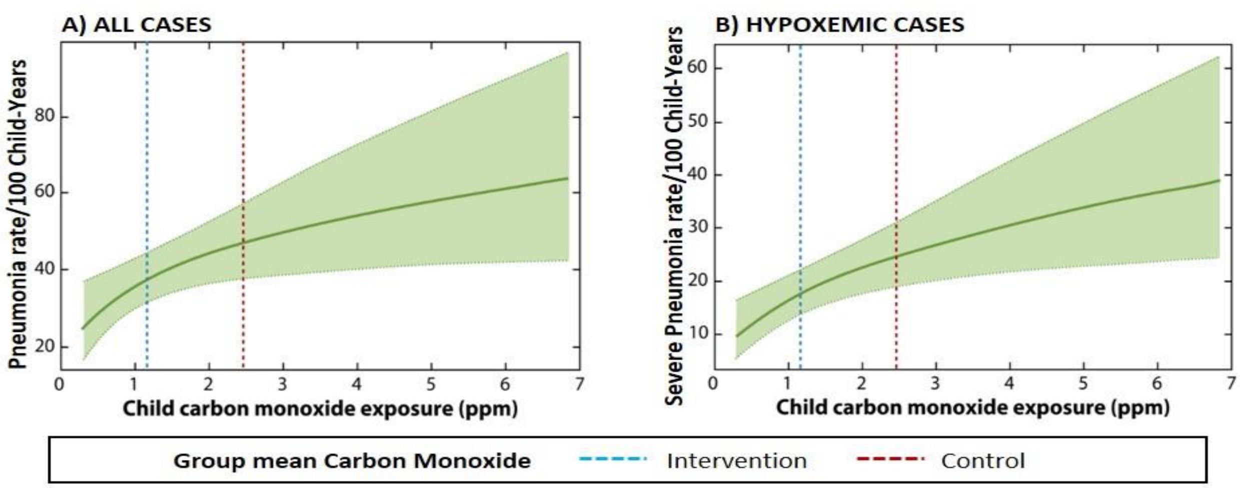



*Figure 2.1: Physician-Diagnosed pneumonia (low oxygen saturation) due to CO exposure*

Note. Adapted from Annual review of public health) (Smith et al., 2014)

## 2.3 Economic and Environmental Impact

The global environmental impact of burning biomass is often stated or addressed (and rightly so,) as a problem that affects poor countries and or the poor but in the United Kingdom (Smith et al.) …" Solid fuel emissions were derived as 24.7 μg m−3 ppm−1 relative to CO for Manchester. " (Allan et al., 2010). India and China (although not always placed in the category of poor countries) hold about a third of the World's population; in 2000, 86% of their combined Black Carbon (BC) emissions were the household use of coal and biomass. (Chafe et al., 2014)

Since poverty reduces energy potential, hence the tendency to rely on biomass fuels and coal. The consequences of reliance on solid fuels often lead to deforestation with a heavy environmental price tag. Cooking stoves have been promoted as a solution, highlighting the climatic, environmental and health benefits as was the case in a 2011 World Bank report. Hopefully, technological advances would improve the efficiency of the stoves thereby leading to a reduction in all form of carbon emissions such as carbon monoxide ($CO$) and carbon dioxide ($CO_2$). (Martin et al., 2011).

## 2.4 Existing Solution to Solid Fuel Emissions

There exist lots of ambitious and bold ideas as to how to reduce indoor air pollution (IAP) from solid fuels, most of which include controlling the source of the pollutants. Some of the solutions to reducing IAP involve regulating and reducing outdoor air pollution. Sources of IAP include outdoor air that contains constituents of industrial and automobile exhaust or emissions, smog and other particulate matter, flows indoor thereby affecting IAP. (Jacobson, 2012)

Studies evident from the application of the WHO guideline for source and exposure control indicate to have had a tremendous impact on the health outcomes related to indoor air pollution. The health risk for children and adults were found to have significantly reduced by 20% to 50%, whereas the Integrated Exposure Response functions (IERs) required that WHO guideline levels should be no higher than 35 milligrams per cubic metre (35 mg/m$^3$ ) PM to keep any health risks minimal. Also, the WHO 24 hour average guideline complaint stoves (compliant for $CO$ levels of 7 mg/m$^3$) within the solid fuel context, greatly reduced pollution but for the unimproved noncompliant cases that retained hundreds of mg/m$^3$ of particulate matter (PM). (Bruce et al., 2015)

**2.4.1 Conventional solutions.** These types of methods deal with simple preventive measures that do not usually involve any advanced technology and most often than not tackle the indoor pollution problem by using rudimentary means. These methods occasionally involve improvisation and employment of solutions from the following perspectives, presented by the United States Environmental Protection (EPA) and the WHO Guidelines for indoor air quality: Household fuel combustion. According to the EPA (2016), the basic techniques for an improved IAQ must involve the following:

- Source control
- Improved Ventilation
- Air cleaners (**EPA, 2016**)

***2.4.1.1 Source control.*** In this project source control is considered to involve any action taken by the user that affects the source of pollution directly or indirectly. These would include how the home is designed, ventilation, use of alternative cooking and heating devices like stoves or cookers use solar energy or electricity. Source control is considered as one of most cost-efficient and effective ways for IAQ improvement that consists of effecting a significant reduction or elimination of pollutants by the simple removal of the source or sources. The source could be isolated, contained or sealed in an appropriate enclosure. For example, sources of pollutants containing particulate matter or pollutants like asbestos. Other solutions might focus on changing the fuel type (say, from wood or coal to gas, solar or electricity) or use a more efficient stove or burner. Alternatively, the kitchen could be separated from the main house to minimize risk to the household or other users.

In a nutshell, controlling the source of indoor pollution is like closing a water tap, the tighter you close, the lesser the water flowing out. (EPA, 2016) According to the WHO Guidelines for indoor air quality: Household fuel combustion, WHO (2018), based on the protection of health in relation to indoor air quality, recommendations have been made for fuels types and technologies for specific pollutants. (WHO, 2018)

***2.4.1.2 WHO guidelines*** These guidelines by themselves are not solutions, they However, provide a comprehensive, ethical and basic standard by which all measures are taken and solutions to curb pollution must follow to ensure a significantly healthy environment. The WHO (2018) has therefore recommended specific guidelines for the most common and the most potent indoor pollutants. The Guidelines for Indoor Air Quality for Selected Pollutants such as CO are as follows:

- Exposure to CO must not push the carboxyhaemoglobin (COHb) (resulting from reaction of CO with the Haemoglobin (Hb) in the blood) levels to values exceeding 2% of the blood haemoglobin for a typical indoor situation, 100 mg/m3 for 15 minutes and 35 mg/m3 for an hour are recommended for exposures occurring no more than once a day. (WHO, 2018)
- When exercising the WHO guidelines recommend mean concentrations of for exercises at 10mg/m3 for 8 hours, provided the levels of exposure occur within a day, and for light exercises only. When people are not exercising but going about daily life, 7 mg/m3 is recommended for 24 hours exposure. (WHO, 2018)

Studies carried out in San Marcos Province, Cajamarca Region, Peru showed, carbon monoxide ($CO$) levels dropped by 28% of usual kitchen concentrations in households with the fully functional OPTIMA-improved stoves compared with the control stoves. Also, the OPTIMA-improved stoves had a 17% lower $CO$ (n = 25) personal exposure. It should be noted that, though not statistically significant, these results indicate the efficiency and functionality of cooking (wood or coal) stoves are significant factors that could improve indoor pollution. (Hartinger et al., 2013)

Although exposure patterns vary due to individual (age, socioeconomic status, time spent in cooking area) and household differences (fuel/stove type, cookhouse ventilation, use of biomass for heating), use of solid fuels in traditional stoves results in air pollution exposure levels that can reach 50 times greater than the World Health Organization (World Health Organization) guidelines for clean air, particularly for women and children who typically spend more time inside the home than men. (Anenberg et al., 2013; World Health Organization, 2015)

**2.4.2 Innovative and Technological Solutions.** The Solutions related to innovation and Technology, are amongst the most efficient solutions in dealing with indoor pollution especially if the focus is to sense-and-detect gaseous pollutants in the household. Detection devices vary from simple smoke detectors to more complex smoke detection systems like the Loepfe, Mueller, Tenchio, and Vollenweider (2011) "Smoke detection by way of two spectrally different scattered light measurements", system which uses the principle of scattering of light or diffraction to detect the presence of smoke and or other PMs. (Loepfe et al., 2011). An alternative system consisting of a wireless network of sensors. Yang's (2014, p2) wireless sensor network (WSNs) deploys a group of autonomous nodes that communicate with the monitored infrastructure wirelessly provide a command and control monitoring of the environmental condition. (K. Yang, 2014).

Another system developed by Kim. Jung and Kim (2010), is a system that integrates sensor network with the ventilation and air conditioning system of the home to monitor and maintain the indoor air quality to acceptable levels. The system simply measures the concentrations of pollutants such as CO, $CO_2$, and sounds the alarm when levels are higher than the healthy levels. (Kim, Jung, & Kim, 2010)

## 2.5 Universal Design Traits

When a system's design is based on UD principles, having a succinct understanding of the UD concept is imperative during the description of the system throughout the whole design process. The UD concept itself is an idea that deals with a social construct based on the philosophy of addressing social infrastructure and technological design by the virtues of inclusion rather than exclusion. The idea of inclusiveness is the recreation of a social structure by design, legislation and implementation, that permits people, irrespective of their cognitive, mental or physical impairments, to have the ability to use and access environments such as homes, parking, playgrounds, parks and workspace and places. Inclusiveness should be in every aspect of life, particularly domestic and public utilities like toilets with taps and door handles, home and workplace electronics, computers, and telephones. (Imrie, 2012). Usage and access to these by all is important, especially if the inability to access some public space or utility could exclude some users. Such exclusion could possibly constitute an infringement on user's or person's civil and or social rights.

UD is defined as " the design of products and environments to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design." (*Steinfeld & Maisel, 2012*). UD is also sometimes referred to as inclusive design or "Design for all". There are however variations in the concept, depending on the context and or domain, which could be cultural, professional, scientific or otherwise. The differences in the school of thoughts and interests have resulted in different names for the idea of 'Design for All'. However whether Universal Access, Inclusive Design or Design for All, the focus still significantly remains on the accessibility and usability of interactive systems by the most extensive range of users possible. (Persson, Åhman, Yngling, & Gulliksen, 2015)

The origins of UD is not very clear, however, a number of ideas by some writers and publications point to the 1960s USA expressive civil rights campaign by the well accomplished and academically competent Vietnam era survivors and veterans, as the catalyst. (Imrie, 2012). As per Steinfeld & Maisel (2012), "The relationship between the social order and spatial order of society is one of the most important topics in Universal design" (p. 9). (Steinfeld & Maisel, 2012) Design for All is an appealing concept offering innovation and the potential to design despite the many challenges involved. This concept has evolved from the social sphere of Scandinavian tradition to include design relating Corporate Social Responsibility (CSR), to business potential. Design for All in the Scandinavian indicates the State-of-the-Art of Denmark, Norway, Sweden and Finland from a common review and joint projects in Scandinavia, selected case studies carried out on a country-by-country review over the past 15 years. (Bendixen & Benktzon, 2015)

Universal design has made significant gains in many different fields and particularly in education, where Universal Design for learning (UDL) has established special attention to the field through the promotion of inclusion by easing access to the curriculum. There are other educational models of UD that is, Universal Design of Instruction (UDI) and Universal Instructional Design (UID). (Rao, Ok, & Bryant, 2014)

## 2.6 Limitations

There are many systems in the market that have been developed for the purpose of household air pollution (HAP) detection and warning, that work well and do the job they were designed for. However, despite the technological advances from the simplest to the most sophisticated detection systems, the following limitations are still quite common:

- Chirping: Some indoor smoke detectors for homes have a tendency of producing a chirping noise when the battery power becomes weak or run out. The chirping noise then becomes a nuisance to the user, who then removes the battery and may neglect or forget to replace it. When this happens, the entire household would be at risk of suffering effects of pollution which might include death.
- Loud Noisy Alarms: Many smoke detectors on the market are equipped with very noisy alarms or sirens that are sometimes a nuisance to users, who would then disconnect the battery from the device thereby risking their health and possible death from pollution.
- Lack of multiple feedback: Most available systems, from simple smoke detectors to the most innovative indoor air pollution detection systems, usually do not have multiple feedback. In most cases, the feedback alert to users is in auditory form, with few systems having both auditory and visual feedback. The user can see a small blinking light and hear a loud noisy alarm when the system detects smoke or other gaseous pollutants levels above the threshold.
- Sensor position: The position of the detection device or system in the home could also affect the functionality of the system. If the sensor is placed too far from the source of pollution it might detect the pollution when the levels are already too high. On the other hand, if it is placed too close to the source, it might frequently make false alarms if heat or vapour strikes it. Therefore, the position of the sensor matters much to its sensitivity and functionally.

## 2.7 Summary

All accounts and sources reviewed, (WHO, EPA, and Our World in Data) indicate that indoor burning of solid fuels, for cooking, heating or otherwise, presents a serious health hazard of global proportions. However, despite the extensive and exhaustive study and research, indoor pollution still remains a global health problem with mostly women and children as the primary victims as already discussed in section 2.2, illustrated in Table 2.2 and in *Figure 2.1: Physician-Diagnosed pneumonia (low oxygen saturation) due to CO exposure*

Note. Adapted from Annual review of public health) (Smith et al., 2014)Figure 2.1. This gives the impression that perhaps there should be a change in the approach of dealing with the problem, given that the current state of the art of preventive and detection measures and technology are relatively flawed.

The aim of the project is to design an indoor air quality sensor warning system for homes using solid fuels, that is accessible and usable have universal design approach that integrates an IAQ sensor network Human Computer Interaction. This system would have a wide range of detection of gaseous and PM emissions or pollutants and harness the potentials of a mobile platform to alert the users with auditory, visual and tactile feedback. This feedback capability alone will render the system significantly accessible and hence usable to a wide range of users.

## 3. Project plan

The project plan covers the progress of the project throughout all three phases of its progression, from research and development to the documentation of the whole thesis, notably; Master Thesis phase 1 (MT1), Master Thesis phase 2 (MT2) and final phase (MT3). The plan is presented in a Gantt chart format displayed in Table 3.1. There are 20 activities that cover a 12 months period (from 1st April 2018 through March 2019) within the two academic year master's programme.

*Table 3.1: Gantt chart detailing a Project Plan for all three phases of the Master Thesis*

| | **Activity** | **Year 1** | | **Year 2** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **From 1st April 2018 through 31st March 2019** | **Months** | | **Months** | | | | | | | | | |
| | | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
| | Meeting with supervisors | | | | | | | | | | | | |
| | **Master thesis phase 1 (MT1)** | | | | | | | | | | | | |
| **1** | Write Plan, Project description, objectives and Literature review | | | | | | | | | | | | |
| **2** | State Problem, complete Literature. Write Research questions | | | | | | | | | | | | |
| **3** | Abstract, Submit & Prepare for Oral presentation | | | | | | | | | | | | |
| **4** | **First stage work on prototype** (Connections on Arduino board) | | | | | | | | | | | | |
| **5** | Presentation of MT1 & continue work on the prototype | | | | | | | | | | | | |
| | **Master thesis phase 2 (MT2)** | | | | | | | | | | | | |
| **6** | Design laboratory experiment and write Methodology | | | | | | | | | | | | |
| **7** | Write system description and Design | | | | | | | | | | | | |
| **8** | **Second stage prototyping** (Networking & link Mobile platform) | | | | | | | | | | | | |
| **9** | Prepare prototype for testing and interviews | | | | | | | | | | | | |
| **10** | Design interviews for user testing, write ethical considerations | | | | | | | | | | | | |
| **11** | Analyse User testing and laboratory results | | | | | | | | | | | | |
| **12** | Continue work on system design & Finalize MT2 | | | | | | | | | | | | |
| **13** | Proofreading, check and submission and Presentation | | | | | | | | | | | | |
| | **Master thesis phase 3 (MT3)** | | | | | | | | | | | | |
| **14** | Total revision of work on thesis so far (including the **prototype**) | | | | | | | | | | | | |
| **15** | Finish system description and analysis | | | | | | | | | | | | |
| **16** | Revise Methodology and Results | | | | | | | | | | | | |
| **17** | Write discussions and Conclusion and update Abstract | | | | | | | | | | | | |
| **18** | Finalizing Phase 3, Revise headings, titles and abstract | | | | | | | | | | | | |
| **19** | Proofreading, corrections, Final submission and presentation | | | | | | | | | | | | |
| **20** | Documentation, thesis writing, prototyping and testing | | | | | | | | | | | | |

At the top of the Gantt chart is a slot for meetings with the supervisors, just before the first activity, indicated by a yellow bar. These meetings are scheduled to take place every other week during the whole research, development and documentation period of the thesis, as can be seen from the Gantt chart (Table 3.1). The rest for the plan is divided into 3 main sections covering MT1, MT2 and MT3 in grey, charcoal and black colours in their respective order.

The different stages in the project plan Gantt chart are also colour coded. The yellow bar is for the meeting with supervisors, the red bar is the time for working on the prototype, the grey bar for MT1, the light-dark (charcoal) bar for MT2 the dense black bars for MT3 and the green bars indicate final work and presentation of each phase of the Master thesis. It should be noted that, since some of the detailed requirements of MT2 & MT3 are still pending, the plan has been made slightly generic for those phases to accommodate any future alterations or adjustment to the thesis writing process. Also note that work on the prototype has been allocated 2 hours a day for weekdays, till the end of May 2018 and 3 hours a day from 1$^{st}$ June 2018 until 31$^{st}$ of August 2018.

### 3.1 Master Thesis phase 1

This is the first of three phases of writing the master thesis covers first 5 activities on the Gantt chart with a duration of about 2 months, that is, from 1$^{st}$ April 2018 to 31$^{st}$ May 2018. For this phase, it is required that the introduction, the Literature study or review, research questions, problem statement and project objective be stated and or defined exhaustively. The required total word count for this phase is between 7000 and 10000 words, thus by writing an average of 200 words every day, for 40 days would easily get to 8000 words with some time to spare.

The first stages of the design and development of the prototype also begin in this phase with a simple basic connection of wires, components like LEDs and a sensor on the Arduino board. In summary, the first five activities of the plan (as per the Gantt chart in Table 3.1) lays out phase one of the master thesis. Which includes the foundation of the project from the planning of the whole thesis, to a literature review and an outline of the objectives and present some research questions. These questions would then have to be subsequently answered during the course of writing the first two chapters and the rest of the thesis.

### 3.2 Master Thesis phase 2

The second phase of the project represented in 8 activities (activities 6 to 13) in the Gantt chart starting with the design and setup of a laboratory experiment and writing the methodology. The essence of the laboratory experiments is to test various gas or IAQ sensors for their detection capability and range. According to the plan the system would have to be described at this stage, its design and its features, prior to commencing second stage prototyping. Without a prototype, there would be no testing, and without testing, there can be no results. When the prototype is ready and tested in the laboratory, it will then be tested in the field by potential users of the system and the users would then be evaluated via already designed interviews.

The various research, tests and feedback from users would then present a better understanding of the systems functionality and the potential of ethical issues that may arise. The ethical considerations made before testing and interviews could then be amended during the analyses of the User testing and laboratory results. To finalize MT2 a lot of proofreading, checking and proper documentation must be assured before submission and Presentation. At the end of this phase, it is required that there should be a well-documented methodology, results, and ethical considerations.

## 3.3 Master Thesis phase 3

Being the final phase of the master thesis, MT3 is the most crucial phase of thesis writing. It involves the total review of all work done on the thesis through MT1 and MT2, thus in the plan, this phase begins with, total revision of work done on the previous phases, including prototyping. In the Gantt chart plan, MT3 is covered by 6 activities running from activity 14 to 20 in which the system description and analysis must be completed, methodology and results revised, discussions and Conclusion written and then the abstract is updated. To finalize Phase 3, the headings, titles, body, every aspect of the thesis is thoroughly reviewed, proofread, corrected and properly documented to APA standards prior to the final submission and presentation.

# 4. Methods

## 4.1 Research Methods

In his book, The Research Act: A Theoretical Introduction to Sociological Methods, Denzin (2017) states; "… If each method leads to different features of empirical reality, then no single method can ever completely capture all the relevant features of that reality; …". (Denzin, 2017). The nature of this project required a systematic collection of data during its research and development characterised by a series of phases linking laboratory experiments and testing, field-user experiments, testing and feedback. Following Creswell & Clark (2017) writings, by analogy would imply the following:

i) All research data collection in the field-user phases, by design, would be a collection of words (for example, interviews), implying a qualitative research method.

ii) Laboratory research data collection would constitute a collection of numbers, indicating a quantitative research method.

