A POINT-OF-USE WATER TREATMENT SOLUTION

Providing safe water to households in Addis-Ababa with a new jerrycan cap

Matteo Thissen

July 2022

TU Delft Delft University of Technology

Quooker®

A POINT-OF-USE WATER TREATMENT SOLUTION

Providing safe water to households in Addis-Ababa with a new jerrycan cap

Matteo Thissen
4482026
Master Thesis - Integrated Product Design
Delft, July 2022

Education
MSc. Integrated Product Design
Faculty of Industrial Design Engineering
Delft University of Technology

Supervisory Team

Henk Kuipers	- Project Chair
Tomasz Jaśkiewicz	- Project Mentor

Collaboration

Roemer Linkers	- Quooker International BV
Machiel van Dooren	- Made Blue Foundation

EXECUTIVE SUMMARY

For many people around the world, water access is a major problem and a daily struggle. Today, up to almost one billion people still lack access to safely managed drinking-water. Especially in sub-Saharan Africa this remains a major issue for many countries. With this project, Quooker wants to help people in these regions gain access to safe drinking-water and help improve the quality of life.

To limit the scope, and make the project more manageable, the focal point is the urban areas of Ethiopia, and in particular Addis-Ababa. In urban areas, the concern surrounding drinking water is the degrading water quality rather than access to water. Improving the water quality is an area in which Quooker can use its expertise.

In Addis-Ababa, people have access to water from a tap point outside their homes. On average, people can get water from these tap points once a week. To bridge the periods of intermittence in the water supply, people store the water in jerrycans at home. During this 'Water-Journey' the water quality degrades due to user interactions and poor sanitation. In the end, only 24% of the water consumed by people can be considered safe to drink.

During this project, I developed a product that helps the people in Addis-Ababa treat their water at home by building on and using the expertises of Quooker. The design process focused on providing people in Addis-Ababa with an affordable, reliable and long-lasting product. To achieve this, different water treatment methods were analysed. UV-C was chosen as the preferred method due to its long lifespan and potential to innovate. Because UV-C is a novel technology in the context, this project became a feasibility study for the implementation of UV-C as a water treatment method in Addis-Ababa.

The end-result is the UV-Tap (figure 1), a jerrycan cap with an integrated disinfection system. It disinfects the water with UV-C light at the same time as it dispenses it., which kills the pathogens present in the water. With the UV-Tap a household can treat up to 15.000 L of water before components need to be replaced. This equals to approximately 3.5 years of drinking water for a household of 4 people.

Figure 1: Render of the final design of the UV-Tap.

TABLE OF CONTENTS

DESIGN BRIEF 7

DESIGN APPROACH 9

PART ONE - CONTEXT
- 1.1 ETHIOPIA 12
- 1.2 URBAN ETHIOPIA: ADDIS-ABABA 15
- 1.3 PERI-URBAN ADDIS-ABABA 17
- 1.4 WATER CHALLENGES 20

PART TWO - PROVIDING SAFE DRINKING WATER
- 2.1 WATER USE IN A HOUSEHOLD 24
- 2.2 APPROACHES TO SAFE WATER 28
- 2.3 WATER QUALITY 29
- 2.4 A NEW WATER-JOURNEY 31

PART THREE - A NEW WATER TREATMENT SOLUTION
- 3.1 WATER TREATMENT METHODS 34
- 3.2 METHOD SELECTION 39
- 3.3 OPPORTUNITIES OF UV-C 46

PART FOUR - UV-C
- 4.1 INTRODUCTION TO UV-C 50
- 4.2 UV-C PRODUCT ANALYSIS 53
- 4.3 UV-C IDEATION 56
- 4.4 UV-C CONCEPT DETAILING 64
- 4.5 CONCEPT CHOICE 75

PART FIVE - PRODUCT DETAILING & DEVELOPMENT
- 5.1 PROTOTYPING EXPLORATION 78
- 5.2 FUCNTIONAL PROTOTYPE 82
- 5.3 PROTOTYPE VALIDATION 90
- 5.4 THE UV-TAP 94

PART SIX - REFERENCES 122

DESIGN BRIEF

This assignment is executed for the Dutch company Quooker. Founded in 1987 by father and son Henri and Niels Peteri, Quooker specialises in the development of boiling water taps.
Quooker was the first to develop such a tap, and innovation runs deep in the company values. Newer innovations consist of their high-vacuum insulated tanks and all-in-one taps. They manufacture high-quality products for the higher market segments. Especially in recent years, the Quooker has become a must-have in many kitchens and is a market leader.

For the past six years, Quooker has been cooperating with the Made Blue Foundation. This is an NGO focused on water and sanitation problems in developing countries. Made Blue makes arrangements with companies to raise funds to set up drinking water and sanitation projects. Quooker's donations have made it possible to provide over 400 million litres of water in these six years of cooperation. For each COMBI+ Quooker (one of their products) sold, each household saves approximately 4200L of water a year, which is then donated to Made Blue.

Instead of continuing to donate money, Quooker wants to contribute more actively to the global safe drinking-water problem. Over the years, Quooker has not only gained knowledge on boiling water, but also on several water purification technologies themselves. With that knowledge, combined with their expertise in manufacturing and product development, the aim is to help people in developing countries gain access to safe drinking water.

Quooker

Expertises

- Product development
- High-end technical products
- Manufacturing processes and machines
- Knowledge on water (quality)
- Knowledge on water treatment methods
- Innovative Company Mindset

MADE BLUE

Expertises

- Experience with managing drinking water projects in sub-Saharan Africa
- Knowledge of the sub-Saharan African context

Project Scope

Access to safe water is vital for people's health and sanitation. Improving their overall quality of life. Today, there are still many people that get ill from drinking unsafe water. There are still 2.2 billion people worldwide who lack access to safely managed drinking water (WHO, 2019). In 2015 the United Nations determined 17 goals for the world to reach by 2030, the so-called Sustainable Development Goals (SDGs). One of these goals is SDG 6; Ensure availability and sustainable management of water and sanitation for all. To reach this goal by 2030, the rate at which people have got access to safe drinking water needs to improve drastically. At the current pace, by 2030, there will still be 1.6 billion people lacking safe drinking water.

Many countries struggling with access to safe water can be found in sub-Saharan Africa (SSA). In this region, people deal with water shortages daily (dos Santos et al., 2017). This problem was recognized several decades ago, and many governments, NGOs and donors have tried to improve the situation and help people. Due to a lack of (financial) resources and infrastructure many of these projects have not been able to provide long term solutions.

Quooker's goal, in collaboration with Made Blue, is to present a solution that will help solve this problem and result in a long term solution. This graduation assignment aimed to identify a significant cause of the lack of safe drinking water in sub-Saharan Africa and deliver a concept for a solution that builds on Quooker's expertise. This project will mostly be focused on product development, making it possible for future assignments to focus on the implementation and long-term vision for the product.

In the orientation phase of the study, this project's scope has been narrowed down to one of the countries in SSA, Ethiopia. Made Blue has managed many projects in Ethiopia and thereby has gained a lot of knowledge and expertise on the local context that can be used to contribute to this project.

Ideally, this research would have been executed in Ethiopia, to get more familiar with the context and obtain concrete information on the context first hand. Unfortunately, at the time, this was not possible due to COVID-19 restrictions and an escalating civil war in Ethiopia. Most of the findings are based on desk research and input from experts familiar with the Ethiopian context. For that input, I relied on Made Blue, Jerry (the jerrycan water filter) and Aqua for All. They are very familiar with the context and have provided a lot of valuable input that shaped the research of this project.

Figure 2: Person in Ethiopia collecting water in a jerrycan at a communal tap point.

DESIGN APPROACH

This project is subdivided into five parts, concluding with a product proposal. The project follows a variation of the double-diamond design method. During the design process I will switch between diverging and converging phases to find unique and insightful information that I can then use to define problems and make choices.

The first part of the report aims to identify the safe drinking-water problem. I will do this by researching the geographical and cultural context of Ethiopia and narrowing down the scope of this study in several steps. Specifically looking at the role and factors of influence on drinking water. Resulting in a clear cause for the problem.

The second part of the report talks about the identified approaches that can be followed to address the problem. These approaches will then be further explored, after which the most is promising selected. This section then provides a direction for the rest of the project.

Part three of the report is the start of the ideation phase. Here possibilities within the approach are explored and subsequently the most suitable method is selected.

Having defined the best approach and method, I will start working towards possible solutions. Here, the possibilities within the selected parameters and the choice for a final direction are discussed.

In the last section of the report, part five, this final direction is worked out in detail, considering all identified requirements throughout the research phase. As the end result of this phase, the final concept is presented.

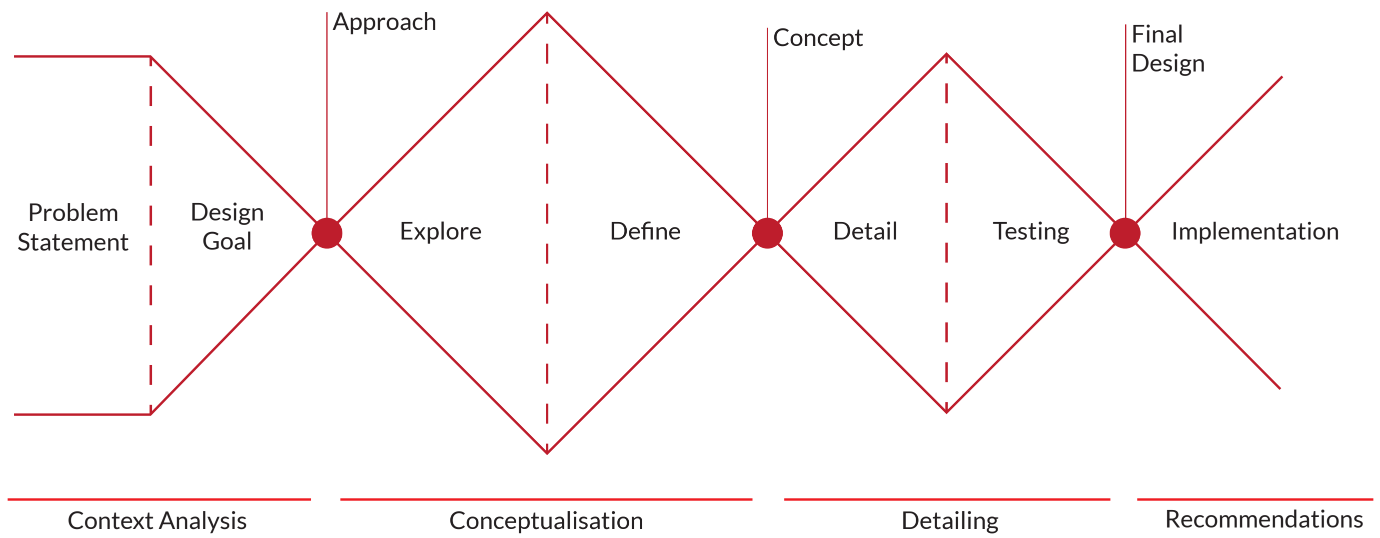


Figure 3: Visualisation of the design process.

PART ONE

CONTEXT ANALYSIS

In any project where scope is unfamiliar it is crucial to get a proper understanding of cultural, socio-economic and geographical context. Understanding these aspects helps direct the design process towards a solution that fits the local needs. The context analysis starts with a short exploration of Ethiopia as a country before diving deeper into the water problem. In the end, presenting the main cause for why so many people still suffer from waterborne diseases

1.1 ETHIOPIA

This chapter briefly discusses Ethiopia's culture, before diving deeper into the problems surrounding safely managed water. Then, I will identify how the safe drinking-water problem manifests itself in Ethiopia and which groups suffer the most from lacking water quality.

Located in the 'Horn of Africa' near the east coast, Ethiopia is a unique country. Due to a broad mix of ethnic and religious groups Ethiopia has, and still is, experiencing many internal conflicts. The combination of the continuous conflicts and a communist regime has slowed down economic prosperity up until recently. In the past decades, with consecutively stable regimes Ethiopia has experienced a period of prosperity, making it the country with the second-highest GDP in East Africa (Statista, 2021). Because of this stability you can now find many projects managed by charities and non-profits here.

Ethiopia is geographically diverse, with lowlands in the southeast and high plateaus in the north and west. At around 2000 m of altitude, these high plateaus constitute a favourable climate and house many major cities.
With a population of approximately 114 million, it is the second-largest nation in Africa (Worldometer, 2020). Around 40% of the population is 15 years old or younger (Demographic development of Ethiopia United Nations, 2019), making the need for progress in housing, safe water and other social facilities even more pressing in the future (The World Factbook, 2021).

Urbanisation

In Ethiopia, as in many other countries in sub-Saharan Africa (from now on referred to as SSA), there is a major demographic shift in progress. In the past decade, many people have started to move from rural areas to cities (figure 4). Currently, around 20% of the Ethiopian population lives in urban areas, but the prediction is that by 2035 this will be 30% (Gebre-Egziabher, 2019).

In the SSA focus of NGO's over the past decades has been primarily on improving access and water quality in the rural areas. This focus, combined with the rapid urbanisation has led to only marginal improvements of water quality and access in urban areas. Over the past decade, only an additional 4% of the urban population gained access to improved water sources (WHO & UNICEF, 2015).

The increasing population, leads to a shortage of resources, facilities, and housing. Translating this to the water problem, it is clear that people in the urban context mainly struggle with the quality of the water available. In the rural areas the problem centres more often around access to water in general (WHO et al., 2019).

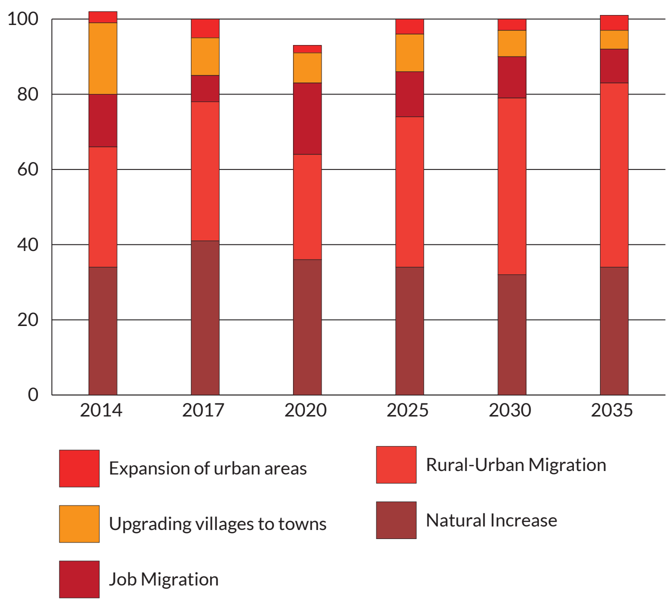


Figure 4: Reasons and predictions for urban population growth in Ethiopia (Gebre-Egziabher, 2019).

Drinking Water

Many people have the perception that people in SSA have to gather water from polluted lakes and rivers, as shown in figure 5. It is true that many people in SSA still have to rely on unimproved sources of water, like rivers and lakes, but this isn't the case everywhere.

Unimproved sources are sources of water that cannot be considered to provide safe water for consumption. These are unprotected from faecal contamination, animals, rainwater run-off etc., making them very likely to contain pathogens (bacteria, viruses, and protozoa). Sources that are likely to be free from pathogens are called improved sources, connected to deep aquifers or protected from contamination through infrastructure. Figure 6 gives a few examples of these types of water sources.

In many cases, people living in rural areas still have to rely on unimproved sources while people living in urban areas often do have access to improved sources (WHO et al., 2021). Figure 7 illustrates the differences in water quantity and access for rural and urban areas in Ethiopia. Interesting to note is that even with access to improved sources, only 40% of the water can be considered safe for consumption.

Improved Sources	Unimproved sources
- Piped Water (into dwelling)	- Unprotected Dug Well or spring
- Public Tap or Standpipe	- Vendor-provided water
- Tube Well or borehole	- Tanker Truck Water
- Protected dug well or spring	- Surface Water (rivers, lakes, etc.)
- Bottled Water	

Figure 6: Different types of improved and unimproved water sources. (WHO & UNICEF, 2010).

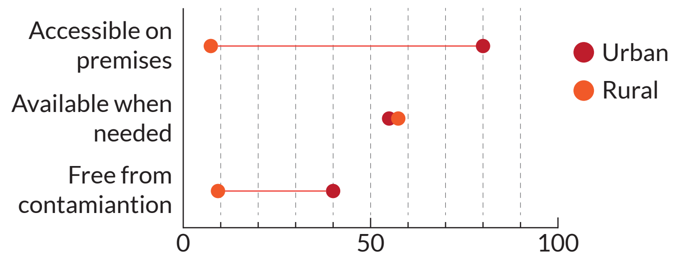


Figure 7: Statistics on water availability and quality in rural and urban Ethiopia (UNICEF & WHO, 2019).

Figure 5: People getting water in the rural areas of Ethiopia.

Because only 40% of the water is safe for consumption many diseases in Ethiopia are water-related (WHO et al., 2021). People get ill by ingesting water contaminated with pathogens. Human or animal faeces containing pathogens, are the most common cause of water contamination.
Ingestion of contaminated water is one of the most common ways to transmit diseases, but certainly not the only one. Food is also a very common transmitter due to poor hygiene or the use of contaminated water for food preparation. Furthermore, people use their hands for eating while they have as poor hygiene.

Diarrhoea
Diarrhoea is a leading cause of death and illness all over the world. Annually 4 billion people suffer from it and killing 1.8 million (WHO, Western Pacific Region, 2014). In Ethiopia, 15% of all deaths are from diarrhoea (World Life Expectancy, n.d.). In almost 60% of the cases where people die of diarrhoea, the cause lies with unsafe drinking water and poor hygiene (Grönwall & Danert, 2020). The majority of those people are children under the age of 5 in developing countries (WHO, 2008).

Sanitation

Access to safe water and sanitation are two areas that go hand in hand and have a significant influence on people's health. Proper sanitation relies on access to enough water, soap, and education. On the other hand, safe water is more easily achieved when proper sanitation is in place. Most infections and contaminations happen due to a lack of basic sanitation and hygiene. Other reasons for the many widespread water-related diseases are a lack of knowledge of the causes of illness and people not caring enough because they are used to the consequences.

Healthy people of middle age care less about water safety. They have built a resistance for illnesses throughout their whole life and are therefore affected less by illnesses. For children, the elderly, and the ill, the same disease can be life-threatening. Because of this vulnerability many children die before they reach the age of 15. Even so, 40% of the Ethiopian population are children and therefore water-related disease can have huge impact on a large part of the population.

In Ethiopia there are two water related problems to solve, water quality and water access. In rural areas the issue for people primarily lies in gaining access to water sources, whereas for people living in cities the main issue is the quality of the water.

Because of the expected growth of cities, solving water related issues for the urban context becomes more relevant for the future. Furthermore, Quooker can be of more value in solving the issue of water quality in the urban areas. Therefore, the rest of the context analysis, and the project as a whole, will continue with a focus on water quality in urban areas.

1.2 URBAN ETHIOPIA: ADDIS-ABABA

Focusing on urban areas helps to scope the project down and limit the factors to which a solution needs to comply with. To make the research more relevant and accurate together with Made Blue we decided to focus on a specific city, Addis-Ababa. This city will work as a case study for the urban context in Ethiopia.

Addis-Ababa is a relevant context for this project for two reasons:
[1] Many NGOs and water related projects start in this city. This means that there is a proper infrastructure in places that makes implementation of new solutions and access to resources easier.
[2] Most of the research on water in Ethiopia is focused around Addis-Ababa and having detailed information will help in the development of a relevant solution. Furthermore, the experts on Ethiopia that I have contacted are very familiar with this city and can therefore provide detailed information.

Water Supply in Addis-Ababa

In Addis-Ababa, there is an intricate system in place to provide people all over the city with water. This system delivers water to more than 94% of the people in Addis-Ababa (CSA, 2017). Most people have taps installed outside their homes or use communal tap points that are shared with multiple households. The Addis-Ababa Water and Sewage Authority (AAWAS) is responsible for supply and maintenance of this network.

The fact that 94% of the city has access to this supply system makes it seem like a well functioning system, however, in practice there are still many issues to be resolved. Intermittence of the water supply is not uncommon. Often due to unforeseen maintenance or a water shortage (Adane et al., 2017). In these situations, the AAWAS, to manage demand and supply, provides different districts in the city with water on different days.
These interruptions usually last from 1 up to 9 consecutive days. Since these happen frequently and are unscheduled, households store plenty of water to bridge these periods. Ordinarily, people have access to water from water taps once a week (O. De Gruijter, personal communication, 15 November 2021).

