Measuring surface water quality using a low-cost sensor kit within the context of rural Africa

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ABSTRACT

Monitoring water quality is done for a variety of reasons, including to determine whether water is suitable for drinking or for agricultural purposes. In this research we have developed a low-cost IoT water quality measuring device that is designed to operate within the context of rural Africa. This paper presents a five-step iterative method in order to develop such a device. Firstly, we have selected appropriate water quality sensors and described why these parameters are useful. Secondly, we developed a water quality monitoring device that takes the contextual requirements and constraints of rural Africa into account. Lastly, the device is tested and evaluated in order to find out whether the requirements are met. This research presents a method to design IoT devices for development areas. We present the different steps in the iterative methods and describe design options for the design questions in those steps. Additionally, information is provided on how to effectively measure water quality using low-cost sensors. In the end, the evaluation shows that the developed device is low-cost and successfully able to measure water quality parameters over a longer period of time.

KEYWORDS

ICT4D, water quality monitoring, low-cost sensor kit, IoT4D

1 INTRODUCTION

Measuring surface water quality has been done for decades for a variety of reasons. Among those reasons are to find out whether water is drinkable or if it can be used for agricultural purposes [3]. Traditional methods to determine water quality can be time consuming and expensive [18]. Water samples are sent to a laboratory and those samples are analyzed there. Using this method of water analysis it is not possible to determine water quality ad hoc. For example in the context of rural Africa, a farmer wants to know if the water from the river can be used to water his or her crops. If the farmer has to wait a few weeks to find out whether the water at that moment is suitable for watering crops, the results are not relevant anymore when they arrive. The water composition could have been changed since the samples were taken. A more suitable method of determining the water quality would be a device that provides information about the water quality instantly. This device should be affordable from a financial perspective. Using such a device has multiple advantages over traditional water quality measuring approach: water quality can be measured instantly, measurements can be taken continuously and measuring can be done by stakeholders itself instead of being dependent on a laboratory. A disadvantage of using a low-cost sensor kit is that fewer water parameters can be measured and these measures are potentially less accurate.

Measuring water quality can be helpful for at least two of the 17 United Nations Sustainable Development Goals[1]. Goal 6 is about "Clean water and sanitation". Millions of people die every year because of poor water supplies and sanitation. By measuring and monitoring water quality, the collected data can be used to get an understanding of the pollution in the water. Sustainable Development Goal 14 is about "Life below water". This involves the life inside the seas and oceans. The underwater life is affected by multiple factors, including pollution of all kinds.

In this research, we will develop a low-cost water quality measuring device. This device (or sensor kit) is designed to function within the context of rural Africa. This means that there will be various requirements and constraints that are related to this context. To be able to develop the water quality measuring device, the following research questions will be answered:

1. *What is an effective design of a low-cost water quality measuring kit within the context of rural Africa?*
1.1 *What are the requirements and constraints of the system design with respect to the context of rural Africa?*
1.2 *What are appropriate sensors to measure water quality for the measuring kit?*

The meaning of the word effective in the first research question is explained in more detail in the two sub-questions. For the purpose of our research, we define effectiveness as how well the system conforms to the requirements and constraints. For example, if there is no internet connection available, alternative methods for connectivity should be included in the system design. Additionally, there is a trade-off between the building costs and measuring quality. This also involves the selection of appropriate sensors. Sensors are considered appropriate for this context, if they are low-cost and still provide correct information about water quality parameters.

This paper presents a design method for IoT devices for development (IoT4D). The five step methodology that will be presented provides an experimental and iterative method for developing IoT devices for development. Additionally, we will show how to make informed design decisions by listing design questions and their related design options. The water quality measuring device that is going to be developed, demonstrates how the presented methodology is useful for IoT4D in practice.

[1] https://www.un.org/sustainabledevelopment/sustainable-development-goals

2 RELATED WORK

2.1 ICT4D context

In this research, we focus on implementing an ICT solution within rural Africa. This results in multiple requirements and constraints that are specifically related to this context. ICT research for development is called Information and Communication Technologies For Development (ICT4D or ICTD). More specifically, ICT4D is defined by Gyan as the use of ICT in socio-economic and international development. This includes disadvantaged population all over the world, but more often ICT4D is related to developing countries [10]. Ali et al. mention three benchmarks that are important for successful ICT4D projects: context, community participation and sustainability. However, sustainability seems to be conflicting with ICT in general, which is changing often. Therefore, Ali et al. qualify sustainability of ICT4D projects as an unrealistic concept and that pursuing sustainability leads to project failures [1].

Implementing an ICT system within developing countries raises multiple challenges that are not obvious or present in first-world countries. Users of ICT systems often have limited education, are underemployed and have low incomes [25]. On the other hand, stakeholders of such systems are usually from different countries and have different sociocultural backgrounds [26]. This can complicate determining the goals of a project. Pitula et al. described other challenges of the complicated context in which ICT4D projects operate, related to infrastructures, power supplies, connectivity and extreme operating conditions. Additionally, three main components of ICT4D projects are described: 1) infrastructure development, 2) create ICT capacity and 3) providing the digital service. The first component relates to the required infrastructure to operate the system. The second component relates to the capacity to use and maintain the system. Finally, the third component relates to the value of the service itself [26]. Because network connection is extremely unreliable or not available at all in rural areas of developing countries, other techniques are used to make the web accessible. Research of Valkering et al. focuses on transmitting data via SMS in rural areas [36]. Most of the challenges listed above are also relevant for our research. Solutions to overcome power and connectivity issues should be investigated in order to design a usable water quality measuring device for rural Africa.

According to Tongia et al. many ICT4D project fail either partially or completely. This is caused by an incomplete problem definition or by the metrics used for evaluation [34]. Other research confirms that most ICT systems for development do indeed fail [12, 26]. Among the reasons for failure is the gap between the design of the system and the reality. Stakeholder participation is crucial in order to ensure that the system is adopted to the local context. Agile and iterative design methodologies have proven to be effective when participatory approaches are used [8]. The findings of the previously mentioned researches are relevant for our research. It indicates that the local context should be taken into account in both the system design phase and other phases (like the evaluation phase) in order to succeed in this context.

2.2 Water quality measurement

Water quality can be determined using the physical, chemical and biological properties of water [35]. The Environmental Protection Agency of Ireland described 101 parameters to determine water quality [33]. Below a selection of those parameters are listed and categorized by the previously mentioned quality property categories. Firstly, physical parameters include for example pH and temperature. Secondly, chemical parameters include dissolved oxygen and other measures of how much of a certain substance is present in water. Lastly, biological properties include measures of bacteria and viruses (e.g. Salmonella) [33]. The listed properties are relevant for this research because they can be measured using low-cost sensors. A study of Rao et al. describes a low-costs water monitoring system that is measuring some of the parameters that were described earlier. This includes temperature, pH, electrical conductivity and dissolved oxygen [27]. The findings of Rao et al. are relevant for this research since they also involve building a low-cost water quality measuring system.

For amateur aquaponics and gardening, water quality monitoring often happens using low-cost sensor kits[2,3]. These sensors are often controlled by Arduino prototyping boards. Due to the open-source nature of these projects, multiple tutorials are published online by the Arduino community[4]. These amateur projects can be interesting to our research since the same goal is pursued: measuring water quality with cheap sensors. Although the goal is the same, the environment in which the device operates is different.

A Dutch NGO called AKVO is focusing on measuring water quality in a cost effective way using smartphones[5]. They use multiple methods in order to determine the quality, for example test strips are used to measure certain parameters. The smartphone camera is then used to photograph the test strip in order to capture and store the measuring results. AKVO has developed a lens for a smartphone camera as well. With this lens it is possible to determine certain water quality parameters [21]. Using a smartphone, the prices of sensors kits can decrease significantly. However, there are multiple downsides of this method. The most obvious downside is that a smartphone is needed (which is not always available, especially in rural areas of Africa). Additionally, this method is not very suitable for monitoring water quality over a longer period of time (water quality cannot be measured autonomously). Our research differs from the previously discussed projects since we focus specifically on the use in rural Africa. The measuring kit will not be dependent on a smartphone and is therefore suitable for autonomous continuous water quality monitoring.