Consequently, by virtue of the implementation of both quantitative and qualitative methods or at least one of each method where it is applicable, as already described in the project, it would imply that the research method is a mixed method. (Creswell & Clark, 2017)

As already established, the research method most suitable for carrying out this research project would be a mixed method. In a paper (prepared by Wisdom and Creswell (2013) both Ph.D. holders from George Washington University and University of Nebraska, Lincoln respectively) titled, Mixed Methods: Integrating Quantitative and Qualitative Data Collection and Analysis While Studying Patient-Centered Medical Home Model, mixed method research is defined as, "an emergent methodology of research that advances the systematic integration, or "mixing," of quantitative and qualitative data within a single investigation or sustained program of inquiry." (Wisdom & Creswell, 2013). This methodology is deployed with the assurance that delivers an exhaustive symbiotic interaction of quantitative and qualitative data offering a near-perfect convergence to the goals and objectives of the study. (Wisdom & Creswell, 2013)

### 4.1.1 Mixed method.

In an Editorial (in a leading global Nursing research Journal, WILEY,) titled: "Mixed Methods Research: The Issues Beyond Combining Methods," when examining and discussing the act of research mixing or integration, Halcomb (2019) writes, "First, integration refers to the approach whereby qualitative and quantitative data are concurrently collected and analysed separately before being integrated in the interpretation phase. Second, connection involves one approach being built upon the findings of the other approach."(Halcomb, 2019). Also, in an attempt to provide a comprehensive definition for mixed research method, Johnson, Onwuegbuzie, and Turner (2007) put together a good number of definitions from prominent and leading researchers. A few samples of these definitions are quoted in the following listing:

**Steve Currall:** 'Mixed methods research involves the sequential or simultaneous use of both qualitative and quantitative data collection and or data analysis techniques.'

**Marvin Formosa:** 'Mixed methods research is the utilization of two or more different methods to meet the aims of a research project as best as one can.'

**Burke Johnson and Anthony Onwuegbuzie:** 'Mixed methods research is the class of research where the researcher mixes or combines quantitative and qualitative research techniques, methods, approaches, concepts or language into a single study or set of related studies.'

**Udo Kelle:** 'Mixed method means the combination of different qualitative and quantitative methods of data collection and data analysis in one empirical research project.' (Johnson et al., 2007)

Figure 4.1 displays an Illustration of how the mixed approach relates to the two coactive data collection methods of qualitative and quantitative nature, how they intersect and how the resultant deductions at the point of intersection are exploited.

The nature of this project required a systematic collection of data during its development that was characterised by a series of phases, notably, the experimental phase (with laboratory experiments and field-user tests), the feedback phase (That is, laboratory experimental results and the field-user responses or feedback).

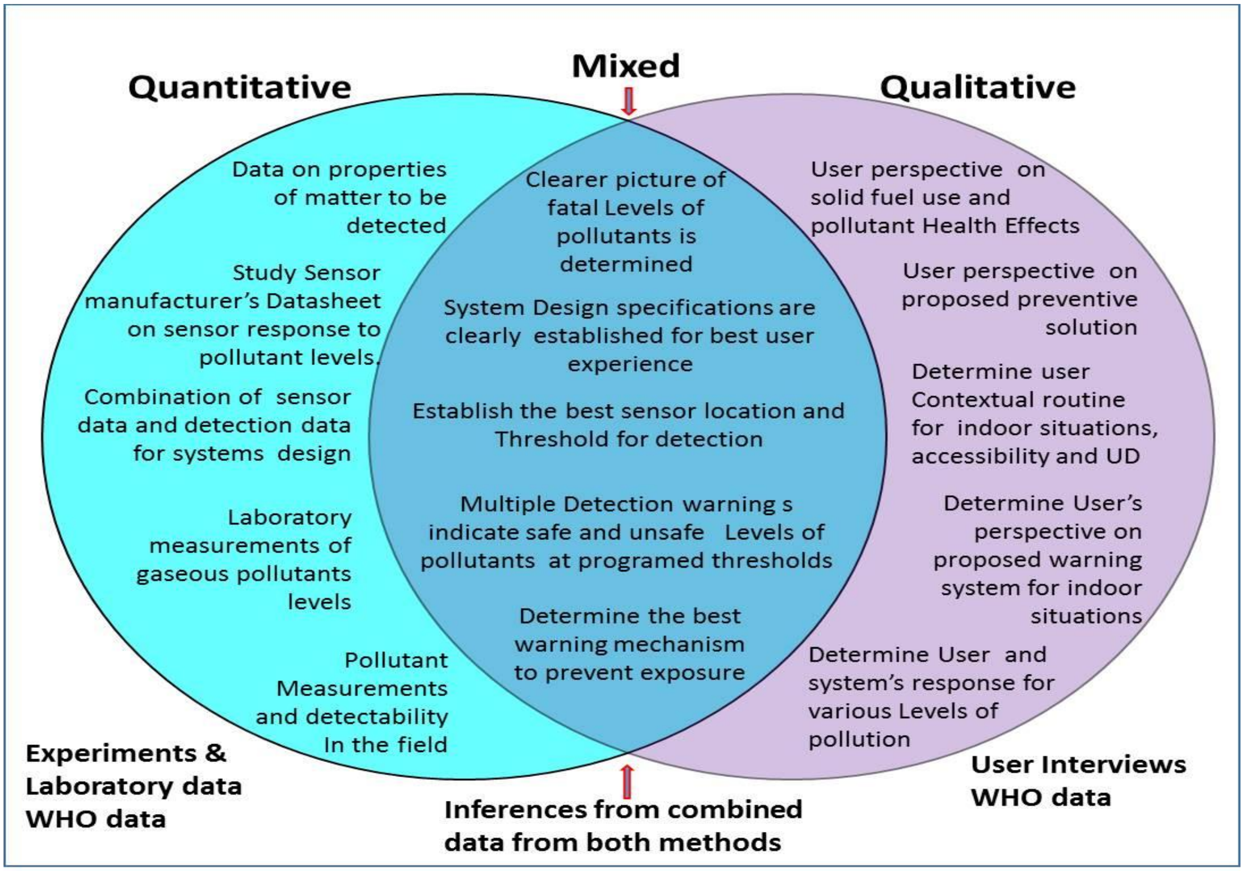



Figure 4.1: Illustration of the Mixed Approach resulting from the combination of Qualitative and Quantitative data.

The expectations of this information and or data are that these will lead to the determination of:

I. Fatal pollution levels or threshold (safe and unsafe levels) for multiple detections
II. The best warning mechanism for exposure prevention.
III. The threshold for detection and the best sensor locations on the infrastructure
IV. The system design specifications that would provide the best user experience.

**4.1.2 Quantitative data.** The source of quantitative data was basically numeric data from the laboratory test of the system and sensor reading for various test samples. Particulate matter such as smoke could not be tested in the laboratory because it was not equipped for such a test hence the risk of fire and or also due to the respect for the fire code. However, some tests were carried out in the field and the test showed the system responded to alcohol, Smoke, IPG which could be very convenient for an experiment. A separate test was conducted with CO using standards sensor and the system's sensor (Test-Sensor). The details about the sensor are discussed in section 5.1.1.1 and the experiment conducted with the sensor in the laboratory together with all data collected is described in Appendix D. The method is a descriptive research method that uses hypotheses and involves predictions.

The research questions are structured, that is, differences between variables and their relationships can be examined. The quantitative research method uses analysis based on statistics, requiring a statistical report. It is more rigid and deductive. Thus, the method would be suitable for evaluating the use of and Mobile App. Since the related question would be more focus on the usability of the system and App.

**4.1.3 Claims validation and testing the bases for the hypothesis.** There are containing factors that led to the research and development of the system COZiN as a technological solution to an acute global problem. Starting with the claims made by the world health organization WHO, and other sources that contributed to the development of the system hypothesized as a solution. The international organizations such as WHO and Our World in Data are considered as credible sources and hence data from these sources need no further authentication but would be used to validate the claims that form the bases of the hypothesis during the research and development of Cozin.

**Claim 1: A Huge Section of the World's Population Use Solid Fuels for Cooking.**

Figure 4.2, shows a graphical plot that identifies various world regions and the percentage of their population using solid fuels. Although the percentage of people depending on solid fuels for cooking has greatly declined from the levels in the 1980s by 2010, World dependency by population dropped from above 60% in 1980 to below 60% in 2010. Despite the downtrend, percentages in regions such as Africa and Southeast Asia remain significantly high above 60%.

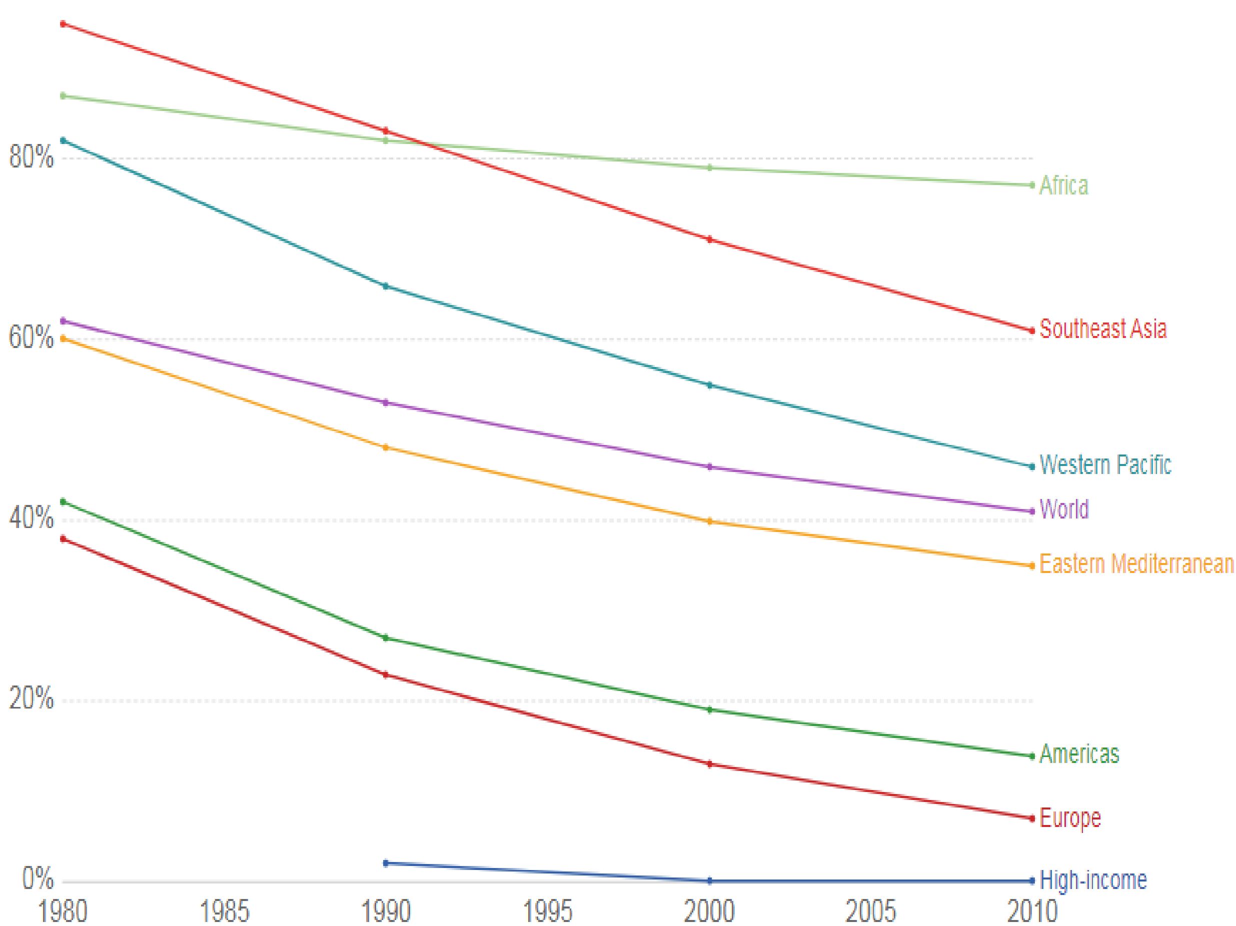



*Figure 4.2: Use of Solid fuels by percentage of the population.* (Our World in Data, 2013)

Note. Screenshot from Our world in Data; Original: Bonjour et al. (2013); (Our World in Data, 2013)

**Claim 2: The Health Effects of the combustion of solid fuels is a Global Epidemic**. As already discussed in the previous section dealing with health effects, many studies have shown that the effect of burning solid fuel is far more serious on children than on adults as indicated on

Table 2.2. In a WHO study in 2002 on the Burden of disease by country due to IAP from solid fuel use for the year 2002. *Table 4.1* compares the burden of disease in three countries, notably Cameroon, Mozambique and Norway. Although there is no data value on the total number of deaths in Norway, it is safe to assume the values are considerably low given only less than 5% of the population use solid fuels, hence the risks and morbidity are lower.

*Table 4.1: Burden of disease due to indoor air pollution from solid fuel use for the year 2002.* World Health Organization (2007)

| Country | Population Using Solid Fuels (%) | Total Deaths Attributable to Solid Fuel Use | National Burden of Disease Attributable to Solid Fuel Use (%) |
|---|---|---|---|
| **Mozambique** | 80 | 9 700 | 2.4 |
| **Norway** | <5 | - | - |
| **Cameroon** | 83 | 12 900 | 5.5 |

Note. Adapted from “Indoor air pollution: National burden of disease estimates,” p.2-4, WHO (2007).

By contrast, 80% and 83%  of the populations of Mozambique and Cameroon, the total deaths attributed to solid fuels is 9700 and 12000, leading to a national burden of disease of 2.4 and 5.5% respectively. This data also substantiates the graphical data displayed in Figure 4.2, where a high population dependence on solid fuels is indicated amongst developing countries. Figure 4.3 shows a bar chart that highlights the differences between Mozambique, Cameroon and Norway in terms of percentage of solid fuels usage by population, the morbidity associated with solid fuels and the National burden of diseases by their respective percentages.

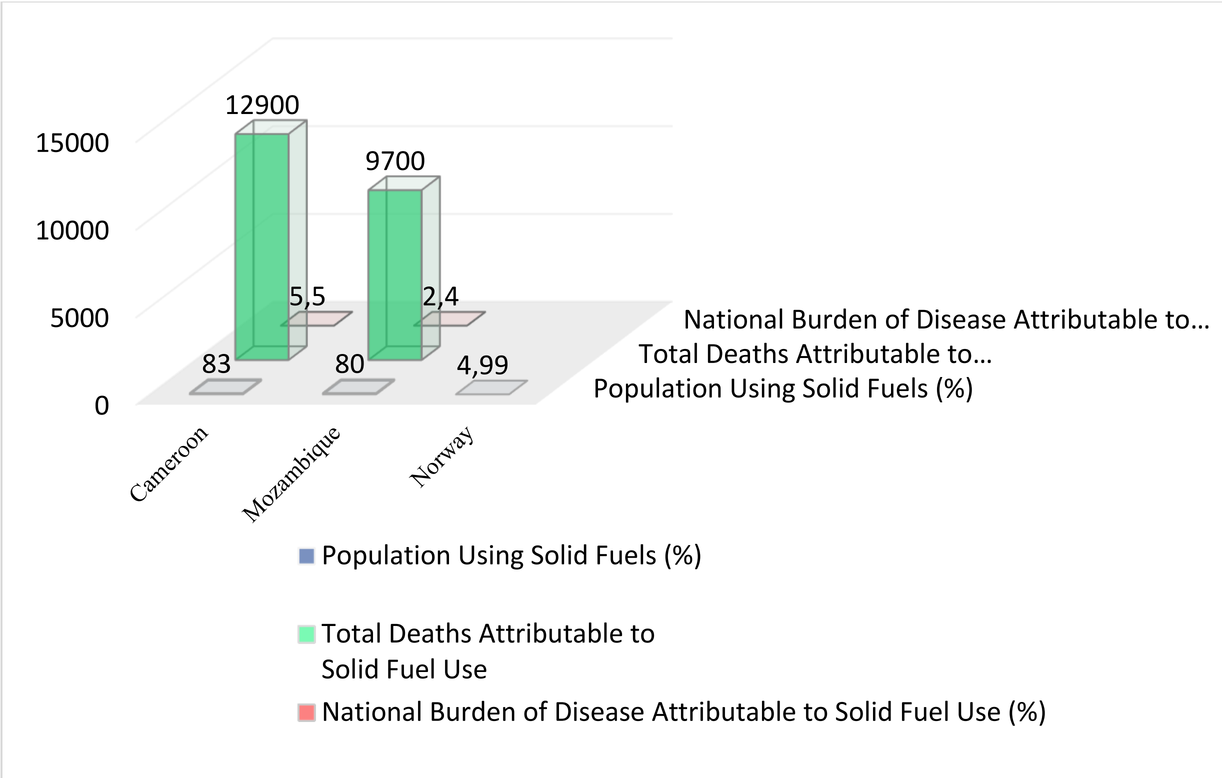



*Figure 4.3: Burden of disease due to IAQ comparing three countries.* (World Health Organization, 2007)

Note. The chart has been generated using data copied from "Indoor air pollution: National burden of disease estimates," p.2-4, WHO (2007).

### 4.2 Data Collection and Analysis

First, data from the WHO research and other international organisations regarding the effects of the use of solid fuel and how it affects the IAQ and hence the health of the users was used to state the problem and establish a hypothesis. The second part of the data collection which was mostly quantitative data came from studies already carried out by the WHO potential users' testing and laboratory results gotten from measurements when testing the system but also most importantly the qualitative data from the interviews with users.

**4.2.1 Qualitative data.** The qualitative research method is not very predictive, which would suggest that the outcome may vary or change during the research. The research questions are basically designed to answer the questions of “What” and “How” which would imply discovery or exploratory type questions. Qualitative research method requires no hypotheses hence the data collection is usually in the form of words via interviews and documents like newspaper articles, journals and other publications, which could also include audio-visual materials. The aforementioned reason would imply a lot of field work is necessary to collect data from respondents in case of administering a questionnaire or an interview. This could be relevant for the social aspect of the topic that might involve the health issues the system COZiN and its mobile App are being developed for.

**4.2.2 Designing interviews for user testing.** In all, there were 6 interviewees or participants 4 male and 2 females. The two female participants were from different households. Three of the males and one of the female participants were from the same household. Each participant was given a unique identification number shown and described in Figure 4.4. The idea of interviewing more than one person per household where possible turned out to be an important decision, it was interesting to see if the ideas and responses would be similar or differ per respondent form the same home.

The participants are classified by UID as follows: #111-F. #222-M, #333-M, #436-M, #534-F, #535-M. it can be seen that #111-F and #534-F are both female participants, #333-M, #436-M, #534-F and #535-M, are from the same household, just a few examples to show the role of the UIDs in the research analysis.

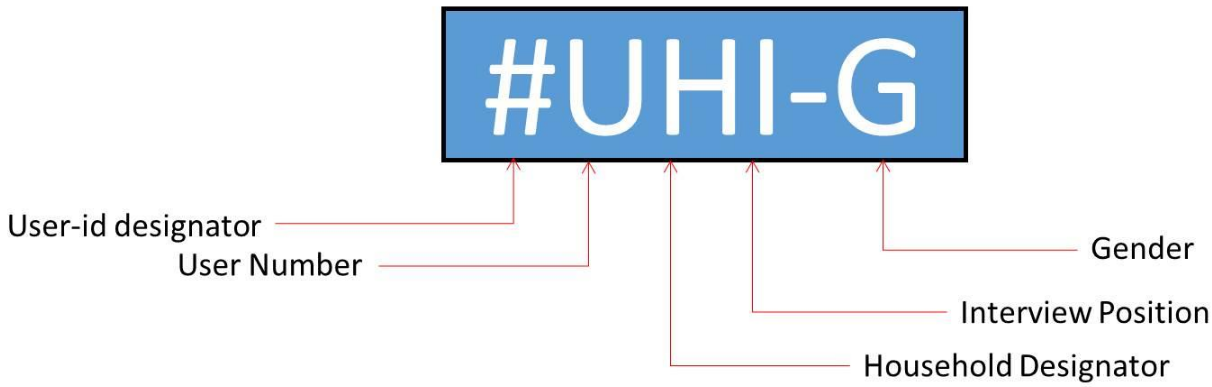



*Figure 4.4: User Identification Number and Significance*

The User Identification number or (UID) was introduced to ease identification of the participants while maintaining their anonymity and right to confidentiality. It should be noted that the letter '**G**' for gender is substituted by '**F'** for female and '**M'** for male in the actual UIDs. The UID also helped in the analysis of the data as it made it easy to identify the user by household, It and the position during the interview, as shown in Figure 4.4. In so doing, any trends, variations or similarities in the responses can be traced and analysed with relative ease.

***4.2.2.1 Interview schedule.*** There were six participants that could be divided into three groups representing three different households and all participants were interviewed in a face-to-face session. All interviews were scheduled according to mutual consent and at the convenience of both interviewee and interviewer. The whole process went through an orderly sequence that began with opening the interview, the body, pre-closing and closing of the interview. The full structure of the interview schedule is illustrated in the following listing:

**Opening:** Welcome greetings to the interviewee**,** Good morning (good afternoon or Evening) and welcome, while ensuring that the participant or interviewee is comfortable enough and ready. At this point, it must have been determined whether an interpreter would be needed or not.

**Introductory Statement**: The interviewer states what the interview is about then followed by a short negotiation process to determine whether the participant consenting or declining. For example: “We are about to interview you about this system COZiN, first we will test it then ask you some questions. If that would be all right with you, make yourself comfortable and we will begin when you are ready.”

**Basic Information**: It is important to get some information about the interviewee if possible, within the confines of the consent form the participant has signed. Then the basic Questions would be asked accordingly.

1. Do you always use solid fuels (that is; coal, wood, charcoal, dung …) for cooking or for other purposes?
2. How often, (for cooking or heating or otherwise) indoors?

**Body (Starting with possible observed effects):**

3. Do you currently have or have experienced any problem(s) resulting from (or attributed to) the use of solid fuels?
4. The system under test is called COZiN. Is the name COZiN recognizable to you?

**Accessibility and Universal design Aspects:**

5. How easy is it (was it) to install the mobile App?
6. Do you think the mobile app is (was) easy to use?
7. Is (was) the system useful to you? If yes, How useful?
8. Would you like one installed in your home?
9. Would you buy the system if it were available for sale?