This system however, is still better than in most other cities. Research from the Central Statistical Agencies of Ethiopia (2017) has found that the water coming from the tap is safe for consumption in approximately 85% of the cases. The AAWAS monitors the water quality on several aspects, these are; physical, chemicals and biological contamination.

Physical
These are all the characteristics of the water that our senses can perceive. Factors that fall in this category are; turbidity, odour, taste, and colour. The most crucial factor is turbidity, which indicates the cleanliness of the water. The research found that the more turbid the water is, the more likely it contains pathogens (WHO, Western Pacific Region, 2014).

Chemical
Under chemicals, there is a wide variety of substances present in water. The most commonly found in groundwater are; arsenic, fluoride, magnesium, and calcium. Of these, only arsenic and fluoride cause serious illness on a large scale (WHO, 2006). Whereas pathogens have immediate effects on people's health, chemical contamination can take years to manifest (WHO, 2011).
Removing chemicals from water can be difficult, especially when dealing with different types of chemicals at the same time; each requires another method to remove.

Biological
Water contains many biological contaminants and living organisms. Within biological contaminants, pathogens are organisms that cause diseases among people. Pathogens present in the water are the main reason behind most drinking water related illnesses.
Pathogens are divided into three categories: bacteria, viruses, and protozoa.

The AAWAS mainly relies on groundwater and aquifers for the supply of water. At their water treatment plants, the groundwater is treated to remove chemicals, physical contaminants and pathogens. After the water has been treated, it is distributed through a network of pipes to supply people all over the city with water. The process from source to the household is visualised in figure 8.

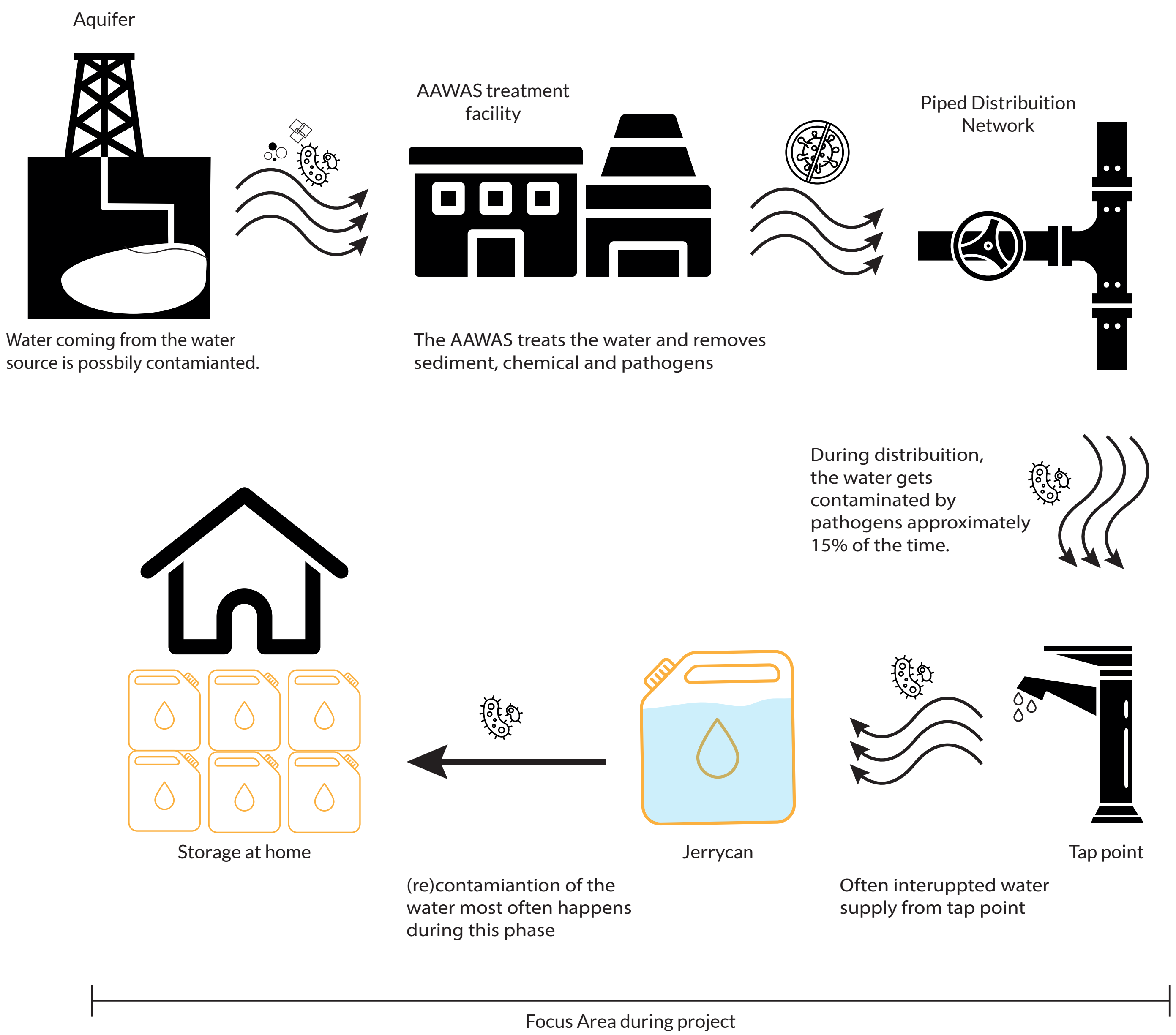


Figure 8: All the steps the water goes through, from the aquifer to the consumer. With all the phases wherein contamination can happen are marked.

1.3 PERI-URBAN ADDIS-ABABA

Almost everyone in Addis-Ababa access to the AAWAS water network, however, this does not mean that everyone in the city always has access to safe drinking water. In this chapter, I will focus on one of the groups that suffer most from the irregular water supply; the peri-urban households of Addis-Ababa.

Addis-Ababa is a city with approximately 5 million inhabitants (Addis Ababa, Ethiopia Population Stat, 2022). Many of these people live in the peri-urban areas of the city. The peri-urban areas mark the transition from the urban to the rural environment and can be categorised as slums. In Addis-Ababa, these parts are not only found on the borders of the city, but are spread throughout the city (T. Merton, personal communication, 12 November 2021). This results in frequent shifts between infrastructure and housing facilities. While the peri-urban parts can often be classified as slums, the urban parts are more modern with many flats.

In 2005, to reduce the housing shortage in Addis-Ababa, the government started to build many condominiums (Melesse, 2020). These replaced many hand-built houses that are typical for the peri-urban neighbourhoods. This has led to many people relocating since they are often evicted from their current homes and can't afford to live in the new, more expensive flats. This means that families now have to move farther away from the city centre where water supply and other services are worse. Figure 9 shows the location of the larger peri-urban neighbourhoods in the urban area of Addis-Ababa. The map show the residential areas in grey and the peri-urban neighbourhoods in red.

Around 80% of the houses in the peri-urban areas can be considered to be in 'slum-condition' (Weldeghebrae, 2021) and are typically illegally built with no tenure rights. These neighbourhoods lack access to infrastructures such as healthcare, drainage, and waste management. Estimations are that less than 10% of the liquid waste of households and industry is adequately disposed of, while the rest ends up in rivers and rainwater channels (Kasa et al., 2011). This way of waste management also deteriorates surrounding water sources, making the water unsuitable for consumption (figure 7). The lack of these services combined with the high population density leads to many problems such as; a high mortality rate, high crime rate, spreading of diseases, and waste dumps (Keffa, 2014).

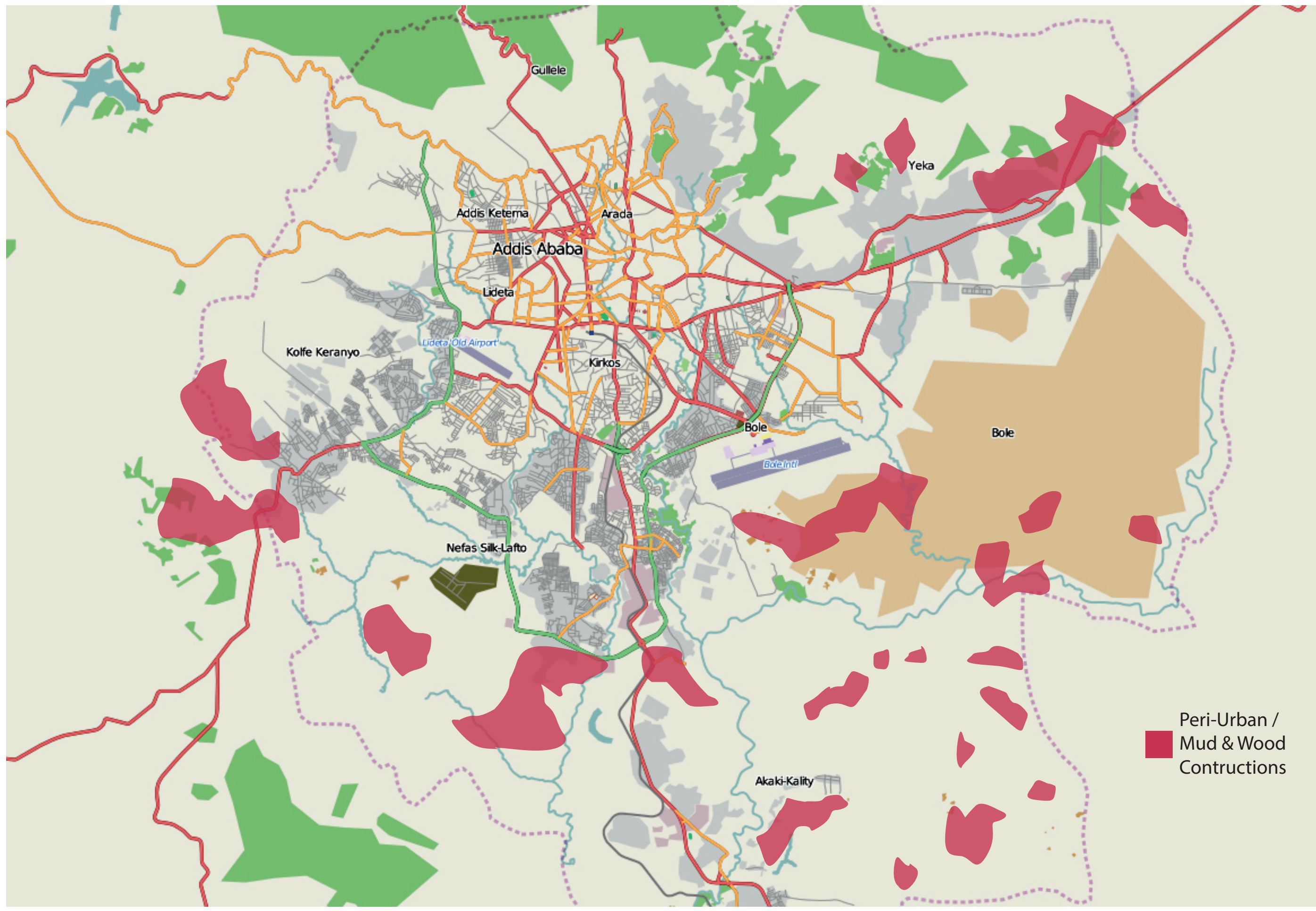


Figure 9: Map of Addis-Ababa with all the differnt land uses, infrastrucutres and buildings.

Water Access for Households

People living in the peri-urban parts of the city are poor and have limited resources. As a household they earn around $100/month (Alemayehu, 2008) of which 1-5% can be spent on water. Additionally, people are willing and capable to spend between $6-$10 on a solution that improves the water quality (O. de Gruijter, personal communication, November 15, 2021).

The water taps through which people have access to the AAWAS' supply network are rarely found inside homes. In poorer neighbourhoods, it is common for households to share water taps (figure 10). This means that transportation of water in containers is always necessary to get the water inside their homes. In Appendix B the peri-urban household is analysed a more in depth.

Furthermore, the supply network is unreliable and therefore households need to store water at home in containers., typically jerrycans. A household, usually of 4 people, stores between 100-200 litres, which equals to 5-10 jerrycans.

Research executed by the company Jerry found that in Addis-Ababa around 80-85% of the households rely on jerrycans for water storage.
Rich households bridge the periods of interrupted water supply by installing large water tanks or buying water from vendors. These vendors sell bottled water and deliver it to people's homes (Made Blue, personal communication, 8 October 2021). Most households in the peri-urban neighbourhoods cannot afford this and must therefore collect and store large quantities of water in jerrycans. Then they have to make sure it lasts for the whole duration of the interruption (which is unknown beforehand) (T. Tola, personal communication, 1 October 2021).

According to national and international guidelines, the quantity of water available to all people should be 50–100 litres per person per day, or an absolute minimum of 20 litres per person per day (UNDP, 2006). A study conducted by Adane et al. (2017) showed that around 80% of the population of Addis-Ababa has to do with less than this minimum requirement of 20L.

The new buildings that force people to relocate make it difficult to develop a solution for an entire community or multiple households. Poor waste management combined with the need to store large quantities of water at home leads to diseases and contaminated water. Because peri-urban households only have $0.30 a day at disposal for water they cannot afford a constant supply of safe water. They need to store the water in jerrycans and have only a limited supply, often less than 20 L per day per person. These households are willing and capable to spend around $10 on a solution that can provide them safe water on a daily basis.

Figure 10: People filling their jerrycans at a tap point in the community.

Figure 11: Typical house in the peri-urban context of Addis-Ababa with unproper waste management.

1.4 WATER CHALLENGES /CONCLUSION PART 1

The water supply and access to safe water in Addis-Ababa is far from optimal. This chapter discusses the challenges that need to be overcome to supply the peri-urban households with safe water.

The 'drinking water problem' manifest itself differently in different parts of Ethiopia. In rural areas, the main issue for most households is the lack of access to water sources, whereas in the urban context the main concern is the quality of the water consumed.

For this project, I chose to focus on the urban scope, and specifically on the peri-urban neighbourhoods of Addis-Ababa. This choice was influenced by stakeholders and an increasingly higher need for safe water in urban areas. The issue of water quality, rather than water access, makes it a much more relevant problem for Quooker with its expertises. Secondarily, people living in the peri-urban areas have limited resources and thereby suffer the most from the poor water quality. Given the current increase in the urban population the difficulties for this group will only increase in the future.

Although the drinking water provided by the AAWAS to local tap-points is safe for consumption 85% of the time, it often gets recontaminated before the actual consumption. When people consume the water, it can be considered safe in only 24% of the cases. The way the households store and transport the water before consumption is the main cause for the degradation of quality.
These interactions contaminate the water with pathogens, which is why in the remainder of this study, I will focus on biological contamination.

Problem Definition

"The water from the tap is not always safe for consumption and the quality further decreases in between the tap-point and the point of consumption."

During the context analysis, I had to make several choices that limited the research scope. This was necessary to be able to gather abundant meaningful information while at the same time keeping the project achievable within the timeframe of a graduation project.

A major choice was to focus on urban and 'improved' water sources instead of rural and 'unimproved'. On one hand this limited the relevance of the potential solution to only a part of the population in SSA, while at the same time it might be more relevant in the future as the trend of urbanisation is global.

By using the peri-urban area of Addis-Ababa as reference for further analysis, the question is pertinent as to how far this reduces the relevance for other urban areas in SSA.
In a future study it can be determined how to make the findings and results of this project relevant for all the urban areas of SSA or even the rural areas.

Water contamination is more complex than it might appear at first glance. There are multiple moments when contamination may happen. A detailed investigation into different moments of contamination is essential to identify opportunities for improving the quality of water that eventually becomes consumed.

Figure 12: Areal shot of the transition between the peri-urban neighbourhoods and the newly built condominiums

PART TWO

PROVIDING SAFE DRINKING WATER

Now that we have an overview of the project's context in Addis-Ababa, we can dive into water uses and the daily water activities for households. This will help understand the requirements that need to be met to provide safe water.

2.1 WATER USE IN A HOUSEHOLD

Each week, when water from the tap is available, many households across Addis-Ababa go through the same ritual; the so-called Water-Journey. This Water-Journey exposes how and when people contaminate the water. Understanding this journey will help determine what type and at what stage taking action will most effectively address the problem.

Water Containers

Most households in peri-urban Addis-Ababa rely on jerrycans for collecting and storing water from the taps. The yellow jerrycans, as seen in figure 13, can be found in many households. Each household often has specifically appointed jerrycans used for drinking water. These are the newer and cleaner ones. Because jerrycans filled with water are bulky and heavy, for purposes other than storage and transportation different containers are used. People mostly rely on jugs, watering cans or utensils to retrieve and use the water for daily activities.

For drinking water, PET bottles or jugs are used as intermediate containers, easing the interaction by not having to fill a glass directly from a jerrycan. For showering and toiletry, people use watering cans, while for dishes and clothing, they have tubs (Dollar Street - Gachinco, 2019).

The yellow jerrycans are originally used as cooking-oil containers. These are typically bought together with multiple households. After all the cooking-oil has been used, one of the households gets to keep the empty container. This system is used to save costs and make the oil more affordable.

Figure 13: Examples of containers for storage and uses of water.

Figure 14: Multipurpose use of a jerrycan. In this case used as a water dispenser.

The Water-Journey

The Water-Journey (figure 15) is a visualisation of all the steps the drinking water goes through between the tap-point and the moment of consumption.
The Water-Journey is subdivided into 5 main steps, each of which represent a moment where the water can get contaminated. Each of these steps shows possible reasons for the contamination and the influence it has on the water quality.

In the end, there are three possible outcomes of the Water-Journey. Those outcomes are:

1. The water is safe for consumption, the water from the tap was safe and no contamination by user interactions has taken place.

2. The water is not safe for consumption, this can be caused by the user interactions or the water being contaminated in the water supply pipelines.

3. The water was safe, but users interacting with the jerrycan have contaminated the water. Rendering it unsafe for future consumption.

The goal of the Water-Journey is to identify how and when the water or containers get contaminated. From examination of the Water-Journey we learn two things:
[1] Every user interaction presents a risk of contaminating the water and/or jerrycan.
[2] The water from the tap point might be contaminated and thereby contaminate the jerrycan as well.

Due to the degradation of water quality between tap point and consumption in the current journey, there is only a 24% chance of ending with Outcome 1. Outcome 2 and 3 together are responsible for the other 76%.

To increase the chances of ending the Water-Journey with Outcome 1, which is preferred there are two possible approaches. These are discussed on the next page.

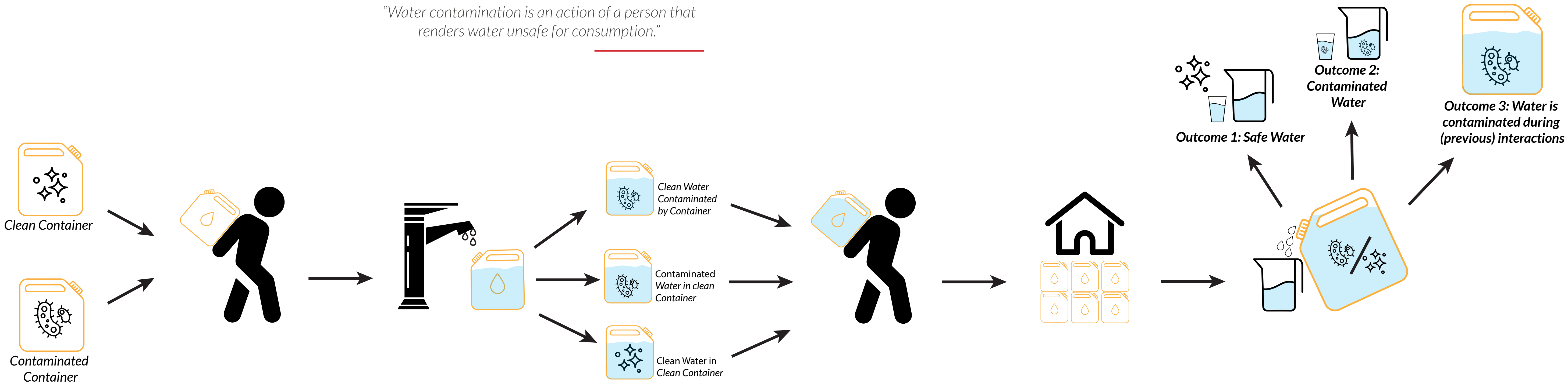
"Water contamination is an action of a person that renders water unsafe for consumption."