2.3 IoT for Development (IoT4D)

As has been described in the previous section, the measuring device will not be dependent on a smartphone and is able to autonomously measure water quality. The device can be considered as an Internet-Of-Things (IoT) device since it makes it possible to get access to physical real-world parameters [37]. This is an IoT device that is specifically designed to operate in a development context, therefore this research field can be called IoT4D. The device is able to measure physical parameters that are related to water quality. The measured

[2] https://kijanigrows.com/

[3] https://www.cooking-hacks.com/documentation/tutorials/open-aquarium-aquaponics-fish-tank-monitoring-arduino/

[4] https://www.instructables.com/id/20-Gallon-Aquaponics-System-With-Arduino-Monitorin/

[5] https://akvo.org/products/akvo-caddisfly/

data can be accessed in real-time via the internet. Closely related to IoT are Wireless Sensor Networks (WSNs). These networks consist of often small and low-cost sensor nodes that are connected to a larger network [17]. A special category of WSNs are Environmental Sensor Networks (ESNs). The goal of such networks is to monitor data of the natural environment [11]. According to Hart et al. ESNs will cause a revolution for environmental sciences. For example because of the development of hazard response systems or by the creation of new models of the environment.

WSNs do not only show potential for the developed world, but according to Zennaro et al. developing areas and countries can benefit from WSNs as well [38]. They advocate the use of WSN4D (Wireless Sensor Networks for Development) since this not only helps solving development problems, but can also be useful for other research activities. Zennaro et al. mention multiple challenges for deploying WSNs in developing areas, these challenges are similar to the challenges found by Pitula et al. for ICT4D projects in general [26]. This includes issues with power availability, deployment costs and the operating conditions of the devices. For our research the findings about the ICT4D and WSN4D challenges are useful, because the found challenges also relate to the development of the water quality measuring kit. For example, if the device is going to be used in an IoT setting, the price should be low enough in order to deploy multiple devices at a certain location.

3 METHODOLOGY

This section presents a methodology for developing IoT4D devices. In order to do so, we have created the IoT4D development life cycle, which is displayed in Figure 1. This is an iterative, experimental life cycle which consists of five phases. The iterative nature of the life cycle is based on the idea that the device is improved and adapted to new or changing requirements over time. The experimental part of the methodology is about development as an experiment, without a lot of planning in advance. This experimental approach is useful in order to get results quickly. This is especially suitable when the requirements are largely unknown or not strictly defined, as is often the case in ICT4D projects [2].

The methodology that we present in this section is based on an agile software development life cycle. This life cycle has been adopted in order to suit IoT4D design. As mentioned in the related literature section, agile and iterative design methods are suitable for ICT4D projects [8]. The first step of the methodology is to ensure that the context and use case becomes clear. This because ICT4D projects often fail due to incomplete problem descriptions or context analysis [34]. Getting an understanding of the context also relates to the final step: Testing and evaluation. This step is an significant factor in determining whether projects fail or not. With the wrong evaluation metrics, a project could be considered as a failure, while this is not the case. The parameter selection step of the methodology is not part of the original software development life cycle. This step is relevant for IoT4D because parameter selection often requires domain specific knowledge and it can be time consuming. Additionally, the parameter selection has a significant impact on the overall system design. Therefore, parameter selection is a separate step in the methodology.

The life cycle can be used by starting at phase one and continue to the next phase when ready. Since the life cycle is iterative, after finishing phase five, phase one will be executed again. The proposed experimental character of the life cycle also encourages to go a phase back if needed. In Diagram 1 this is depicted as a dashed arrow, which is pointing back to the previous phase. For example, if during the device design phase it turns out that a certain parameter is not very suitable for measuring, it makes sense to go back to the previous phase and reconsider what parameters should be measured. Maybe the parameter is replaced by another one, or it is completely left out. We will now explain each of the phases in more detail. Per phase, research challenges are listed. These focus on challenges that arise when creating IoT devices for development.

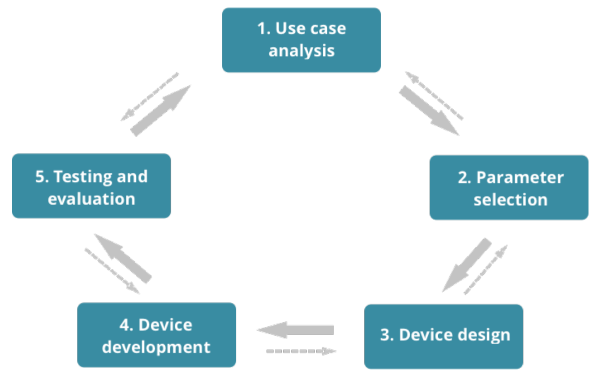

Figure 1: IoT4D experimental development life cycle

3.1 Use case analysis

To start with developing IoT devices, a use case analysis is needed. The use case analysis ensures that the system requirements become clear. As has been mentioned in the related work section, ICT4D projects often fail because of poorly defined problem definitions [34]. Therefore, carefully conducting this first step of the life cycle increases the changes for a successful IoT4D project. In order to list the system requirements, it is needed to include the stakeholders into this process. Questions like: who is interested in the data that the IoT devices produce, or who wants to pay for the system, are relevant for the use case analysis. Elicitation techniques like interviewing or workshops can help in this process. However, for ICT4D projects challenges arise because of the often remote locations where the final products are going to be used. Travel costs can be high and it might be hard to reach the locations. Another challenge is about the context which is often unknown to the researchers involved [2]. A result of the use case analysis can be a list of system requirements or textual use case descriptions.

Summarized research challenges:

- *Conducting research at location is expensive or not possible*
- *Context is largely unknown*

3.2 Parameter selection

When the use case becomes more clear, relevant measurement parameters should be selected. In the first place, based on the use case, the parameters are selected. After the parameters have been selected, it should be checked whether it is possible to measure the parameters within the constraints of the project. Some constraints of IoT4D devices are that the devices should be low-cost and that they should not require a lot of maintenance. Certain parameters can only be measured with costly sensors or using complicated lab procedures. If there is no low-cost alternative to measure this parameter, the parameter should be left out. There is a trade-off between relevance and costs of the sensors that can measure the parameters. In addition to this, more expensive sensors often produce more accurate sensor data. Dependent on the use case, the most appropriate sensor should be selected. While the use case analysis is important for the parameter selection, a literature study should be conducted as well. Often similar IoT devices have been created already and the literature review helps in deciding what parameters can be useful for measuring. The final result of selecting parameters is a list containing all appropriate parameters. This list includes background information about the relevance of measuring a certain parameter and background information about the parameter itself.

Summarized research challenges:

- *IoT4D related sensor constraints, like: low-cost and maintainable*
- *Trade-off between relevance and costs*

3.3 Device design

As has been described in the related literature section, multiple challenging factors should be taken into account during the system development. These factors are mostly related to the environment in which the device is going to be deployed. To be able to find out how these constraints affect the design of the device, the constraints are listed together with the possible design options. Although constraints are mainly dependent on the use case, some factors are recurring in many IoT4D projects. A list of design options is shown below. This list is based on challenges found by Pitula et al. [26].

- **Power supply**: power net, battery, solar panels, smartphone battery
- **Connectivity**: smartphone app, GPRS, LoRa, SMS, save on SD card
- **Communication**: smartphone app, LCD screen, web interface
- **Operating conditions**: waterproof housing, industrial sensor, lab sensors

In order to make an informed decision on how to handle these challenges, all possible options should be considered. Listing the design options and selecting the most appropriate options helps to find out what the most effective system design is. Not only the selected options are interesting, but the design rationale of the decision is also helping in describing how an effective design looks like. An appropriate method to visualize the design space is the QOC (Questions - Options - Criteria) modeling notation [22]. In Figure 2 is shown how a QOC model looks like. Each design option has advantages and disadvantages for specified criteria. A design option that supports a certain criterion is connected with a solid line. A design option that challenges a criterion is connected using a dashed line. In the end, the usage scenario of the device has the most impact on what options are suitable for the final design.

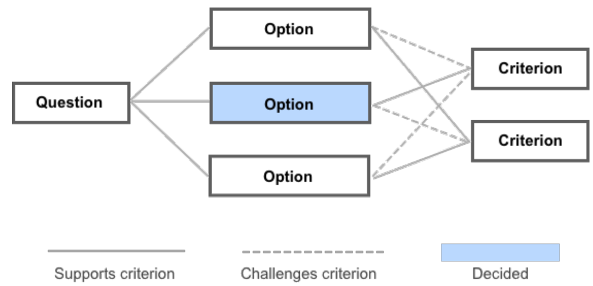

Figure 2: Example of QOC modeling technique

Summarized research challenges:

- *Design challenges recurring in IoT4D projects:*
  - *Power supply*
  - *Connectivity*
  - *Communication*
  - *Operating conditions*

3.4 Device development

Using the system design that has been decided upon in the previous phase, the actual device can be developed. Dependent on how extensive the previous phase has been conducted, a lot of decisions have been made already. Consequently, the development phase consists mainly of developing the actual device. Open source prototyping platforms are suitable for low-cost IoT devices. Some of these platforms include Raspberry Pi and Arduino. Since these platforms are open source, other platforms exist that are very similar. The platforms are used to control the sensors that are needed for the device. It processes and stores the incoming sensor data. The device development phase also includes making the housing, prototyping (for example using breadboards) and soldering wires.