**Pre-closing:** We are almost at the end of the interview and I have few questions left for you.

10. What aspects of the system do you like the most? You could give your dislikes as well.
11. How much do you think you would be willing to pay for the system?
12. What is your general thought about the system and the whole experience?

**Closing:** That was the last question. Would you like us to go through your answers? If not, then thank you for your time and have a good day.

***4.2.2.2 A pre-interview pilot study.*** In the pilot, the potential users had difficulties answering professionally designed questions but once they were engaged in a conversation in which questions were asked in a more simplified manner, they were more inclined to answer. A pattern soon emerged, which led to the design of the question in the categories discussed in the previous subsection (subsection 4.2.2.1).

## 4.3 Challenges

There were a lot of challenges encountered during the research, these were mostly due to difficulties associated with Logistics, Communication and Accessibility presented serious constraints to the research, particularly during the user testing phase of the system and interviews. Amongst the different challenges and difficulties encountered during the research and development of the system, excluding those principally related to the hardware development, the points to be noted are as follows:

I. Low Statistical Samples
II. Lack of test samples
III. Language Barrier
IV. Lack of participants for Accessibility Evaluation
V. Lack of logistical support

**4.3.1 Low statistical samples in the target area.** From the get-go, preliminary questioning of people (particularly around the Maputo central area) at random revelled that many people do use solid fuels like charcoal and wood, but the use is outdoors and not indoors. The research study was for indoor use only, which means that homes were solid fuels are used indoor had to be located for the study to continue. This was no easy task because the researcher had to rely on other people who had their day jobs to attend to besides helping in the search for homes qualified for user testing.

Lack of test samples the system under test was still in the rudimentary state and there were no commercial samples that users could test at their discretion. It was also expressed in the interviews, by respondent or participant number #534-F: *It would have been good if we had a commercial sample of the system to try on our own*.

**Lack of participants for Accessibility Evaluation:** The inability to test the system or interview people with disabilities was a great handicap to the study. Getting the opinion of people with visual impairment, for example, would have given a better evaluation of the accessibility potential of the system. Nevertheless, the use of personas compensated for the lack of respondents or participants with impairments.

**Language and cultural barrier**: One of the problems encountered during the research process, especially when carrying out the interviews, was the language barrier. Since the research was carried out in Mozambique where the official language is Portuguese, it was difficult to interview participants in the survey, so interviews had to be conducted with the aid of an interpreter.

**Lack of logistical support:** during the research, there were not adequate facilities at the disposal of the researcher to ease the workload such as computers and other laboratory equipment needed to make the necessary measurements.

**4.3.2 Personas.** Personas are the fictional characters that are used or created to represent the diversified range of users and potential users of a product or service. (FutureLearn, 2017). They are created based on real data that represent a group of users with shared interests, characteristics and objectives. The introduction of personas was an attempt in the research involving the user to compensate for the lack of users experience for people with disabilities. Personas had to be used to demonstrate how the system would support the needs of users with different kinds of disabilities and how they would cope or fare with using the system. The idea of personas was retrieved and adapted for use here from the online course, Digital Accessibility; (FutureLearn, 2017; Marsh, 2018).

***4.3.2.1 Persona characteristics.***When building the profile of persona that represents a specific user base on the data and observation or good understanding of the user's profile, one would have to consider all the persona components relevant to the study or project during the user testing phase of the research. No matter the nature, type or relevance of the research all components are important but not necessarily relevant to the construction of the character of the persona as a reflection of an actual user profile. Some of the components of the persona would certainly contain some kind of background information or story, some qualities unique to the persona character that bare a direct relation to requirements defined by the project, and of course the behaviour sure that the context is preserved. (Marsh, 2018)

The research aims to achieve a design that as inclusive as possible which requires a study or research that would cover every detailed information in relation to the users' demands and needs. In other to achieve this goal the use of personas must be well characterised and structured to reflect the actual users as much as possible therefore the persona is built to a certain degree of exactitude to include a photo, name, age, education and to a certain extent social status or even a complete persona lifecycle from birth through adulthood to family planning (A concept presented by Adlin and Pruitt (2010) in a book The Essential Persona Lifecycle: Your Guide to Building and Using Personas. However, the persona characters used in subsection 4.3.2.2 would include only the most essential attributes related to the project. (Adlin & Pruitt, 2010; Marsh, 2018)

***4.3.2.2 Persona experience.*** **Karol–Deft:** Karol, 55, having recently acquired a commercial version of the indoor air quality warning system COZiN. A traditional system like the smoke detector currently installed in her kitchen has a very loud alarm which she cannot hear and flashes a red led light she cannot see when she is not in her Kitchen. However, with system COZIN, she can install a network of three sensor nodes in different parts of her house starting with the kitchen. She can also connect her mobile phone to the system and receive all warning signals on her mobile phone via Bluetooth. Cozin provides Visual, Auditory and tactile feedback warning signals with its onscreen display, voice alert and phone vibration features. The mobile vibration is what helps Karol the most. Best of all with the system COZiN now installed in her home, Karol can always monitor the air quality in her kitchen, and her neighbours would never complain of any loud noise (she cannot even hear) coming from her house again.

**Xendu–Visually Impaired:** Despite his condition, Xendu 22, is a geek; he likes to play around with his computer and occasionally writes computer code. He wants to study programming, he owns a smartphone and he lives in a rural area near Maputo the capital city of Mozambique, with his grandparents who use charcoal for cooking. Xendu is using Cozin and likes almost everything about it. The system notifies him of the air quality in his room which is the closest to the kitchen of the other rooms in the house. He can connect his mobile phone to the system and get real-time information via Bluetooth, he may not be able to see the visual displays on the screen, but he can feel the warning vibrations, hear the audible warnings alarms and voice notification. The system's multilingual capability also allows Xendu as a user to set the voice notification language to his preferred language Portuguese.

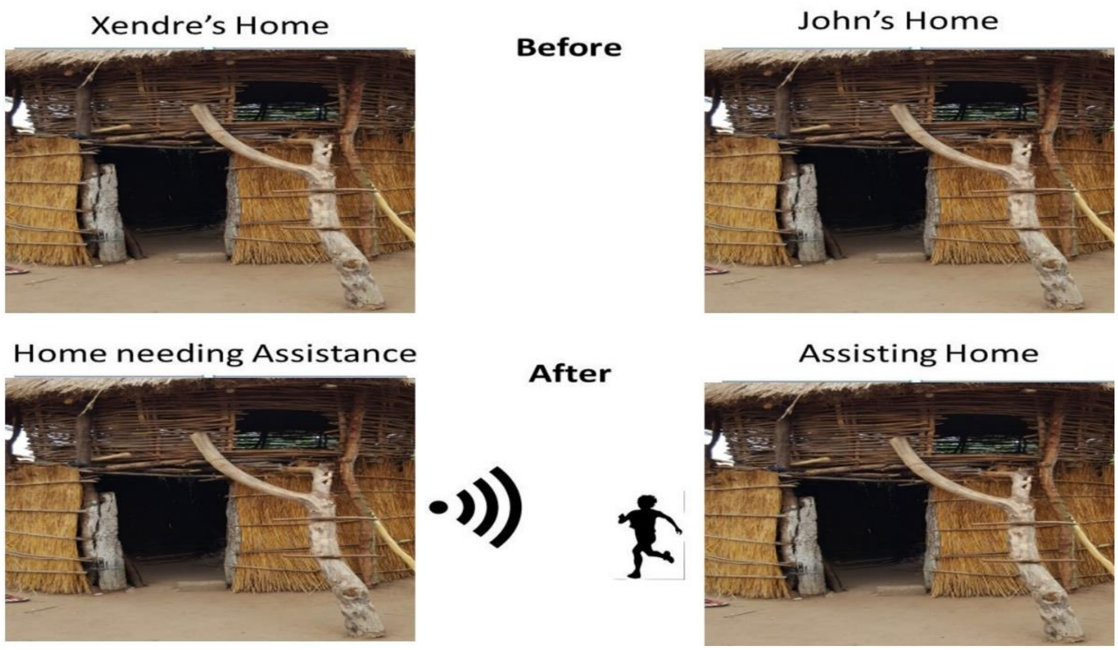



*Figure 4.5: Demonstrating the Assistive Capabilities of system COZiN*

Node. The image (taken with Samsung Galaxy S6 Smartphone) is that of a real-life kitchen taken during the research in Mozambique.

**John–No Apparent Impairments:** John is a childhood friend to and neighbour to Xendu, he is already in university, where his studies ICT and has already figured out the future potentials of Cozin. He wants to exploit some of the intrinsic hardware and software capabilities of COZiN, that allows for the possibility to modify the software to increase hardware functionality. John is particularly interested in networking his own system with that of his neighbour and friend Xendu. This is possible if the sensor nodes of both systems are within communication range of each other, but a few changes must be made to the software.

Consider Figure 4.5, it shows the homes of Xendu and John in a before and after modification scenario. Before modification, the system works fine with its default settings. However, after modifying the software (which is built on the Arduino open-source platform) with just few lines of code, John can now receive sensor readings from Xendu's home on his own Cozin system which means he can also get the alerts and warning signals and can thus offer assistance to Xendu, if need be. Say for example that smoke ($C0$ or $C0_2$) was building up in a neighbour's house, and the neighbour was impaired such that it became difficult to respond.

The neighbour could otherwise be risking death but for the fact that your own IAQ detection system is connected (networked) to his or hers, then you would be able to get the signal and hence act accordingly to save someone's life. Now imagine the neighbour was a family member or relative, this possibility and capability will certainly be extremely useful. This scenario was just to highlight some of the capabilities of system Cozin and the assistive UD features its carries

**Ngong – motor Impaired:** Ngong is motor impaired, recovering from an accident he had a few years ago. He is in his late forties and has difficulties moving his fingers. However, he would still be able to use the COZiN Mobile App because it is a dedicated app, the user does not need to constantly input any data or press key and buttons on the mobile or smartphone. There are no complex gestures required to use the app and only connect-and-disconnect (large enough not to miss) buttons are used.

### 4.4 Ethical Considerations

In design ethics, the Value Sensitive Design approach (VSD); as laid out (originally)by Friedman, Kahn, & Borning, 2008; Van Den Hoven, (2008) is widely appreciated and attempts to constantly influence technology design from conception and throughout the whole design process.  Within the concept of VSD moral values are respected and considered the base of this philosophy. These values are therefore embedded at every stage of the designs such that human design results in morally decent designs. VSD ethics are thus for the most part principled around human happiness, that necessitates ones consent to everything personal, could private property, human and civil right, confidentiality (Friedman, Kahn, Borning, & Huldtgren, 2013; Fuchs & Obrist, 2010).

HCI ethical issues addressed by fundamentals principle expressed in VSD for consideration in society is as defective as all other approaches dealing with computer ethics simply because these are arbitrary, non-philosophical principles. There no clarity to their essence and yet these ideas have been chosen, whereas in a contrasting view that encourages cooperation and participation to a stratified society designed around the information that would indicate the degree of compliance to the said principles. (Fuchs & Obrist, 2010)

**Privacy concerns:** Most people would like their privacy to be respected, so some measures were taken to make sure that all personal and private information about participants in the interview were duly and fully respected. A consent form was drafted such that all privacy concerns of the interviewee were addressed with the full assurance that they will be regarded with the utmost respect. The consent form was a two-page document consisting of English and a Portuguese translation. The Portuguese version was officially translated with the cooperation and assistance of the Eduardo Mondlane University in Maputo, Mozambique.

**Cultural concerns**: During the interview, the use of an interpreter familiar with the local customs and ethics was imperative so, one was sought for. Each participating home was represented by at least one person, therefore in cases where more than one person was interviewed in any household; all the interviewees had to sign a separate consent form. Some Incentives were given to all participants by household. That is, each household received a low-cost smartphone with basic features.

On one occasion, when a member of a potential test-home was approached for a possible interview, a member of the household had to direct the research team to the local traditional rulers for consent and permission. This was done as an act of courtesy to the local customary laws and respect for traditional authorities, who were happy to receive the team and expressed their interest in participating in the test. The decision was later taken not to conduct the testing and interview in the local leader’s compound because there were no more gifts or incentives left for them. The reasoning was that it might be problematic, seem unfair or at least look odd if other participating households had received phones and the home of the local traditional ruler did not. This obviously does not mean that there would have been some resentment, but it does highlight the cultural concerns and how it might have affected the user testing and interviewing process.

# 5. System Description, Design and Functionality

As already discussed in the project description (section 1.1), the system's design emphases are focused on Universal design hence, the system is optimized for inclusivity and accessibility. Figure 5.1 shows a typical illustration of a scene depicting how the indoor air quality monitoring system's setup, operation and the possible future development into a system concept called "Cozin". Cozin comes from **Cozinha,** which means kitchen in Portuguese. Looking at the figure, one can see the figure of an adult person and that of a child standing a kitchen with a stove or fireplace close to the right-hand corner of the room, using solid fuel for cooking.

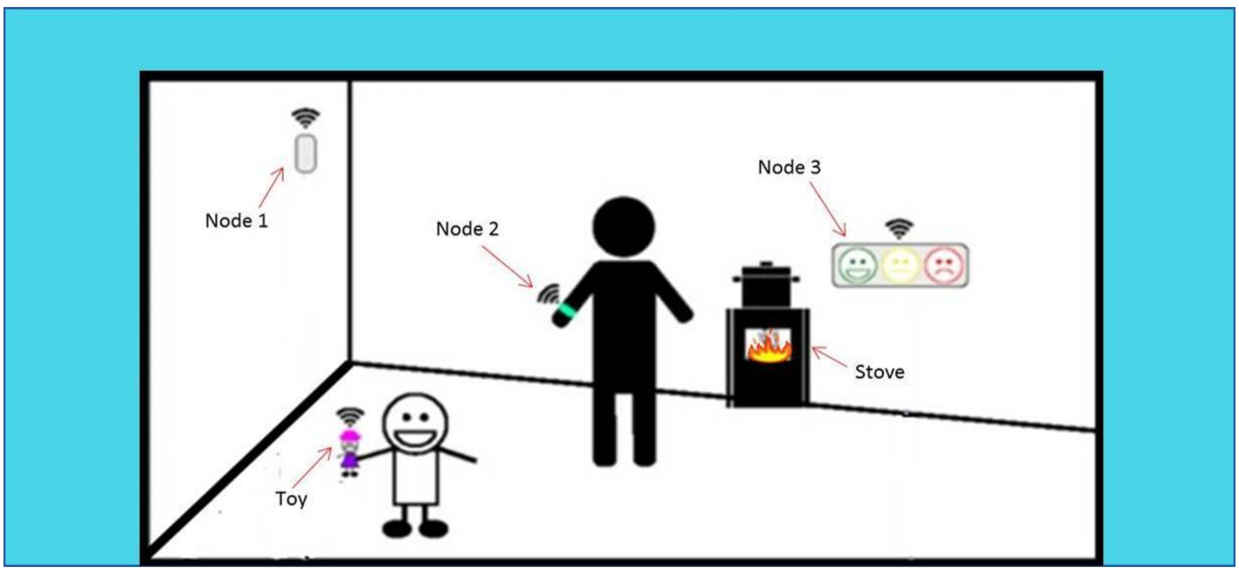



*Figure 5.1: An illustration of the functionality of the IAQ monitoring system (the Cozin concept).*

The child is holding a toy which has a miniaturized sensor-node embedded in it and there are several other nodes labelled node 1, node 2 and node 3. Node 1 and 3 are part of the infrastructure (mounted on the wall or ceiling), while node 2 is wearable and the toy is portable. All sensor-nodes are connected in a network. Node 3 has a Bluetooth link to a mobile smartphone where the system displays the status of the air quality in the room. The basic function of the system and the concept of Cozin is the design of a sense-detect-warn system that monitors the Indoor Air Quality and notifies the user, by means of three different IAQ status Codes as discussed in system description, section 5.1, Figure 5.5.

The system constitutes an RF wireless network of sensor nodes with a Bluetooth link to an Android Smartphone to increasing its Universal Design capabilities. Although the Illustration in Figure 5.5 shows three nodes, there could be more. The IAQ monitoring system also has the potential to link to wearable devices (for example, Bracelet or wristband) with pulse-vibrate capabilities. It should, however, be noted that one of the nodes could be the specially designed wearable or the system could simply connect to the wearable device via Bluetooth.

## 5.1 System Description

During the design of the system, it was important to consider the most essential features that would render the system inclusive to address the needs of users with disabilities or impairments. In this regard, the system's design consists of two main blocks. That is the HARDWARE Unit and the MOBILE APPLICATION. How both blocks connect and operate together is illustrated in

Figure 5.3 under the system description.

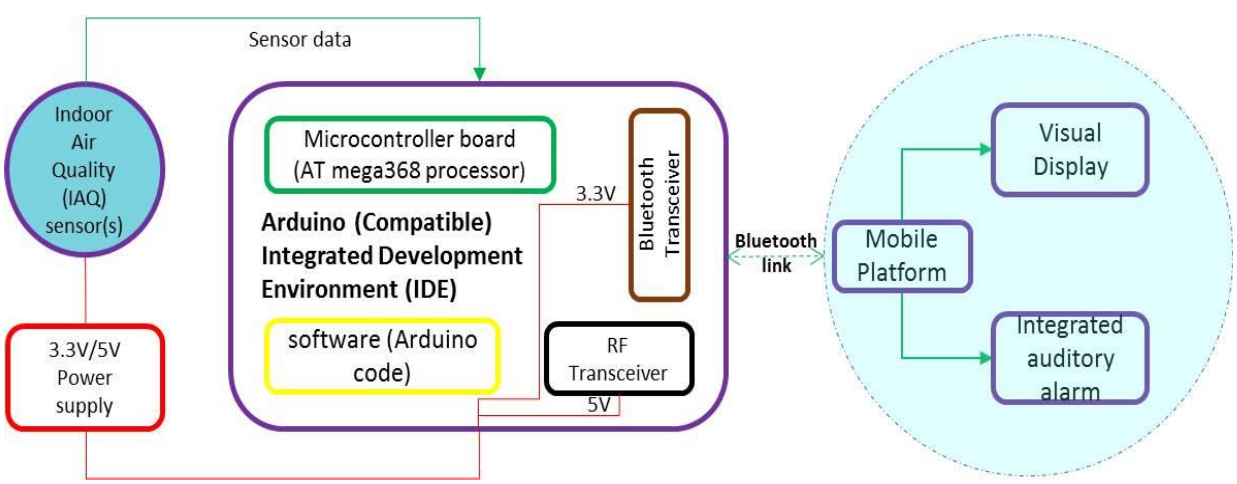


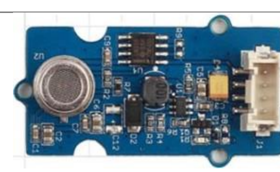

*Figure 5.2: System Block Diagram showing all the main features*

The hardware is essentially a sensor and a microcontroller unit (MCU) powered by an ATmega328 microprocessor and connected with a Bluetooth and RF transceivers to form a sensor-node. On the other hand, the mobile app section includes a mobile software application that sends feedback to the hardware and smartphone. The detail description of the different parts of the hardware will be discussed in the subsequent subsections.

**5.1.1 Hardware.** The hardware part of the system mainly includes the sensor, the microcontroller and microprocessor, the Radio Frequency (RF) and Bluetooth transceivers. The system's hardware is one of the most fundamentally important parts of the project and since the system is supposed to be simple, cheap and easy to maintain, the hardware must reflect the outlined characteristics. Known for its simplicity and versatility the Arduino platform carries most of the characteristics describe and is, therefore, a suitable choice for the prototype and hence the project.

***5.1.1.1 Sensor.*** The sensor is an important part of the system and is responsible for the proper detection of the dangerous emission the user is to be warned against. In section 44 of Dictionary of Computer Science, Engineering and Technology Laplante (2017) defines a sensor as, " a transducer or other device whose input is a physical phenomenon and whose output is a quantitative measurement of that phenomenon." (Laplante, 2017)

*Table 5.1: Features of the Grove- Air quality Sensor v1.3.* (Seeed Technology Co., 2019)

| Features | Technical details | |
|---|---|---|
| **Low power consumption** | Dimensions | 40mm x20mm x15mm |
| **High sensitivity** | Weight | G.W 11g |
| **Tiny outline** | Sensor type | Winsen MP503 |
| **Responsive to a wide scope of target gases** | Power | 5V or 3.3V |
| **Cost efficient** |  | |
| **Durable** | | |
| **Compatible with 5V and 3.3V** | | |

Note. Table adapted and image copied from Seeed Technology Co., Ltd. https://www.seeedstudio.com/category/Grove-c-1003/category/Sensor-for-Grove-c-24/Grove-Air-quality-sensor-v1-3.html.

Examples of such physical phenomenon measured by a sensor include; temperature, Humidity, pressure and then outputs voltages or currents proportional to the measurable quantity. (Laplante, 2017)

The sensor required for the project should be able to detect gaseous pollutants and emissions (including Carbon monoxide CO and particulate matter like smoke) from burning solid fuels such as wood, coal and charcoal. There are many commercially available sensors that have these characteristics. One such example is the Grove - Air quality sensor v1.3. Its characteristics as displayed in Table 5.1 meets most of the requirements for use in the project and is, therefore, a suitable choice. More technical information about laboratory testing and sensor calibration is found in Appendix D, particularly in Figure D.1.