Preventing Contamination
If the goal is to prevent recontamination at least two things need to be done.
[1] You need to make sure that no user interaction can contaminate the water or jerrycan.
[2] Secondly, you need to make sure that the water that enters the jerrycan is not contaminated (which might require water treatment).

This approach needs to cover the whole Water-Journey to make sure it is effective.

Water Treatment
Another approach could be, not to prevent contamination, but deal with it by treating the water. The water treatment needs to happen as late as possible along the journey, to reduce the risk of contaminating the water after the treatment. Ideally the water would be treated at step 5.

The notion is that after step 5 of the Water-Journey, the jug/glass will have little to no influence on the safety of the water due to the short period of time the water is stored in those containers.



Step 0. *The storage containers are not always clean. Incorrect cleaning can lead to water contamination.*

Step 1. *Users interacting with the jerrycan, for example, by unscrewing the cap, can contaminate the jerrycan.*

Step 2. *At this point, the users do not influence the contamination, the water from the tap, can or cannot be contaminated.*

Step 3. *During the transport and interaction with the jerrycan the users possibly contaminate the water or jerrycan.*

Step 4. *During storage it is possible for pathogen concentrations in the water to rise.*

Step 5. *Users' interactions with the jerrycan can contaminate the water at home.*

Figure 15: The Water-Journey

2.2 APPROACHES TO SAFE WATER

As long as people have to transport and store water by themselves, there will be risk of water becoming contaminated and unsafe to drink. A solution to this problem could be applied at different moments in the Water-Journey. The analysis of the Water-Journey identified two main approaches: preventing contamination and water treatment.

Preventing Contamination

Before the water reaches the water taps, the AAWAS treats the water and can often be considered safe to drink. Contamination of the water is not only a health issue, but is also a waste of resources spent by the AAWAS. Preventing recontamination is therefore a valuable approach to keeping the water safe for consumption. Within prevention, two different approaches can be taken; impeding and informing.

Impeding (re)contamination

Impeding stands for limiting the user's actions, to minimise the risk of contaminating the water. By developing a container or utensil in such a way that by using it, contamination of the water by users becomes unlikely.

Informing & Incentivising

By providing people information or incentives to handle the water more carefully and raise awareness of the consequences of their actions can improve the water quality. It can help in reducing the risk of the water getting contaminated by the users because of a better understanding of how they get ill and how to prevent it.

Water Treatment

Water treatment deals with the consequences of contamination by treating the water. The water can be rendered safe for consumption through various methods of water treatment.
Not all the water coming from the tap is safe for consumption, sometimes it gets contaminated in the water pipelines, therefore, it is necessary to implement water treatment as an approach. Without water treatment, there is no way to guarantee to the consumers that the water is safe to drink, as they can't influence the water quality coming from the tap. The possibility to implement water treatment in the last phase of the Water-Journey (before consumption) makes contamination after the treatment very unlikely, since there are few user interactions afterwards.

Figure 16: A woman using the stored water to wash clothes. These type of interactions can cause (re)contamination of the storage containers.

2.3 WATER QUALITY

There are three main categories of contaminants of water; chemical, physical, and biological (see chapter 1.2 for more detail). In this report the focus will be on biological contaminants since these can be tackled at a household level and are the most predominant cause for water related health issues.

Pathogenic Contamination

Atnafu et al. (2021) has done extensive research into the water quality in Addis-Ababa. During this research they have looked at the types of pathogens present in water from the tap and water from the storage containers found at homes.

This research focused only on bacteria and protozoa and did not consider viruses, since these require much more complex and expensive testing. For this same reason, up until now, minimal research has been done into viruses present in water in Ethiopia or SSA. Therefore, little knowledge is available on viral infections related to water. The research by Atnafu et al. (2021) shows that the pathogens present are primarily bacteria and some protozoa, figure 177 shows a detailed overview of the found pathogens.

These insights make it possible to design a more effective solution because it is now clear the types of pathogens need to be addressed. With this information it is possible to develop a water treatment device with a specific focus and make sure that the chosen method of water treatment can handle the pathogens of figure 14.

Bacteria	Protozoa
Legionella	*Cryptosporidium*
E. coli	*Hartmannella (host for legionella)*
Streptococci	*Acanthamoeba (host for legionella)*
Proteus	
Pseudomonas	
Klebsiella	
Acinetobacter	

Figure 17: Pathogens present in tap water and water stored in households in Addis Ababa (Atnafu et al., 2021).

Infective Dose

Ingestion of contaminated water does not always lead to illness; if the concentration of a specific pathogen is low enough, the immune system can deal with it. The minimum dose for a person to get ill is called the infective dose. For infants, young children, the elderly, and the ill, this dose is much lower than for adults. As we have seen in chapter 1.1, around 60% of the Ethiopian population can be attributed to one of those more vulnerable groups. This means that for the majority of the population, it is even more important to consume safe water, as the consequences for these vulnerable groups are more severe. The infective dose also differs for each type of pathogen.

Residual Chlorine

The AAWAS makes sure that the water that leaves the treatment plant has some residual chlorine to deal with biological contamination in the distribution system. Research by Kidane Mekonnen (2015) into the levels of residual chlorine at tap points has shown that most of this residual chlorine is absorbed in the piped network. This means that the water tapped into jerrycans doesn't contain any chlorine and doesn't offer prolonged protection during storage.

Water Quality Assessment

Water safety is determined by measuring pathogen concentrations in the water. The water can be contaminated by different pathogens; testing for each one of them is difficult, expensive, and time-consuming.
Pathogens from human or animal faeces are usually the cause for water contamination, and therefore most tests are developed to test for faecal contamination. These tests can check for total coliforms, faecal coliforms and Escherichia coli (E. Coli). Faecal coliforms are a subcategory of total coliforms, and E. coli is a type of faecal bacteria, see figure 18 (WHO, Western Pacific Region, 2014).
If E. coli is present, there is faecal contamination, and that means that it is likely that there are other pathogens present as well, meaning that the water is unsafe to drink (Brandt et al., 2017). The high chance of finding E.coli in the water at homes is due to the use of water and jerrycans for sanitation and the toilet (figure 19). Having proper water dispensing tools in place can reduce the risk of user contaminating the water.

For piped water in general, most regulatory bodies worldwide regard the maximum concentration of pathogens <1 CFU/100mL of a water sample. This means that there should be less than one coliform unit (CFU) present in 100 mL of water (WHO, 2021). This is the same baseline used by the Ethiopian government and AAWAS, see Appendix A. When there is less than 1 CFU/100 mL, there is a low risk of pathogenic contamination.

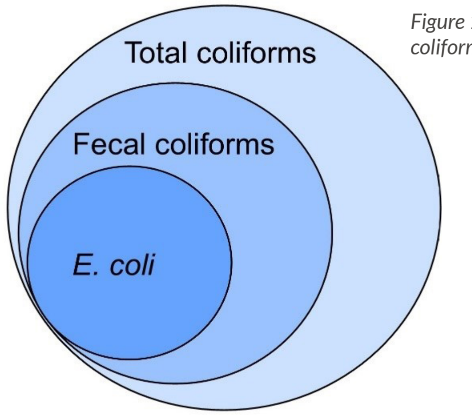


Figure 18: Sub-categories of coliforming bacterias.

Figure 19: Most households use the plots or yards adjacent to their homes for daily activities involving water. The unhygienic surroundings present a high risk of contamination of the water.

As long as the AAWAS cannot manage to provide safe water to the people's homes without interruptions, it isn't possible to really change the current Water-Journey. People will have to keep storing and transporting water themselves meaning that during storage and user interactions the water quality will deteriorate. Although AAWAS guarantees that almost all of their water provision is uncontaminated, in practice only 24 precent of the water can be safely consumed. The analysis of the Water-Journey clearly showed that there is the most to gain by improving the way households have to store water and interact with the jerrycan.

The most viable option to improve the water quality is by adding steps to the Water-Journey that ensure safe water for the consumer. This can be done through prevention or treatment of the contamination. Because the water supplied by AAWAS is not 100% safe, water treatment is necessary, no matter the chosen approach.
Although I recognize the importance of preventing contamination, and will take it into account in the ideation phase, in this study I decide to focus on water treatment.
It is also in the field of Quooker's knowledge and expertise, as they have already used and researched various water treatment technologies.

Because the AAWAS treats the water they provide, and households only (re)contaminate the water biologically, the solution will only focus on this type of contamination. This makes it possible to design a very effective product since it only has to target one type of contamination. However, this does limit the deployment of the product, since it only fits scopes identical or very similar to Addis-Ababa. Obviously it is preferred to develop a solution that can be applied in as many situations as possible, but by narrowing the scope down it is more likely that the solution will actually have a significant impact. If the scope is kept too broad, there is the risk of developing a product that does not specific needs.
Whereas developing a product for a narrow scope can be scaled up for different scopes afterwards.

Water treatment can happen at any stage of the Water-Journey, but intervening at a later stage takes away the risk of users recontaminating the water after the treatment.
Efficient and safe water extraction from jerrycans will ease the interaction and improve the user's experience. Reducing the chance of the user contaminating the water.

Design Goal

Develop a solution that treat water for biological contamination, fit for use by households in peri-urban Addis-Ababa

To achieve the design goal, and guide the ideation process, a criteria list developed by the WHO (2014) was used. The WHO subdivided the criteria into five main categories:

- Effectiveness
- Appropriateness
- Acceptability
- Cost
- Implementation

I used these criteria to determine and specify the requirements for this project. On this page I will give an overview of the requirements I consider most important to reach the design goal. Appendix L contains the complete list of requirements and a more detailed description of the WHO criteria.

Usability for Children
A large part of the population are children, and these are also one of the groups most vulnerable to waterborne diseases. Therefore, it is important that the solution can be used by children from 5 years and older.

Fit with Water-Journey
The jerrycan is an intricate part of the Water-Journey for most household, and therefore it is important that the solution does improve interaction with it and reduces the chance of contamination.

Low Cost Price
Peri-urban households in Addis-Ababa have very limited financial means. Research showed that the households can afford to spend between \$6-\$10 on a water treatment solution. The aim should be to develop a solution that can be sold for less than \$10.

Water Quality
The most crucial requirement, the solution needs to provide safe water. To do so, the water after treatment should always have a CFU concentration lower than 1 CFU/100mL.

PART THREE

A NEW WATER TREATMENT SOLUTION

Before being able to start with the ideation and the development of a solution, one water treatment method has to be selected. In this part, I will choose one treatment method that will form the basis for the next phases of the project. I will describe the selection process and explain the relevance of the selected criteria that were used to make the method choice.

3.1 WATER TREATMENT METHODS

The first step of the process to improve the Water-Journey is defining what water treatment method is best suited for the design goal. There are many different water treatment methods and in this chapter these water treatment methods and products are analysed and evaluated.

The analysis involved methods and products familiar and used in the local context, but also new treatment methods that have not (yet) been implemented in SSA. Each of the methods and products were assessed based on its features and evaluated based on the criteria and information gathered during the context analysis (Part 1 & 2).

Water Treatment Methods

This section discusses the takeaways and insights from the analysis of several water treatment methods. A complete overview and extensive explanation of each method can be found in Appendix D.

Locally Used Methods

For the peri-urban households in Addis-Ababa, there are currently just a few different methods people can rely on to treat their water, these are: filtration, boiling, solar disinfection (SODIS) and chemical disinfection (most of the time the chemical is chlorine). Figure 20 shortly summarises the insights and the (dis)advantages of the analysis of these methods.

Method	Positive	Negative	Remarks
Boiling	*Is effective against all types of pathogens.*	*There is need for expensive fuel (wood, gasoline) and it emits CO2.*	*One of the few methods equally effective against all pathogens.*
Chlorine	*If correctly dosed, the residual chlorine makes it suitable for prolonged storage.*	*It takes 30 min for chlorine to make the water safe. It alters the taste and smell of water.*	*Chlorine can be removed with active carbon filters.*
Ceramic and Membrane Filters	*Can be impregnated with silver to also kill the pathogens.*	*Filters can clog up during their lifetimer.*	*The cheapest option is to have gravity propelled filter products.*
SODIS	*It's free to use, it relies on solar radiation.*	*Very slow treatment, it takes 6-48h, depending on the sun.*	*Requires small transparent containers to work (< 2 L).*

Figure 20: Reveiw of currently used methods

Figure 21: A woman using a water filter at home.

Alternative Methods

Besides the methods currently used by households in Addis-Ababa, there are many other options to treat the water. Most of these are used in a totally different context, such as water treatment plants and for outdoor activities. An exploration of these methods can provide an option to develop a more sophisticated and efficient water treatment solution. The type of methods and the results of the examination of the alternative methods can be found in figure 22. A more detailed description of each of these methods can be found in Appendix D.

Method	Positive	Negative	Remarks
Ozone	*It is effective against all pathogens and does not alter water properties.*	*Complex to use within the context.*	*To make ozone UV-light is required.*
Iodine	*Iodine crystals can treat large volumes of water.*	*Affects physical properties of water just like chlorine.*	*Vitamin C can be used to counter iodine taste a colour of water.*
UV-C	*UV-C LEDs have a long lifetime and kill pathogens quickly.*	*Requires electricity and relies on more delicate technology.*	*Only kill pathogens directly exposed to UV-C light.*
Electrolysis	*It is a cheap and easy way to make chlorine.*	*Disinfection through chlorine, so it's an extra step.*	*Requires brine to work.*
Electric Boiling	*Boiling water without using any fuel.*	*Does require a lot of electricity (high peak load).*	*The power network in Addis-Ababa is unreliable*
Hollow Fiber Filters	*Backflushing can prolong filter lifetimes.*	*It is expensive to filter viruses.*	*Requires pressure to push the water through the filter.*
Active Carbon	*Improves water's phyiscal properties.*	*Doesn't remove pathogens.*	*Can be made from locally sourced organic materials.*

Figure 22: Review of alternative used methods

Water Treatment Products

After looking into possible water treatment methods, the research shifted towards the analysis of existing water treatment products. Taken into consideration were products used in the local context and products of the outdoor sports industry. Products resembled implementable solutions in the context as they are efficient enough for use in a household and relatively cheap compared to industrial or integrated water systems (treatment systems installed directly to the pipes in people's home).
The products' analysis and test results are discussed below, while an overview and explanation of each product can be found in Appendix E.

Figure 23: Examples of products used for drinking water treatment. LRTB: Steripen, Aqua Pure, Steripen prefilter, Lifestraw.

Locally Used Products

At first glance at the solutions in figure 25, the methods and products' simplicity is noticeable. Many of these solutions rely on low-tech and feel more like DIY solutions. Not only does that make these solutions seem less attractive to users, but also less effective. It doesn't urge users to implement them and show their actual value, especially in the context of Addis Ababa, wherein people already have access to clear water (to many people, the water seems safe for consumption upon visible inspection). The summarised analysis of these products can be found in figure 24.

Alternative Products

Besides the product currently used in SSA, there are many other water purifying products available. For this, I've looked into products of the outdoor market. Interesting to see was that the analysed electronic products seemed more developed, and more consideration was put into integrating the user's interaction in the product. Except for the Lifestraw and the Steripen (see figure 23), the products didn't provide any method to tell the user if the disinfection was successful. For dosage-dependent solutions, like chlorine and iodine, there is no way of telling if the dosage was correct and killed all pathogens.

Method	Positive	Negative	Remarks
Lifestraw	*Filters up to 4000 L, very easy and intuitive to use.*	*Mouthpiece and wrong side of filter can get contaminated.*	*Not very suitable for at home use.*
Madi Block (currently used in SSA)	*Simple to use and can treat large volumes of water.*	*Slow in water treatment, it takes up to 12 hours to treat 20 L.*	*Has not been guaranteed to provide safe water.*
Aqua Pure	*Easy to use and suitable for large volumes.*	*Electrical device and more complex than other products.*	*Takes user interaction and needs into consideration.*
Anti Chlorine	*Counters (partially) the chlorine taste and smell in water.*	*Inhibits the possibility for prolonged storge with chlorine.*	*Current use interaction not ideal for at home use.*
Quooker AC Filter	*Improves water quality.*	*Does not work against pathogens.*	*Granular AC filter requires less pressure to work.*
PUR/Aquatabs (currently used in SSA)	*Disinfection works well in turbid water as well due to flocculant.*	*Uses chlorine as a disinfection agent and still requires filtration when used in turbid water.*	*Mostly used as an emergency or as last resort. For daily use, it is quite expensive.*
Steripen	*Fast disinfection of water and lasts up to 3000 L.*	*Requires clear water and is delicate.*	*Uses a mercury lamp to generate UV-C light.*

Figure 24: Review of water treatment products

Figure 25: A bio-sand filter in use.

Choosing a technology

The analysis explored the features and functionalities of products and methods, evaluating them based on the criteria and information gathered during the context analysis. The analysis revealed that there are too many methods to explore in detail and understand properly. Therefore, a preliminary selection is required, with the goal of finding the most promising of treatment methods.

The selection needs to provide methods that can solves the identified problem and that at the same time are suitable for further development from the point of view of the stakeholders. For this, I not only determined potential showstoppers for each method, but also looked at the integration with the stakeholders for development effort and appeal.

- Development Effort: To what extent is it possible to assess the feasibility of a potential solution (in terms of development time and money). The more difficult it is to estimate, the more likely it is that the development process will derail or be stopped without result.
- Appeal: To what extent can expertise that is available within Quooker be used in future development with a certain method.

Figure 26 shows a basic evaluation of the methods, in Appendix L a more extensive one can be found. Based on this selection process, three methods remained that require a more thorough examination. These methods are:

- Filtration
- Iodine
- UV-C

Treatment Methods	Potential cut-off criteria
Sedimentation	Water Quality and Water Source
Chlorine	Water Taste, Smell, and Colour
Boiling	Ongoing Costs and Time of Treatment
SODIS	Water Quality and Water Source
Filtration	Costs, Lifespan
Reverse Osmosis	Local Availability, Costs, Training
Electrolysis	Water Taste, Smell and Colour, Costs
UV-C	Local Availability, Costs, Water Source
Ozonation	Local Availability, Costs
Iodine	Water Taste, Smell and Colour, Costs

Figure 26: Potential cut-off criteria identified for water treatment methods.

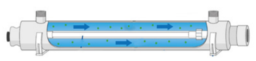
3.2 METHOD SELECTION

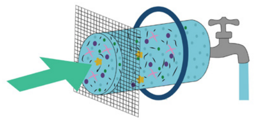
Selecting one water treatment method will help later on in the design process. The focus of the ideation can then be solely on the integration of the method into a product, instead of also having to compare several treatment methods. To be able to make an informed choice between UV-C, filtration and iodine, a more thorough analysis of these methods is necessary. In this chapter, the working principles and the critical aspects of each of these methods will be discussed. Finally, one method will be selected for development into a water treatment solution.

Method Detailing

In the next steps of this chapter, the findings summarised in the table of figure 27 are corroborated and explained. The WHO criteria form the basis for this more in-depth analysis. The table highlights some of the findings of this analysis. What stands out at a first glance is that none of the methods really compare with each other, sure some parameters have similar results, but in general the methods score very differently from each other. Each have their own strength and weaknesses.

Interesting to note is that none of the three methods provide equal effectiveness against the different types of pathogens. This is actually the most important aspect of the method, as achieving a concentration of 1 CFU/100 mL is one of the crucial criteria.





		UV-C	Filtration	Iodine
Water Quality	Bacteria	Effective	Effective	Effective
	Viruses	Not very effective	Not very effective	Effective
	Protozoa	Effective	Effective	Not very effective
Price / L of water (capital costs + ongoing costs)		0.00017 $/L	0.003 $/L	0.00038 $/L
Total Litres (lifetime)		+100.000 L (+10 years)	+/- 4000 L (1 year)	+/- 5000 L (1 year)
Time of Treatment (for 1 litre)		< 1 min	< 1 min - 1 hour	+/- 30 min (independent of volume)
Water Properties (taste, smell & colour)		None	Removes potential turbidity or other particles	Alters the taste and colour of water. This can be reversed by adding vitamin C.
Perception of Technology		New technology that is unknown to people	Familiar and widely implemented technology	Unused method in SSA, but very similiar to chlorine

Figure 27: The three selected methods from the ideation session.

Filtration

Filtration as a means for water treatment is one of the most widely used methods due to its versatility. Filters can be used in different contexts (with different water qualities) and still deliver consistent results.