Since this methodology has an iterative and experimental approach, the system design can still change. This is one of the challenges in this phase. Since potentially major requirements or design changes can occur, some development work may be redundant or needs to be done multiple times. This is a consequence of the experimental approach of developing. The result of the development phase is a testable device, that is going to be tested and evaluated in the next phase.

Summarized research challenges:

- *Changes in requirements or design can cause major system changes*
- *Since experimental development is conducted, some developed parts can become redundant*

3.5 Testing and evaluation

After the device has been created, the design and functionalities should be tested and evaluated. The testing part includes testing the device in a lab setting and afterwards in a real world location and scenario. Testing the device at the location for which it is designed can be expensive or impossible. Stakeholders should also be included during the testing phase. Their feedback can be used to improve the device in the next iterations. Especially when the devices are designed for remote areas, it is often not possible to test (each iteration) at the real world location. Since testing the device is still important, a replacement location should be used. A disadvantage of this approach is that the outcomes of these tests might not be the same as when tested in a real world scenario. As has been mentioned several times already, the often long distances to the target locations is a recurring challenge in ICT4D projects.

After the testing, the test results should be evaluated. The evaluation part can consist of different evaluation metrics. For example, a basic method of evaluating the device is finding out whether the device was able to capture the desired parameters. This means that the system is evaluated on whether is it functioning according to the system design or not. Another evaluation metric, which is often done in research that is involved with low-cost sensors kits, is comparing the sensor accuracy with professional equipment. This evaluation method is for example used by Rao et al. [27]. Finally, the overall system design can be evaluated. This can be done by analyzing the design decisions that have been made. In order to do so, one should use the use case requirements to evaluate against. For example, when a device should be low-cost, an evaluation about the costs can be made. In the end, it is important to choose the right evaluation metrics or goals in order to get a correct understanding of whether the device design is effective or not.

Summarized research challenges:

- *Testing often not possible at location, but in a lab setting > causing potentially unrealistic results*
- *Stakeholder communication, hard or not possible at all*
- *Unclear evaluation metrics/goals*
- *Due to unrealistic testing, wrong evaluation results*

4 CASE STUDY

This section implements the case study of the water quality measuring device. The design process of the device follows the steps from the previously presented methodology. In total three iterations of the methodology are executed. In the following subsections, the results of the third and final iteration device are discussed. This because the device is improved based on the results of the previous iterations. The last section describes how the multiple iterations differ from each other and describes what has been improved per iteration.

4.1 Use case analysis

This research was initiated by the request of locals in Burkina Faso to measure and monitor the quality of the water from a well. Their reason to know the water quality is mainly to find out whether the water is drinkable or not. So the first requirement is that a device should be created that is able to measure surface water quality. The second requirement for the device is that it should be a low-cost device. The budget constraint is mainly because of the development context in which the device is going to be used. For the rest, there was not a strict problem description. As mentioned before, this is often the case in ICT4D projects. In order to be able to develop an (IoT) device that was able to measure water quality, two use case scenarios are created. Using these two scenarios, design decisions could be made. In the following sections, the two scenarios are described.

4.1.1 Water quality measurement on demand. The water quality kit is designed to be used on demand. This means that when locals want to know certain water quality parameters, they take a sample of the water and put in inside a cup. Afterwards, the sensors of the measuring kit are also placed in the cup to measure the water quality. Using the measuring kit using this method has implications for the system design. Firstly, powering the kit becomes less of an issue since the kit could be powered by the user (e.g. via a smartphone or a power bank). Secondly, connectivity and communication can also be handled via the smartphone. Lastly, more (expensive) sensors could be connected to the kit because it will not be left unattended. In this case it is less likely that the device is going to be stolen. In contrast to the continuous measuring scenario (that will be discussed in the next section) fewer sensors kits have to be created to be effective which is another reason why sensor pricing is less of an issue. A disadvantage of this method is that most water quality parameters are only relevant if measured for a longer period of time (like temperature, dissolved oxygen and oxidation reduction potential). This means that their value itself (without the ability to measure changes) is not very helpful in determining water quality. A continuous water quality measuring approach would overcome this problem.

4.1.2 Continuous autonomous water quality measurement. In contrast to measuring on demand, it is possible to do continuous measurements. Multiple sensor kits will be placed at different locations, and they will constantly collect information about water quality. This is done using an Internet of Things (IoT) approach, which will connect the sensors to the internet. This has implications for the system design, including questions regarding: how to power the system, how to communicate the data to the stakeholders and how to handle connectivity? Possible answers to these questions are: using solar power, communicate data via a web Graphical User Interface (GUI), connectivity via GPRS. Additionally, the pricing of the sensor kit becomes more important since the kits can be stolen or damaged and because multiple sensor kits have to be created.

4.2 Parameter selection

In Table 1 a list of six water quality parameters that are useful for this research is displayed. In this table the parameters are listed together with a description and a standard for drinking water. These standards come from both the United States Environmental Protection Agency (EPA) and the World Health Organization (WHO). Some of the parameters provide a clear safety range for drinking water. For example, water with a pH below 6.5 should not be drunk. But a parameter like temperature does by itself not provide information about whether the water is drinkable or not. A bottle of water that has been heated by the sun can still be perfectly drinkable. However, when measured for a longer period of time, monitoring the water temperature can provide helpful insights into the water quality. The final parameter list is composed based on existing literature of research concerning water quality measurement [14, 27, 28, 35, 37].

Table 1: Overview of selected water quality parameters

Parameter	Short description	Drinking water standard	Reference
Total Dissolved Solids (TDS)	Parameter to measure the total amount of dissolved solids. A higher TDS might be an indication of pollution in the water.	<600 mg/L	WHO [9]
Dissolved oxygen (DO)	The amount of oxygen that is dissolved in the water. Low levels of dissolved oxygen can be due to high water temperatures or can be indicative for bacteria in the water.	>5-9.5 mg/L	WHO [7]; EPA[6]
Oxidation Reduction Potential (ORP)	The ability of water to either accept or release electrons. Bacteria are killed by increasing the ORP level.	No guideline	NSW[7]; EPA [13]
pH	Measure to determine whether the water is acidic (pH <7) or basic (pH >7). Water with a low pH contains elevated amounts of toxic metals.	6.5<pH<8.5	EPA[8]
Temperature	High water temperatures can cause the growth of microorganisms and can effect the taste and smell of the water.	No guideline	WHO [9]
Turbidity	Measures suspended particles in the water. The more particles, the more change of microorganisms in the water (which can be attached to the particles).	<5 NTU	WHO [9]

According to Tuna et al. the following parameters are main parameters to measure water quality: electrical conductivity, dissolved oxygen, nitrate, pH, temperature, turbidity [35]. For the remainder of this section, each selected parameter will be discussed in more detail. The reasons for monitoring these parameters will be mentioned and additional background information will be provided.

4.2.1 Total Dissolved Solids (TDS). This parameter measures the amount of solids that are dissolved in the water. The parameter is related to the conductivity of water [30]. For example, the more salts are dissolved in water, the higher the TDS and conductivity become. Because there parameters are closely related, conductivity sensors can be used to estimate the TDS in water. Another closely related parameter is the salinity of water. Salinity is about the saltiness of the water. This parameter is often derived from the conductivity of water. TDS is measured in milligram per liter (mg/L). High TDS values are indicative for pollution in water.

4.2.2 Dissolved Oxygen (DO). The amount of oxygen that is present in the water. Dissolved oxygen in water is vital for aquatic life, including fish and plants. Low levels of dissolved oxygen can cause fish mortality and water odors [4]. The amount of oxygen is related to the temperature of water. Due to the characteristics of water, the higher the water temperature, the lower the amount of dissolved oxygen in the water is. The amount of dissolved oxygen in water is an indication of the overall river health [15]. This parameter is sometimes used as single parameter to access the quality in a river stream. Measuring and monitoring dissolved oxygen is helpful in determining the overall water quality. Dissolved oxygen is measured in mg/L or as percentage of air saturation. Air saturation of 100 percent means that the water holds as much oxygen as it can. Although no exact water standard is provided, the WHO indicates that water should have a minimum dissolved oxygen level that ranges from 5 to 9.5 mg/L (dependent on the water temperature) [7].