***5.1.1.2 RF Transceiver.*** In the Dictionary of ICT Collin (2015) defines a transceiver as, "a transmitter and receiver, or a device which can both transmit and receive signals. …" The RF (Radio Frequency) transceiver provides a wireless connection between the sensor-nodes such that each node has two-way wireless communication with the other when in range. For the purpose of carrying out this project, a communication range of at least two metres is required. So, the RF transceiver should have an operation range greater than 2 metres. The HC-12 is a multi-channel wireless RF transceiver module with a frequency bandwidth of 433.4-473.0 MHz and a Channel-frequency step of 400 kHz for all 100 channels. It has a maximum transmitting power of 20dBm (that is 100mW), reception sensitivity of -117dBm at a baud rate of 5000bps (which can be changed using AT-Commands) and a communication range of 1Km in open air. ("HC-12 Module User Manual V1.18," 2012)

***5.1.1.3 Bluetooth transceiver.*** The role of the Bluetooth transceiver is to connect the Hardware wirelessly to a mobile phone running a mobile App that manages the communications and data transfer between the phone and the main system hardware. Bluetooth is a network technology that has a communication operation range of about 1 to 10 to 100 metres that uses radio wave in the 2.4Gz band that can transmit to a certain degree through walls. It is primarily used for communications between portable devices such as notebook computers, smartphones and also between computer peripheral devices like mouse and keyboard.(Affairs, 2002; Butterfield & Ngondi, 2016)

***5.1.1.4 Micro-controller unit.*** The microcontroller unit (MCU) is a part of the hardware that is responsible for carrying out computations that run the whole system and process sensor data. To meet the requirements of this project the MCU must be simple but powerful enough to process sensor and other useful system inputs and must operate on an open source platform. The Microchip ATmega328p is an 8-bit MCU that combines 32kB ISP read-while-write capable flash memory and an operational voltage between 1.8-5.5 volts. (Microchip Technology Inc., 2018)

*Table 5.2: Features of the ATmega328p microcontroller* ("Arduino BT," 2019)

| Microcontroller | ATmega328P |
|---|---|
| Operating Voltage | 1.8-5.5 V |
| Digital I/O Pins | 14 (of which 6 provide PWM output) |
| Analog Input Pins | 6 |
| Flash Memory | 32 KB (of which 2 KB used by bootloader) |
| SRAM | 2 KB |
| EEPROM | 1 KB |
| Clock Speed | 16 MHz |

Note. Adapter from Main Arduino Board Bluetooth overview summery on Arduino website ("Arduino BT," 2019).

The ATmega328P MCU is compatible and has been adopted for use on many MCU board systems operating on the Arduino platform and is, therefore, a suitable choice for this project. Table 5.2 shows more features and characteristics of the MCU.

**5.1.2 Software** The software that runs the system combines the sketch (an Arduino C-language code written in the Arduino IDE) and the mobile app (Developed in the MIT App Inventor 2) installed in the smartphone paired to the hardware via a Bluetooth connection. A sample of few lines of the Arduino c-language code is shown in Listing 5.1 (full sketch is found in Appendix C, Listing C.1). The hardware programmed via the serial port of the ATmega328P MCU where it is uploaded and stored into the flash memory of the chip. The choice of the Arduino platform makes it easier to work with since it comes with both hardware and software open source platform with lots of supporting documentation and easily downloadable from the Arduino website. The concept of Arduino is the phenomenon surrounding a system cohesively built to create a platform that incorporates: an integrated circuit or a chip, a PCB, a manufacturer, programming language and computer architecture. It empowers and induces creativity in a growing community of developers, hobbyists and others. (Kulkarni, 2017)

```
int Get_SensorData() {
  int Sens_Data = analogRead(_SensOput);
  return Sens_Data;
}
```

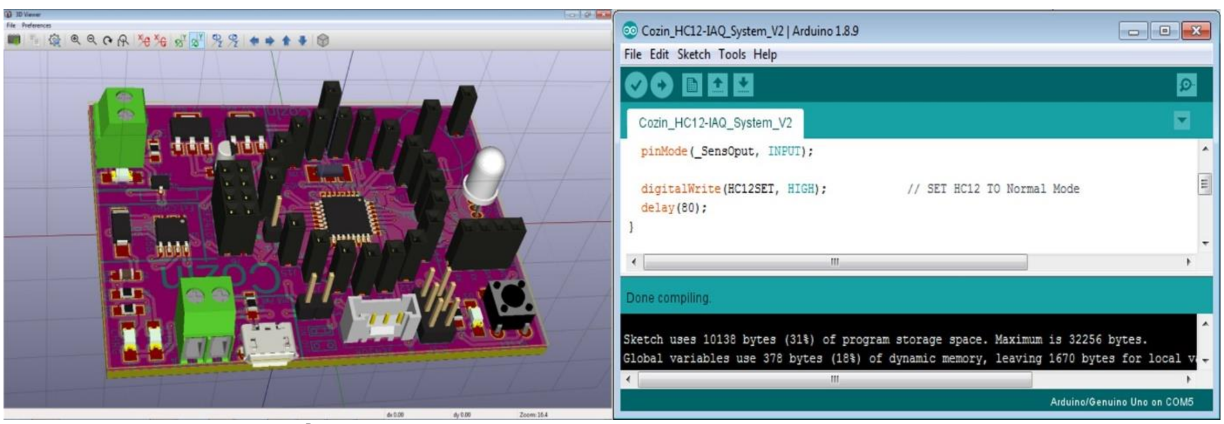
*Listing 5.1: A fragment of the main Arduino c-Language sketch running the system's hardware*

Note. Copied from the main c- code in the Arduino IDE also displayed in Listing C.1.

The snippet of code in Listing 5.1 is a subroutine that deals with the collection of data (stored in the variable '_SensOput') from the sensor via the 'analogRead' function and returns the variable 'Sens_Data, to which the data value has been assigned. This value will then be retrieved in from the variable in another function for further processing.

### 5.2 System Design

The system is designed for simplicity, flexibility, portability and accessibility hence the features that would enhance these characteristics were incorporated into the system's design from the beginning and implemented throughout the design process. The hardware, software and mobile app are all built on open-source platforms. For example, the Hardware unit's Printed Circuit Board (PCB) schematics and layout were designed with the KiCad Electronic Design Automation (EDA ) Suite. Likewise the Arduino Integrated Development Environment (IDE) Figure 5.3B was used to code software sketches (A Sketch is a small c-language program written in the sketch editor of Arduino IDE) running the processor.




A B

*Figure 5.3: Screenshots of 3D view of the system COZiN in KiCad EDA (A) and the sketch in Arduino IDE (B)*

"KiCad is an open source software suite for Electronic Design Automation (EDA). The programs handle Schematic Capture, and PCB Layout with Gerber output." (KiCad, 2017) The suite is available to a wide range of users since it runs on all the major Personal Computer (PC) Operation Systems (OS) such as Windows, Linux and Mac, it is developed with the collaboration of the European Organization for Nuclear Research (CERN[2]) and licensed under GNU GPL v3.(KiCad, 2017). Open Source, according to O'Neill and Williams (2013) in the book Arduino

[2] Originally in French, CERN stands for Conseil Européen pour la Recherche Nucléaire.

means, "… everything about the project is available for everyone to look at and use. From the electronics designs used to build the physical device to the code."(O'Neill & Williams, 2013)

The PCB of the system is designed such that all the input/output pins, ports and other connectors and components fully support the hardware's compatibility with the Arduino platform. This is especially essential to ensure the ease of loading the any Arduino bootloader that supports the ATmega328P microprocessor and hence smooth programming of the hardware via the serial port.

Figure *5.3*A shows a three-dimension view of the hardware module designed in the KiCad EDA for the system.

**5.2.1 Sensor node.** A wireless sensor node is a piece of hardware with its own embedded microcontroller, an RF transceiver, transducers like a gas or temperature sensor and a power supply that renders it autonomous. (Güngör & Hancke, 2017). "A typical sensor node comprises the following units: sensor, communication, microcontroller, memory and power." Senouci and Mellouk (2016). Sensors are usually known to be devices that have the ability to respond to some physical quantity such as pressure by producing an electrical current or voltage which are easier measurable quantities that can be automatically interpreted and processed. A sensor node sometimes referred to as mote, is a device that integrates sensors and other components that contribute to the processing of data collected by the sensor. (*Senouci & Mellouk, 2016*)

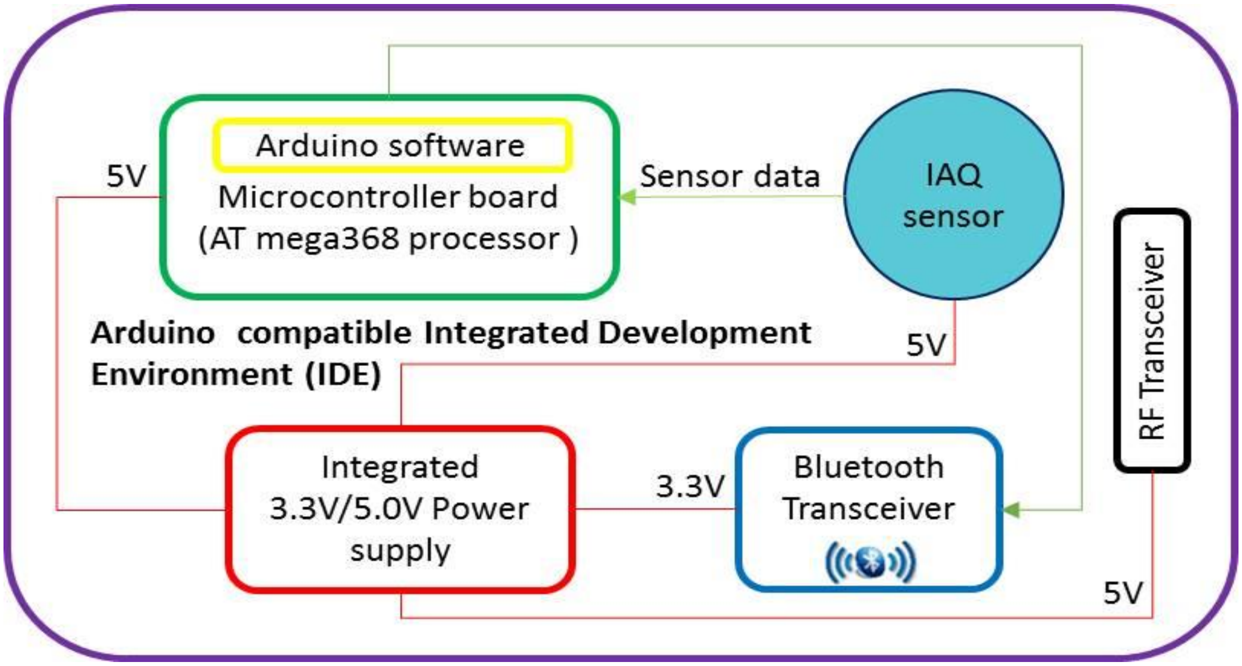



*Figure 5.4: Diagram showing all the major components of the Sensor Node*

The sensor node module displayed in Figure 5.4 is made up of components such as the Grove air quality sensor, HC-12 RF transceiver module, HC-06 Bluetooth module, ATmega328P MCU and a power supply. The node is autonomous; it can process sensor data independently and can connect to other nodes in the network. The system has an important feature programmed in the MCU that enables each node to share information and allows each node in the network to receive and transmit sensor data even the sensor was connected to only one of the nodes. It should also be noted that the system will not work or commence network communication if the was no sensor connected. It will also indicate an error message and sound an error alarm.

**5.2.2 Designing the PCB.** The PCB design process is the most important step leading towards the design and construction of the system's prototype. This process starts with the schematic drawings of the circuit's design in the Electronic Schematic Editor (Figure B.1) otherwise known as **Eeschema** in the KiCad EDA. "Eeschema is a schematic capture software distributed as a part of KiCad …"(Charras & Tappero, 2017a). The schematic file from Eeschema is the used to generate a PCB layout also called **PCBnew,** which is a powerful PCB design tool that runs (in the KICad EDA,) on Microsoft Windows and other major operating systems.(Charras & Tappero, 2017b). When the PCB design and the component footprint association are completed, the KiCad EDA in the PCBnew environment (Figure B.2 *and* Figure B.3*),* the Gerber files are then generated and sent for PCB production. The resulting PCB is displayed in Appendix B Figure B.4 and Figure B.5 is essentially the prototype of the system, a complete sensor node. It is portable, can be powered with solar energy, it can operate independently or cooperatively in the network, with other nodes.

## 5.3 System Concept and Functionality

Considering Figure 5.5, one can see how the nodes connect to each other and to the smartphone via a Bluetooth serial communication link. The three colour code notification smileys an also shown near the smartphone. Suppose there was a change in the IAQ in a room where solid fuel was being burnt, with the system installed, the one or more sensors on the sensor-nodes might pick up bad emissions. When this happens, the sensor node’s internal processing unit will process and determine if the IAQ is good, poor or bad by analysing the sensor data for pollutant levels. A good IAQ level is indicated by a glowing GREEN light emitting diode LED. However, if the IAQ is poor, the LED will glow YELLOW and sound the alarm, on the other hand, if the IAQ was bad the LED will be RED.

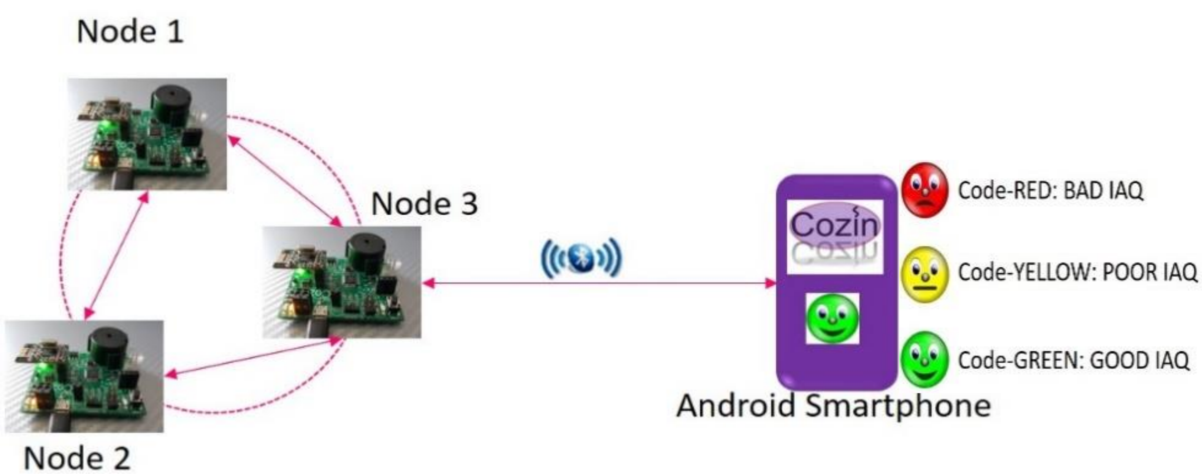



*Figure 5.5: Network communication, system function and notification*

The sensor data is also transmitted via Bluetooth to the smartphone where a special mobile APP will analyse the data and display the sensor reading on the phone's screen. The phone will also display the Green or Yellow or Red emojis on the screen with an audio message that would say “Code-Green, Good air quality” if the IAQ was good or “Code-yellow, Poor air quality” if the IAQ was poor and code-Red, Bad air quality if the IAQ was bad. The transition between the different level of indication and notification depends on the sensor readings in PPMs. Except for when the IAQ status was good, the system (Sensor-Node) will sound alarms different in tone and frequency depending on whether the IAQ status was poor or bad. It should be noted that, if the IAQ was poor or bad, the system sends notification (which includes the vibrations from the smartphone) persistently until the user takes appropriate action or actions. Such action could be opening the window to get in some fresh air or to facilitate the escape of harmful gases. However, when the IAQ status returns to good, the notification comes once and stops. The system will also notify the user with a sound tone periodically and light up a blue LED if there were no sensor connected to any of the nodes that constitute the network.

Taking a flashback, earlier in section 5.1 under the system description, looking at Figure 5.1, where the concept of a toy with an embedded sensor node was discussed. Now, also taking in consideration WHO data (as per

*Table 2.2*) that women and children are the groups most affected by IAP. Such a toy is designed to work only when the air quality status in the room is good and stop working when the pollution levels in the room become critical. When that happens, it is expected that the child will complain to the mother and she would take one or more of the following actions:

I. Let the child out of the room or kitchen into another room
II. Open the windows or take appropriate measures to ensure proper ventilation of the room.
III. Check, control the source, or stop if possible, the pollution from the source

After taking such action the levels of pollution would start to drop until the IAQ status returns to *‘Good’* again. Then with the IAQ status *Good*, the child’s toy would start to work again. With time, parental guidance, education and maybe basic infant instinct, the child would eventually learn that his or her toy does not work under certain conditions. It follows by implication that the child would hance avoid playing in such potentially polluted areas. Note that since the system is a network of sensors working together, the IAQ status notification happens on every node, could be through the activation of the auditory alarm or the indications on the connected smartphone. These features are expected to improve accessibility and user experience in homes where the system would be or has already been installed. Other more technical aspects of the system's functionality are presented in Appendix B.

# 6. Results

There is hardly any research that can be considered exhaustive; there will be some new study or findings and or improvement could still be made upon the work done by other researchers. However, at the end of every research, the findings and their implications must be presented as some results. This research was based on a construct whose validity depends on answering three research questions notably:

**i.** Could the system be used to effectively detect gaseous emissions, indoor air pollutants and alert users, considering that all WHO and field user data used in the development of the system are accurate?

**ii.** How does the system compare to the current state of the art of similar systems, in terms of detection, accuracy, range and feedback?

**iii.** What aspects of the system make it universally designed and or Accessible with-respect-to outreach and impact on user experience?

## 6.1 Compliance with Universal Design Principles

Cozin was designed to comply with the principles of Universal Design (UD) and the results obtained from laboratory tests show that the system does comply to a significant degree with at least five UD principles. COZiN's mobile interface offers the simplicity of use and enhances the user experience especially for people with disabilities. The app is simplified with a few OneTouch button functionality with no complex gestures required. The depth and the manner in which the system is compliant with these principles are described as follows:

- ***Equitable Use:*** The system can be used by professional and nonprofessional, most mobile users including people with disabilities such as the visually impaired and people with auditory impairments as has been demonstrated by the personas in section 4.3.2.2. The Mobile Application delivers three types of feedback information: auditory, tactile and Visual. The App also offers the system multiple language operability hence giving the system (COZIN) some accessibility features that make it equitable to a wide range of users.

- ***Flexibility in Use:*** The system, COZIN is relatively flexible. In its current state of development, the system provides many different functionality options the user can choose from and in its advanced state, when fully developed the system would have the potential to be customized to fit any user's needs. From the very beginning of the design and development process, the hardware is intrinsically built so that the user can choose to include additional features, personalized to meet his or her needs.
- ***Simple and Intuitive Use:*** The COZIN mobile interface is very intuitive and from all the surveys interviews, an overwhelming majority of the respondents said the COZIN mobile App was simple and easy to use (one touch to connect, one-touch 'ON', one-touch 'OFF'). Since no special training required, anyone with basic mobile phone knowledge can use the system with relative ease. The fundamental significance of linking the system to the mobile platform offers and ensures many users the opportunity to share their experience, ideas, suggestions for improvements and updates. Hence COZIN can be used intuitively.
- ***Perceptible Information:*** The pectoral screen display, contrast and colour representation is good. All alphanumeric characters are displayed with a font size of about 15 to 20-point font. Information is conveyed with images and colour to increase perceptibility and understanding. COZiN also provides visual, auditory and tactile perceptual feedback which significantly diminishes the need or use of screen reader support or program.
- ***Tolerance for Error:*** Cozin has a subroutine in its programming that gives it the ability to indicate an error if the sensor fails or gets disconnected. From the point of conception and throughout the whole development process, the system was built with open source hardware and software. This open source architecture empowers a tech-savvy-user who may wish to carry out simple maintenance on the system without the need of an expert. The mobile platform provides the user with all the security advantages already existing on any Android smartphone.

## 6.2 Experimental Lab Results

The laboratory experiment conducted with different elements notable, Alcohol, carbon dioxide, smoke, liquified petroleum gas (LPG) and carbon monoxide and the detection response by the system can be summarized in as follows:

*Table 6.1: Tabulation of Results from laboratory experiments with systems sensors*

| Test Carried out | Sensor response |
|---|---|
| Alcohol detection | Possible (Uncalibrated) |
| $CO_2$ detection | Possible (Uncalibrated) |
| Smoke detection | Possible (Uncalibrated) |
| LPG detection | Possible (Uncalibrated) |
| CO detection | Possible (Calibrated) |

The range and sensitivity detection in meters and PPM respectively, are still to be determined in subsequent testing and cross-referencing with the sensor manufacturer's datasheets.

## 6.3 Recurring Patterns and Health Outcome Indicator

The results are separated by category and listed by the question and some of the recurring patterns are briefly discoursed and shown in Table 6.2. Health Outcomes were not specifically evaluated for lack of the proper tools. Consequently, the participants were not particularly interviewed on that. However, the use of personas certainly compensated to some degree for the lack of evaluation on health outcomes by addressing accessibility for people with impairments.

**6.3.1 Recurring Patterns.** During the analysis of the results of the interview, it was necessary to group the question that showed some recurring patterns in the responses or answers to them. These were designated as GR1 and GR2 and were analysed as in the following outline:

**Question GR.1:** The first group of questions with similar response turned to also be those that the respondents answered eagerly and with ease. The responses to Questions 8, 9, 10, and 12 had the most consistent answers from the users. The responses have been tabulated in Table 6.2. All the respondents were given the freedom to ponder over a question that they needed more time to be sure and clarifications were given when it was necessary. The participants could also ask questions but it turned out however, that the four questions in the outline showed the participants had no such problems.