Proof of method

There are many types of filters, but the basic working principle is the same for all of them. Filters block all particles that are larger than the pore size, which is predetermined based on the requirements. Figure 28 illustrates this basic working principle. The precondition for a filter to work is that some sort of pressure is necessary to push the water through the filter. This pressure can come from gravity alone, but this will make the filtration process quite slow, +/- 1 L/hour. Therefore, most products that use filters rely on mechanisms to increase this pressure and speed up the filtration.

The filter determines the lifetime of a water treatment product. On average **a filter will last around 4000 L**, but this can vary and is largely dependent on the water source quality. **The filter's lifetime can be improved by allowing for back-flushing** within the design. Back-flushing is done by pushing clean water through the filter in the reverse direction, removing particles blocked in the filter. Filters come in all sorts and sizes, making it possible to find one that fits well with the desired product design and functionality.

Filters are very well suited to **remove bacteria and protozoa**, but when it comes to viruses this becomes more difficult. Viruses are the smallest of all pathogen types, see Appendix D for a size comparison between different particles in water. Having a filter with such a reduced pore size not only increases the costs of the filter, but also causes the filter to clog up faster and reduce its lifetime.

Water filtration products used in the context of SSA costs around $15-$20. **The filter itself is responsible for approximately $3-$5 of the total costs** (personal communication, O. de Gruijter, 1 March 2022). So, a product with a replaceable filter can reduce the costs for the user in the long term. Although, **it is not always the case that households can afford or are willing to buy replacement filters.** Replacing the filter adds to the complexity of installation. It needs to be installed correctly without having the user contaminate the filter on the 'clean' part, otherwise it would defeat the purpose of the filter in the first place.

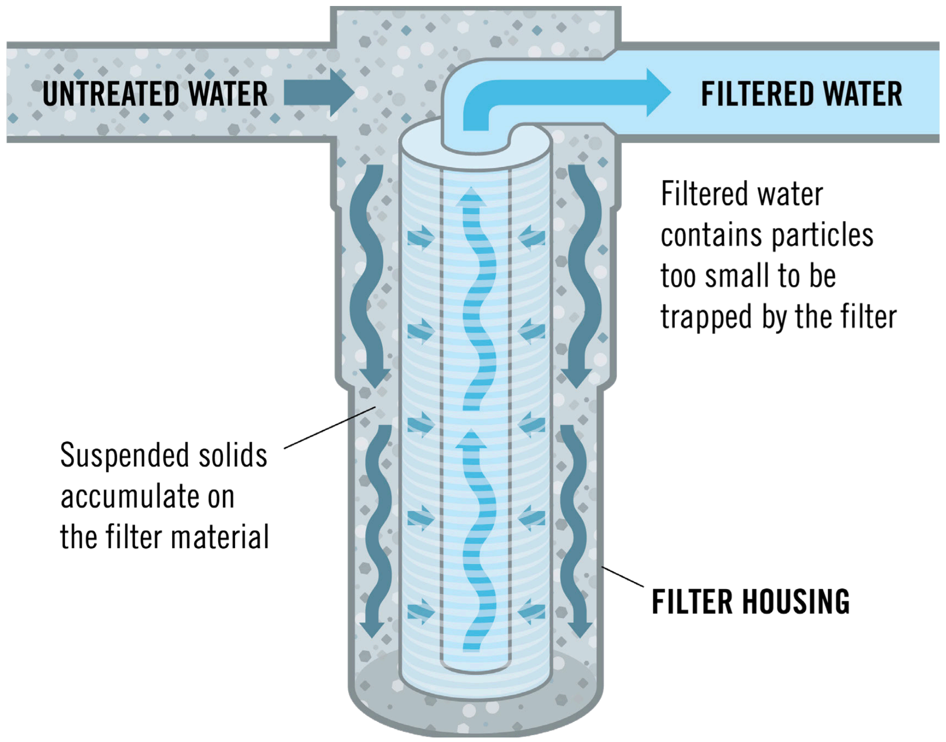


Figure 28: The basic working principle of a filter visualised.

Implementation

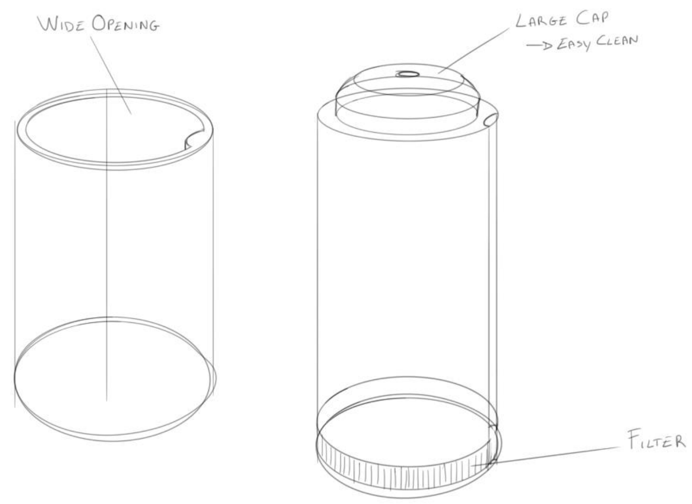
Filtration is a method that is currently used in many water treatment products in SSA and Ethiopia specifically. It is one of the most common methods found in households, and many are familiar with its operating principle. It is a principle that is simple and easy to understand, and this makes people trust it to use to treat their water.

Because it is such a common method, local repair and spare parts are often available. Especially since filters need to be replaced once or twice a year. At the same time, this also means that people are familiar with this process and can do it themselves, for which some basic training or instructions will be required.

Ideation

Products that use pressure to push water through the filter membrane are preferable due to the faster treatment. Keeping the mechanism to apply this pressure as simple as possible has a few advantages. The first of which is that the simpler it is, the fewer components it contains, and there are fewer components to break down. In all probability, this will also reduce the costs of the product.
This is also the idea behind the sketches of figure 29. The bottle with integrated filter consists of two parts, one that is filled with water and one that is used to push the water in the secondary container. The top container has a filter at the bottom and fits tightly in the outer shell with a o-ring seal. Pushing the top container down in the exterior shell forces the water through the filter into the top container. This is a very simple mechanism, allowing people to quickly filter 1L of water.

One of the strong features of filtration systems is that they deliver consistent results, no matter the incoming water quality. This means that products using filters can be used in a wider scope, places where the water quality is not as good as in Addis-Ababa.



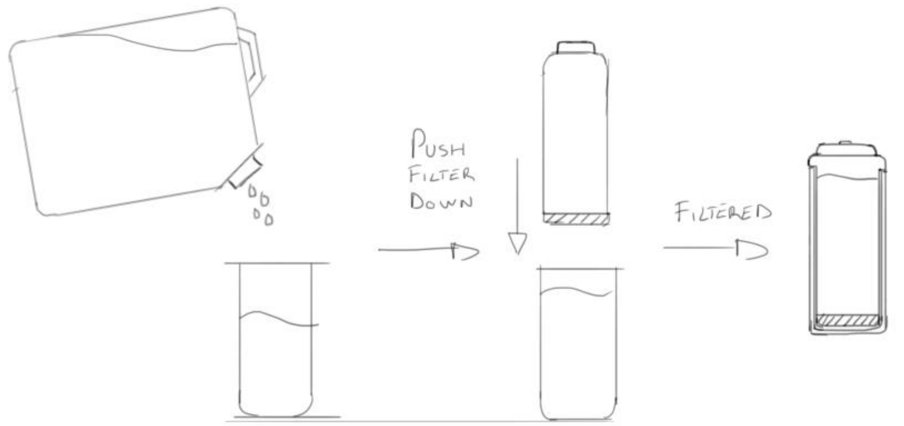


Figure 29: First idea of how a filter could be implemented into a solution. The wide neck of the bottle makes it easier to pour water in from the jerrycan.

UV-C

Using UV-C to disinfect water is a relatively new method. Originally applied in water treatment plants, it has recently found its introduction to consumer products with UV-C LEDs.

Proof of method

UV-C is light that is not visible to the human eye. It disinfects the water by damaging the DNA structure in cells (figure 30). It renders pathogens harmless by first stopping the reproduction process and ultimately killing them.

Since UV-C radiation is light, **it only disinfects those areas that are exposed.** This means that **the water needs to be clear** and contain few particles that can obstruct the light and 'shield' the pathogens.

For disinfection with UV-C to work, you need a container for the water that does not obstruct the light and a UV-C lamp. There are two types of lamps, pressurised lamps and LEDs. In this project, I will focus solely on UV-C LEDs because they are better suited to consumer use. They are not delicate and can operate in short disinfection cycles.

UV-C has not yet been widely implemented as a water treatment method in this context. This is because there are several challenges to overcome. One of the main challenges is the use of electronics, not only does this require electricity but these electronic components can make it a delicate product.

The use of electronics in an environment close to water is far from ideal and presents a challenge as well. Supplying power to the UV-C LEDs should not be a problem since electricity is available, however, the power grid is not reliable, and thus **batteries are required**. This will make the overall product more complex and expensive. Adding a battery will probably increase the price with $0.50-$1.00.

The price of UV-C LEDs varies a lot depending on the specifications of the LED. The price can range from $1 up to $20. For this project, an average LED is sufficient, the more expensive ones are designed for specific high-end/industrial purposes. **The estimated costs for LEDs in this project amount to around $5.** UV-C LEDs have significantly reduced in price in recent years, and especially with the COIVID-19 pandemic, it is expected that these prices will continue to drop in the future (UVC LEDs vs Lamps - Klaran, 2022).

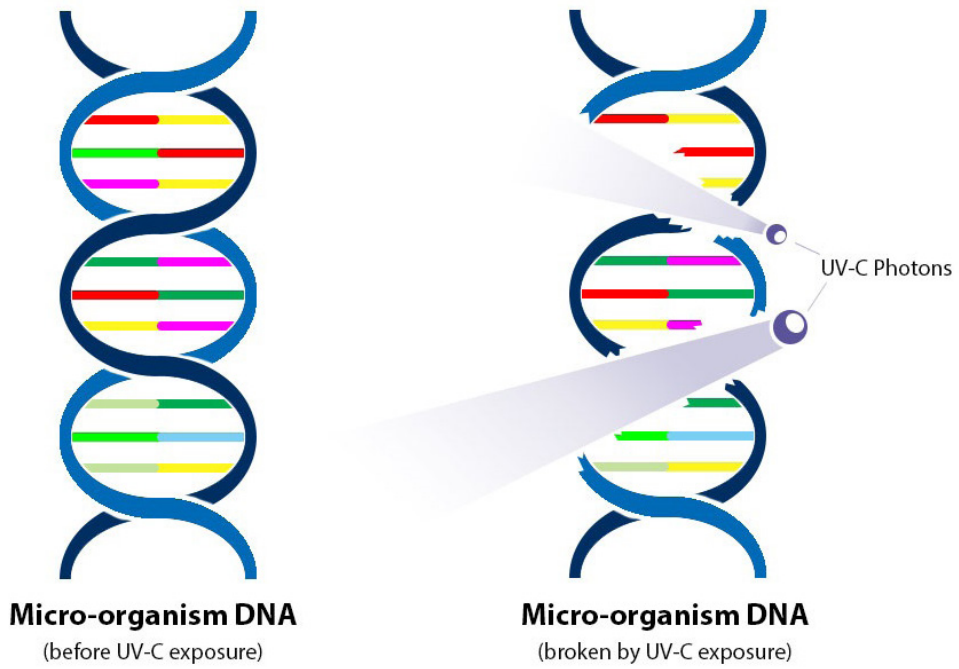


Figure 30: UV-C exposure disrupting the DNA.

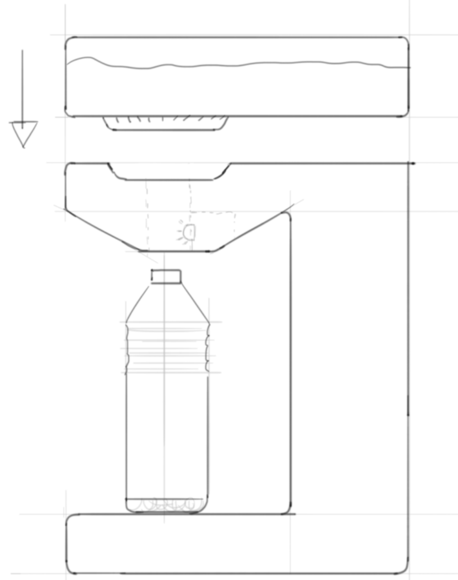
Implementation

UV-C is a new technology in Addis-Ababa, this has some advantages and disadvantages. People for instance are probably still unbiased, no positive or negative stigma exist yet. A new and innovative technology requires to be tested and validated in Addis-Ababa among the peri-urban households to see their perception on UV-C.

UV-C and the technology surrounding it, is not widely available in Addis-Ababa. That means that Quooker is designated to fulfil the manufacturing and repair of the product. For manufacturing this is not really an issue, however, for repair this presents a much more challenging aspect. The skill and knowledge is missing at a local level and therefore, it is important to design a sustainable and durable product. One of the strong suits of UV-C LEDs is that they can last up to 10.000 hours, more than enough for 10 years of water disinfection. If every minute that the LEDs are on, 1 L of water is disinfected, this would amount to more than 600.000 L of water disinfected. This is more than any household would ever be able to consume. The expectation is that the component that is going to be decisive for the lifetime of the product is the battery, seen as these rarely last more than a couple of years. These can, however, be replaced easily.

Ideation

UV-C LEDs are very small, and that makes the possibilities for the implementation into a product numerous. It makes it possible to design any desired configuration, enabling customisation to the specific needs of the context and water journey. For example, by making it easier to pour water from a jerrycan into a bottle, as sketched in figure 31. Here, the product is designed to improve the usability and interactions with a jerrycan. The components responsible for the disinfection are small and that makes it possible to easily integrate them within the while maintaining functionality and usability.



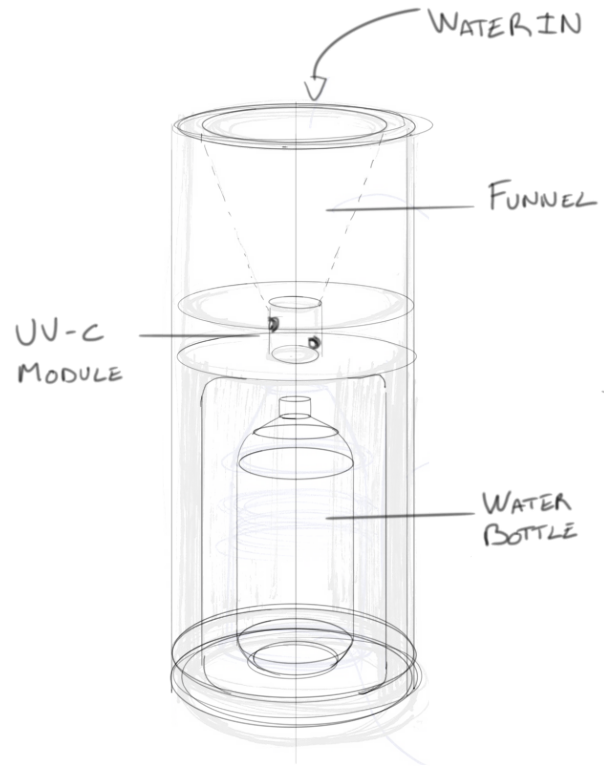


Figure 31: First ideas for a UV-C water treatment product. On the left a 'coffee machine' like device with a separate water container for an easier interaction with the jerrycan. On top a bottle filling station with a funnel that channels all the water to the UV-C LED.

Iodine

Iodine is a chemical element with a variety of purposes. Ranging from medicine and animal feed to colour dyes. It also proves to be an effective method to treat water and kill present pathogens.

Proof of method

In many aspects, iodine works the same as chlorine. It is a chemical disinfectant that kills the pathogens by binding with proteins present in the cell structure, denaturalizing them. This disrupts the cell wall and, in essence, destroys the whole cell (visualised in figure 32). It is effective in dealing with bacterial and viral contamination, but for to kill protzoa it requires a higher concentration. Furthermore, if dosed correctly, iodine can also **ensure prolonged safety throughout the storage**, preventing the growth of pathogens.

Just as with chlorine, the WHO recommends waiting 30 minutes after adding the iodine to the water, to be certain the water is safe to drink. The main difference with chlorine is that iodine exists in crystal form. Iodine crystals only release a small amount of iodine each time they come into contact with water. Just **8 grams of iodine crystals can disinfect around 5000L** of water (Layton, 2022). The costs for the 8 grams of crystalline iodine is around $2, making it a relatively cheap and interesting method to apply in this context.

However, just as with chlorine, **iodine also affects the taste and colour of the water,** making it unpleasant for consumption. It is possible to counter this change by adding vitamin C to the water. The **vitamin C reacts with the iodine molecules, precipitating them and thereby removing the colour and unpleasant taste.** The vitamin C can only be added after the 30 minutes of disinfection have passed. Otherwise, it is possible not all pathogens are dead.

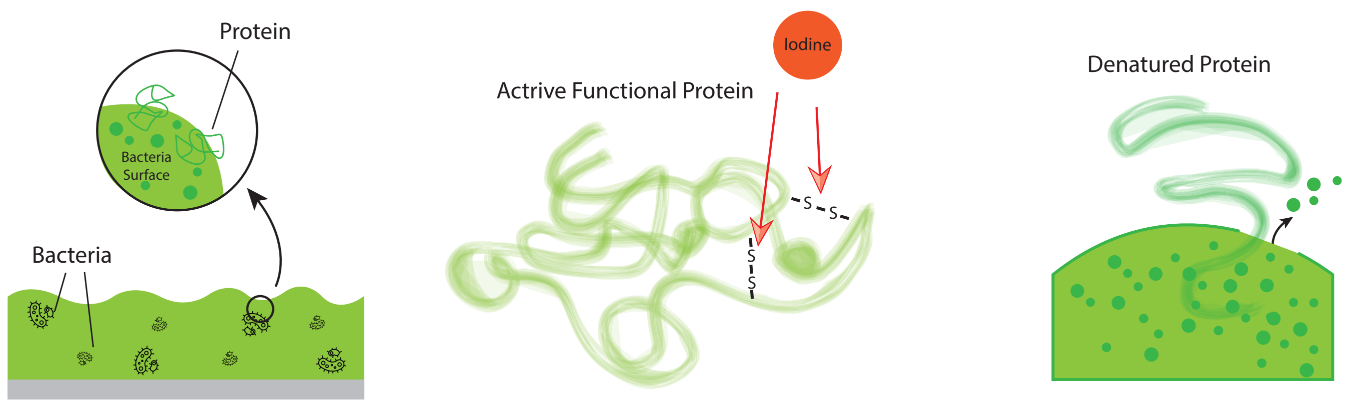


Figure 32: How idione kills pathogens.

Implementation

Iodine is not yet used as a water treatment method in Addis-Ababa. Therefore, there isn't a supply network in place that provides iodine and vitamin C so that people can easily buy 'refills' to keep the product operating. Refilling the product would be a regularly occurring situation, and a properly designed system needs to be developed for it. This system should ensure availability and distribution of iodine and vitamin C. It is a fairly simple method, there is not really a way for people to 'destroy' or damage the method itself (as would be possible with a filter or LED).

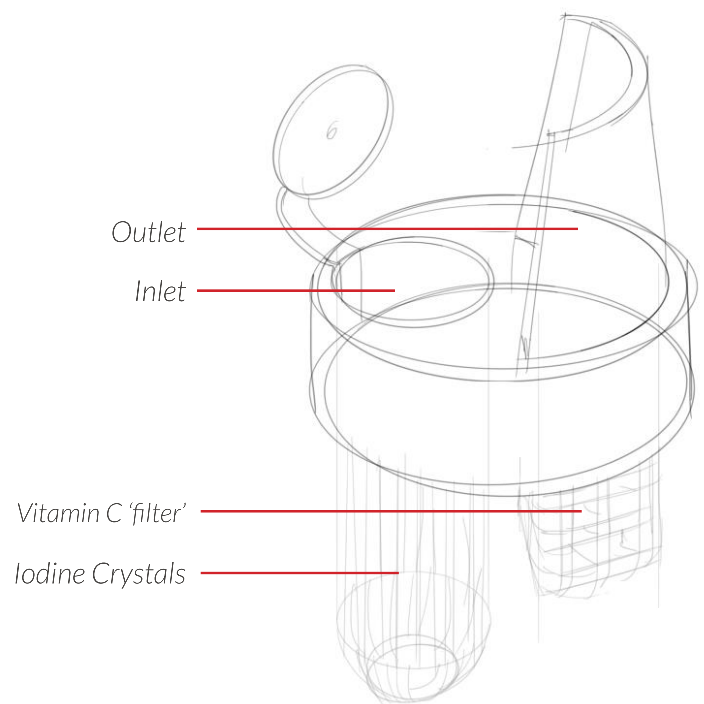


Figure 33: First ideas for an iodine-vitamin C water treatment product. The jerrycan cap has separate in and outlets. The inlet makes sure that for all the water that goes into the jerrycan, a bit of iodine dissolves. When the user then wants to fill a jug, for example, the water passes through the outlet, which has a vitamin C 'filter'. This 'filter' removes all the iodine taste and colour, returning the water to is pleasant taste.