4.2.3 Oxidation Reduction Potential (ORP). The ability of water to either accept or release electrons. Higher ORP levels kill bacteria in the water. ORP is measured in millivolts (mV). For example, chlorinated water in swimming pools has a high ORP level, and therefore bacteria cannot survive in this water.

4.2.4 pH. Pure water has a pH value of 7. If the pH is greater than 7, the water is basic. If the pH value is below 7, the water is acidic. According to the WHO, the pH value of water is one of the most important water quality parameters [9]. The pH of drinking water should be in between the 6.5 and 8.5. The temperature of the water influences the pH of the water. The lower the temperature, the higher the pH value. Just like the Dissolved Oxygen parameter, aquatic life can only survive in a certain pH range. If the pH is too low or too high, fish will not be able to survive, which affects the overall health of the water. Monitoring pH values can be helpful since small changes in pH can have a major impact on the overall water health.

[6] https://www.epa.gov/national-aquatic-resource-surveys/indicators-dissolved-oxygen
[7] http://www.health.nsw.gov.au/environment/factsheets/Pages/orp.aspx
[8] https://www.epa.gov/dwstandardsregulations/secondary-drinking-water-standards-guidance-nuisance-chemicals

4.2.5 Temperature. The temperature of water alone does not provide information about the water quality. However, when monitored over a longer period of time, this parameter can provide valuable insights about the water quality. In addition to this, many other water quality parameters are influenced by the water temperature (for example TDS, DO and pH). For some water quality sensors to operate, the water temperature value is needed in order to measure the correct values. Higher water temperatures support the growth of microbial growth [9]. According to the WHO, water temperature should be measured at the very least to monitor a water supply system. This because it is a simple test that can easily discover possible problems. In addition to this, the water temperature is the most important factor that determines the growth of Legionella.

4.2.6 Turbidity. The turbidity of water is a measure to determine the amount of suspended solids in the water. The measuring unit of turbidity is called NTU (Nephelometric Turbidity Units). The higher the NTU value, the more turbid the water is. Turbid water can be caused by: clay, silt, organic and inorganic matters and microorganisms [20]. Solids in water can cause growth of harmful microorganisms and therefore low turbidity of water is preferable [19]. The naked human eye is able to detect turbidity levels in water from 5 NTU and higher [6]. The drinking water standard according to the WHO, is below 5 NTU [9]. This means that only water that looks completely clear to the human eye, is suitable for drinking purposes.

4.3 Device design

In the methodology has been described that the design decisions will be modeled using QOCs. In the QOCs that are shown in this section, the decided option is displayed as a blue box. This decided option is the option that has been chosen for the system design in our research. In order to model the design space for IoT applications in general, three recurring design challenges are modeled: power supply, connectivity and communication. Most IoT applications that are designed for rural areas within a development context face these challenges.

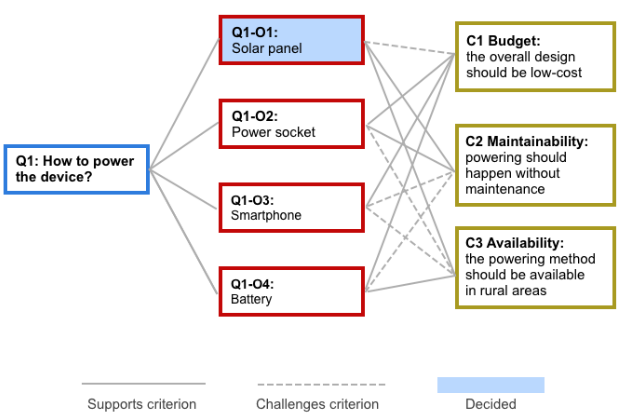

Figure 3: QOC for power supply

4.3.1 Power supply. This design decision involves the power supply of the device. The often remote areas and the autonomous nature of the device are most important for the final decision. Most existing IoT solutions at this time moment assume a perfectly reliable power source, while this is often not the case [38]. Therefore, one should not only think about how to power the device, but also about what should happen when there is a power interruption.

- **Q1-O1 Solar panel**: A solar panel is the most expensive variant of the listed options. This option is very suitable for remote areas with sufficient sunlight. Solar panel solutions are often combined with batteries in order to be able to operate during day and night time.
- **Q1-O2 Power socket**: Powering the device via a wall socket is cheap and convenient. However, this option often not available in rural areas. If this option is available, one should take into account that the grid might have power outages.
- **Q1-O3 Smartphone**: Connecting the device via a smartphone is a cheap option and can be suitable if measurements are only needed on demand. This option is only suitable if the device is not used for autonomous water monitoring.
- **Q1-O4 Battery**: Use a battery/power bank to power the device is a cheap option. This options requires maintenance since the battery needs to be charged or replaced over time. The battery can be combined with a solar panel to make autonomous operation possible.

Rationale for decided options Q1-O1 (solar panel) and Q1-O4 (battery): In a remote area, a power socket is often not available. In order for the device to operate in an autonomous setting, a solar panel is the only possible option left. In this case, the option is combined with a battery. This battery ensures that the device can still operate if there is not sufficient sun to power the device (for example during the night or cloudy conditions).

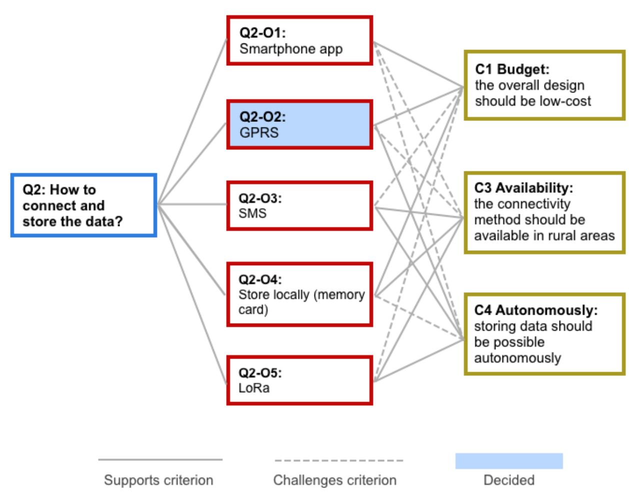

Figure 4: QOC for connectivity

4.3.2 Connectivity. When the device is used to monitor water quality over time, connectivity of the device should be considered. This means that the device needs to send and store the data of the sensors. A distinction exists between long-range and short-range communication techniques. Short-range communication is communication between devices of a maximum of several kilometers (option Q2-O5). This is often used to let sensors nodes connect to a base station that collects the data and sends it to the cloud [29]. Long-range communication on the other hand is used to send the actual data to the cloud (option Q2-O1 until Q2-O3). Solutions that use short-range communication are more suitable for applications where multiple sensor devices are deployed in the same area.

- **Q2-O1 Smartphone app**: If the device is connected to a smartphone, the smartphone's connectivity options (like GPRS) can be used to send the data to a server. This option requires that a user owns and connects a smartphone. And although the device is not operating completely autonomously, continuous monitoring is possible if the data is stored locally as well.
- **Q2-O2 GPRS**: This option is easy to implement, but is dependent on the availability of GPRS on location. In addition, to equip each individual senor device with a GPRS module can be costly in case multiple devices are deployed.
- **Q2-O3 SMS**: Sending the data via SMS is an alternative when GPRS is not available. Sending data via SMS can be costly but might sometimes be the only available communication option.
- **Q2-O4 Store locally**: Storing the data on an internal memory card is a cheap option. However, it requires somebody to upload the data manually to a server.
- **Q2-O5 LoRa / Zigbee**: The setup of a LoRa / Zigbee network is costly and only suitable if a larger amount of sensor modules is being deployed. If such a network is available already, this can be a good option. Although LoRa and Zigbee networks are not the same, they have the similar advantages and disadvantages in this QOC and are therefore grouped together in this model.

Rationale for decided option Q2-O2 (GPRS): The decided option is the most convenient one, since it ensures that the device can operate autonomously, and no extra infrastructure is needed. Depended on the amount of data that is transmitted, GPRS is generally cheaper than SMS. A downside of relying on GPRS is that it not always available, especially in rural areas this is the case. In the areas where the water quality device has been tested, GPRS was available. If GPRS is not available in an area, an alternative option should be chosen.