**Question GR.2:** Questions where classified into the following categories:

- User identification,
- Potential hazards
- Systems Usability and operability
- General opinion

*Table 6.2: Recurring Patterns from the interview Results and the most consistent responses.*

| Number | Question | Participant response |
|---|---|---|
| 8 | Would you like one installed in your home? | All participants said, yes, they would. |
| 9 | Would you buy the system if it were available for sale? | All participants said, they would, but at an affordable cost. |
| 10 | What aspects of the system do you like the most? You could give your dislikes as well. | (As a dislike) All participants said they worried about the Potential cost. |
| 12 | What are your general thoughts about the system and the whole experience? | All participants said they were generally Positive about the system. |

Note. Data and information collected from interviews during user testing.

**6.3.2 Health Outcome Indicator.** Although the evaluation of health outcomes from the use of solid fuels was not the focal point, of the research, the interviewees were still asked if they had experienced any health problems whatsoever, they thought was a consequence for using solid fuels. A question to which most of them answered they had not. It should, however, be noted that there was at least one person (participant number #333-M) among the interviewees who specifically stated that he had migraines. A follow-up question was then asked to ascertain how the respondent could be so sure. He then responded he experienced that only when he was using charcoal for cooking. That answer clarifies that the migraines could have only resulted from the use of charcoal, possibly due to inhalation of toxic fumes and other gaseous or particulate matter from the burning charcoal.

# 7. Discussions and Conclusion

## 7.1 Reasoned Comparative Discussion

There were challenges all through the interviewing process, as there was no possibility for online interview except face-to-face interviews. Researching a system like Cozin that is packed with innovation and other technological features is a big challenge. In a simple interview, the interviewee might be carried away with the technology in a way that might influence the answers or responses to the interview. In an interview particularly in cases where one must rely on the internet, the difficulties in question design, clarity, delivery and all that goes into the questioning and understanding of the responses from the interviewee, cannot be overemphasized. Although the internet is known for its convenience when it comes to communication, it can be disappointingly annoying if the network connection of one or both participating parties in the interview is poor. Otherwise, online interview would be a useful tool for reaching out to a wider range of respondents in a survey.

Any research interviews conducted with the use of the internet must ensure both interviewee and interviewer have a good bandwidth, network and data connection. Otherwise using a video chat, for example, may result in the video or audio quality being so poor that the interviewee might just give up. Also, depending on his or her time and location the interviewee or interviewer might only be available when one or both were in a noisy environment, such that, the interviewing process becomes relatively difficult if not impossible. Despite all these difficulties with online interviews, the face-to-face interview proved to be also challenging. However, with the right questions, careful planning, good timing and self-control and discipline the interviewing process would prove to be an exciting and enjoyable exercise.

There are many kinds of difficulties associated with research and development of assistive technology. Care must be taken not to choke the research paper or thesis with too much technical information that might confuse the readership or even dissuade them from reading what could have otherwise been an exciting paper on an interesting project. Finding the balance is key but certainly not an easy task. The author would have to carefully consider how to structure the presentation of findings and facts and relate them to the system being developed. Starting a project would sometimes lead to a point where some element of major importance to the project is needed but the developer might not be versed with it but since cancelling the project is not an option, some further study or research would have to be done.

During the development part of this project, a difficult situation associated with the software development for the mobile app arose. The app was crucial for the accessibility of the system, but the developer/inventor had no prior knowledge or experience in mobile programming, so it became necessary to improvise. Thankfully nowadays people seek solutions to every problem on the internet, that is how the MIT App Inventor was discovered and adapted for use in the development of the system. Owing to its simplicity and ease of use the App Inventor proved to be a very useful tool. It took less than 24 hours to figure out how it works, and a test program was ready with the next 2 days. In about a weeks' time after that, the first version of the mobile app was ready and has since been constantly improved and refined for better quality, simplicity and usability.

## 7.2 Conclusion

Although the whole project was a difficult task, the research and development process was challenging but it was also such a fun and an interesting experience. Occasionally the difficulties would fade away with the prospect and notion of creating or working on a system that would save lives and could potentially be a game changer for HAP. Every objective set forth at the start of the project has been met. The concept works and interviews show user interest to say the least. Although most accessibility features were only tested with personas, there is little doubt the system would excel among a wide range of users.

Jacob and Furgerson (2012), clarifies a lot in the following quote from The Qualitative Report (TQR) article volume 17 number 42, titled: Writing Interview Protocols and Conducting Interviews: Tips for Students New to the Field of Qualitative Research;

> As qualitative researchers who conduct interviews, we are privileged to be able to do research by talking to others, and we hope that our tips help students new to the method conduct interviews that are interesting and lead to a new understanding about the human condition. Researchers need people's stories for many reasons. They help us describe people, explain phenomena, and can lead to improvements in many fields of study. (Jacob & Furgerson, 2012)

A mixed research method combining both qualitative and qualitative methods of research and analysis had been chosen and used to carry out and implement this project and the results achieved from the research have been outlined. Finally, to address whether the research questions were answered, a cross-examination of the methods and the results with the system development would show if the project achieved the objectives inferred.

The research questions dealt with; Research System Design and Development, System functionality and Efficacy, Usability, Accessibility, impact on users and User Experience. It was hypothesized in the problem statement and in section 4.1.3 that a technological solution would detect the pollutants and hence warn the users of the indoor air quality. This would then lead to a reduction in the impact of the effect of indoor pollution from using solid fuels. The system had to be universally designed. The system description and functionality show its compliance with 5 UD principles in terms of functionality, efficacy, usability as was evident from the responses to the interview during user testing. Also, the system accessibility was demonstrated by the persona characters used in subsection 4.3.2. Essentially all three research questions have been addressed and answered in sections 4, 5, and 6 covering the research method, system description, design and functionality and the results respectively. Also, all four objectives beginning from the collection and analysis of data from WHO, through the determination of what gaseous pollutants are the most dangerous and how to enhance detection (Appendix D) according to WHO guidelines and introducing HCI for innovation and better accessibility (2.5, and 5.1) to the design and prototyping (Appendix B and Appendix C).

A lot was learnt about carrying out research by interview, a fraction from the task and from the interviewees too. However, this report should not be considered as exhaustive, it stands more of a basic approach to exploring and doing research on Assistive technologies and this system, Cozin, as was named, is still very much subject to improvements. The interview design and questions would also need to be improved upon. Possibly, better than some erstwhile studies, new studies where user testing, interviews and or other research methods would certainly lead to improvements. Not only in the research methods used but also to improve the systems for better accessibility, usability, user experience and affordability.

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# Appendices

## Appendix A

## Universal Design Principles

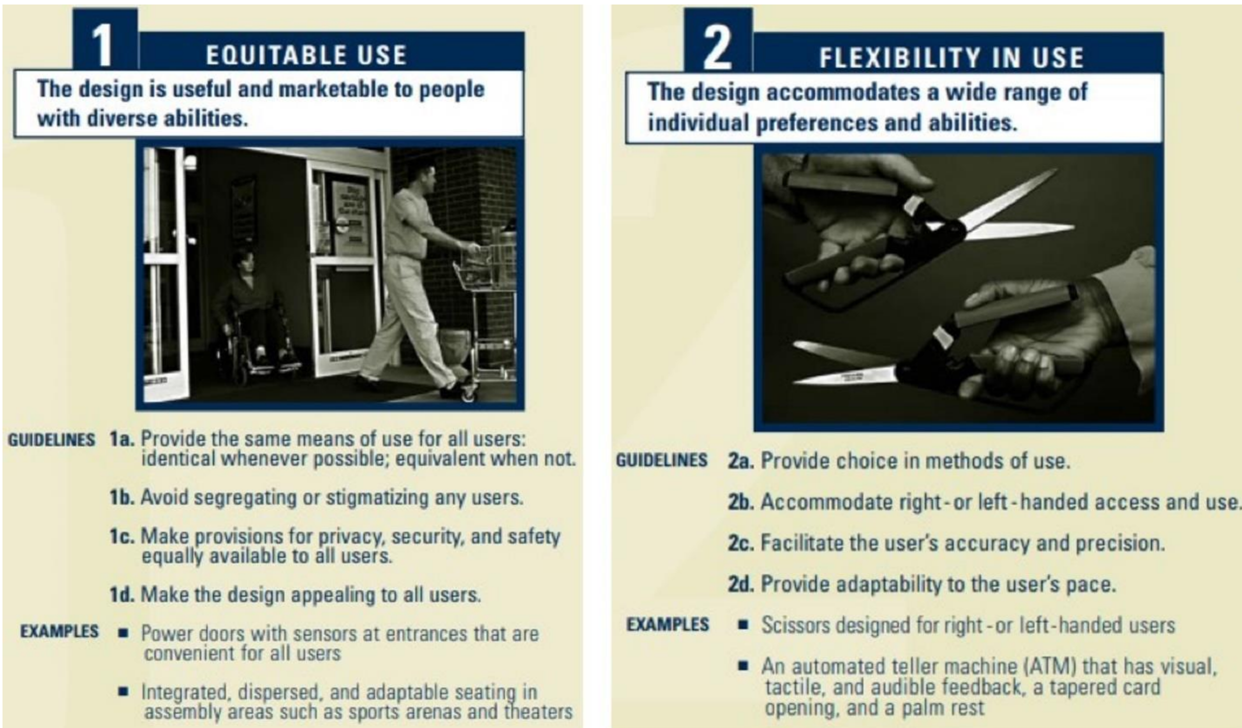


*Figure A.1: The First and Second Principles Of Universal Design* (The Center for Universal Design, 1997)

Note. Reprinted (and adapted) from Google Arts & Culture, "The Principles of Universal Design," v.2.0 14/1/97. Image created by The NC State University, Center for Universal Design, College of Design.

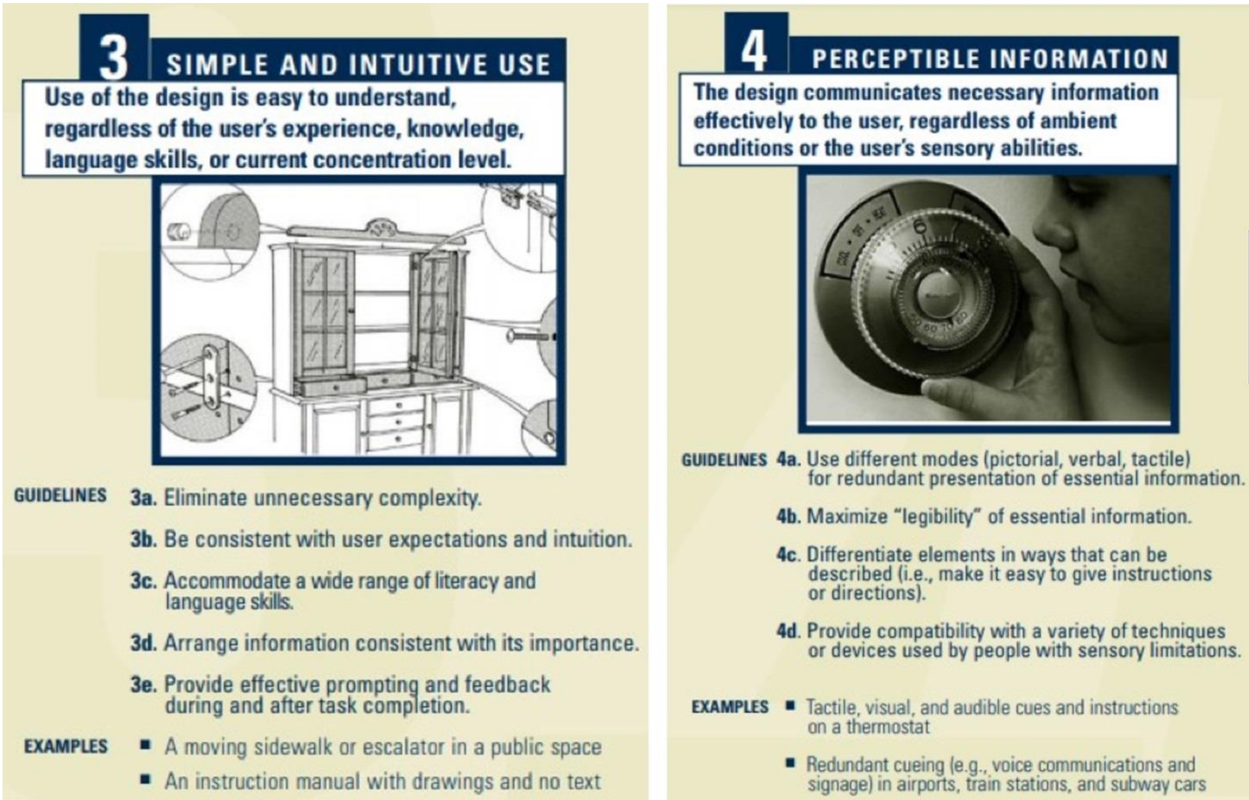


*Figure A.2: The Third and Fourth Principles of Universal Design* (The Center for Universal Design, 1997)

Note. Reprinted (and adapted) from Google Arts & Culture, "The Principles of Universal Design," v.2.0 14/1/97. Image created by The NC State University, Center for Universal Design, College of Design.

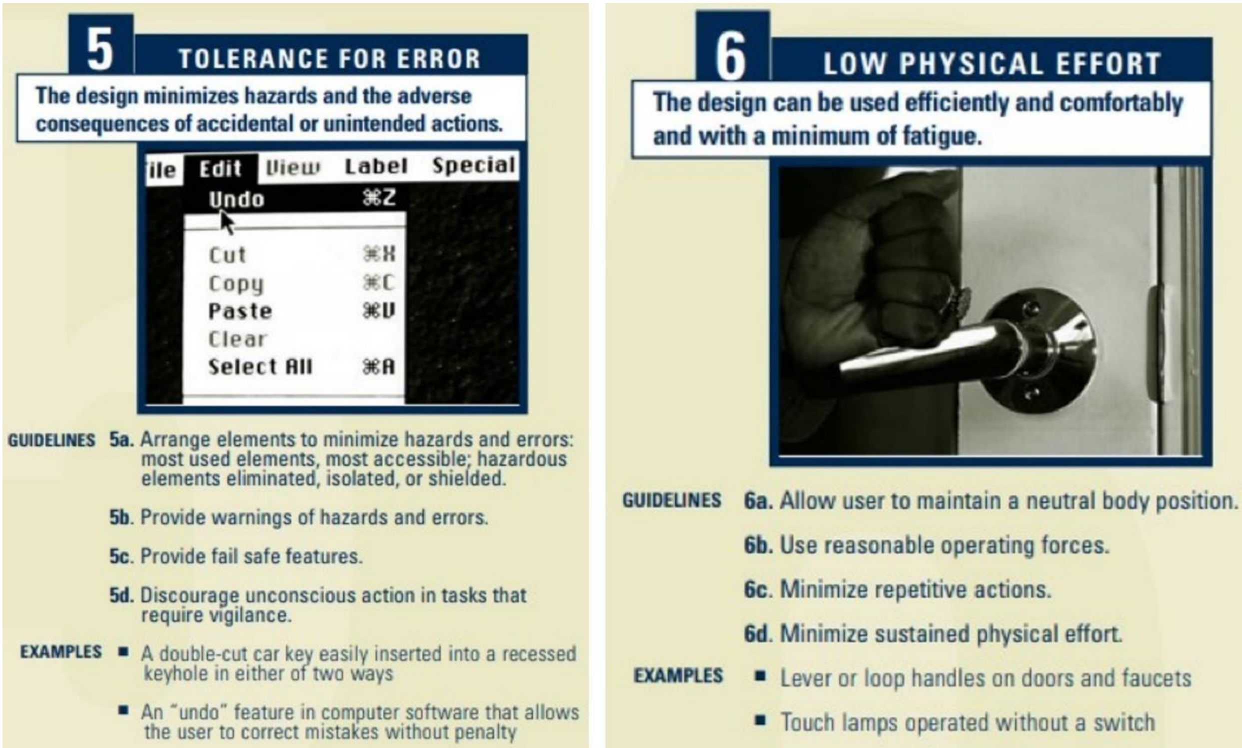


*Figure A.3: The Fifth and Sixth Principles of Universal Design* (The Center for Universal Design, 1997)

Note. Reprinted (and adapted) from Google Arts & Culture, "The Principles of Universal Design," v.2.0 14/1/97. Image created by The NC State University, Center for Universal Design, College of Design.

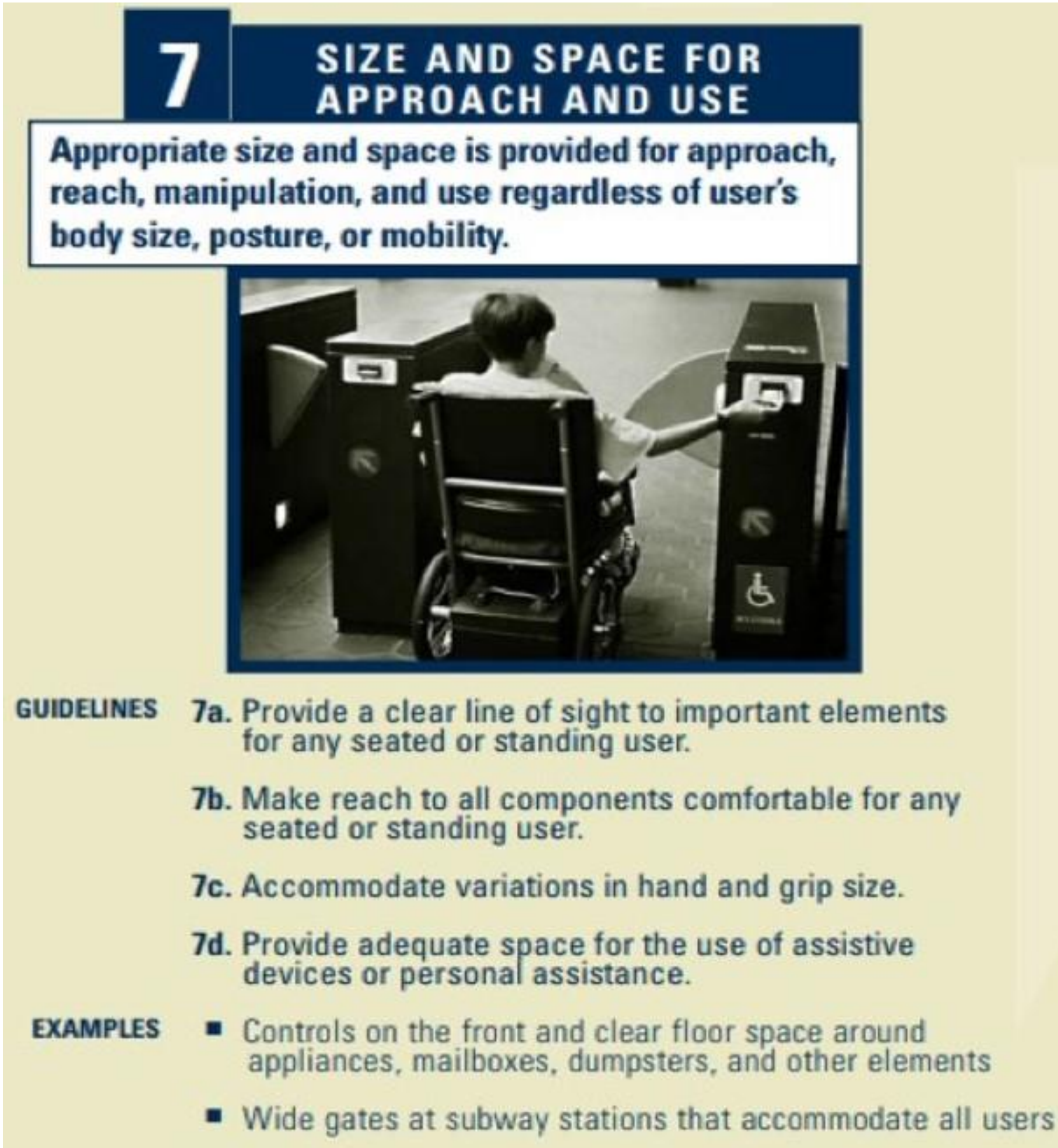


*Figure A.4: The Seventh Principles of Universal Design* (The Center for Universal Design, 1997)

Note. Reprinted (and adapted) from Google Arts & Culture, "The Principles of Universal Design," v.2.0 14/1/97. Image created by The NC State University, Center for Universal Design, College of Design.