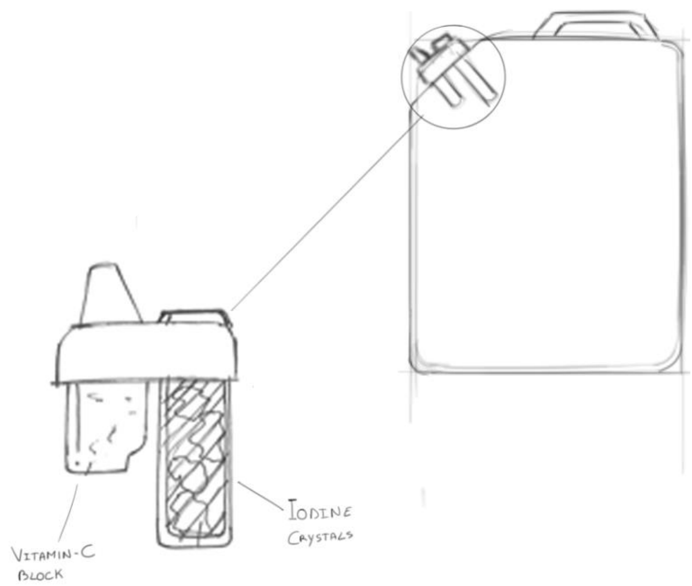
Ideation

Combining the iodine with the vitamin C can provide an exciting direction to explore further because its advantage can be twofold. Not only does it disinfect the water, but the addition of iodine and vitamin C also have a nutritional value.

Adding iodine to water has a long-term advantage because, if dosed correctly, some residual iodine will be left in the water, making it possible to store it for more extended periods without the risk of recontamination.

Figure 33 shows the first sketches of this method's implementation ideas. The working principle of this idea is as follows: by having water flowing through the crystals on the inlet and over the vitamin C on the outlet, integrating the disinfection and taste adjustment into one solution. Making a very simple but effective replacement of the jerrycan cap.

The main issue with the implementation of iodine with vitamin C is that the concept needs a thorough proof of technology. Although independently the ideas work, disinfection with iodine crystals and iodine removal with vitamin C, a combination of both has not been used in the envisioned manner. Determining the right dosages, validating how much iodine the crystals dissolve in the water, how well vitamin C removes taste and colour, those are all challenges that need to be addressed for implementation.



3.3 OPPORTUNITIES OF UV-C / CONCLUSION PART 3

Within the timeframe of this project, it is necessary to select one treatment method. This makes it possible to explore one method more thoroughly and work towards a detailed concept.

The first step of the selection process of the method, was to explore and identify different water treatment methods. This exploration provided nine different methods, of which three were selected for a more detailed analysis. The three methods are; filtration, iodine and UV-C. This analysis entailed diving deeper into the working principles, the implementation in Addis-Ababa, and product development for each of the three methods. The table of figure 34 presents the results of this analysis.

These results reveal that there is not one perfect method, all have their (dis)advantages. The two most promising methods are 'UV-C disinfection' and 'filtration'.

	Filtration	UV-C	Iodine
Strenghts	*- Tested and validated in the SSA context - Users are familiar with the method*	*- Long lifetime - Low price/L*	*- Safe water storage - Effective for all pathogens*
Weaknesses	*- Filters need to be replaced - Need frequent replacement*	*- Requries Electricity - Complex and new technology in the context - UV-C can be harmful*	*- Changes water taste, which can be mitigated with vitamin C - Iodine crystals and vitamin C need to be replaced. - Treatment cycle time (~30min)*
Design Opportunities	*- Convenient filter replacement - Improve on filter lifetime*	*- New technology that offers room for innovation*	*- Combine the simplicity and effectivesness with good tasting water*
Design Challenges	*- Little room for innovation*	*- Durability and implementation in the context*	*- Validation of the working principle, checking if the change in taste can be neutralised*

Figure 34: Comparison between filtration, UV-C and iodine as a water treatment method.

Filtration presents itself as the more 'safe' option, meaning that with this method the end results of the project is more likely to fulfil the technical and context requirements. Filtration is the safe option because it validated in SSA, it performs well in the context and many people are familiar with the method. This reduces the need for user training, and also means that it is more likely a proper manufacturing and repair system can be setup. At the same time this also means that there is little room for innovation with filtration, as many different product relying on filters have already been designed.

UV-C presents a more risky approach. A solution that differentiates itself from others, and relies on more advanced technology. The challenges with UV-C lie in the development of a reliable and durable product and the acceptance of the technology by the peri-urban households. It does however offer the possibility to develop a new type of product for the Ethiopian market that provides safe water at a very low price.

After consultation with Quooker, UV-C was chosen as the method to pursue this project with. The possibility of innovation with UV-C, which is something that runs deep in the Quooker company values, was the deciding factor. The project will therefore make a first attempt at enabling the validation of a UV-C water treatment product within the context. The validation of UV-C will require more research into the theoretical aspects of the technology, how it works, but also on the applicability, to determine requirements and implementation possibilities of the technology.

Figure 35: Example of a bottle cap with integrated UV-C LEDs. Highlighting the possbilities and compactness of the technology

PART FOUR

UV-C

In this phase, the goal is to develop ideas and concepts by experimenting with UV-C and combining the gained knowledge of peri-urban Addis-Ababa with the technology. At the start additional research into UV-C is presented before moving towards the actual development of ideas, ending with a concept proposal.

4.1 INTRODUCTION TO UV-C

To be able to develop a well-functioning device that uses UV-C as a means of disinfection, it is vital to have a clear understanding of the technology. This chapter provides more in-depth knowledge on the basic principles of UV-C and the essential requirements for such a product to work.

Theory behind UV-C

UV-light is emitted in three different ranges, A, B and C, and does not fall within the visible light spectrum for humans (see figure 36). Of the three, UV-C has the shortest wavelength, making it very energy-dense.

Due to the short wavelength UV-C contains a lot of energy, which makes it very harmful to the cell structure of all living organisms. The sun emits all three types of UV-light is. However, the atmosphere and the ozone layer block most of the UV-B and all UV-C. That is why organisms, and therefore pathogens, are able to withstand UV-C radiation.

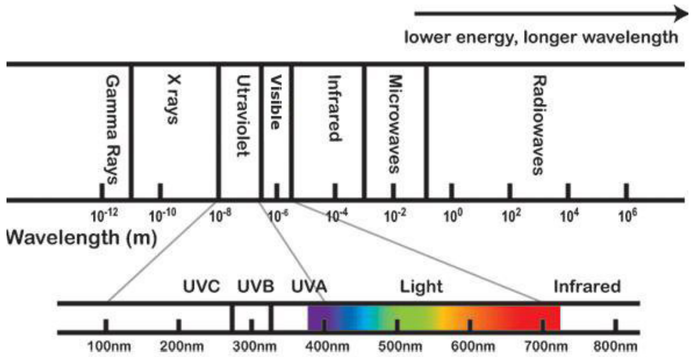


Figure 36: Wavelengths of the light spectrum. The wavelength of UV-C ranges between 100 nm to 280 nm.

Working Principle

UV-C works as a disinfectant because it destroys the internal cell structure. The UV-C radiation is absorbed by the DNA which is then damaged. In the case of pathogens, which are unicellular organisms, this means that they will no longer be able to reproduce and essential cell functions stop, ultimately leading to their death.

The two most important aspects of a UV-C system are the light source (emitting the UV-C radiation) and the reactor (the chamber holding the water). Figure 37 shows a simplified version of such a system.

Parameters that greatly influence the effectiveness of the water treatment are the UV-C intensity and the exposure time of the pathogens to the light. If a pathogen is not directly exposed to the UV-C light, it will have no effect. The LED specifications determine the UV-C intensity, while the reactor design mainly influences the exposure time.

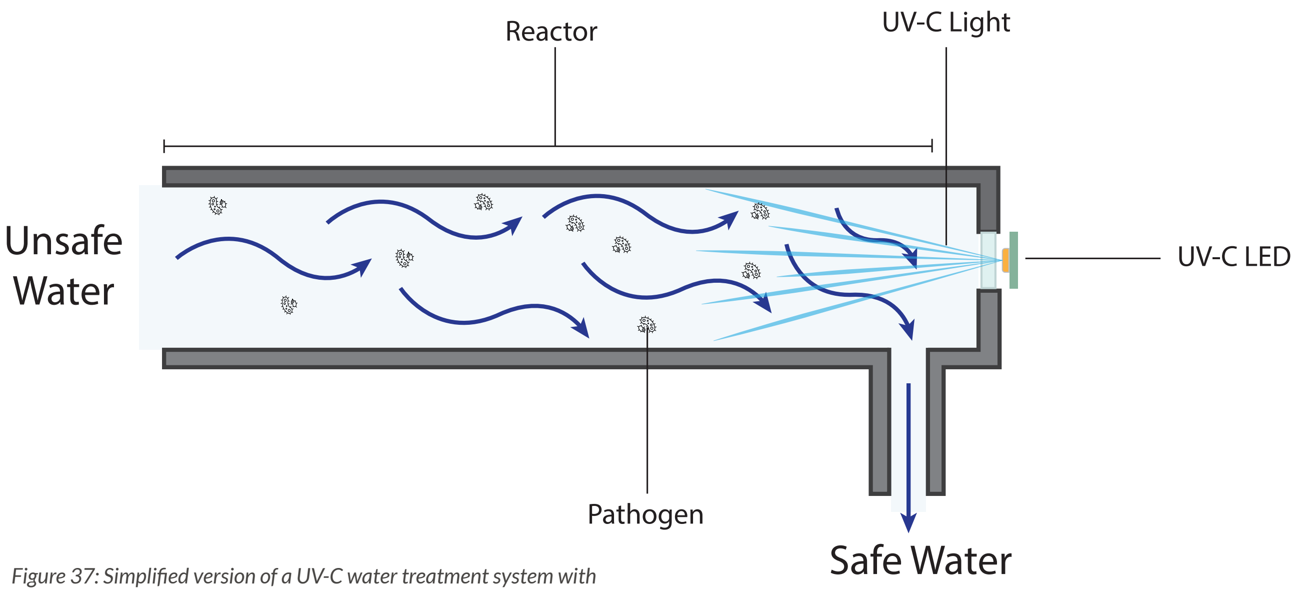


Figure 37: Simplified version of a UV-C water treatment system with the basic components.

Practical application UV-C

To properly understand the disinfection process, it is important to understand the principle of the degree of disinfection. This is specified by the so-called 'log reduction' (logarithmic reduction). Log reduction indicates the percentage of pathogens inactivated by the disinfection process. Figure 38 shows how log reduction compares to the percentage of pathogens inactivated.

Log Reduction	Reduction Factor	Percentual Reduction
1	10	90%
2	100	99%
3	1.000	99.9%
4	10.000	99.99%
5	100.000	99.999%
6	1.000.000	99.9999%

Figure 38: Log reduction table

The goal of the final product is to deliver safely drinkable water. Therefore, it is important to determine what log reduction of pathogens is necessary for water to be considered safe. After conferring with Danny Harmsen from the KWR (a Dutch water research institute), we determined that for the context of this project, the minimally to be achieved log reduction should be log 2, and preferably, log 3 (D. Harmsen, personal communication, 8 February 2022). This was determined mostly by D. Harmsen's knowledge and experience with UV-C combined with the expected water quality, pathogens present in the water and maximum cost price of the device.

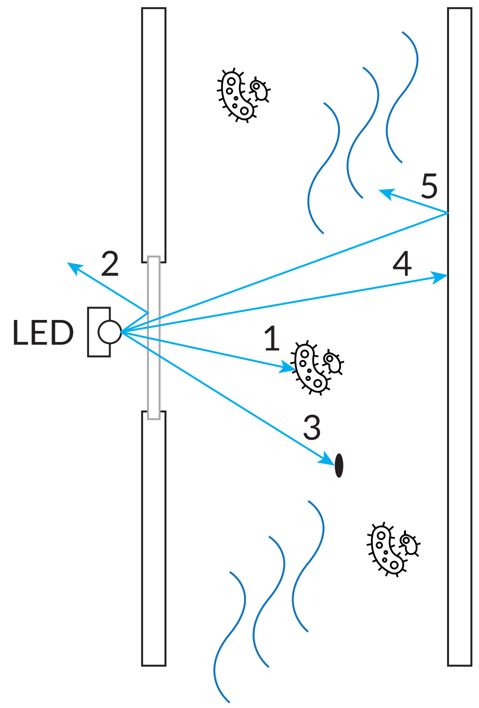
Achieved Log Reduction

Two factors determine the achieved log reduction, the UV-dose each pathogen absorbs and the type of pathogen. For pathogens, the maximum UV-C absorption happens between wavelengths of 260 nm and 270 nm (Bilton & Kahn, 2018).

The UV-C dose is the total UV radiation absorbed by the pathogen and is expressed in mJ/cm^2. The following equation determines the UV-C dose:

$D = I * t$ — *D = UV-C dose (mJ/cm^2)*
I = Intensity (mW/cm^2)
t = Irradiation time (s)

Not all radiation emitted by the LED reaches the targeted pathogen. The reactor design and LED specifications are crucial factors in the delivery of the UV-C dose. Figure 39 shows which factors can influence the delivered UV-dose, through absorption and reflection of UV-C. In Appendix F, a more detailed explanation of factors affecting the reactor design can be found.



1: Efficient use of irridiation
2: Refelction by quartz glass
3: Absorption by particles in the water
4: Absorption by reactor
5: Reflection by reactor

Figure 39: Absorption and reflection in UV-C reactor

Each pathogen differs and therefore requires different doses to achieve the same log reduction. Appendix F gives an overview of the dosages necessary for the pathogens identified in chapter 2.3. The pathogen with the highest required UV-C dose are:

log 2 reduction = Streptococci 8.8 mJ/cm^2
log 3 reduction = E. coli 10.5 mJ/cm^2

The device will therefore need to deliver at least 8.8 mJ/cm^2 for it to be effectively killing all identified pathogens and achieve a log 2 reduction.

UV-C LEDs

The UV-C LED is the most crucial part of the product. There are many LEDs available, the parameters that vary are:
- Radiant power
- Radiant intensity
- Wavelength

Therefore, the choice of LED is a critical aspect of the design process since it can significantly influence the overall design of the system and its efficiency.

Figure 40: Example of an UV-C LED

Radiant power

UV-C LEDs are not very efficient, and the UV-C radiation emitted is a lot less than the power consumed. The radiant power of LEDs is referred to in mW and greatly influences the intensity and UV-dose.

Wavelength

As previously discussed, the wavelength can is important to target pathogens efficiently. Numerous LEDs with different wavelengths can be designed to fit the necessary function. Ideally the LEDs would emit UV-C at a wavelength of 265 nm, but any LED within the range of 260-270 nm should suffice (see Appendix F).

LED Costs

Not only are LEDs the most crucial parts of the design, but they are also the most expensive component. According to the required specifications, costs start at $1.50/LED and can go up to $10/LED or even more. Therefore, it is crucial to design a product that uses the most cost-effective set-up of LEDs and reactor design.

Radiant Intensity

LEDs do not equally distribute the radiation. As you can see in figure 41, the ideal spot with the highest radiation is between 20-40 degrees from the centre of the LED. Above 60 degrees, almost no radiation is emitted.

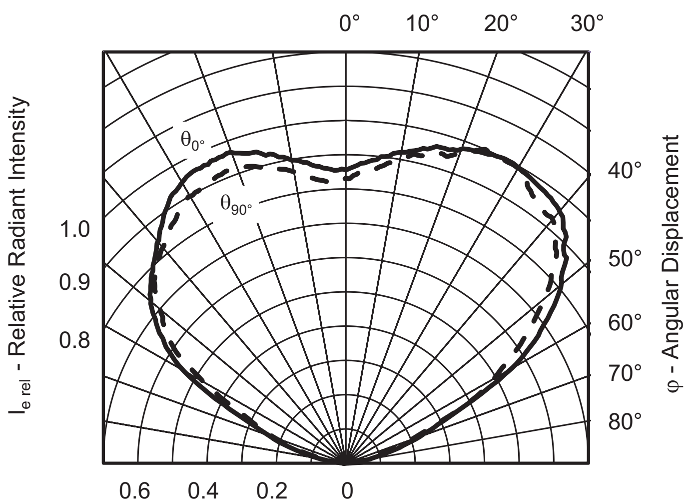


Figure 41: Example of a radiant intensity graph of a UV-C LED, the intensity differs for each angle the pathogen is at from the LED.

4.2 UV-C PRODUCT ANALYSIS

To better understand design considerations concerning UV-C and how the identified requirements can best be achieved, four existing UV-C disinfection products have been analysed on aspects as to efficiency, components, and reactor design. These findings will help lay the foundation for the UV-C water treatment product for peri-urban Addis-Ababa.

These four products have been selected because they provide insights into different aspects of the design of UV-C reactor. Each of these products use UV-C technology differently. Understanding the differences and (dis) advantages of each will help in the development of a new product. A complete analysis of the products can be found in Appendix G.

Healter Bottle Cap

Aftermarket cap that can be mounted to drinking water bottles for disinfection of the water.

Steripen Aqua

Mostly used for outdoor hikers to disinfect drinking water. Instead of Leds it still relies on old fashioned mercury lamps.

Philips Sanitation Box

This is a sanitation box developed to disinfect small personal effects.

Klaran WS Series

UV-C system that is mounted to the water pipes at home and disinfects the water coming out of the faucet.

Figure 42: Overview of analysed and tested UV-C disinfection products.

Functionality

The first step in analysing the product was to test their functionality and how to use them. And although these products were not designed for use in peri-urban Addis-Ababa, learnings could still be derived from design choices, product features and functionality.

Flowing vs Stagnant water systems

From this analysis, two types of disinfection systems came forward: stagnant and flowing water systems. A flowing water system, such as the Klaran WS Series operates by having the water move along the LED. This way all the water is irradiated. A stagnant system (Steripen and Healter) places the LED in a position that it can irradiate the whole volume of the reactor.

A flowing system requires pressure to push the water through the system, whereas a stagnant system can just be placed on top or in a container. The Healter cap, for example, can be used for different types of bottles, since it doesn't have a reactor; the bottle itself will be the reactor. This applies to any type of container.
The Klaran WS has its own reactors, which guarantees a higher performance and consistent disinfection.

Figure 43: Healter cap using the bottle as reactor chamber.

User Feedback

UV-C does not provide a physical barrier to guarantee the disinfection of the water, the user needs to be informed whether the LED is turned on and disinfecting the water. Without this piece of information, there is no way for the user of knowing whether the water is disinfected. They all have an LED light informing the user of the disinfection process being in progress, be it in different ways of showing this.

A major drawback of the Klaran device is that it requires two steps to disinfect the water, firstly you have to turn on the device before you can open the tap to access the disinfected water.

As to the disinfection process itself, the devices rely on different irradiation times (ranging from 48 seconds to 8 minutes) and use different UV-C LEDs, meaning that a comparison isn't really possible.

Health & Safety

Since UV-C radiation can be harmful to skin and eyes (see Appendix F) all devices have safety features to prevent contact. Where the Klaran relies on a passive feature, the LED is completely enclosed by the casing and no light can escape. The other three products use sensors to determine whether it is safe to turn the light on (figure 44).

Figure 44: The philips sanitation box with integrated safety sensors to register if the lid is closed.

Components

Dismantling of the products revealed that most of them have very similar components that result in the same functionality. In figure 45 an overview of the components from the Healter cap are shown. This gives a representative view on the components needed for a UV-C system.

Casing
The casing ensures all electronics are protected from water and dirt and provides some robustness to the design

Sensor
The sensor is installed for safety purposes. It registers if the cap is placed on a bottle, otherwise the LED won't turn on. Thereby ensuring the user is not exposed to UV-C light.

PCB
The PCB has the Controls for the user integrated and is connected to the LED and sensor.

Battery
In 'disinfection mode' this battery can last up to a month of disinfecting the water for 30 min every hour.