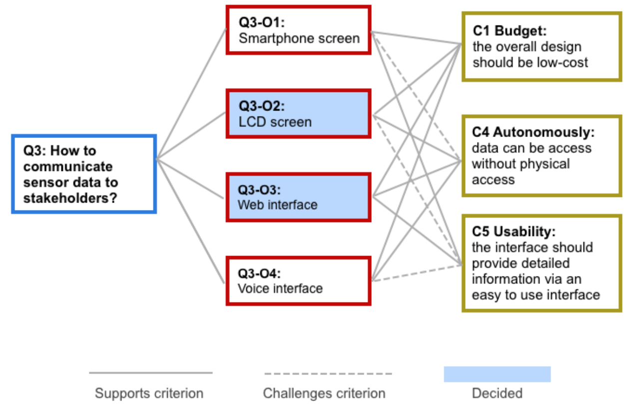

Figure 5: QOC for communication

4.3.3 Communication. In order for the device to be useful, the data should be communicated to the stakeholders. Communication is closely related to connectivity Q2, so deciding on one option influences the most appropriate options of the other question. For example, if in Q2 the decided option is to perform connectivity via a smartphone, communication via this smartphone could be a sensible solution.

- **Q3-O1 Smartphone screen**: A smartphone screen is a cheap way of showing sensor data, it can also show detailed charts. This option requires users to have and connect a smartphone at location.
- **Q3-O2 LCD screen**: This is a cheap option that can provide information quickly. A disadvantage is no detailed information can be shown, and that stakeholders need to be physically close to the device in order to be able to read the sensor data.
- **Q3-O3 Web interface**: A web interface can provide detailed information about multiple devices at the same time. This can be useful for research from a different location then where the device is placed.
- **Q3-O4 Voice interface**: A voice interface is useful for illiterate people, or for users without a smartphone/computer. It is not suitable for providing detailed information.

Rationale for decided options Q3-O2 (LCD screen) and Q3-O3 (Web interface): The water quality device should work for two different use cases, therefore two different options have been chosen. The first decided option, LCD screen, is a cheap method to quickly provide users with basic information. This screen can only be used if somebody has physical access to the device. In addition to this, no detailed information can be displayed on this screen. On the other hand, the web interface can be used to access the data remotely, and is able to display detailed information. Option Q3-O4 has not been chosen, since this option is only useful in very specific use cases. For example, when no internet connection is available and physical access is hard or not possible at all.

4.4 Device development

As has been explained in the methodology, the development phase consists of the actual building and programming of the device. This includes: creating the housing, buying microchips, prototyping, soldering and writing code. To begin with, the housing of the device has been designed with a 3D modeling tool. A custom device design has been created to ensure that the device has small dimensions, while still being able to fit all components in. Afterwards the model has been created, this housing was printed using an Ultimaker 2+ 3D printer. In Figure 6 a picture of the final device has been displayed. No lid has been attached to the device, so the internal components are visible.

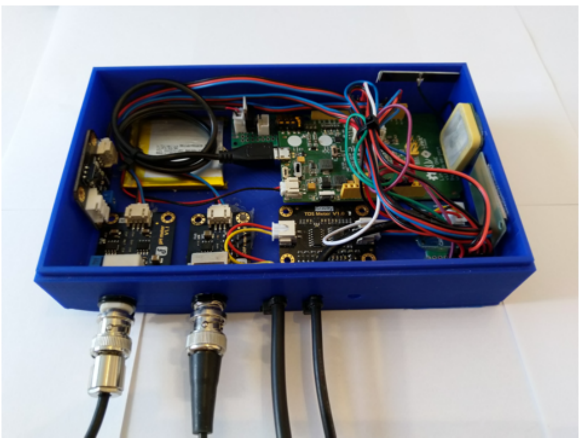

Figure 6: Water quality measuring device

4.4.1 Main controller. The sensors are controlled by the LinkIt One[9] Micro Controller Unit (MCU). The LinkIt One is compatible with the Arduino platform. This means that code written for the Arduino platform also runs on the LinkIt One. We have chosen for this platform because it is an inexpensive and open-source I/O platform that is often used for prototyping [5]. Another reason for choosing this platform is the availability of analog I/O pins which is necessary for reading analog values from various water sensors. For example, Raspberry Pi, which is another popular platform, does not support analog inputs by default. Advantages of using the LinkIt One over the standard Arduino boards, include: built in GPRS, GPS, WiFi, battery controller and a SD card slot.

The code that runs on the LinkIt One is set of C/C++ functions. The source code to run the water quality device can be found online on Github [10]. The readme file in this repository provides information about the settings that can be changed in the code. Some settings, like the GPRS interval, influence the power usage of the device. The more often the data is sent to the cloud, the more power this will cost. A landing page for the device itself can be found online via: https://aoelen.github.io/compteur-deau/. This web page provides general information about the device. It also includes the schematics and 3D design source files. These resources can help to rebuilt the device by anyone who is interested.

[9]http://wiki.seeedstudio.com/LinkIt_ONE/

[10]https://github.com/aoelen/compteur-deau-device

4.4.2 Hardware components. The hardware components that are used for the final device, are listed in Table 2. A cost specification of each single component is shown as well. Among the hardware components are the sensors that are part of the final device. The listed sensors consist of both a sensor controller and a sensor probe. The sensor controller is a small PCB that ensures the sensor data can be read by the Linkit One. This controller is built into the water quality device. The sensor probe is connected to the outside of the device and can be easily replaced by other compatible sensor probes.

Table 2: Hardware specification of final device

Type	Description	Costs USD
Haoshi H-101	Industrial pH sensor	$56.95
LinkIt One	Development board for sensor control	$59.00
DFRobot analog TDS sensor	TDS sensor	$12.90
DS18B20	Temperature sensor	$6.90
TSD-10	Turbidity sensor	$9.90
DFRobot ORP sensor	ORP sensor	$89.05
Seeed Studio Solar panel	1.5W Solar panel	$8.40

4.4.3 Schematic overview. In Figure 7 a block diagram of the final device has been displayed. The device has five sensors as input: TDS, temperature, pH, turbidity and ORP sensor. They are connected to the Micro Controller Unit (MCU), which is the Linkit One. A GPS antenna ensures that the location of the device is captured as well. The MCU has multiple outputs, since multiple usage scenarios are combined in this device. Firstly, the data is stored on the SD card which is inserted in the Linkit One itself. Secondly, the parameters are displayed on the LCD screen. Lastly, the data is sent to the cloud. After sending the data to the server, the data is stored in a MySQL database.

The device operates as follows:

(1) Set up device (connect sensors, turn on power bank)
(2) Put the sensors in the water
(3) *Water quality on demand use case:* water quality parameters appear on LCD screen. LCD background is green if the parameters are in a safe range, the background becomes red if values are outside the safe range
(4) Water quality parameters and location are sent to the server

4.4.4 Different lids for use cases. The device has two different types of lids. One lid is most suitable for the "on demand" use case, while the other lid is suitable for the autonomous measuring use case. The first lid has an LCD screen built in. This screen is used to communicate the sensor data to the user. Since it is possible to directly communicate the data to the user, this lid is suitable for the water quality on demand use case. In order to power the device,

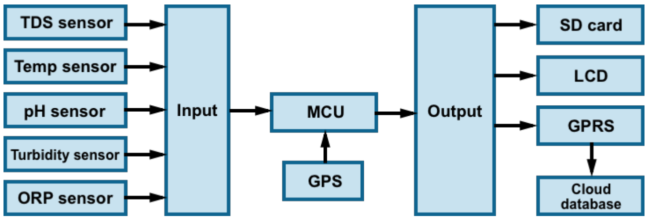

Figure 7: Block diagram of final device

the user should connect an external power source. The second lid has a solar panel built in. With this solar panel the device is able to autonomously measure the water quality. With this lid the device is able to operate in an IoT setting and is therefore suitable for the continuous autonomous water quality use case. By separating the two lid designs, the system design becomes more effective and costs can be saved since only necessary components need to be bought.

4.4.5 Powering using solar panel. In one of the design QOCs, the powering aspect of the device has been discussed. As has been described in the previous section, powering using a solar panel is the most suitable option in case the device should operate in an autonomous setting. For this, a 1.5 Watt solar panel is used. In order to ensure that the device keeps working, even without enough sunshine to power the device, a battery in installed in the device. For this a 1000mAh Li-Ion battery has been used. The battery is connected to the built in battery controller at the LinkIt One. A voltage regulator is used to ensure that the charging amperage is never exceeds 5 Ampere. The battery level, and data about whether the battery is charging or not, is sent to the cloud every time sensor data is captured and transmitted.