# Appendix B

## Hardware and Screenshots of System's PCB Designs

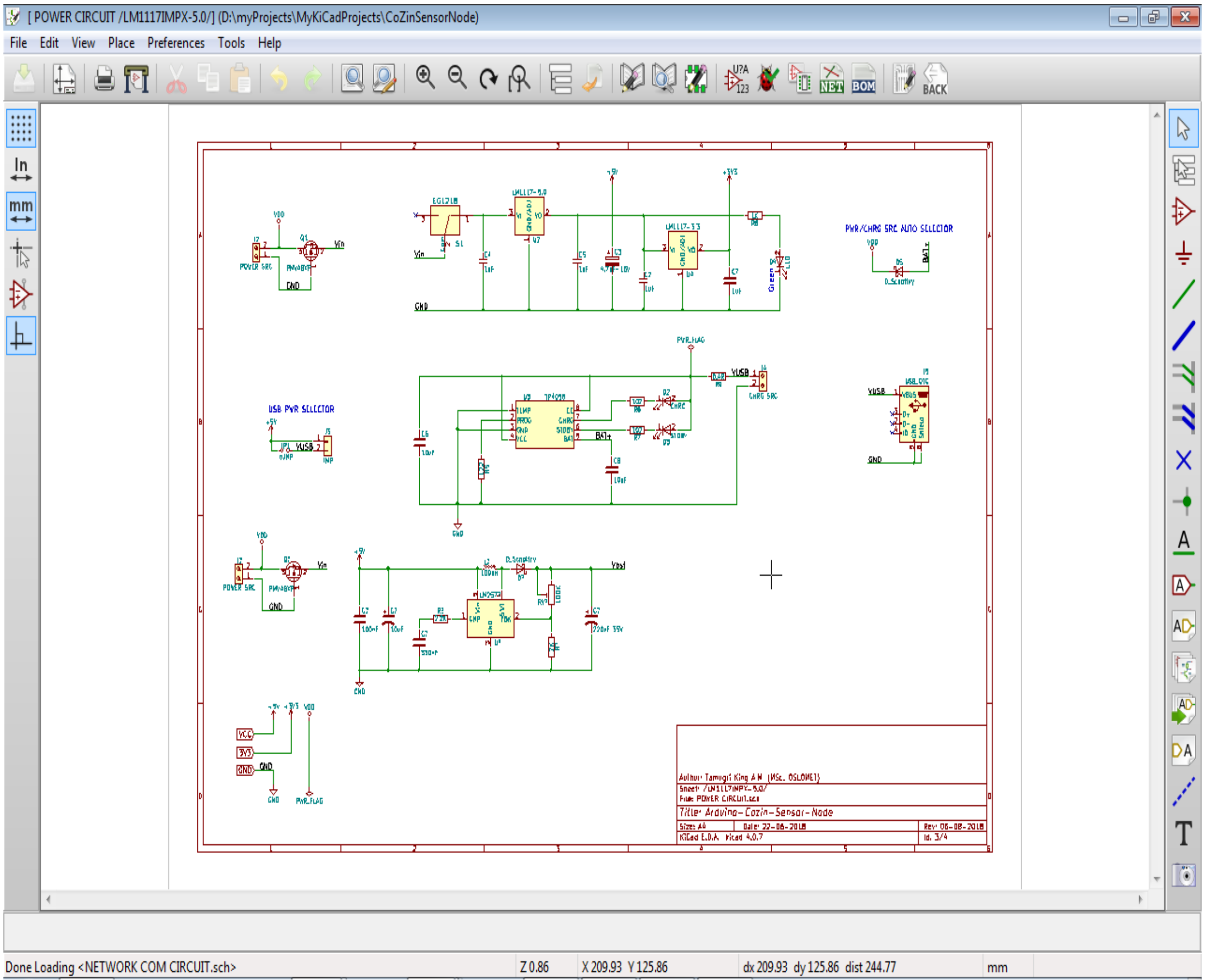

*Figure B.1: Screenshot of system prototype Hardware PCB circuit design schematics*
Note. Screenshot from KiCad EDA (computer program)

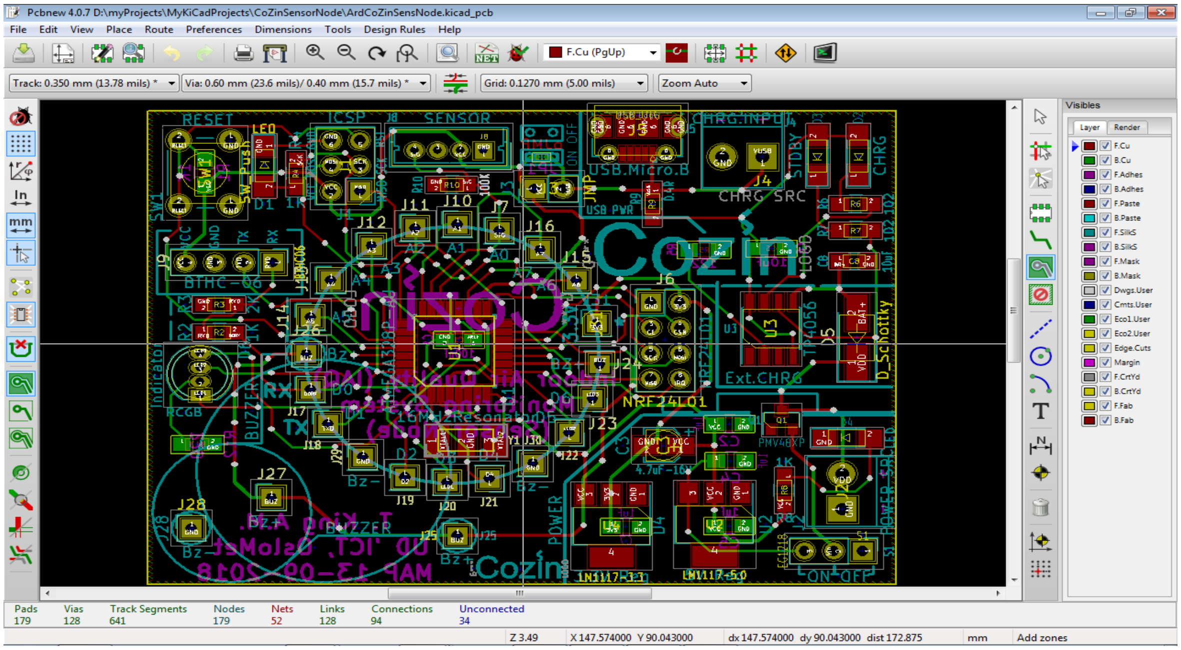

*Figure B.2: Screenshot of system prototype Hardware PCB design layout, default view*

Note. Screenshot from KiCad EDA (computer program)

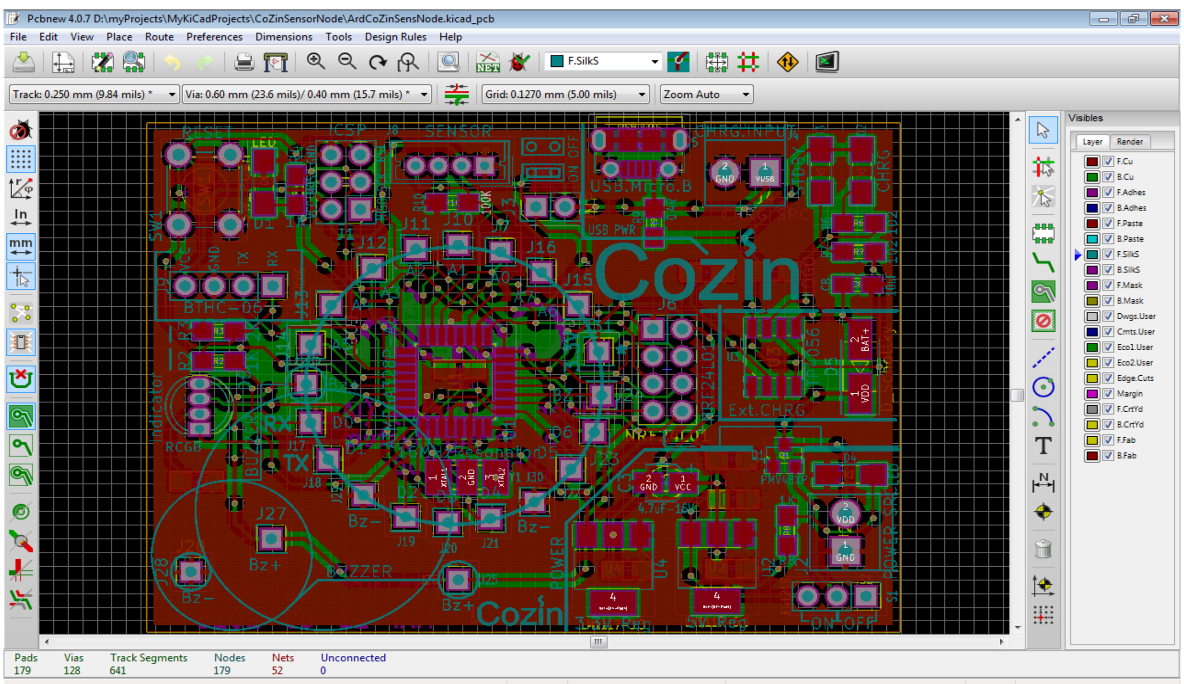

*Figure B.3: Screenshot of system prototype Hardware PCB design layout, OpenGL view*

Note. Screenshot from KiCad EDA (computer program)

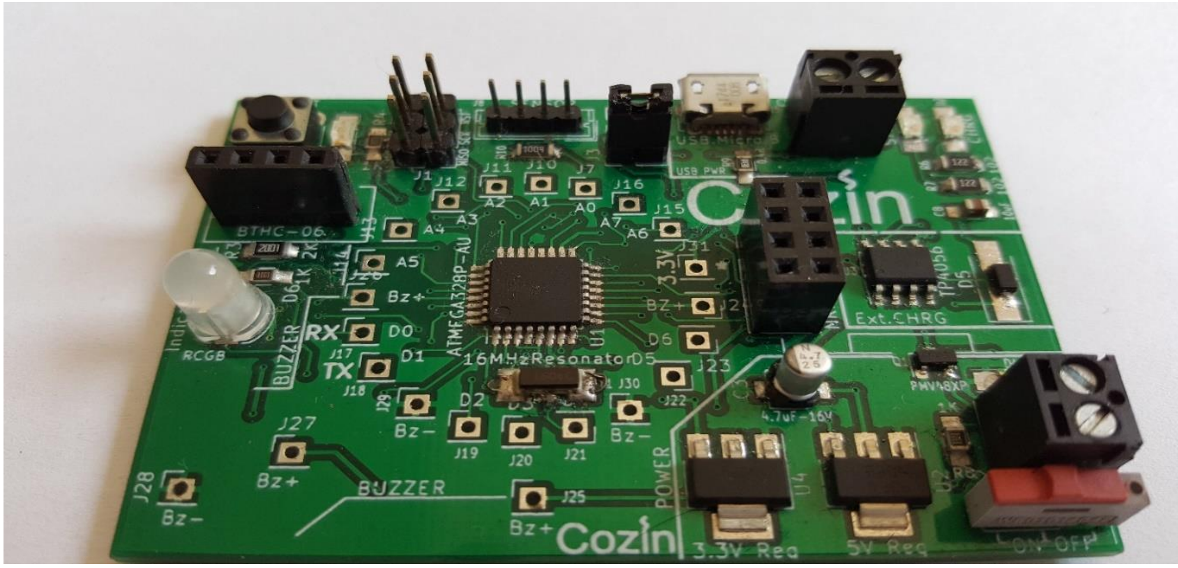


*Figure B.4: A Picture of A fully complete Prototype of Sensor Node (Finished PCB with components)*

Note. Image taken with Samsung Galaxy S6 (Smartphone)


*Figure B.5: A Picture of A fully complete Prototype powered with USB cable*

Note. Image taken with Samsung Galaxy S6 (Smartphone)

## Appendix C

### Software: Arduino C-Language Code and Screenshots of Mobile App

```
/*************************************************************************
SCHOOL:       OSLO METROPOLITAN UNIVERSITY
PROGRAMME:    UNIVERSAL DESIGN OF ICT
COURSE:       MASTER THESIS PROJECT
TITLE:        INDOOR AIR QUALITY SENSOR WARNING SYSTEM FOR HOMES USING
              SOLID FUELS: A UNIVERSAL DESIGN APROACH INTEGRATING SENSOR
              NETWORK WITH HUMAN COMPUTER INTERACTION
*************************************************************************
NAME:               TAMUGRI KING A. M.
STUDENT ID#:        S320799
DATE:               24/08/2018
LATEST UPDATE:      12/12/2018, 01/02/2019, 29/03/2019
*************************************************************************
THIS PROGRAM ESSENTIALLY SAMPLES DATA FROM AN AIR QUALITY SENSOR AND THEN USES
AN HC-12 TRANSCEIVER TO TRANSMITS AND RECEIVE DATA TO AND FROM OTHER SENSOR
NODES A SENSOR NETWORK FOR MONITORING INDOOR AIR QUALITY (IAQ)
*************************************************************************/


/*¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤ GLOBAL VARIABLES ¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤*/
#include <SoftwareSerial.h>

SoftwareSerial HC12(9, 11);              // HC12 TX, HC12 RX
int iEMA = 0;
int RED = 3;
int BLUE = 5;
int GREEN = 6;
int BUZZER = 7;
int HC12SET = 8;
int _SensOput = A0;

void setup() {

HC12.begin(9600);                        // Serial port to HC12
Serial.begin(9600);                      // Serial port to computer

        pinMode(RED, OUTPUT);
        pinMode(BLUE, OUTPUT);
        pinMode(GREEN, OUTPUT);
        pinMode(BUZZER, OUTPUT);
```

```
	pinMode(HC12SET, OUTPUT);
	pinMode(_SensOput, INPUT);

	digitalWrite(HC12SET, HIGH);		// SET HC12 TO Normal Mode
	delay(80);
}

/*¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤ TRANSMITS DATA VIA HC12 TRANCEIVER ¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤*/
void Transmit(String TxData) {

	HC12.print(TxData+'?');				// Send that data to HC-12
	delay (100);
}

/*¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤ GET RECEIVED DATA VIA HC12 TRANCEIVER ¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤*/
int Receive() {
String RxData = "";
	while (HC12.available()) RxData = HC12.readStringUntil('?');
	delay (100);
	return RxData.toInt();
}

/*¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤ GET SENSOR DATA ¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤*/
int Get_SensorData() {
	int Sens_Data = analogRead(_SensOput);
	return Sens_Data;
}

/*¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤ FILTERING DATA ¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤*/
#define N 16

float ExMoAvFilt(int Smpl){

float d_Sum;
	float alFa = 2/(1+N);
	for(int k = 1; k <= 5; k++) d_Sum += Get_SensorData();
	float EMA = d_Sum/5;
	EMA = (Smpl*alFa)+(EMA*(1-alFa));
	return EMA;
}// End filt.

/*¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤ MAIN SYSTEM FUNCTION ¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤*/
void loop() {
```

```
char q = '0';
	//while (q != '#') WelcomeScr(q);	// comfirm ID and start system
	int _SensData = Get_SensorData();
	if (_SensOput == 0) _SensData = (Receive());
	else Transmit(String(_SensData));
	String _pStr = ((Cozin2MobCom(ExMoAvFilt(_SensData)) +
String(ExMoAvFilt(_SensData))));
	Serial.println(_pStr);
}

/*¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤ SOUND THE ALARM  ¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤*/
void set_Alarm(int x, int z) {
  if (x != 0 || z != 0) tone(BUZZER, x, z);
  else noTone(BUZZER);
}

/*¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤ SIGNALING IAQ STATUS ON MOBILE & RGB  ¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤*/
String Cozin2MobCom(float IAQdata) {

String _Str;
int goodIAQTshold = 45;				// Set Threshold Value For Good IAQ
int poorIAQTshold = 100;			// Set Threshold Value For POOR IAQ

	if (IAQdata > poorIAQTshold) {		// Watchout for BAD IAQ threshold
		digitalWrite(RED, HIGH);
		digitalWrite(BLUE, LOW);
		digitalWrite(GREEN, LOW);
		set_Alarm(850, 100);
		delay (100);
		set_Alarm(580, 100);
		_Str = "BAD_IAQ: ";
	}
	else if (IAQdata >= goodIAQTshold && IAQdata <= poorIAQTshold) {
		for (int i = 2; i > 0; i--) {		// Set LED to YELLOW (RED & GREEN)
			set_Alarm(600, 100);
			digitalWrite(GREEN, LOW);
			digitalWrite(RED, HIGH);
			delay (60);
			digitalWrite(RED, LOW);
			digitalWrite(GREEN, HIGH);
			delay (60);
		}
		delay (1000);
		_Str = "POOR_IAQ: ";
```

```
	}
	else if (IAQdata < goodIAQTshold && IAQdata > 0) {
		set_Alarm(0, 0);
		digitalWrite(RED, LOW);
		digitalWrite(BLUE, LOW);
		digitalWrite(GREEN, HIGH);
		_Str = "GOOD_IAQ: ";
	}
	else if (analogRead(_SensOput) == 0) {// ERROR
		digitalWrite(RED, LOW);
		digitalWrite(GREEN, LOW);
		digitalWrite(BLUE, HIGH);
		for (int i = 4; i > 0; i--) {
			set_Alarm(600, 100);
			delay (120);
		}
		delay (510);
		_Str = "ERROR(!): ";
	}
	return _Str;
}
/*¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤ WELCOME SCREEN ¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤¤*/
void WelcomeScr(char p){
	_Str = "STARTING: COZiN";
	p = Serial.read();
	delay (1000);
}
/*END WELCOME SCREEN*/
```

*Listing C.1: Arduino C- Language Code (Sketch) running the system (Cozin) Hardware*

Note. Sketch Copied from Arduino IDE (computer program)

There are many commercially available programming tools and platforms (of which the Android platform is one of the largest, based on the number of phones running it) use to develop mobile application such as **Appcelerator**, **PhoneGap** and **Xamarin** which makes use of C# (meaning C-Sharp). Others include, **NativeScript** (that employs JavaScript), **MonoCross** which is compatible with C# and **Microsoft .NET**. Some beginners level developers even try their luck with **Microsoft Visual Studio**, which also incorporates C# and Visual Basic. However, the MIT App Inventor 2 differs from all these other mobile app developer's tools for being an opensource mobile app development too amongst other reasons.

"Mit App Inventor is a free drag-and-drop, block-based visual programming language that enables people, regardless of their coding experience, to create mobile apps for Android devices." (Kamriani & Roy, 2016)

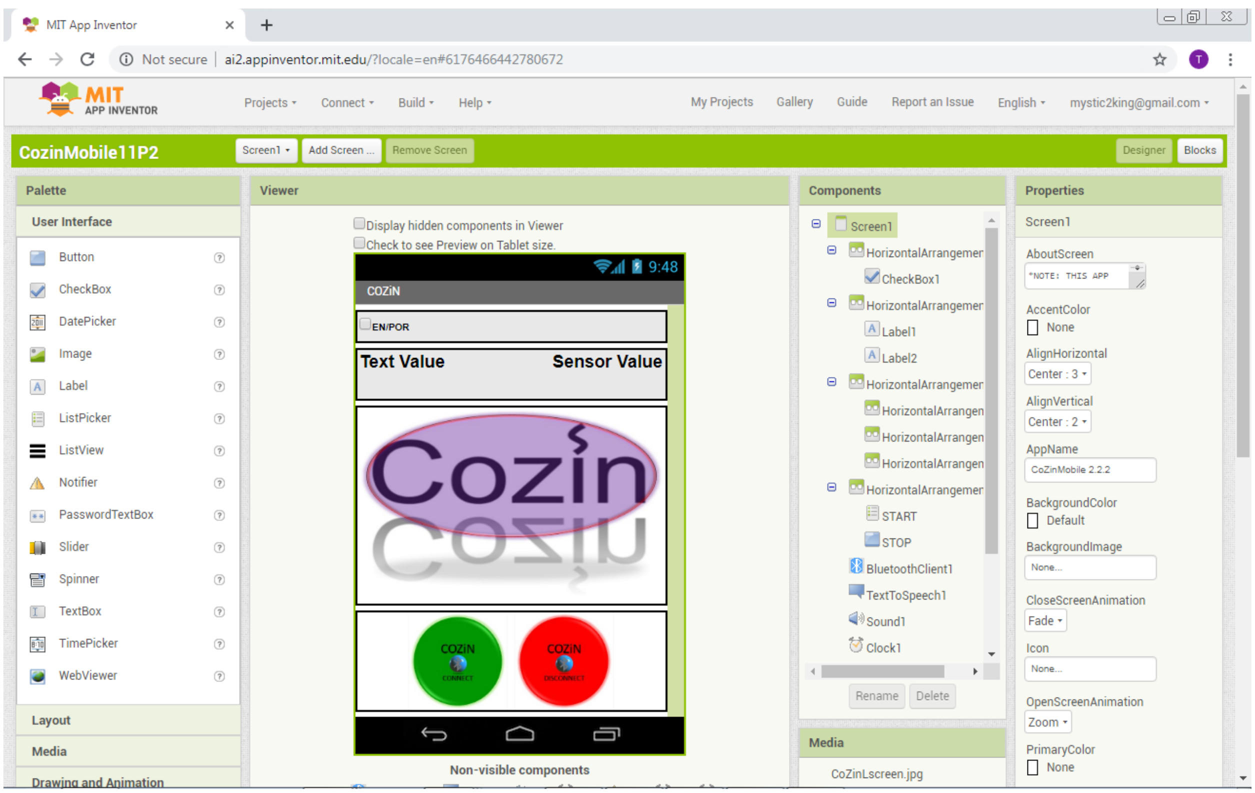


*Figure C.1: The MIT App Inventor: Designer View*

Note. Screenshot of MIT App Inventor Designer view: Opensource Online Visual Programming on cloud.