LED
One LED is used to provide disinfection and is connected to the PCB.

Quartz
The quartz glass has a high transmittance of UV-C therefore making it an ideal material to protect the LED from the water while letting the UV-C radiation through.

Seals
To ensure that the connection between the quartz glass and the casing and other critical points is waterproof O-rings are used

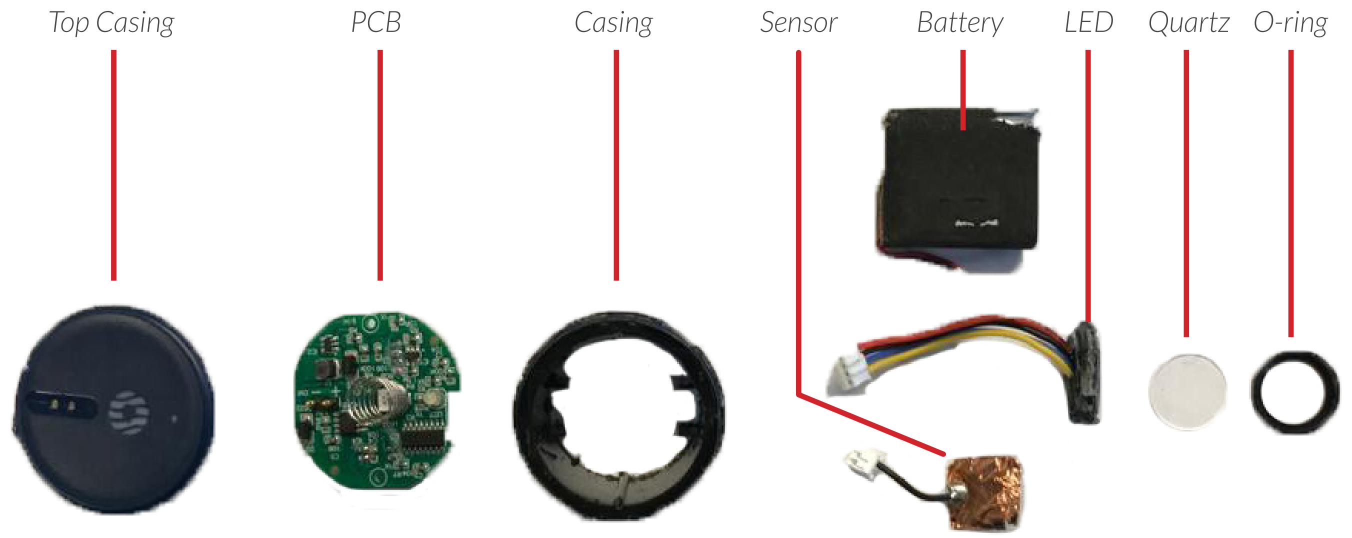


Figure 45: Overview of the componets of the Healter bottle cap.

4.3 UV-C IDEATION

During the ideation, all the knowledge on UV-C, the local context and the water journey is combined to work on ideas and present viable concepts. The ideation process is directed by design guidelines that are shaped based on requirements and insights gathered throughout the research.

Requirements

In chapter 2.4 the main requirements of the context analysis have been discussed. This list of requirements is further completed with knowledge gained from the UV-C analysis. The complete list can be found in Appendix L, here only the main requirements derived from the UV-C analysis are discussed.

Safety

UV-C is harmful to humans as well and therefore, the user needs to be protected from exposure. The device needs to have built-in features that prevent exposure under any circumstance.

User Feedback

Because the user cannot directly see if the UV-C LEDs are working (UV-C light is invisible and harmful to the eyes) the device should have a way to inform the user the device is active

UV-C Dosage

The UV-C dose is crucial for the device to work. If the dose of 8.8 mJ/cm^2 is not achieved the device defeats it purpose. If this dose is not delivered it also means that the requirement of <1 CFU/100mL cannot be achieved.

Design Guidelines

Aside from all the predetermined requirements and functionalities, the ideation phase is also influenced by insights from the research that cannot be defined as requirements. These aspects should be considered within the product design and are discussed in the visual and text below.

Simpleness & Affordability

The peri-urban households have limited financial resources, therefore it is crucial to keep the capital and ongoing costs to a minimum. This means that the product should only contain components that play an active role in water safety and usability. Keeping the product as simple and small as possible reduces manufacturing and transport costs, in the end making the product cheaper for the user.

Preventing (re)Contamination

Most of the research so far has focused on water treatment. This is not the only approach to improve water quality. So, in the ideation phase, some attention will also go to include features to prevent contamination by the users.

Water journey

Integration into the water journey is one of the most important aspects of the product design. And one of the main concerns therein is the interaction between user and jerrycan. Improving this interaction can contribute greatly to the adoption of the solution.

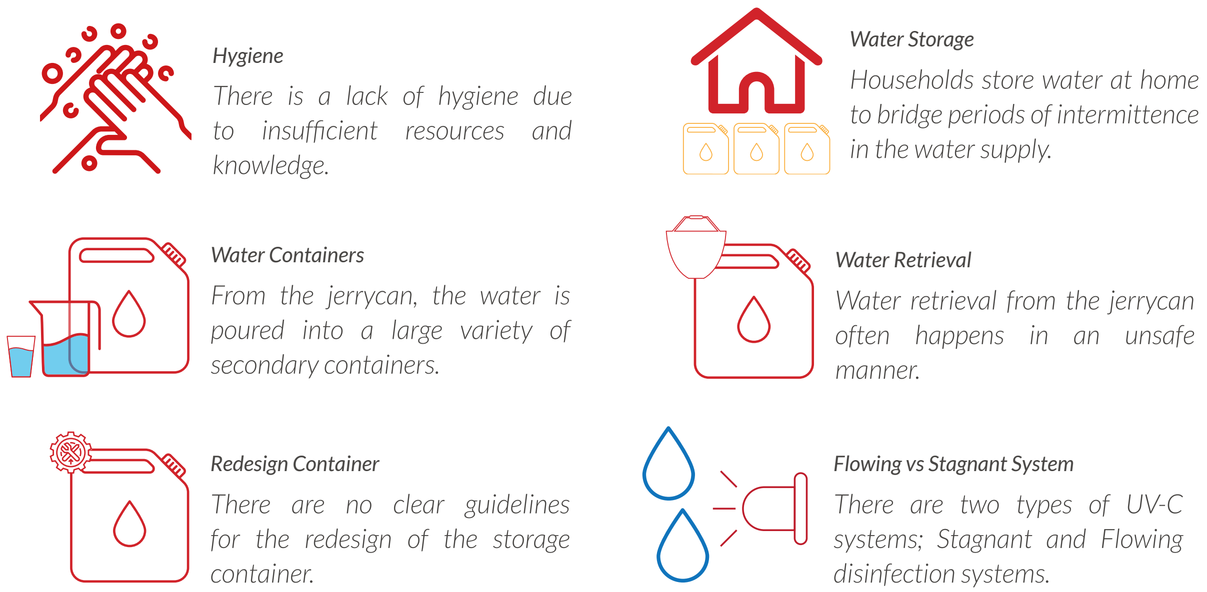


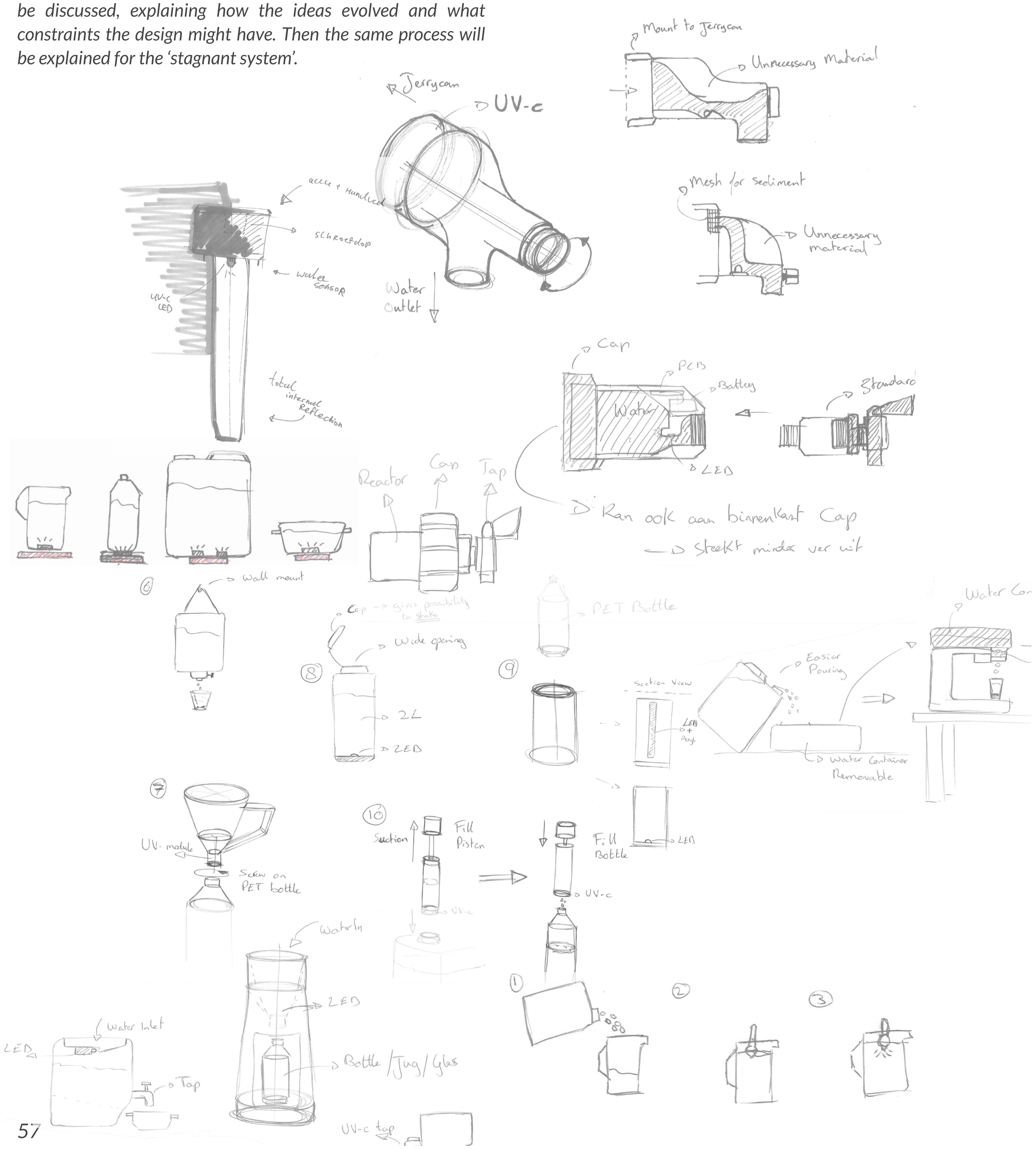
Figure 46: Interesting insights gathered during the research phase that are relevant for the ideation process.

Shaping the Ideation

The first ideation round (visualised in figure 46), considered the requirements and design guidelines. The result from this session has led to realise that both types of UV-systems should be explored independently.

Firstly the ideation process of the 'flowing system' will be discussed, explaining how the ideas evolved and what constraints the design might have. Then the same process will be explained for the 'stagnant system'.

Figure 47: Overview ideas from the first ideation session with UV-C.



Flowing System

To develop a well-functioning flowing UV-C system, the reactor design is crucial in the efficiency and effectiveness of the whole product. The goal for the ideation of the 'flowing system' was to develop a product that would leave ample space to integrate a well designed reactor.

Dispenser

The first design is a water dispenser from which water can be tapped. Where the common containers use a filter, in the new design a UV-C LED is used (see figure 47). In this way, the relatively unknown UV-C system can be integrated into a recognizable design, allowing it to be better adopted by the population of Addis-Ababa. Many people are familiar with these types of water dispensers, as shown in figure 23.

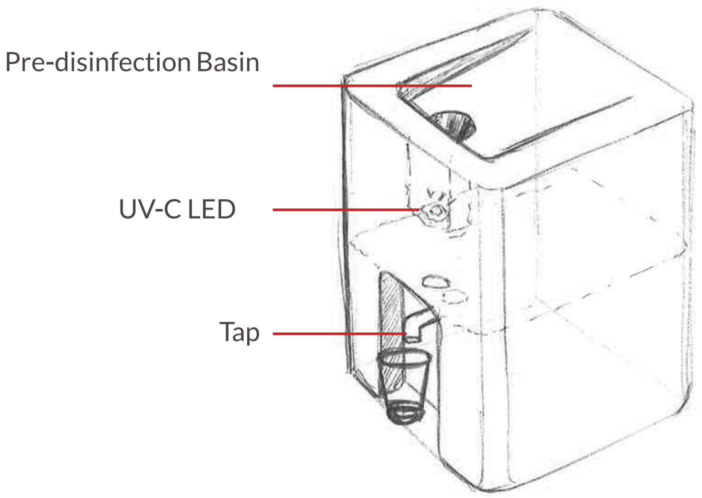
The size and shape allow designing this dispenser as something that people are proud to own and maybe even could show as a sort of status symbol.

This water dispenser is filled on top by pouring water from the jerrycan into the pre disinfection basin. From here the water flows through a UV-C system into the clean main basin where the water will be stored until the tap is opened.

In this product, the most important guidelines are combined. It prevents recontamination by limiting risky user interactions by having a tap installed to retrieve the water.

The 'active' components of this design, the UV-C system and tap, are a small part of the overall product. The large container around these components adds some value to the product, but that does not weigh up against the disadvantages. It does take up a lot of space, not only in the homes, but also during transport. The costs of manufacturing and transportation of such a large product will increase the price. That, for a component that is not vital in providing safe water.

Therefore, the design iterated towards a product that integrated the same features but into a more compact solution



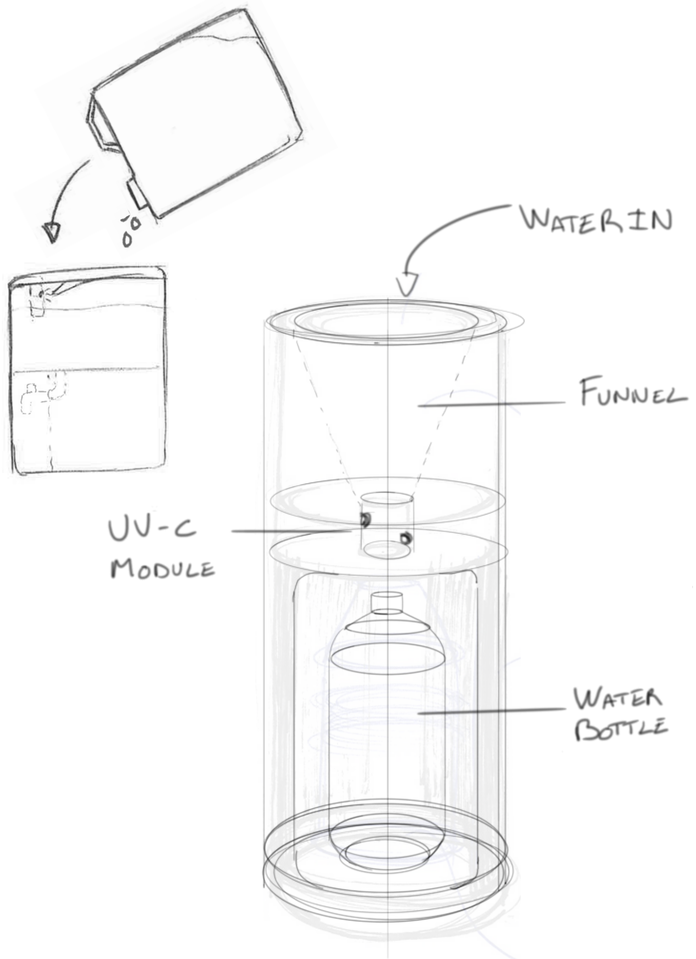
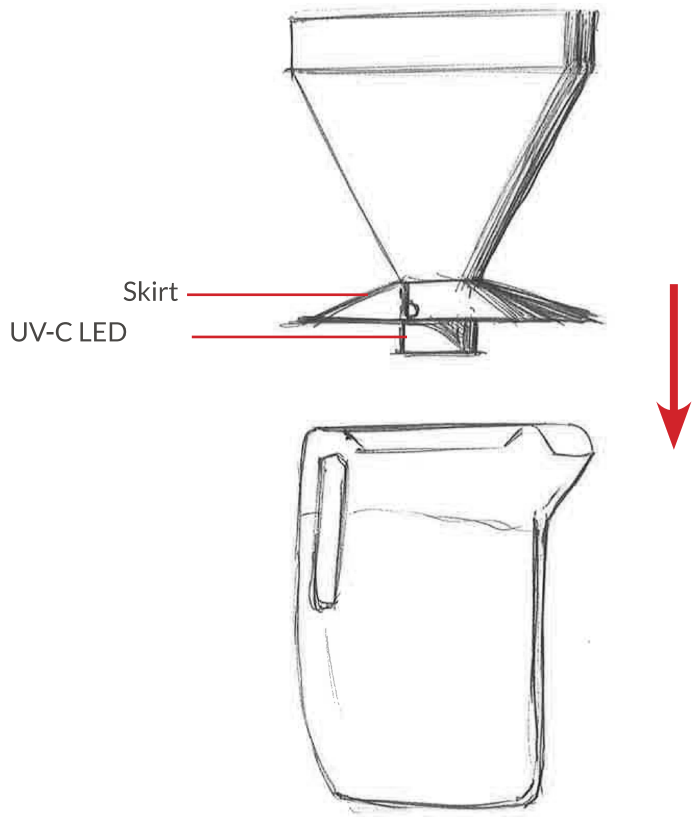


Figure 48: Water dispenser with UV-C disinfection system integrated.

Funnel

With the funnel design the goal was to integrate the features of the dispenser concept into a more compact design.

The funnel is mounted on the container at disposal to the users, also removing the need to develop a container. Then, from the jerrycan, the water is poured through the funnel into the container. In the narrow part of the funnel, the UV-C system is installed and will disinfect the water flowing past it.
The design of the funnel can be optimised to work with different containers by smartly developing a one-size-fits-all design.
By adding a thread, the design can be optimised, but not limited, to work with PET bottles. By fixing the funnel onto a bottle the interaction and the filling of the bottle becomes easier and provides fewer interactions that could potentially recontamination the water.
Or, when used for jugs, an additional skirt can be used to prevent untreated water from entering the jug in the case of spillage. This skirt also ensures the funnel is steadily placed on the jug, leaving two hands free to handle the jerrycan.
Furthermore, the funnel, being a small and open product, is easy to clean reducing the chances of recontamination.



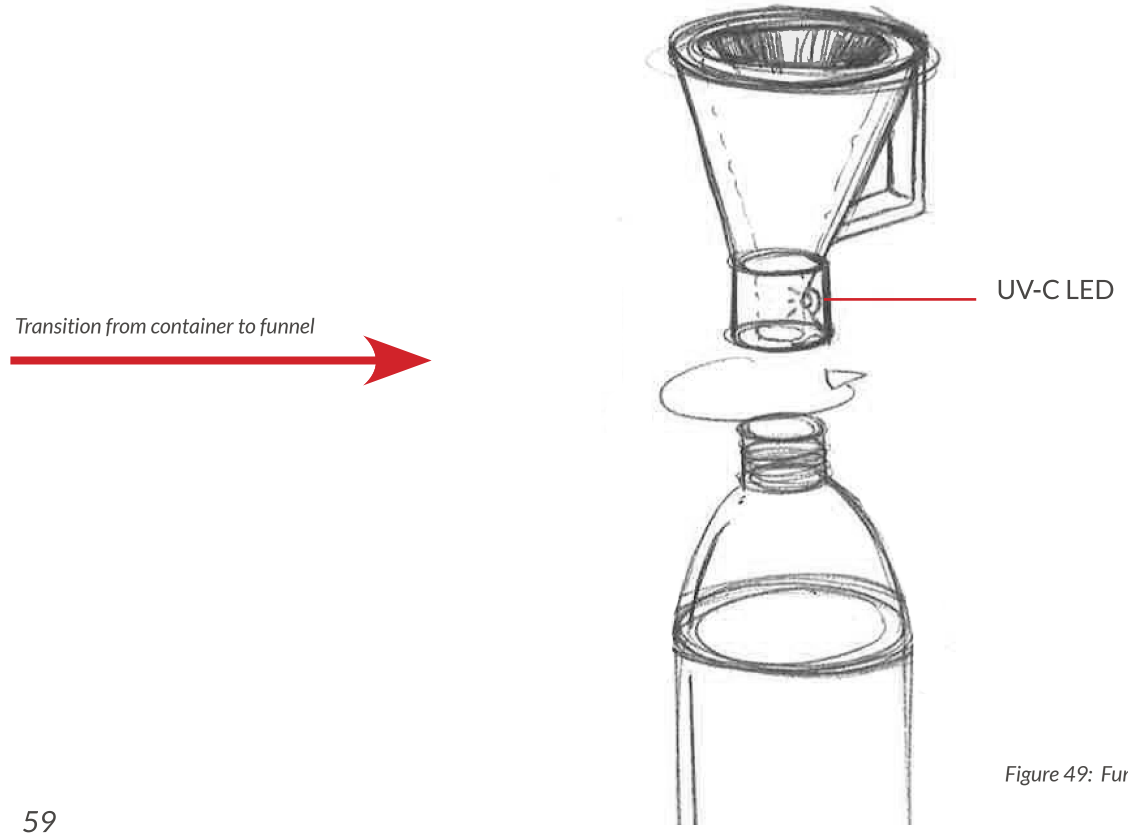


Figure 49: Funnel with integrated UV-C LED.