4.4.6 Web interface. In order to communicate the water quality parameters, a web interface has been created. The rationale for using a web interface has been explained in Section 4.3.3. The online interface displays the data that the device has sent to server. Using the time range selector, it is possible to monitor and compare water quality parameters over time. The map shows the location of where the device was used to measure water quality. The interface supports multiple languages: English, French and Dutch. It is possible to add more languages if this would be needed for a specific use case. The web interface has been written in PHP (using the Laravel framework[11]). Laravel has been chosen so that extending the interface in the future by other developers will be easier. MySQL is used to store the data. The source code of the program can be found online[12]. Figure 8 displays a screen shot of how the interface looks like.

4.5 Testing and evaluation

4.5.1 First iteration device: testing in Rural Africa. After the development of the first iteration device, the device was shipped to Burkina Faso for testing in the field. The device was used to measure the water quality from a well in a local village. A photo of the well is displayed in Figure 9. The main goal of this testing was to

[11]https://laravel.com
[12]https://github.com/aoelen/compteur-deau

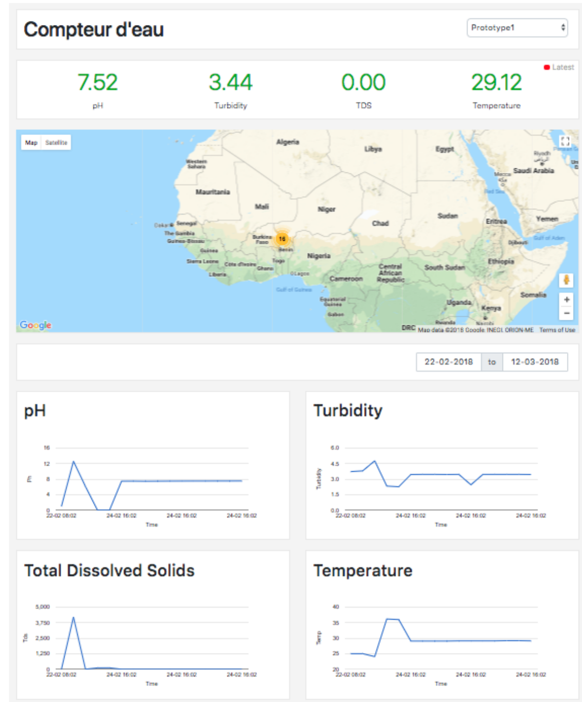

Figure 8: Online interface screen shot

find out whether the overall device design would be suitable for the purpose of measuring water quality. This includes testing the robustness of both the housing and the sensors. Another testing objective was to find out whether the device would be able to transmit the sensor data to a cloud server. For this purpose a prepaid sim card was installed in the device.

During the transportation of the device, some internal cables came loose. Because of this, the device could not be started anymore. It was possible to reconnect the cables during the trip. After fixing the device, it was located at the well. The device was successfully able to connect to the local GPRS network. Sensor data has been sent to the cloud and stored in a database. The data of the measured water quality parameters is available online via: [24] (file name: data-iteration1.csv). The water quality parameters that were measured were not outside the drinking water safety ranges, as listed in Table 1. All sensors measured realistic values, indicating that they were operating correctly. Only the TDS sensor stopped measuring values after a several realistic measures. This was found out later, so it was not possible to check locally why this happened. Most likely some internal cables came loose again, since this happened before. In addition to the testing itself, a local stakeholder orally requested whether the device would be able to detect arsenic in the water. Using the sensors equipped with the device, this is not possible. However, this question led to new research into a test strip reader (see Section 5.5). When the researcher left the testing location, the water quality device was given as a present to the locals. After this moment, no new water quality parameters were measured. This indicates that the device was not used anymore.

Multiple conclusions were drawn from this first field test. The first conclusion is that the main functionalities of the device were working correctly. This means that the sensors were able to correctly measure water quality parameters. Additionally, the device was successfully able to connect to the local GPRS network and to transmit the data to the cloud database. This indicates that the design decision to use GPRS for data transmission was indeed a correct decision. Another outcome of the field test was that the robustness of the device needed to be improved. This means ensuring that the internal cables were connected in a way that they will not come loose anymore. This will also ensure that the TDS sensor will provide correct values in the future.

Figure 9: Well used for testing

4.5.2 Second iteration device: water samples in lab setting. While the first test was conducted in the field, the second test was performed in a lab setting. For this test, nine water samples were collected in Ghana and Burkina Faso. These samples were used to test the second iteration device on. The measured water quality parameters are available online: [24] (file name: data-iteration2.csv). Most parameters did not exceed the drinking water standards, apart from the pH of some samples. The pH of three samples was below the EPA guideline (below pH 6.5). The device was equipped with a new sensor: the ORP sensor.

In addition to the sample testing, tests were conducted to find out what happens in case of sensor malfunctioning. This was done in order to evaluate the reliability and robustness of the device. Tests show that the device keeps working even when a sensor is not connected or broken. When a sensor brakes, the recorded data shows values close to zero. This is due to the analog connection type of the sensors. Even when a sensor does not record information, the analog values will fluctuate around zero. One of the reasons for this to happen is because the port is influenced by other analog input ports.

The tests show that the device was successfully able to capture water quality parameters for the "on demand" use case. Some pH measures were outside the EPA range, indicating that it was a useful decision to equip the device with a pH sensor. The tests also show that the newly connected ORP sensor is working correctly. Tests show that when a sensor brakes, the device keeps on working and is still able to capture the other sensor data correctly. This shows that the device is reliable in the sense that a broken sensor does not break down the whole system. In order to determine the effectiveness of the device in an IoT setting, more tests need to be conducted. Testing should not happen using water samples in a lab setting, but the device should be tested outside, preferably for multiple days. Only then it is possible to draw conclusions on the effectiveness within an IoT setting.

4.5.3 Third iteration device: testing in IoT setting. In order to test the water quality meter in an IoT setting, the device was placed near an outside water tank in the Netherlands. The device was measuring water quality for multiple consecutive days. This was done in order to find out whether the device would be able to operate for multiple days. One of the findings is that the battery capacity of 1000mAh is not enough to power the device without interruption. When every 15 minutes data is sent to the cloud over GPRS, the battery lasts for 8.5 hour. By turning of GPRS, the battery lasts for 17.5 hour (an increase of 106%). When GPRS is turned off, the data is only saved locally on the SD card. Cloud storage is often desired in an IoT setting, and therefore completely turning off GPRS is not an option. A possible solution is to increase the interval of sending water quality parameters to the cloud. For example, data could be queued and sent to the cloud every 24 hours. Another option is to increase the capacity of the built in battery.

The device is equipped with a solar panel, this means that the battery is charged while being in operation. However, during our tests in the Netherlands there was not enough sunshine to charge the battery. This is mainly due to the kind of voltage regulator that has been used. The minimum input of this regulator is 7V. This means that when the output voltage of the solar panel comes below 7V (then happens when it is partially cloudy), the battery is not charged at all. Replacing the voltage regulator with different model is possible solution. Another option is using a larger solar panel that produces an output voltage of at least 7V even when it is cloudy.

Apart from the issues with the battery, the device was successfully able to monitor the water quality of the water tank in an IoT setting. The data has been sent via GPRS to the cloud environment at the specified interval of 15 minutes. In order for the device to be used in a real-life IoT setting, the housing needs to be improved. Right now, the housing is not fully waterproof. This can be fixed by attaching rubber rings to to lid and connector holes. Some connection cables need to be replaced by waterproof versions. During the testing, the device was wrapped in a plastic bag, to prevent water from coming in. In the end, the evaluation shows that the device is able to measure water quality both on demand and in an IoT setting. With minor adjustments to the device itself, it can be deployed in a real-life setting.

4.5.4 Building costs. One of the requirements of the device, was that it should be a low-cost device. The overall costs of the device are around the 250 USD. To find out whether this is indeed a low-cost device, the building costs need to be compared against similar systems. As can be seen in Table 2, the price of the sensors determines the largest part of the overall device costs. This means that when comparing to similar water quality devices, it is important to consider what kind of sensors are used.

An example of a commercial water quality device is the 90-FLT which costs 3,400 USD [38]. Compared to our device, this device does measure two additional parameters: conductivity and dissolved oxygen. It does not measure ORP, which our device does. When our device would be extended with a conductivity and dissolved oxygen sensor, the additional costs would be around 240 USD (169 USD for the dissolved oxygen sensor[13] and 70 USD for the conductivity sensor[14]). The total price of our device would be 490 USD in that case. Compared to the total price of the 90-FLT, this is around seven times cheaper. Another comparison can be made with the low-cost water quality device created by Rao et al. [27]. This device measures the same parameters as the 90-FLT and the building costs are around 1,040 USD. The device developed in our research is more than two times cheaper.