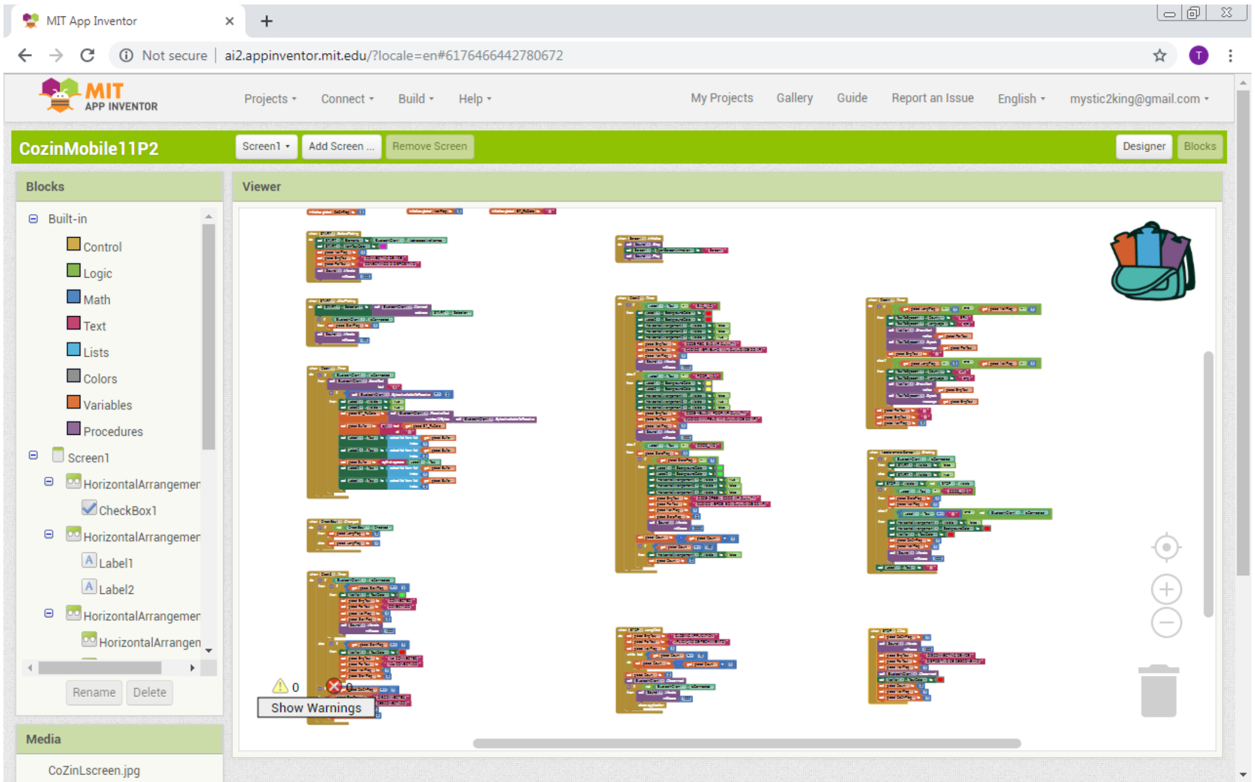


*Figure C.2: The MIT App Inventor Block visual programming interface View*

Note. Screenshot of MIT App Inventor Designer view: Opensource Online Visual Programming on cloud.

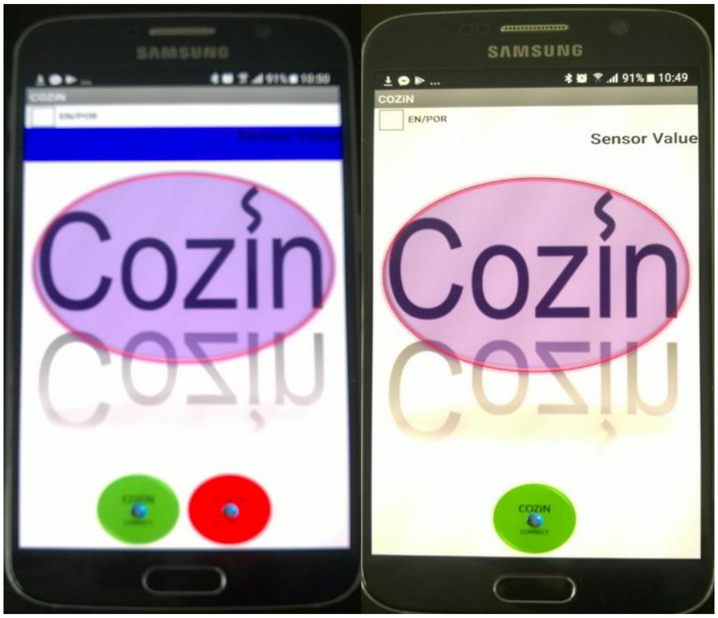


*Figure C.3: A picture of a Smartphone Running the Cozin Mobile App*

Note. A snapshot of the Cozin app as it appears of the phone running it.

Appendix D

Laboratory Experimental Procedure and Results on Sensor Calibration

A simple laboratory experiment was conducted to test the sensor (which is a grove air quality sensor) to compare the readings with a standard sensor in order to ascertain that the readings or measurement of the system are concurrent with standardized ppm unit measurements.


*Figure D.1: A cluster of pictures showing the sensor calibration process setup in the laboratory*

**Apparatus setup and procedure**: The setup was simple; a transparent 20 litre bucket was used to collect fumes from a diesel generator and the lid was closed. Back in the laboratory the both the standard and the test sensors were placed in the bucket containing CO reach fumes from the exhaust of the generator at the same time as shown in Figure D.1. The standard sensor can be clearly seen on the table on the right side of the figure and the text sensor connected to computer and the bucket with both sensors in it, on the top and bottom left. The readings of both sensors are closely monitored while carefully adjusting the test sensor to ensure reading match. Occasionally the experiment is stopped to make changes in the code as part of the calibration.

**Results:** The procedure is repeated until both sensor outputs are similar. Then the test sensor has been calibrated to standard. Table D.1 shows the data downloaded from the standard sensor. The date, time and values taken during the experiment are clearly tabulated. The graph generated (as seen in Figure D.2) was observed to identically close in similarity to the graph generated by the Arduino serial plotter.

*Table D.1: Resultant sensor reading data from Laboratory measurements during system testing and calibration*

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/201914:38:17 | 0 | 0 | 0 |
| 28/Feb/2019 14:38:37 | 20 | 0 | 0 |
| 28/Feb/2019 14:38:57 | 40 | 0 | 0 |
| 28/Feb/2019 14:39:17 | 60 | 0 | 0 |
| 28/Feb/2019 14:39:37 | 80 | 0 | 0 |
| 28/Feb/2019 14:39:57 | 100 | 0 | 0 |
| 28/Feb/2019 14:40:17 | 120 | 0 | 0 |
| 28/Feb/2019 14:40:37 | 140 | 0 | 0 |
| 28/Feb/2019 14:40:57 | 160 | 10.50979 | 0 |
| 28/Feb/2019 14:41:17 | 180 | 27.13297 | 0 |
| 28/Feb/2019 14:41:37 | 200 | 37.12267 | 0 |
| 28/Feb/2019 14:41:57 | 220 | 44.39695 | 0 |
| 28/Feb/2019 14:42:17 | 240 | 50.11428 | 0 |
| 28/Feb/2019 14:42:37 | 260 | 55.90146 | 0 |
| 28/Feb/2019 14:42:57 | 280 | 60.58141 | 0 |
| 28/Feb/2019 14:43:17 | 300 | 64.22836 | 0 |
| 28/Feb/2019 14:43:37 | 320 | 60.01059 | 0 |
| 28/Feb/2019 14:43:57 | 340 | 42.45268 | 0 |
| 28/Feb/2019 14:44:17 | 360 | 35.94352 | 0 |
| 28/Feb/2019 14:44:37 | 380 | 30.67385 | 0 |
| 28/Feb/2019 14:44:57 | 400 | 22.90903 | 0 |
| 28/Feb/2019 14:45:17 | 420 | 18.8236 | 0 |
| 28/Feb/2019 14:45:37 | 440 | 15.70617 | 0 |
| 28/Feb/2019 14:45:57 | 460 | 13.05319 | 0 |
| 28/Feb/2019 14:46:17 | 480 | 11.56815 | 0 |
| 28/Feb/2019 14:46:37 | 500 | 9.687278 | 0 |
| 28/Feb/2019 14:46:57 | 520 | 6.638721 | 0 |
| 28/Feb/2019 14:47:17 | 540 | 6.35375 | 0 |

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/2019 14:47:37 | 560 | 6.698347 | 0 |
| 28/Feb/2019 14:47:57 | 580 | 5.877892 | 0 |
| 28/Feb/2019 14:48:17 | 600 | 4.509358 | 0 |
| 28/Feb/2019 14:48:37 | 620 | 4.515867 | 0 |
| 28/Feb/2019 14:48:57 | 640 | 3.834059 | 0 |
| 28/Feb/2019 14:49:17 | 660 | 3.14606 | 0 |
| 28/Feb/2019 14:49:37 | 680 | 2.239197 | 0 |
| 28/Feb/2019 14:49:57 | 700 | 1.848901 | 0 |
| 28/Feb/2019 14:50:17 | 720 | 0 | 0 |
| 28/Feb/2019 14:50:37 | 740 | 0 | 0 |
| 28/Feb/2019 14:50:57 | 760 | 0 | 0 |
| 28/Feb/2019 14:51:17 | 780 | 0 | 0 |
| 28/Feb/2019 14:51:37 | 800 | 0 | 0 |
| 28/Feb/2019 14:51:57 | 820 | 0 | 0 |
| 28/Feb/2019 14:52:17 | 840 | 0 | 0 |
| 28/Feb/2019 14:52:37 | 860 | 0 | 0 |
| 28/Feb/2019 14:52:57 | 880 | 0 | 0 |
| 28/Feb/2019 14:53:17 | 900 | 0 | 0 |
| 28/Feb/2019 14:53:37 | 920 | 0 | 0 |
| 28/Feb/2019 14:53:57 | 940 | 0 | 0 |
| 28/Feb/2019 14:54:17 | 960 | 0 | 0 |
| 28/Feb/2019 14:54:37 | 980 | 0 | 0 |
| 28/Feb/2019 14:54:57 | 1000 | 0 | 0 |
| 28/Feb/2019 14:55:17 | 1020 | 0 | 0 |
| 28/Feb/2019 14:55:37 | 1040 | 0 | 0 |
| 28/Feb/2019 14:55:57 | 1060 | 0 | 0 |
| 28/Feb/2019 14:56:17 | 1080 | 0 | 0 |
| 28/Feb/2019 14:56:37 | 1100 | 0 | 0 |
| 28/Feb/2019 14:56:57 | 1120 | 0 | 0 |
| 28/Feb/2019 14:57:17 | 1140 | 0 | 0 |

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/2019 14:57:37 | 1160 | 0 | 0 |
| 28/Feb/2019 14:57:57 | 1180 | 0 | 0 |
| 28/Feb/2019 14:58:17 | 1200 | 0 | 0 |
| 28/Feb/2019 14:58:37 | 1220 | 0 | 0 |
| 28/Feb/2019 14:58:57 | 1240 | 0 | 0 |
| 28/Feb/2019 14:59:17 | 1260 | 0 | 0 |
| 28/Feb/2019 14:59:37 | 1280 | 0 | 0 |
| 28/Feb/2019 14:59:57 | 1300 | 0 | 0 |
| 28/Feb/2019 15:00:17 | 1320 | 0 | 0 |
| 28/Feb/2019 15:00:37 | 1340 | 0 | 0 |
| 28/Feb/2019 15:00:57 | 1360 | 0 | 0 |
| 28/Feb/2019 15:01:17 | 1380 | 0 | 0 |
| 28/Feb/2019 15:01:37 | 1400 | 6.054568 | 0 |
| 28/Feb/2019 15:01:57 | 1420 | 9.052065 | 0 |
| 28/Feb/2019 15:02:17 | 1440 | 10.56152 | 0 |
| 28/Feb/2019 15:02:37 | 1460 | 12.68052 | 0 |
| 28/Feb/2019 15:02:57 | 1480 | 13.87818 | 0 |
| 28/Feb/2019 15:03:17 | 1500 | 15.08689 | 0 |
| 28/Feb/2019 15:03:37 | 1520 | 16.36899 | 0 |
| 28/Feb/2019 15:03:57 | 1540 | 16.79162 | 0 |
| 28/Feb/2019 15:04:17 | 1560 | 18.02392 | 0 |
| 28/Feb/2019 15:04:37 | 1580 | 18.71347 | 0 |
| 28/Feb/2019 15:04:57 | 1600 | 19.10773 | 0 |
| 28/Feb/2019 15:05:17 | 1620 | 19.26688 | 0 |
| 28/Feb/2019 15:05:37 | 1640 | 20.02118 | 0 |
| 28/Feb/2019 15:05:57 | 1660 | 20.29582 | 0 |
| 28/Feb/2019 15:06:17 | 1680 | 21.06807 | 0 |
| 28/Feb/2019 15:06:37 | 1700 | 20.98254 | 0 |
| 28/Feb/2019 15:06:57 | 1720 | 21.03672 | 0 |
| 28/Feb/2019 15:07:17 | 1740 | 20.76221 | 0 |

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/2019 15:07:37 | 1760 | 18.32935 | 0 |
| 28/Feb/2019 15:07:57 | 1780 | 16.64502 | 0 |
| 28/Feb/2019 15:08:17 | 1800 | 15.14035 | 0 |
| 28/Feb/2019 15:08:37 | 1820 | 13.49695 | 0 |
| 28/Feb/2019 15:08:57 | 1840 | 12.19296 | 0 |
| 28/Feb/2019 15:09:17 | 1860 | 12.02216 | 0 |
| 28/Feb/2019 15:09:37 | 1880 | 11.52113 | 0 |
| 28/Feb/2019 15:09:57 | 1900 | 10.89605 | 0 |
| 28/Feb/2019 15:10:17 | 1920 | 10.01889 | 0 |
| 28/Feb/2019 15:10:37 | 1940 | 9.819888 | 0 |
| 28/Feb/2019 15:10:57 | 1960 | 9.805653 | 0 |
| 28/Feb/2019 15:11:17 | 1980 | 9.447208 | 0 |
| 28/Feb/2019 15:11:37 | 2000 | 9.709141 | 0 |
| 28/Feb/2019 15:11:57 | 2020 | 8.781152 | 0 |
| 28/Feb/2019 15:12:17 | 2040 | 8.653004 | 0 |
| 28/Feb/2019 15:12:37 | 2060 | 8.769484 | 0 |
| 28/Feb/2019 15:12:57 | 2080 | 8.614397 | 0 |
| 28/Feb/2019 15:13:17 | 2100 | 8.586664 | 0 |
| 28/Feb/2019 15:13:37 | 2120 | 8.646917 | 0 |
| 28/Feb/2019 15:13:57 | 2140 | 8.349588 | 0 |
| 28/Feb/2019 15:14:17 | 2160 | 8.109564 | 0 |
| 28/Feb/2019 15:14:37 | 2180 | 8.27327 | 0 |
| 28/Feb/2019 15:14:57 | 2200 | 8.358093 | 0 |
| 28/Feb/2019 15:15:17 | 2220 | 8.187136 | 0 |
| 28/Feb/2019 15:15:37 | 2240 | 8.361448 | 0 |
| 28/Feb/2019 15:15:57 | 2260 | 8.108924 | 0 |
| 28/Feb/2019 15:16:17 | 2280 | 8.019429 | 0 |
| 28/Feb/2019 15:16:37 | 2300 | 7.75319 | 0 |
| 28/Feb/2019 15:16:57 | 2320 | 8.158801 | 0 |
| 28/Feb/2019 15:17:17 | 2340 | 8.01932 | 0 |

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/2019 15:17:37 | 2360 | 7.954496 | 0 |
| 28/Feb/2019 15:17:57 | 2380 | 7.980802 | 0 |
| 28/Feb/2019 15:18:17 | 2400 | 7.946882 | 0 |
| 28/Feb/2019 15:18:37 | 2420 | 7.869465 | 0 |
| 28/Feb/2019 15:18:57 | 2440 | 7.89847 | 0 |
| 28/Feb/2019 15:19:17 | 2460 | 7.850409 | 0 |
| 28/Feb/2019 15:19:37 | 2480 | 7.784591 | 0 |
| 28/Feb/2019 15:19:57 | 2500 | 8.053226 | 0 |
| 28/Feb/2019 15:20:17 | 2520 | 7.762078 | 0 |
| 28/Feb/2019 15:20:37 | 2540 | 7.792188 | 0 |
| 28/Feb/2019 15:20:57 | 2560 | 7.79512 | 0 |
| 28/Feb/2019 15:21:17 | 2580 | 7.791694 | 0 |
| 28/Feb/2019 15:21:37 | 2600 | 8.112691 | 0 |
| 28/Feb/2019 15:21:57 | 2620 | 8.101442 | 0 |
| 28/Feb/2019 15:22:17 | 2640 | 7.912372 | 0 |
| 28/Feb/2019 15:22:37 | 2660 | 8.037525 | 0 |
| 28/Feb/2019 15:22:57 | 2680 | 8.094918 | 0 |
| 28/Feb/2019 15:23:17 | 2700 | 7.952779 | 0 |
| 28/Feb/2019 15:23:37 | 2720 | 7.943947 | 0 |
| 28/Feb/2019 15:23:57 | 2740 | 8.068933 | 0 |
| 28/Feb/2019 15:24:17 | 2760 | 7.694624 | 0 |
| 28/Feb/2019 15:24:37 | 2780 | 7.736106 | 0 |
| 28/Feb/2019 15:24:57 | 2800 | 7.922608 | 0 |
| 28/Feb/2019 15:25:17 | 2820 | 7.621766 | 0 |
| 28/Feb/2019 15:25:37 | 2840 | 7.699234 | 0 |
| 28/Feb/2019 15:25:57 | 2860 | 7.850152 | 0 |
| 28/Feb/2019 15:26:17 | 2880 | 7.680138 | 0 |
| 28/Feb/2019 15:26:37 | 2900 | 7.83079 | 0 |
| 28/Feb/2019 15:26:57 | 2920 | 7.805226 | 0 |
| 28/Feb/2019 15:27:17 | 2940 | 7.853279 | 0 |

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/2019 15:27:37 | 2960 | 7.69084 | 0 |
| 28/Feb/2019 15:27:57 | 2980 | 8.02562 | 0 |
| 28/Feb/2019 15:28:17 | 3000 | 7.763358 | 0 |
| 28/Feb/2019 15:28:37 | 3020 | 7.679612 | 0 |
| 28/Feb/2019 15:28:57 | 3040 | 7.797303 | 0 |
| 28/Feb/2019 15:29:17 | 3060 | 7.845021 | 0 |
| 28/Feb/2019 15:29:37 | 3080 | 7.615377 | 0 |
| 28/Feb/2019 15:29:57 | 3100 | 7.805474 | 0 |
| 28/Feb/2019 15:30:17 | 3120 | 7.800311 | 0 |
| 28/Feb/2019 15:30:37 | 3140 | 7.517401 | 0 |
| 28/Feb/2019 15:30:57 | 3160 | 7.749795 | 0 |
| 28/Feb/2019 15:31:17 | 3180 | 7.755407 | 0 |
| 28/Feb/2019 15:31:37 | 3200 | 7.894122 | 0 |
| 28/Feb/2019 15:31:57 | 3220 | 7.6917 | 0 |
| 28/Feb/2019 15:32:17 | 3240 | 7.7349 | 0 |
| 28/Feb/2019 15:32:37 | 3260 | 7.645956 | 0 |
| 28/Feb/2019 15:32:57 | 3280 | 7.742516 | 0 |
| 28/Feb/2019 15:33:17 | 3300 | 7.65803 | 0 |
| 28/Feb/2019 15:33:37 | 3320 | 7.600947 | 0 |
| 28/Feb/2019 15:33:57 | 3340 | 7.866349 | 0 |
| 28/Feb/2019 15:34:17 | 3360 | 8.047695 | 0 |
| 28/Feb/2019 15:34:37 | 3380 | 7.479877 | 0 |
| 28/Feb/2019 15:34:57 | 3400 | 7.629049 | 0 |
| 28/Feb/2019 15:35:17 | 3420 | 8.168337 | 0 |
| 28/Feb/2019 15:35:37 | 3440 | 7.792353 | 0 |
| 28/Feb/2019 15:35:57 | 3460 | 7.668617 | 0 |
| 28/Feb/2019 15:36:17 | 3480 | 7.699408 | 0 |
| 28/Feb/2019 15:36:37 | 3500 | 7.579253 | 0 |
| 28/Feb/2019 15:36:57 | 3520 | 7.629979 | 0 |
| 28/Feb/2019 15:37:17 | 3540 | 7.630297 | 0 |

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/2019 15:37:37 | 3560 | 7.535729 | 0 |
| 28/Feb/2019 15:37:57 | 3580 | 7.907892 | 0 |
| 28/Feb/2019 15:38:17 | 3600 | 7.781759 | 0 |
| 28/Feb/2019 15:38:37 | 3620 | 7.580622 | 0 |
| 28/Feb/2019 15:38:57 | 3640 | 7.432704 | 0 |
| 28/Feb/2019 15:39:17 | 3660 | 7.258955 | 0 |
| 28/Feb/2019 15:39:37 | 3680 | 7.523871 | 0 |
| 28/Feb/2019 15:39:57 | 3700 | 7.404749 | 0 |
| 28/Feb/2019 15:40:17 | 3720 | 7.610284 | 0 |
| 28/Feb/2019 15:40:37 | 3740 | 7.446008 | 0 |
| 28/Feb/2019 15:40:57 | 3760 | 7.439649 | 0 |
| 28/Feb/2019 15:41:17 | 3780 | 7.257399 | 0 |
| 28/Feb/2019 15:41:37 | 3800 | 7.551832 | 0 |
| 28/Feb/2019 15:41:57 | 3820 | 7.360883 | 0 |
| 28/Feb/2019 15:42:17 | 3840 | 7.513943 | 0 |
| 28/Feb/2019 15:42:37 | 3860 | 7.321317 | 0 |
| 28/Feb/2019 15:42:57 | 3880 | 7.583771 | 0 |
| 28/Feb/2019 15:43:17 | 3900 | 7.417337 | 0 |
| 28/Feb/2019 15:43:37 | 3920 | 7.613309 | 0 |
| 28/Feb/2019 15:43:57 | 3940 | 7.871932 | 0 |
| 28/Feb/2019 15:44:17 | 3960 | 7.901552 | 0 |
| 28/Feb/2019 15:44:37 | 3980 | 7.449212 | 0 |
| 28/Feb/2019 15:44:57 | 4000 | 7.676558 | 0 |
| 28/Feb/2019 15:45:17 | 4020 | 7.296214 | 0 |
| 28/Feb/2019 15:45:37 | 4040 | 7.287763 | 0 |
| 28/Feb/2019 15:45:57 | 4060 | 7.469354 | 0 |
| 28/Feb/2019 15:46:17 | 4080 | 7.293453 | 0 |
| 28/Feb/2019 15:46:37 | 4100 | 7.359059 | 0 |
| 28/Feb/2019 15:46:57 | 4120 | 7.250837 | 0 |
| 28/Feb/2019 15:47:17 | 4140 | 7.632818 | 0 |