UV-Tap

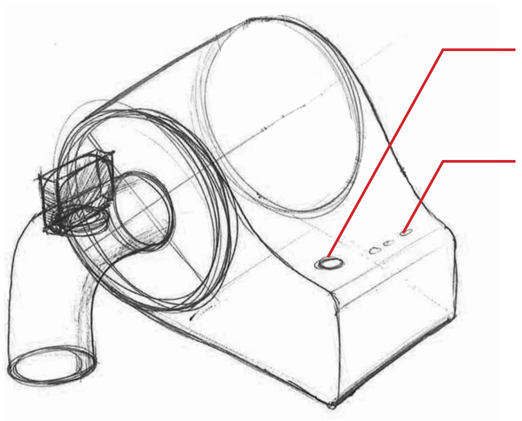
Using a funnel in combination with bottles and jugs leaves much to be desired when it comes to stability. Furthermore, having to deal with numerous shapes and sizes of bottle and jugs, it would be challenging to develop a solution that fits all.

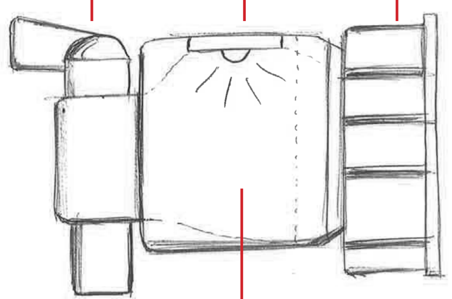
The logical step was to shift to the one container that is (almost) identical for all the households, the jerrycan. Since it is a standardised product, the thread for most of the jerrycans is the same. Research from de Gruijter (2021) in Addis-Ababa revealed that approximately 80% of the jerrycans have the same size of thread (Personal communication, O. de Gruijter, 15 November 2021).

Using a jerrycan cap with an integrated tap and disinfection system that activates as soon as the tap is opened. This makes it possible to tackle both disinfection and water extraction at the opening of the jerrycan.

The water that flows out of the jerrycan is thereby always safe for consumption and is easy to access through the tap. Furthermore, this is an even more compact design, solely focussing on the active component of the product that have a valuable functionality.
An additional advantage this solution has, since the water is flowing through the product, is that it is possible to develop a specific reactor as well. This can be placed on the cap alongside the LED and make the whole disinfection process more efficient.

Furthermore, by placing the jerrycan sideways there is no need for a pumping mechanism, simplifying the entire product.





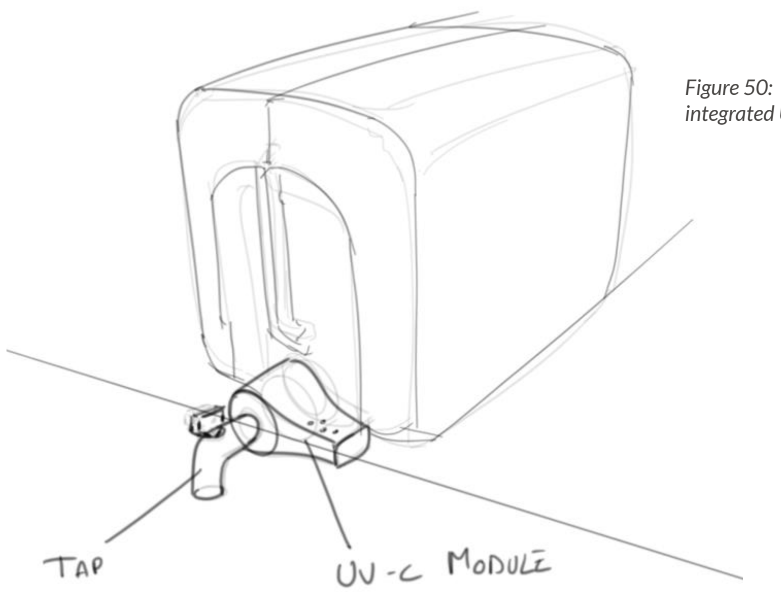


Figure 50: Final concept, a jerrycan cap with an integrated UV-C system.

Stagnant System

A stagnant system requires the water to be standing still in a container. This means that for each cycle, a specific volume of water is disinfected. During this ideation, the goal was to identify how such a system could best be designed to fit the context and identified requirements.
The process for this concept can be characterised by three stages of development, each iterating on the previous one, these three stages will now be discussed and used to substantiate choices for the final concept.

Modules

With a stagnant water system, there is the need for a container, which people already have plenty at home. Be it glass, bottles, jerrycans, or others. It would be interesting and efficient if these existing containers could be used during the disinfection of the water. This saves costs for the final product. To make use of this, there was the need for a small and versatile product that could work with different types of containers.

By using several independent UV modules, that can be placed in different containers, the user can disinfect the water to its needs. These modules can be activated by placing the container on a plate that would activate the LEDs and start the disinfection process. These plates would be responsible for providing each of the modules with the necessary power.

Although a very intriguing as an idea, it is too complex for the context. Using many parts, the design becomes too expensive. Furthermore, it doesn't improve the situation around recontamination of the water. Interactions with these modules is likely to worsen the recontamination, as they would use their hands to place and remove the modules.

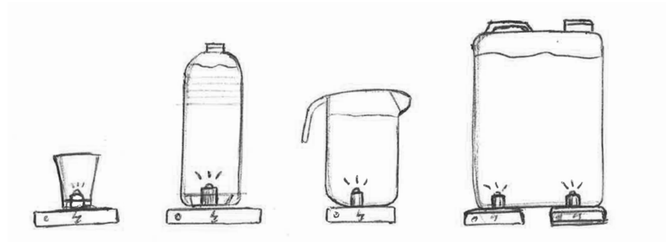
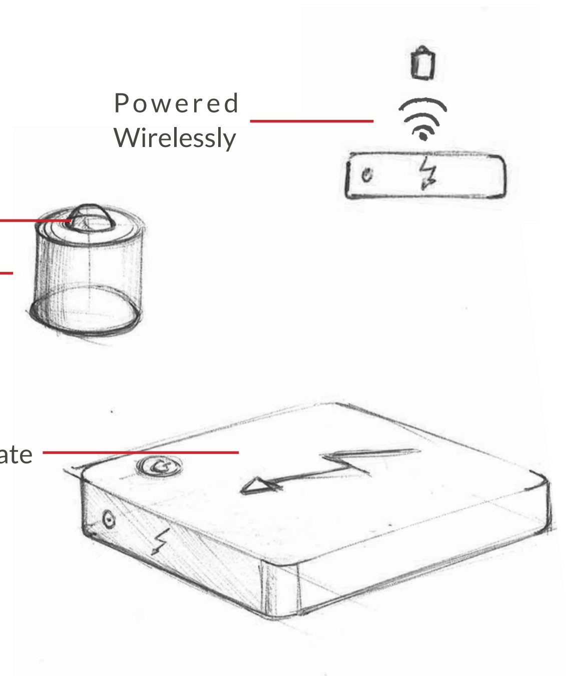


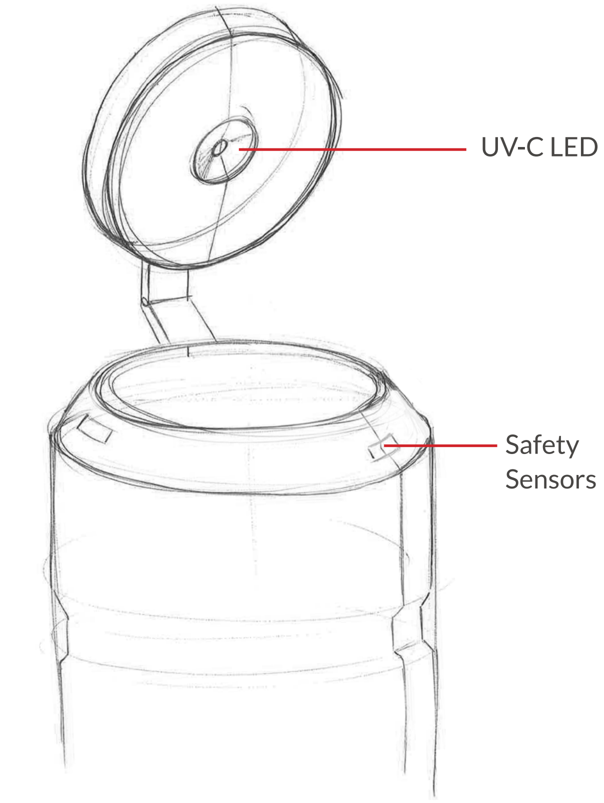
Figure 51: Disinfection by using independent UV-C modules



Bottle

To improve the recontamination issue, the idea evolved into a bottle with the UV-C module integrated in the cap. Redesigning the container also allowed to improve the interaction with the jerrycan. By having a wide opening, it is easy to fill and when pouring from the jerrycan water is less likely to spill.

Furthermore, user's safety can be better managed. Integration in the cap can ensure that the LED only turns on when the cap is mounted on the bottle, preventing users from exposure.
However, the strong suit of using the modules was the versatility for the user. Now the user is limited to this specific bottle and only has the possibility to disinfect ~1L at a time, or has to buy more of these bottles, which would be too expensive.



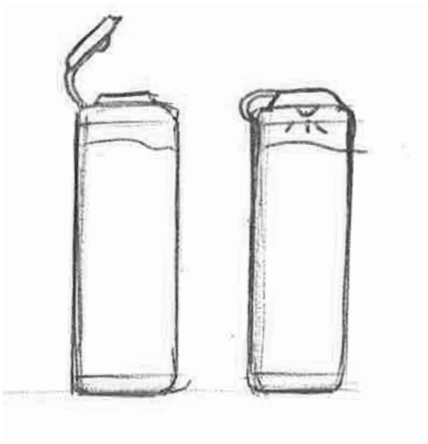


Figure 52: Integration of UV-C into a bottle to improve the interaction with ejrrycan.

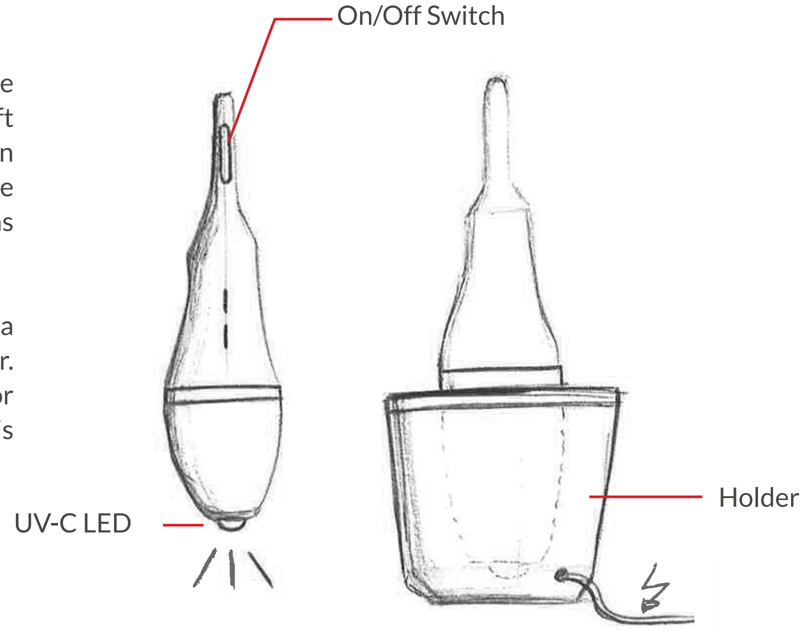
Floater Pen

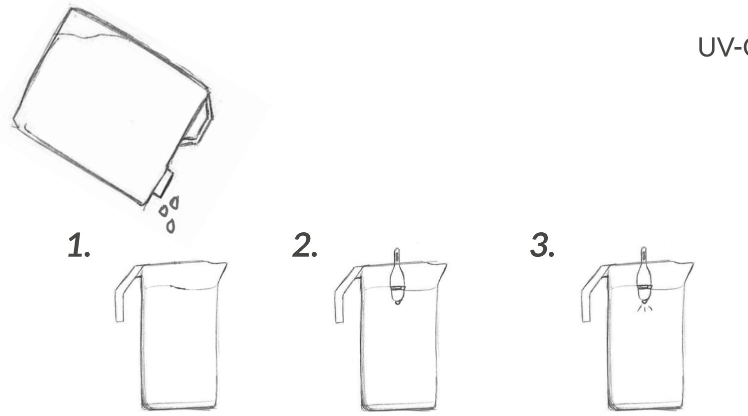
In the final iteration of this concept, the versatility of the modules was combined with the functionalities of the bottle.
Integrating the disinfection module into a float allows for a top-down disinfection and reduced recontamination.

The small design allows usage of any type of container, ranging from PET bottles to jerrycans.

It can actively be used to stir through the water and provide a better disinfection (just like the Steripen) or it can be left floating passively in the container. The active contribution to the water disinfection from the users also raises more awareness on the subject and can maybe even be seen as fun for children.

To prevent recontamination, the device can be placed in a specific holder that ensures the disinfection of the exterior. When placed in the holder, the same UV-C LED used for the water disinfection is activated and the radiation is reflected off the holder onto the surface of the device, and thus disinfecting itself. This same holder is also be used to recharge the device.
For safety purposes, the LED can only be turned on when in contact with water. The top-down direction prevents users from directly looking into the light.





Fill jug with (contaminated) water from jerycan

Place the floater pen in the jug. Activate the floater pen by pushing the switch.

Let the pen float in the jug until the light turns off. The water is now safely drinkable.

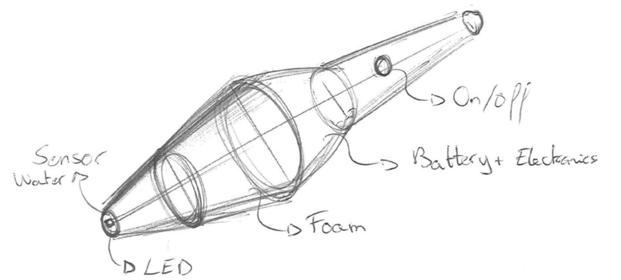


Figure 53: Final concept for stagnant water, a floating disinfection pen.

At this point both the Floater Pen and the UV-Tap are more an idea direction than an actual concept. Both these ideas require more detail and thought to make sure that at the end of the conceptualisation a concept is chosen that can provide a project a realistic and functional solution at the end of the project. The focus of the conceptualisation will be on making sure the final designs meet requirements and can work in peri-urban Addis-Ababa.

4.4 UV-C CONCEPT DETAILING

The Floater Pen (stagnant system) and the UV-Tap (flowing system) are the two final concepts. Before making any final choices, these two concepts need to be further detailed on feasibility and usability, including the identification of potential bottlenecks and how these can be solved.

UV-Tap Concept

Based on the product analysis and the knowledge gathered on UV-C, the 'UV-Tap' concept is here worked out into more detail. First through sketching, and then working towards mock-ups to get a feel for the product.

For this, I looked at the main components and their placement within the product. I did this by building mock-ups of possible assemblies with existing products (parts) and foam models. Figure 53 shows two of these configurations.

In the end I decided to place the Tap-module, unlike in the mock-ups, on the outside of the jerrycan and to merge them with the tap. This has the advantage that there should be fewer issues with the waterproofness since the electronics are not constantly underwater. In addition, turning the LEDs on/off will be a little easier since they are now close to the tap. This makes the opening/closing of the tap easier to combine with the turning on/off of the LED.

Figure 54: Crucial components for the "tap'concept, from left to right: tap, cap, reactor and the UV-C module.

This design choice makes the design and operation of the tap a lot more complex because the light from the UV-C LED must not be obstructed and must be able to irradiate the entire reactor chamber. To solve this problem, I started looking at current jerrycan spouts and how they work. It appears that the watertight sealing is done entirely on the diameter (see figure 54). Because the inner material is slightly stiffer than the outer, and has a slightly larger diameter, it fits very tightly and no water can pass through it. This, while the inner "cylinder" can continue to rotate and thus ensure that the holes align and water can get out (see figure 56).

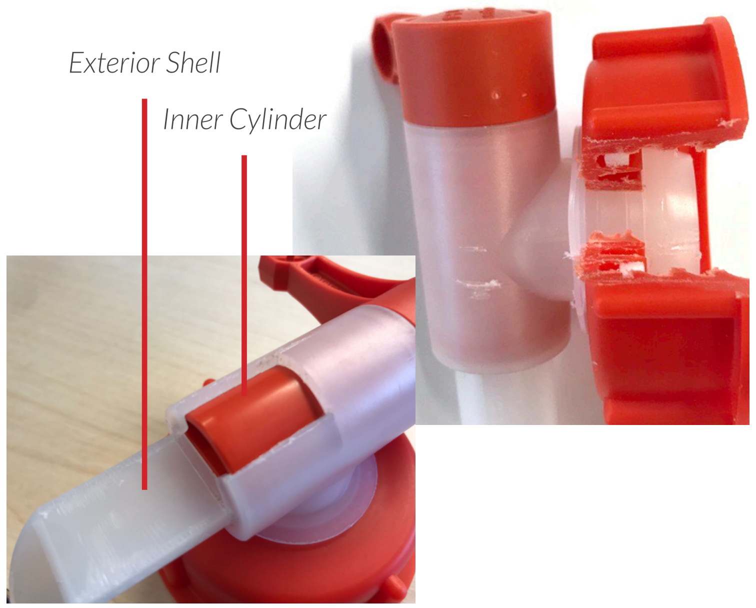


Figure 55: A stiffer and, slightly larger inner cylinder compresses against the exterior shell, creating a waterproof seal.

This system ensures that a watertight seal can be made with a hollow cylinder that allows the UV-C light to pass through the reactor. This eventually led to a design with two main components for the casing, the LED module and the reactor (figure 56).