The cost evaluation shows that the device that has been created in this research is indeed low-cost, especially when compared to professional devices. Of course, not all functionalities of the devices are compared and the professional devices are more reliable than the device made in this research. However, the comparison shows that the device is indeed low-cost, which was one of the requirements.

4.6 Iterative improvements of the device

In total three iterations of the device are created. The result of the final iteration is the device that has been discussed in the previous sections. In this section, the changes and improvements per iteration are discussed.

4.6.1 First iteration. The first iteration of the device consists of four sensors: pH, temperature, TDS and turbidity. The same sensor models were used as in the final device. Also, the MCU was the same type of LinkIt One board. The total costs of the device were around 200 USD. This is cheaper than the final device because in this iteration no ORP sensor was used.

The device was powered using a solar power bank (type Xtorm Magma 3000 mAh). The price of 50 USD makes it a relatively expensive power bank. This is one of the reasons to replace this power bank by a different charging system in the next iteration. The first device was suitable for both of the use cases. This means that both an LCD screen and a solar panel were present.

4.6.2 Second iteration. The development of second iteration device focused on adding more sensors and on improving the construction of the device itself. The added sensor was an ORP sensor. As has been described in the evaluation section, some internal cables came loose during the field testing. The second iteration device is therefore made more robust to prevent this from happening.

In this second iteration, two different types of lids for the device are created. The first lid with an LCD screen and the second lid with a solar panel. By making two types of lids, the device became for effective for a specific use case. Since the second iteration device was only going to be used in a lab setting, the lids were made out of cardboard.

In this iteration, the solar power bank has been replaced by a custom made solar solution. This was done because the use of the power bank had multiple disadvantages. For example, it is not possible to check the battery level, the power bank should be manually turned on and the USB connection to the device is not waterproof. Lastly, an external power bank is a relatively expensive device, with the custom made solar solution the building costs are lower.

4.6.3 Third iteration. No new sensors were added in the third iteration. In this iteration of the device, adjustment have been made mainly to the code, the housing and the internals of the device. In addition to this, the lids are now 3D printed as well. The result of this iteration is the final version of the water quality measuring device. Now the device also records information about the battery: the percentage and whether it is charging or not. The data is helpful in order to find out how effective the solar charging is.

Adjustments have been made to the code of the tool, in order to support both online and offline data storage. Online data storage has already been implemented in the first iteration (so the data is sent to the cloud). Offline data storage is new for this iterations, and supports saving the sensor data to a micro SD card. WiFi is now supported as well. Although WiFi is often not a possible connectivity option in a rural area, it can be useful during the development of the board. To conclude, some adjustments have been made to the online data dashboard. Multilingual support has been added to the dashboard. The battery data is now also displayed on the dashboard.

5 DISCUSSION

In this section the methodology and the results of the case study are being discussed. Some of the results are already discussed in Section 4.5: testing and evaluation. This is because the device evaluation is part of the methodology, and therefore part of the results of the use case.

5.1 Collected data

As described in the results section, the water quality parameters that were measured in a well in rural Africa, did not exceed the drinking water standards. For the water samples that were tested in a lab setting, some of the pH levels were outside of the EPA safety range. This does not necessarily mean that the water should not be drunk, but it is an indication can something could be wrong with the water quality. The water quality measuring device is not able to determine whether water is drinkable or suitable for watering crops. However, with this device is it possible to learn more about the water quality of a certain area or region. Organizations like the WHO stress the importance of monitoring water quality in order to detect abnormalities in the measured results [9]. For example, by monitoring water quality over a longer period of time, one can detect changes in water parameters and can find out why these changes occur. Additionally, an alarm system could be integrated, to warn stakeholders when a sudden change occurs. The actual deployment and monitoring of the water quality for a longer period of time, is out of scope for this research.

5.2 Device usage

The first prototype has been shipped to rural Africa. The device was used by a researcher to measure the water quality at a certain location. After the researcher left, the device was given as a present

[13] https://www.dfrobot.com/product-1628.html
[14] https://www.dfrobot.com/product-1123.html

to the locals. The device could have been used by them, to test the quality of different water sources. However, we did not receive any data from the device, which is an indication that the device is not used anymore. Therefore, one can question whether the water quality on demand use case, is a realistic scenario. In the end, such a device can never give a definitive result about whether the water is drinkable or not. This means that using the device on demand is less interesting to locals. The scenario of monitoring water quality over a longer period of time is more realistic. The device in this scenario works autonomously, and therefore the previously described difficulty does not apply. Additionally, water quality data can be collected more often in an autonomous setting. In the end, this will lead to more useful data for analysis.

5.3 Development costs

In Section 4.5.4 the building costs of the device are evaluated. The evaluation focuses on comparing the costs against other professional devices. This is done to show that the device that has been designed in this research, is indeed a low-cost device. However, this does not mean that our low-cost device is able to replace the more expensive water quality devices. These devices are often more reliable with respect to the water quality data the sensors capture. In addition to this, we did not compare the functionalities between the devices. Therefore, the comparison can only be used to show that our device is low-cost in comparison to the pricing of professional equipment.

The actual development costs are higher than a sum of the component costs listed in Table 2, since some materials are not included in this table. This includes the filament needed for the 3D printer, the wires and other small components needed to assemble the device. The total additional costs are below 10 USD. When the device is going to be deployed in the field, these costs could be decreased. The device can focus on one specific use case, and hardware should be selected specifically for this use case. Additionally, specific sensors should be selected for this use case. For example, the most expensive sensor of the device, the ORP sensor, might not be useful in all cases. If this sensor is left out, the overall device costs are decreasing. In order for the device to operate, some operational costs apply. For example, if data is going to be sent to the cloud, network costs apply. In the case where the first iteration device was sent to Burkina Faso and during the tests in the Netherlands, a prepaid sim card was used. Costs for using phone networks vary around the world.

5.4 Turbidity sensor accuracy

5.4.1 Turbidity sensor range. As has been described in Table 1, the drinking water standard for turbidity is below 5 NTU. The turbidity sensor that has been used for the water quality device (type TSD-10), measures turbidity in a range from 0 to 4000 NTU. The used sensor is shown is Figure 10. The measuring range is relatively large, but this causes the measuring resolution to be low. This type of sensor is often used in dishwashers, where a high resolution is not needed. This means that the sensor is not able to detect small differences in the turbidity level. For example, this sensor cannot measure the exact difference between 5 and 50 NTU. As a consequence, the sensor is not able to measure whether the turbidity level is in between the drinking standard of the WHO.

Figure 10: Turbidity sensor TSD-10

5.4.2 Replacing the turbidity sensor. More accurate turbidity sensors are considerably more expensive than the one used in our measuring device (in the range from 10 to 100 times as expensive). Therefore, the sensor module cannot be simply replaced by a model that has a higher accuracy. Since low-cost turbidity sensors with a higher accuracy are needed to assess water quality in for example low-resource communities, multiple studies are conducted in order to design a low-cost, but accurate turbidity sensor [16, 19]. The studies of Kelley et al. and Lambrou et al. both use the same principle to assess the turbidity of water. A laser diode is used to emit light in the water. A photodiode is mounted at an angle of 90° with respect to the laser diode beam. When the laser beam comes across suspended particles, the laser is scattered and the photodiode will be able to detect some of the scattered light. The more particles present in the water, the more light the photodiode will detect. The turbidimeter of Kelley et al. is open-source and can therefore be rebuilt for our water quality measuring device.

Building a turbidity sensor ourselves is out of scope for this research. The components needed for the sensor need to be very accurate. For example, the photodiode needs to be able to detect small changes in the detected light. Additionally, the sensor needs to be calibrated with a professional turbidity sensor in order to provide correct information about the turbidity. Although we think that a more accurate turbidity sensor would be useful for the measuring device, the current turbidity sensor can still record valuable information. For example, significant changes in the turbidity level of water can be detected. This can happen in case of a flood, or major rainfall.