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/2019 15:47:37 | 4160 | 7.451744 | 0 |
| 28/Feb/2019 15:47:57 | 4180 | 7.417531 | 0 |
| 28/Feb/2019 15:48:17 | 4200 | 7.741659 | 0 |
| 28/Feb/2019 15:48:37 | 4220 | 7.60035 | 0 |
| 28/Feb/2019 15:48:57 | 4240 | 7.393034 | 0 |
| 28/Feb/2019 15:49:17 | 4260 | 7.208967 | 0 |
| 28/Feb/2019 15:49:37 | 4280 | 7.545414 | 0 |
| 28/Feb/2019 15:49:57 | 4300 | 7.437169 | 0 |
| 28/Feb/2019 15:50:17 | 4320 | 7.543694 | 0 |
| 28/Feb/2019 15:50:37 | 4340 | 7.296487 | 0 |
| 28/Feb/2019 15:50:57 | 4360 | 7.370313 | 0 |
| 28/Feb/2019 15:51:17 | 4380 | 7.289581 | 0 |
| 28/Feb/2019 15:51:37 | 4400 | 7.446826 | 0 |
| 28/Feb/2019 15:51:57 | 4420 | 7.2223 | 0 |
| 28/Feb/2019 15:52:17 | 4440 | 7.286284 | 0 |
| 28/Feb/2019 15:52:37 | 4460 | 7.216158 | 0 |
| 28/Feb/2019 15:52:57 | 4480 | 7.224148 | 0 |
| 28/Feb/2019 15:53:17 | 4500 | 7.879597 | 0 |
| 28/Feb/2019 15:53:37 | 4520 | 7.311508 | 0 |
| 28/Feb/2019 15:53:57 | 4540 | 7.256442 | 0 |
| 28/Feb/2019 15:54:17 | 4560 | 7.590559 | 0 |
| 28/Feb/2019 15:54:37 | 4580 | 7.406934 | 0 |
| 28/Feb/2019 15:54:57 | 4600 | 7.163209 | 0 |
| 28/Feb/2019 15:55:17 | 4620 | 7.145022 | 0 |
| 28/Feb/2019 15:55:37 | 4640 | 7.134282 | 0 |
| 28/Feb/2019 15:55:57 | 4660 | 7.203436 | 0 |
| 28/Feb/2019 15:56:17 | 4680 | 7.339561 | 0 |
| 28/Feb/2019 15:56:37 | 4700 | 7.378986 | 0 |
| 28/Feb/2019 15:56:57 | 4720 | 7.237755 | 0 |
| 28/Feb/2019 15:57:17 | 4740 | 7.127179 | 0 |

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/2019 15:57:37 | 4760 | 7.438285 | 0 |
| 28/Feb/2019 15:57:57 | 4780 | 7.106779 | 0 |
| 28/Feb/2019 15:58:17 | 4800 | 7.481915 | 0 |
| 28/Feb/2019 15:58:37 | 4820 | 7.229581 | 0 |
| 28/Feb/2019 15:58:57 | 4840 | 7.416652 | 0 |
| 28/Feb/2019 15:59:17 | 4860 | 7.243182 | 0 |
| 28/Feb/2019 15:59:37 | 4880 | 7.318231 | 0 |
| 28/Feb/2019 15:59:57 | 4900 | 7.550225 | 0 |
| 28/Feb/2019 16:00:17 | 4920 | 7.190902 | 0 |
| 28/Feb/2019 16:00:37 | 4940 | 7.458009 | 0 |
| 28/Feb/2019 16:00:57 | 4960 | 7.269602 | 0 |
| 28/Feb/2019 16:01:17 | 4980 | 7.038383 | 0 |
| 28/Feb/2019 16:01:37 | 5000 | 7.160777 | 0 |
| 28/Feb/2019 16:01:57 | 5020 | 7.32903 | 0 |
| 28/Feb/2019 16:02:17 | 5040 | 7.259501 | 0 |
| 28/Feb/2019 16:02:37 | 5060 | 7.27344 | 0 |
| 28/Feb/2019 16:02:57 | 5080 | 7.345245 | 0 |
| 28/Feb/2019 16:03:17 | 5100 | 7.285755 | 0 |
| 28/Feb/2019 16:03:37 | 5120 | 7.040226 | 0 |
| 28/Feb/2019 16:03:57 | 5140 | 6.945843 | 0 |
| 28/Feb/2019 16:04:17 | 5160 | 7.573963 | 0 |
| 28/Feb/2019 16:04:37 | 5180 | 7.209297 | 0 |
| 28/Feb/2019 16:04:57 | 5200 | 7.351111 | 0 |
| 28/Feb/2019 16:05:17 | 5220 | 7.116344 | 0 |
| 28/Feb/2019 16:05:37 | 5240 | 7.311758 | 0 |
| 28/Feb/2019 16:05:57 | 5260 | 6.98428 | 0 |
| 28/Feb/2019 16:06:17 | 5280 | 7.419619 | 0 |
| 28/Feb/2019 16:06:37 | 5300 | 7.290804 | 0 |
| 28/Feb/2019 16:06:57 | 5320 | 7.086635 | 0 |
| 28/Feb/2019 16:07:17 | 5340 | 7.039164 | 0 |

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/2019 16:07:37 | 5360 | 6.811864 | 0 |
| 28/Feb/2019 16:07:57 | 5380 | 7.226655 | 0 |
| 28/Feb/2019 16:08:17 | 5400 | 7.509119 | 0 |
| 28/Feb/2019 16:08:37 | 5420 | 6.90083 | 0 |
| 28/Feb/2019 16:08:57 | 5440 | 7.013248 | 0 |
| 28/Feb/2019 16:09:17 | 5460 | 7.288889 | 0 |
| 28/Feb/2019 16:09:37 | 5480 | 7.381338 | 0 |
| 28/Feb/2019 16:09:57 | 5500 | 7.62651 | 0 |
| 28/Feb/2019 16:10:17 | 5520 | 7.031739 | 0 |
| 28/Feb/2019 16:10:37 | 5540 | 7.148571 | 0 |
| 28/Feb/2019 16:10:57 | 5560 | 7.226143 | 0 |
| 28/Feb/2019 16:11:17 | 5580 | 6.962889 | 0 |
| 28/Feb/2019 16:11:37 | 5600 | 7.268072 | 0 |
| 28/Feb/2019 16:11:57 | 5620 | 7.419724 | 0 |
| 28/Feb/2019 16:12:17 | 5640 | 7.007983 | 0 |
| 28/Feb/2019 16:12:37 | 5660 | 6.910602 | 0 |
| 28/Feb/2019 16:12:57 | 5680 | 7.090691 | 0 |
| 28/Feb/2019 16:13:17 | 5700 | 7.322123 | 0 |
| 28/Feb/2019 16:13:37 | 5720 | 7.135848 | 0 |
| 28/Feb/2019 16:13:57 | 5740 | 6.952263 | 0 |
| 28/Feb/2019 16:14:17 | 5760 | 7.359814 | 0 |
| 28/Feb/2019 16:14:37 | 5780 | 7.047112 | 0 |
| 28/Feb/2019 16:14:57 | 5800 | 7.001623 | 0 |
| 28/Feb/2019 16:15:17 | 5820 | 6.930443 | 0 |
| 28/Feb/2019 16:15:37 | 5840 | 7.025407 | 0 |
| 28/Feb/2019 16:15:57 | 5860 | 6.959147 | 0 |
| 28/Feb/2019 16:16:17 | 5880 | 7.563033 | 0 |
| 28/Feb/2019 16:16:37 | 5900 | 7.064497 | 0 |
| 28/Feb/2019 16:16:57 | 5920 | 7.231053 | 0 |
| 28/Feb/2019 16:17:17 | 5940 | 6.849135 | 0 |

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/2019 16:17:37 | 5960 | 6.84017 | 0 |
| 28/Feb/2019 16:17:57 | 5980 | 6.927529 | 0 |
| 28/Feb/2019 16:18:17 | 6000 | 6.643529 | 0 |
| 28/Feb/2019 16:18:37 | 6020 | 6.765883 | 0 |
| 28/Feb/2019 16:18:57 | 6040 | 7.203315 | 0 |
| 28/Feb/2019 16:19:17 | 6060 | 7.004635 | 0 |
| 28/Feb/2019 16:19:37 | 6080 | 7.141762 | 0 |
| 28/Feb/2019 16:19:57 | 6100 | 6.753698 | 0 |
| 28/Feb/2019 16:20:17 | 6120 | 6.888741 | 0 |
| 28/Feb/2019 16:20:37 | 6140 | 6.769001 | 0 |
| 28/Feb/2019 16:20:57 | 6160 | 6.68763 | 0 |
| 28/Feb/2019 16:21:17 | 6180 | 6.978519 | 0 |
| 28/Feb/2019 16:21:37 | 6200 | 7.223334 | 0 |
| 28/Feb/2019 16:21:57 | 6220 | 6.814633 | 0 |
| 28/Feb/2019 16:22:17 | 6240 | 6.629005 | 0 |
| 28/Feb/2019 16:22:37 | 6260 | 7.377124 | 0 |
| 28/Feb/2019 16:22:57 | 6280 | 6.846918 | 0 |
| 28/Feb/2019 16:23:17 | 6300 | 6.70645 | 0 |
| 28/Feb/2019 16:23:37 | 6320 | 6.636758 | 0 |
| 28/Feb/2019 16:23:57 | 6340 | 6.559673 | 0 |
| 28/Feb/2019 16:24:17 | 6360 | 6.680528 | 0 |
| 28/Feb/2019 16:24:37 | 6380 | 6.911292 | 0 |
| 28/Feb/2019 16:24:57 | 6400 | 6.792268 | 0 |
| 28/Feb/2019 16:25:17 | 6420 | 6.966634 | 0 |
| 28/Feb/2019 16:25:37 | 6440 | 7.006715 | 0 |
| 28/Feb/2019 16:25:57 | 6460 | 6.721663 | 0 |
| 28/Feb/2019 16:26:17 | 6480 | 6.925625 | 0 |
| 28/Feb/2019 16:26:37 | 6500 | 6.671048 | 0 |
| 28/Feb/2019 16:26:57 | 6520 | 6.845091 | 0 |
| 28/Feb/2019 16:27:17 | 6540 | 7.031453 | 0 |

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/2019 16:27:37 | 6560 | 6.789556 | 0 |
| 28/Feb/2019 16:27:57 | 6580 | 6.924023 | 0 |
| 28/Feb/2019 16:28:17 | 6600 | 6.929053 | 0 |
| 28/Feb/2019 16:28:37 | 6620 | 6.765839 | 0 |
| 28/Feb/2019 16:28:57 | 6640 | 6.999989 | 0 |
| 28/Feb/2019 16:29:17 | 6660 | 6.461283 | 0 |
| 28/Feb/2019 16:29:37 | 6680 | 6.802938 | 0 |
| 28/Feb/2019 16:29:57 | 6700 | 6.808928 | 0 |
| 28/Feb/2019 16:30:17 | 6720 | 6.790987 | 0 |
| 28/Feb/2019 16:30:37 | 6740 | 6.64852 | 0 |
| 28/Feb/2019 16:30:57 | 6760 | 6.597448 | 0 |
| 28/Feb/2019 16:31:17 | 6780 | 6.5582 | 0 |
| 28/Feb/2019 16:31:37 | 6800 | 6.648368 | 0 |
| 28/Feb/2019 16:31:57 | 6820 | 6.705744 | 0 |
| 28/Feb/2019 16:32:17 | 6840 | 6.696778 | 0 |
| 28/Feb/2019 16:32:37 | 6860 | 6.727637 | 0 |
| 28/Feb/2019 16:32:57 | 6880 | 6.711329 | 0 |
| 28/Feb/2019 16:33:17 | 6900 | 6.655923 | 0 |
| 28/Feb/2019 16:33:37 | 6920 | 6.630205 | 0 |
| 28/Feb/2019 16:33:57 | 6940 | 6.926071 | 0 |
| 28/Feb/2019 16:34:17 | 6960 | 6.647466 | 0 |
| 28/Feb/2019 16:34:37 | 6980 | 6.818054 | 0 |
| 28/Feb/2019 16:34:57 | 7000 | 7.233253 | 0 |
| 28/Feb/2019 16:35:17 | 7020 | 6.826322 | 0 |
| 28/Feb/2019 16:35:37 | 7040 | 6.820357 | 0 |
| 28/Feb/2019 16:35:57 | 7060 | 6.484322 | 0 |
| 28/Feb/2019 16:36:17 | 7080 | 6.445799 | 0 |
| 28/Feb/2019 16:36:37 | 7100 | 6.487835 | 0 |
| 28/Feb/2019 16:36:57 | 7120 | 6.880916 | 0 |
| 28/Feb/2019 16:37:17 | 7140 | 6.318429 | 0 |

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/2019 16:37:37 | 7160 | 6.569183 | 0 |
| 28/Feb/2019 16:37:57 | 7180 | 6.506461 | 0 |
| 28/Feb/2019 16:38:17 | 7200 | 6.487117 | 0 |
| 28/Feb/2019 16:38:37 | 7220 | 6.800315 | 0 |
| 28/Feb/2019 16:38:57 | 7240 | 6.577242 | 0 |
| 28/Feb/2019 16:39:17 | 7260 | 6.710677 | 0 |
| 28/Feb/2019 16:39:37 | 7280 | 6.480007 | 0 |
| 28/Feb/2019 16:39:57 | 7300 | 6.265428 | 0 |
| 28/Feb/2019 16:40:17 | 7320 | 6.489797 | 0 |
| 28/Feb/2019 16:40:37 | 7340 | 7.106663 | 0 |
| 28/Feb/2019 16:40:57 | 7360 | 7.184568 | 0 |
| 28/Feb/2019 16:41:17 | 7380 | 6.571418 | 0 |
| 28/Feb/2019 16:41:37 | 7400 | 6.672875 | 0 |
| 28/Feb/2019 16:41:57 | 7420 | 6.518861 | 0 |
| 28/Feb/2019 16:42:17 | 7440 | 6.711867 | 0 |
| 28/Feb/2019 16:42:37 | 7460 | 6.736598 | 0 |
| 28/Feb/2019 16:42:57 | 7480 | 6.414474 | 0 |
| 28/Feb/2019 16:43:17 | 7500 | 6.472251 | 0 |
| 28/Feb/2019 16:43:37 | 7520 | 6.663831 | 0 |
| 28/Feb/2019 16:43:57 | 7540 | 6.298529 | 0 |
| 28/Feb/2019 16:44:17 | 7560 | 6.473566 | 0 |
| 28/Feb/2019 16:44:37 | 7580 | 6.361657 | 0 |
| 28/Feb/2019 16:44:57 | 7600 | 6.796835 | 0 |
| 28/Feb/2019 16:45:17 | 7620 | 6.482027 | 0 |
| 28/Feb/2019 16:45:37 | 7640 | 6.764361 | 0 |
| 28/Feb/2019 16:45:57 | 7660 | 6.719694 | 0 |
| 28/Feb/2019 16:46:17 | 7680 | 6.473708 | 0 |
| 28/Feb/2019 16:46:37 | 7700 | 6.28755 | 0 |
| 28/Feb/2019 16:46:57 | 7720 | 6.795705 | 0 |
| 28/Feb/2019 16:47:17 | 7740 | 6.343338 | 0 |

| Date and Time | Time (s) | Carbon monoxide, CO (ppm) | Photoionization Detector, PID (ppm) |
|---|---|---|---|
| 28/Feb/2019 16:47:37 | 7760 | 6.48351 | 0 |
| 28/Feb/2019 16:47:57 | 7780 | 6.616128 | 0 |
| 28/Feb/2019 16:48:17 | 7800 | 6.434531 | 0 |
| 28/Feb/2019 16:48:37 | 7820 | 6.643321 | 0 |
| 28/Feb/2019 16:48:57 | 7840 | 6.602366 | 0 |
| 28/Feb/2019 16:49:17 | 7860 | 6.493189 | 0 |
| 28/Feb/2019 16:49:37 | 7880 | 6.392487 | 0 |
| 28/Feb/2019 16:49:57 | 7900 | 6.623595 | 0 |
| 28/Feb/2019 16:50:17 | 7920 | 6.217158 | 0 |
| 28/Feb/2019 16:50:37 | 7940 | 3.80564 | 0 |
| 28/Feb/2019 16:50:57 | 7960 | 2.059523 | 0 |
| 28/Feb/2019 16:51:17 | 7980 | 1.532094 | 0 |
| 28/Feb/2019 16:51:37 | 8000 | 0.3101944 | 0 |
| 28/Feb/2019 16:51:57 | 8020 | 0.1687981 | 0 |
| 28/Feb/2019 16:52:17 | 8040 | 0.5504127 | 0 |

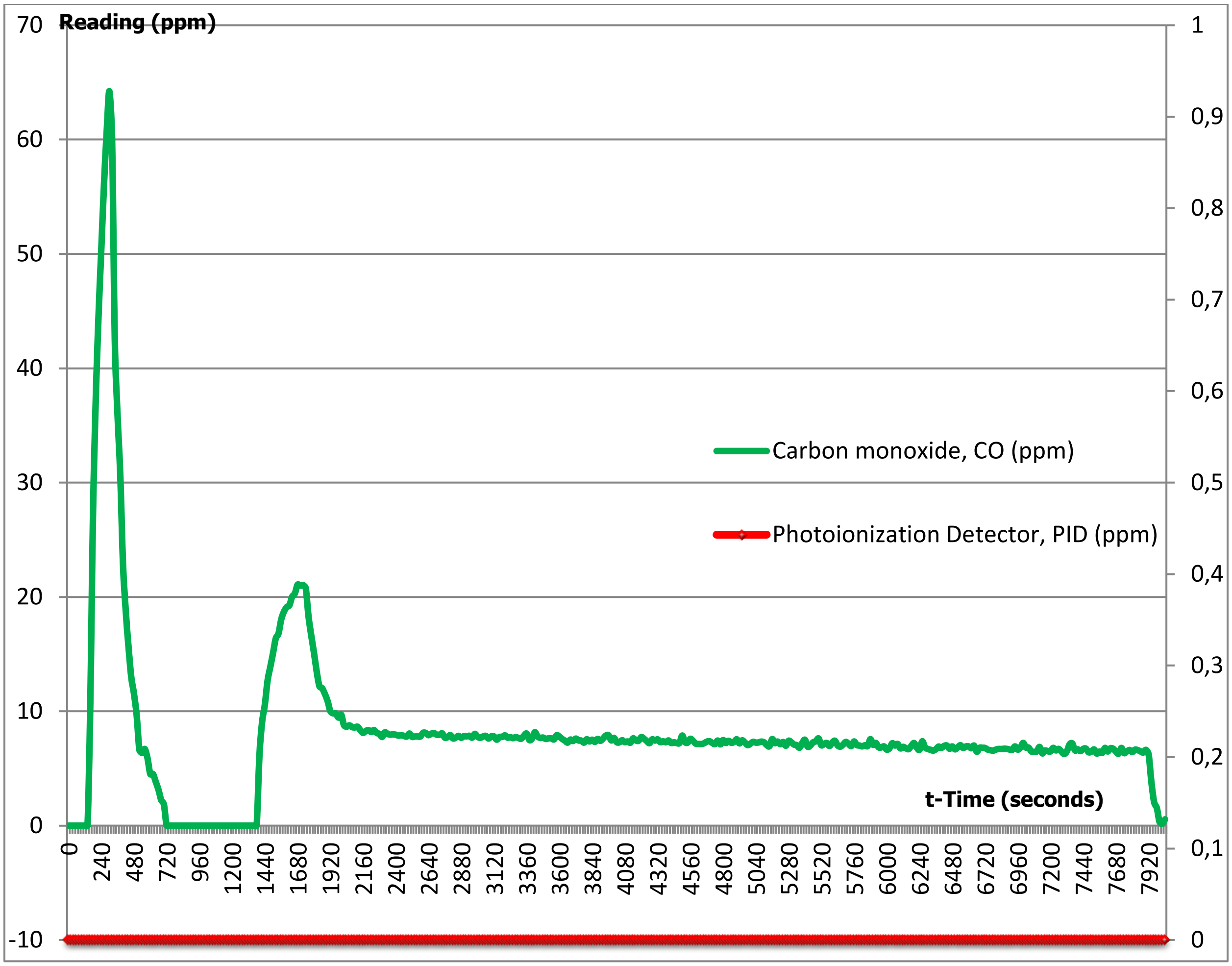


*Figure D.2: A graphical representation of the data collected from measuring carbon monoxide, CO during Laboratory testing.*