5.5 Extra sensor: test strip reader

In the evaluation section has been described that local stakeholders were interested in measuring the amount of arsenic in water. The current device is not equipped with sensors that are able to detect arsenic. High concentrations of arsenic in drinking water are a potential hazard, especially for rural communities in developing countries [31]. The effect of exposure to high concentrations of arsenic can cause various skin diseases, including skin cancer [23]. Since high levels of arsenic are a problem in particular for developing countries, there is the need to monitor the amount of arsenic in water. At this moment there is no low-cost sensor available that is able to detect arsenic in water. A challenge has been created by multiple organizations, including the American Environmental

Protection Agency (EPA) and the Indian Health Service, in order to find a method to measure arsenic with a low-cost device[15]. The prizes of this contest are between 50,000 and 250,000 USD. This challenge shows the urgent need of such an arsenic sensor.

A method to measure arsenic in water, without sensors, is using test strips. By putting the test strips into the water, one is able to determine the concentration of arsenic in the water. A disadvantage of using test strips is that they can only be used once and should be thrown away after use. Additionally, continuous monitoring of parameters using test trips is not possible and it requires that somebody manually puts the test strip in the water and reads the result. Reading test strips results is not fully objective, since most test strips rely on color comparison. One might see a (slightly) different color than somebody else. Because of these limitations, test strips seem not suitable for the measuring device. However, some parameters cannot be measured with low-cost sensors and in such cases test strips can be a useful alternative. In order to measure arsenic, Hach Arsenic Strips can be used [16]. These strips do not produce chemical waste, so there is no need to handle the cleanup of these chemicals. Because of this, this specific kind of arsenic test strip is perfectly suitable for usage in rural areas.

In order to overcome some of the limitations of using test strips, a test strip reader could be developed. This is a device that is able to read the result of the test strip. This has multiple advantages compared to manual test strip reading. Firstly, the device is able to determine the outcome of the test strip objectively. This means that the results of the tests become more reliable. Secondly, in case of color test strips, the test results become quantitative instead of qualitative. Lastly, the test results can automatically being stored in the cloud. The test strip reader can use a RGB sensor or a CMOS in order to detect the color. A 3D design of a test strip reader is shown in Figure 11. In our test setting, RGB sensors were used to detect the colors of the test strips. It turned out that the sensors used (type TCS230 and TCS34725) were not accurate enough in order to detect small changes in the color of the test strips. A solution for this problem is using a CMOS sensor (a camera module) instead of using an RGB sensor. In the end, the test strip reader has not been built for this research. Building the actual strip reader can be part of future research.

5.6 Sustainability

As has been described in the related literature section, sustainability of ICT4D projects is often used as a benchmark to measure project success. A full sustainability study is out of scope for this research. However, since sustainability is a crucial success factor of ICT4D projects, we will discuss some aspects of this subject. Both the hardware and software of the device are open-source. Open-source for ICT4D projects has multiple advantages, some of these benefits are described by Smith et al. [32]. With the respect to the hardware, the advantage is that parts can be replaced with other (similar) hardware without the help of the product developers. This is useful in multiple situations, e.g. if certain components break or if someone wants to expand the system. For some sensors a BNC connector

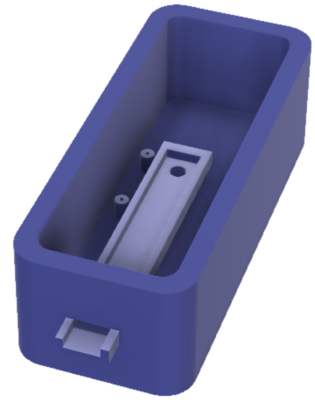

Figure 11: 3D model test strip reader

has been used. This means that when a sensor probe stops working, it is possible to replace this probe by a sensor with the same BNC connector. Since this connection is a common standard, no internal parts need to be replaced. Furthermore, the open-source software also ensures that the system can be expanded or adjusted by any stakeholder. In the end, by using and providing open-source hardware and software, we ensure that the original device developers do not have a crucial role for system operation. This benefits the overall sustainability of the water quality measuring device.

5.7 Future work

5.7.1 Include stakeholders. Only the first iteration device has been shipped to rural Africa. In order to ensure that the device is useful and capable for long-term operation, more devices should be tested in rural areas. Future research could focus on the actual deployment of the water quality measuring device. The feedback from stakeholders and the collected sensor data from the device can be used to evaluate the device and to improve the overall system design. In addition to this, stakeholders can help in determining use cases in which the water quality device can be used. This includes providing information about what kind of water pollution is most common in a certain area and information about who is interested in receiving the sensor data.

5.7.2 Add and improve sensors. As has been described in Section 5.4, the turbidity sensor used in the measuring device is not accurate enough in order to assess whether the turbidity complies with the drinking water standard from the WHO. Future research could focus on improving the accuracy of turbidity sensor. This can be done by implementing the open-source Turbidimeter that has been made by Kelley et al. [16]. Replacing the current turbidity sensor with this open-source version does not require hardware changes on the measuring device itself. The same power output and analog input ports can be used. In addition to replacing the turbidity sensor with a more accurate one, extra sensors can be added in the future. Selecting these extra sensors could depend on the use case for the device. As indicated in Section 5.5, a test strip reader could be useful in case no low-cost sensors are available in order to measure certain

[15] https://www.challenge.gov/challenge/arsenic-sensor-challenge-stage-1/

[16] https://www.coleparmer.com/i/hach-arsenic-strips-arsenic-low-range-test-strips-100-range-0-to-500-pph/0554608

water quality parameters. The actual design and development of such a test strip reader can also be part of future work on the water quality measuring device.

5.7.3 Extend research for other applications. In this research, we focused on using low-cost sensors to measure and monitor parameters specific to water quality. Low-cost sensor kits can be useful for other applications in the ICT4D context as well. For example, it is possible to develop low-cost weather stations using a similar setup as presented in this research. The sensors would be different, but many of the requirements and design options are the same. Another interesting research topic would be reusing old computer hardware. For example, computers have multiple sensors for measuring temperatures. Research could focus on how to reuse such sensors in similar projects.

5.7.4 Validating the methodology. The presented methodology in this research is based on an agile software development life cycle. However, this methodology has only been tested using one case study. More research is needed to test the effectiveness of the methodology, and to improve it where needed. This extra research could consist of extra case studies to find out if the methodology is also suitable and effective for other cases. In the end, the results of these case studies can be used to validate the effectiveness of the overall methodology.

6 CONCLUSION

In this research, a water quality measurement devices has been built. This device has been designed for two different usage scenarios: an on demand water quality checker and as an autonomous IoT device. In the first scenario, one can use the device to test a certain water sample. The device will check certain parameters, and gives an indication about the quality. In the second scenario, the device is installed at a fixed location, and monitors water quality over a longer period of time. The focus of the system design of the device was that it should operate within the context of rural Africa. The main point of this research was to identify the requirements and constraints of deploying such a device in rural Africa. This context is part of the ICT4D research field. Designing a device for this context has multiple implications. This includes that the device should be low-cost, should operate without a stable power source and without a stable internet connection. There are constraints with respect to the operation of the device. For example, system users might be illiterate or are not used to working with ICTs.

The first iteration of the device is tested in the field in Burkina Faso. The second iteration is tested using water samples that were collected at several locations in rural Africa. Some parameters of the tested water samples were outside the drinking water safety ranges. The final device has been tested for multiple consecutive days in a water tank in the Netherlands. As has been described in the water quality parameter section, most parameters only become useful when monitored over a longer time period. Future research can focus on the actual deployment of one or more devices.

In order to answer the main research question, *What is an effective design of a low-cost water quality measuring kit within the context of rural Africa?*, we have shown how an effective design of such a device looks like. Effective means that the system design is suitable to this context with its requirements and constraints. To design such an effective device, an IoT4D methodology has been presented in this paper. This iterative methodology supports experimental development which is suitable when working on ICT4D projects. This because of the usually unknown context and the often changing requirements. Using QOCs, we have shown what kind of different design options are available for the most important design considerations. QOCs for IoT4D are an appropriate method for modeling the design space and making design decisions. This is not only because all options and criteria are listed, but also because of the design rationale of the decided option. The design rationale provides additional information on why a certain decision is most suitable. As has been described in the discussion section, the most suitable option does also depend on the specific usage scenario in which the device will be used. To conclude, a table listing useful water quality parameters is provided. This table gives information about the specific parameters and why they are useful to monitor. Additionally, advice about the parameters in relation to drinking water standards is provided.

The findings and results of the research can be used for future projects that are related to designing IoT devices in for development. This includes research into IoT4D related topics. The methodology presented in this paper shows how such IoT devices can be developed in an iterative and experimental way. The results of case study show that the presented methodology is useful for designing IoT4D devices. The QOCs that are part of the methodology can be used to identify what kind of design options are available during the system design.

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