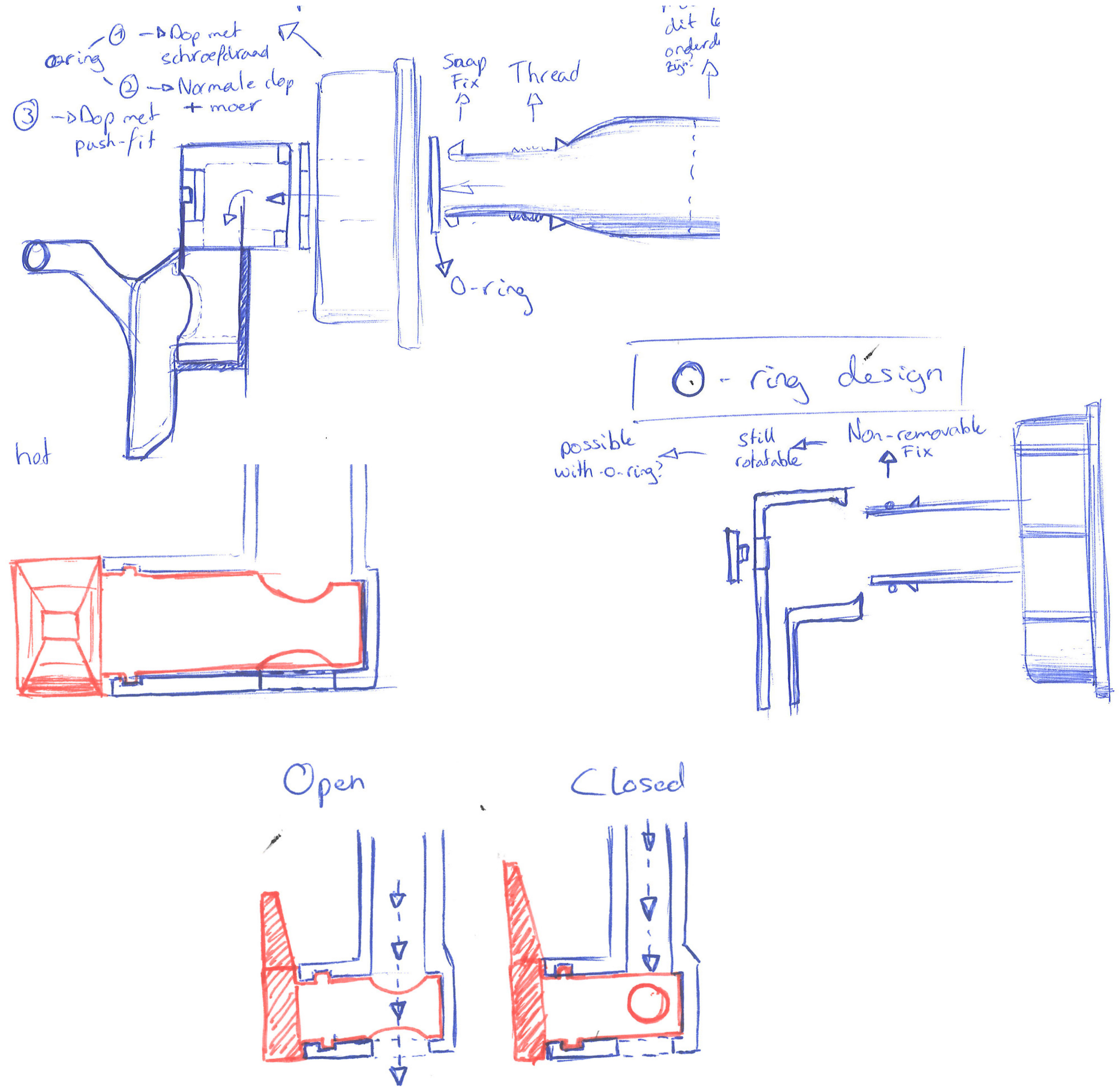


Figure 56: Ideation sketches to shape and combine the different components and the opening and closing of the tap.

UV-C Calculations

With the main design guidelines and an idea of how to implement them, it is now possible to look for the specific LEDs needed. The goal is to find LEDs with the highest possible UV-C output for the lowest possible price. This ensures that the product is as inexpensive as possible while delivering maximum disinfection

The calculations to determine the required UV-C output are quite complex because they depend on many factors. Therefore, for the calculations of the required UV-C output, I used the Klaran Water Disinfection ROI Calculator. This is a calculator tool where you can enter different variables and use them to calculate the required mW UV-C output (see figure 57).
The used variables for this calculator tool are:

Flow Rate: 1.5 L/min
This is the flow rate as determined in Appendix E, based on a minimal acceptable water flow.

UV-C Dose: 8.8 mJ/cm^2
Because the tool did not have the option for a custom UV-C dose, I had to use preset values. The minimally necessary dose is 8.8 mJ/cm^2. Therefore, to make an estimation, I calculated the UV-C dose for both 6 mJ/cm^2 and 12mJ/cm^2 and took the average of these. Since 9mJ/cm^2 (+/- 8.8 mJ/cm^2) is in the middle, this should give an accurate estimation

UV Transmittance: 85%
Unfortunately, it wasn't possible to find any references for the UV transmittance for tap water in Addis-Ababa. Therefore, I took the preset value of 85% that Klaran estimates to be accurate for well and tap water.

Reflectivity: 80%
The reactor material is crucial in the reflectivity, in this case the inside of the reactor is likely to be made from aluminium or PTFE, these have a reflectivity of 80% and 90% respectively (see Appendix F). To be on the safe side, the calculations are made with aluminium.

Product Lifetime 5 years
The lifetime is important because over its lifetime the LED will start to emit slightly less UV-C, and at the end of life it still needs to be able to deliver the minimum necessary dose. As already discussed the product lifetime is probably dependant of the battery. Therefore, it won last more than 4-5 years in all probability.

The results from this calculator tool indicate that they should emit at least 32.25 mW of UV-C. For an overview of the results and more in depth explanation behind the calculations, see Appendix F.

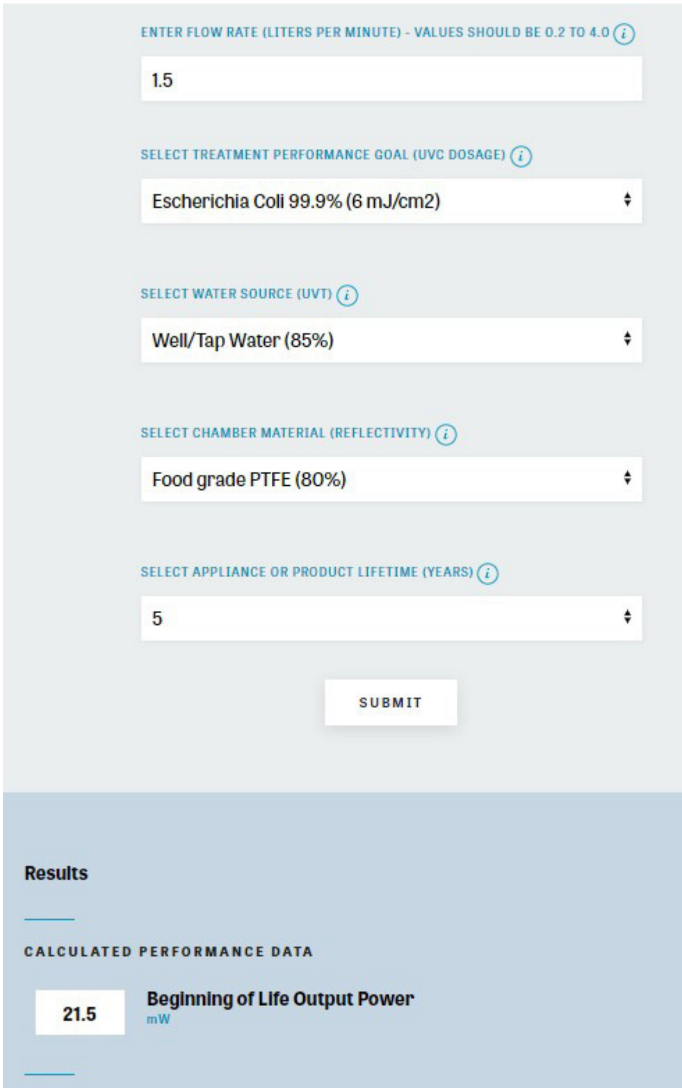


Figure 57: The Klaran Calculator estimates that 21.5 mW LEDs are necessary to provide a dose of 6 mJ/cm^2. For a 12mJ/cm^2 dose an output of 43mW is necessary.

Component: UV-C LED

The next step was to find the LED with the LED with the best fitting specification for the lowest costs. For this, I looked into the available UV-C LEDs at Quooker's suppliers, Farnell and Mouser Electronics. I cross-checked multiple available LEDs until I found the one with the best mW output to cost output.
The VLMU35CB20-275-120 is the LED that fits these requirements best. With an output of 16.3 mW at a cost of €1.80/unit. In Appendix O a more detailed overview of the LED specifications and cost analysis can be found.

This means that for the application of this concept, at least 2 LEDs are required.

Component: Battery

The battery needs to provide energy for two LEDs that have an output of 16.3 mW UV-C at 150 mA. This means that to operate the device for an hour would require 300 mA. To fulfil the requirement of 3-4 days of safe drinking water (see Appendix L), this means that the UV-Tap needs to be capable of supplying 48L (12L a day).
48 L at 1.5 L a minute gives an operating time of at least 32 minutes (48/1.5). So the minimum capacity of the battery should be, 160mAh.

A battery of this capacity would come at costs of approximately $1. This is a lithium-ion battery, which will last somewhere between 3-6 years (depending on the use) and between 500 to a 1000 charging cycles. This will give a lifetime of around 24.000 L to 48.000 L of safe drinking water.

Envisioned Use

Apart from defining the technical aspects of the concept, it is of course also important to see how the concept would work in the context of a household.

Local Context

With the addition of this cap, the can becomes, in effect, a water dispenser. Therefore, I started to look at how and where the jerry cans are stored, how water dispensers are used in people's homes and where they are placed.

Most people store the jerrycans in their kitchen somewhere, behind a curtain or furniture. The water dispenser itself is often placed, if there is room, on the kitchen counter. Otherwise, the dispenser is placed on an elevated plane (such as a stool) to make it easier to use. (O. de Gruijter, November 17 2021, Personal communication)

Figure 58: Tap for jerrycan, integrated with a cap.

The future use of the jerrycan with a UV-Tap installed, could be very similar. The jerrycan will be taken from the storage place, have the UV-C cap screwed on and be placed on the counter or stool. Or maybe even place two jerrycans on top of each other.

User Interaction

To simulate the usage of a jerrycan with the UV-Tap, a cap with a tap was used (figure 61). During this simulation, three main points emerge that are important for the use of this concept:
[1] The user must be able to operate the UV-Tap with one hand, as the other hand might hold a glass or bottle.
[2] The tap protrudes from the can (both at the front and the side), which may make it easy to damage it. A freely rotating tap is desirable
[3] The can must protrude from the ground so that it is possible to hold a glass or bottle underneath.

Furthermore, placing the jerry can in a horizontal position (figure 59) does not really cause any problems. You will notice that the rounded edges allow it to wobble a little, but it remains stable even at low volumes (<3 L).

For the UV-Tap it is also crucial to know what the minimal flow rate should be. Test with different water treatment products and faucets have revealed that the water should be dispensed at a flow rate of at least 1.5 L/min.
In Appendix E an overview of the results of this test is given.

Figure 59: Experimentation with placement of jerrycan and how this affectds the interaction.

Figure 60: Possible usage scenario & stability test.

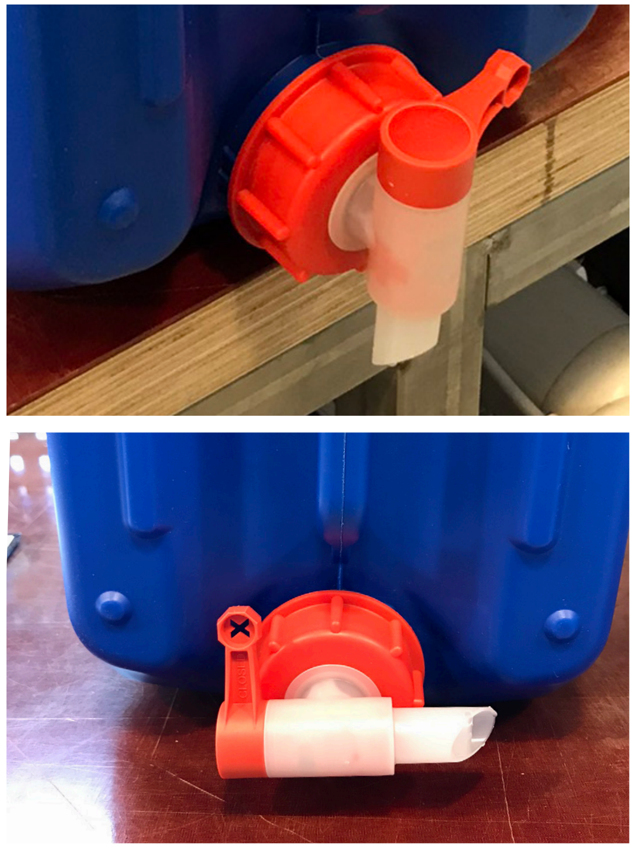


Figure 61: Tap for jerrycan, integrated with a cap.

Costs

Apart from the costs for the LEDs and the batteries, there are of course other components that are part of the product. I have looked at the main components of the product and made a cost estimate based on these. In Appendix K the complete overview and the calculations of the costs can be found. Figure 62 shows an overview of the costs per component. This is a rough estimate of the costs per unit, if 10.000 units were to be manufactured (this number was determined in consultation with Made Blue). Assembly and transportation of the device are not yet taken into account.

Component	Costs
Reactor Casing	$ 0.60
UV-C LED	$ 3.60
Battery	$ 0.90
Aluminium Coating	$ 0.01
Jerrycan Cap	$ 0.25
Electronics (PCB)	$ 1.00
Total	$ 6.36

Figure 62: First estimate of the costs of the UV-Tap concept.

Future Design Considerations

Besides the parts of the concept discussed in this chapter, there are also parts of the concept that have yet to be explored in future detailing of the concept.
Most importantly, how to regulate the airflow into the jerrycan as water is coming out. At this moment the horizontal placement of the jerrycan impedes the air from going in as the water comes and that creates a vacuum inside. This slows the flow rate of the water down to minimum until the air pressure is high enough to force itself in.
Secondarily, more user oriented aspects are to be considered. How to inform the user the UV-C LEDs are on? Is everything working correctly? Is the battery empty or charging? These, and many more, are situations that the users encounter and need to be taken care of.

On a technical level, the most crucial aspect is the validation of the calculations for the UV-C dose. These calculations are just an estimate, and need to be validated with a test to see if the theoretically emitted UV dose is actually achieved.

Having the UV-C reactor connected to the cap means that the product can be easily switched between jerrycans once one is empty. This allows for a smooth transition and always makes safe water available. Important to note here, however, is that this only applies for the same model jerrycans. If other jerrycans have a different size thread, this product won't fit. Fortunately, research by de Gruijter (personal communication, 15 November, 2021) showed that approximately 85% of the jerrycans in Addis-Ababa have the same type of standardised thread, DIN 61.

Floater Pen

The conceptualization of the Floater Pen started with identifying design aspects crucial to its operation. More critical here than with the UV-Tap is the number of LEDs. This has to do with an aspect that has a huge impact on the UV-C dose delivered: the irradiation distance. Figure 63 shows how the distance can affect the UV-C dose for a LED. In Appendix F this is explained in more detail.

The size of the containers people have at home determine the irradiance distance. Ideally, this product can be used in any variety of containers, ranging from a glass to a jug or a PET bottle. The irradiance distance will probably be the longest in a 1.5 L PET bottle because of its height. Usually a PET bottle is around 30 cm high, and this distance is therefore used as the benchmark for the calculations.

For this concept, I relied on the same type of LED as for the UV-Tap since this LED has the best price to mW output ratio I could find. The number of LEDs relates to the mW output, which in turn relates to the time. Figure 64 shows the results of the calculations. In the table, you can see the estimated time necessary and the amount of LEDs, to reach the minimum UV-C dose of 8.8 mJ/cm^2.

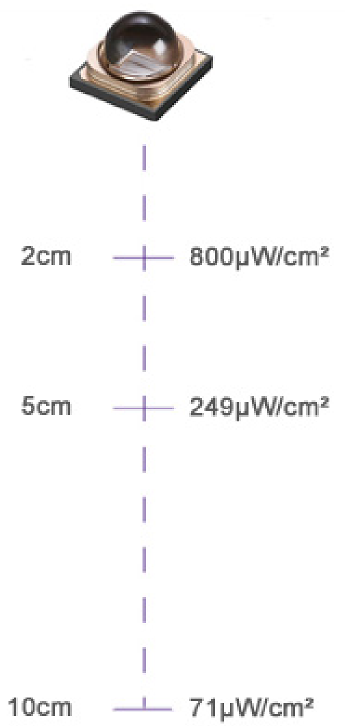


Figure 63: Example of how much the irradiation distance influences the UV-C dose.

UV-C Calculations

To estimate the requirements for the UV-C LEDs to disinfect the water in this concept, a different calculation is necessary than the one used for the UV-Tap concept. The water in this concept is stagnant, and therefore the Klaran Calculator tool cannot be used. To determine the amount of mW needed from the LEDs, it was necessary to do some preliminary calculations. These calculations can be found in Appendix F. Important to note here is that the calculations have been performed for a 1L bottle. As the radiation distance greatly influences the delivered UV-dose it is not realistic to use larger containers. larger container would require much stronger LEDs, a longer irradiation time and more active contribution from the user (by stirring) to ensure all the water is disinfected.

As shown in figure 64, it takes quite some time to disinfect the water, even with a lot of LEDs. The delivered UV-C dose does not increase linearly with the increase of LEDs, and therefore adding more LEDs is actually a cost inefficient way of increasing dosage. The maximum acceptable time for one disinfection cycle should be around 30 minutes, if it takes longer the volume of water disinfected per cycle is just too small. People would run out of water before the new disinfection cycle would be finished.

In the calculations, I assumed that all the LEDs shine on the same point, which is only partially the case in this design. The UV-C rays overlap each other, but do not follow the same path. In the best case scenario, 4 LEDs will be enough to deliver the necessary 8.8 mJ/cm^2 dose. This, however, is not easy to calculate and will therefore have to be physically tested. This is therefore something that will be further elaborated if this concept is chosen as the final concept. For now, it will be assumed that 4 LEDs are enough.

Amount of LEDs	UV-C Output (mW)	Time (min/L)
2	32.6	70
3	48.9	45
4	65.2	32
5	81.5	28
9	146.7	15

Figure 64: Results of calculation for disinfection time with Floater Pen for different amounts of LEDs.

Design Choices

Now that the number of necessary LEDs is known, we can look at how the design of this concept can be shaped. Because the product will have to float, two aspects are crucial:
[1] The depth at which the LEDs are placed, in order to guarantee the best possible radiation.
[2] The weight distribution to ensure balance while floating.

Ideally, the mass of the product should be below the surface of the water in order to ensure that it floats steadily. This will however reduce the effectiveness of the LEDs. The casing underwater will block the radiation and thus create blind spots. As can be seen in Figure 66, ideally the LEDs should be as close to the surface as possible to prevent blind spots. The LEDs could be arranged in such a way that they shine upward, however this would require even more LEDs to cover the whole volume. Furthermore, shining upwards, out of the container could possibly be a safety hazard.

To keep the majority of the mass as close to the water surface, the components will all be clustered together at the bottom, with only the on/off switch at the top. The battery being the heaviest will provide some stability by being placed at the bottom. The On/Off switch is the only component placed high on the handle to make it easy to access and prevent people from getting too close to the water with their hands, limiting the chance of recontamination. The other four LEDs encircle the middle at an angle, shining down and towards the sides, to irradiate all the water (figure 67).

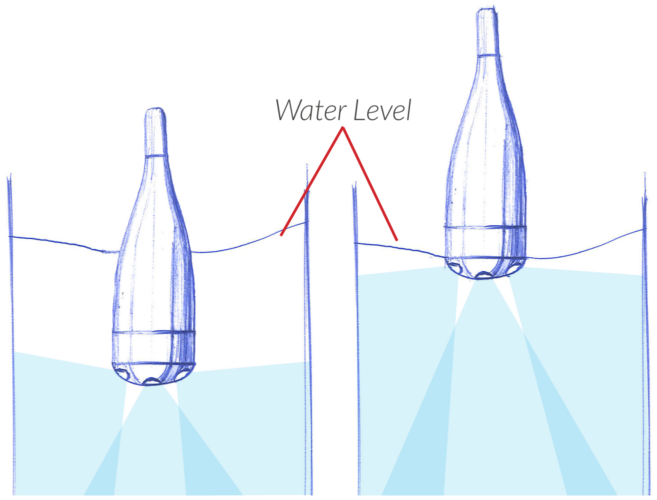


Figure 65: The LEDs need to be placed close to the surface. On the left there is a large volume of water that is not disinfected.

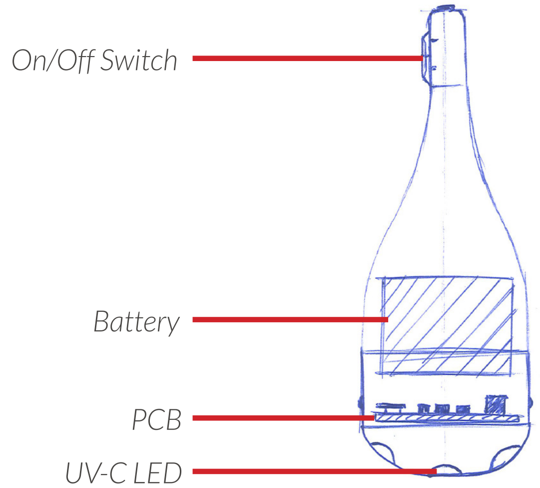


Figure 66: Skethces of components placement of the floater pen.

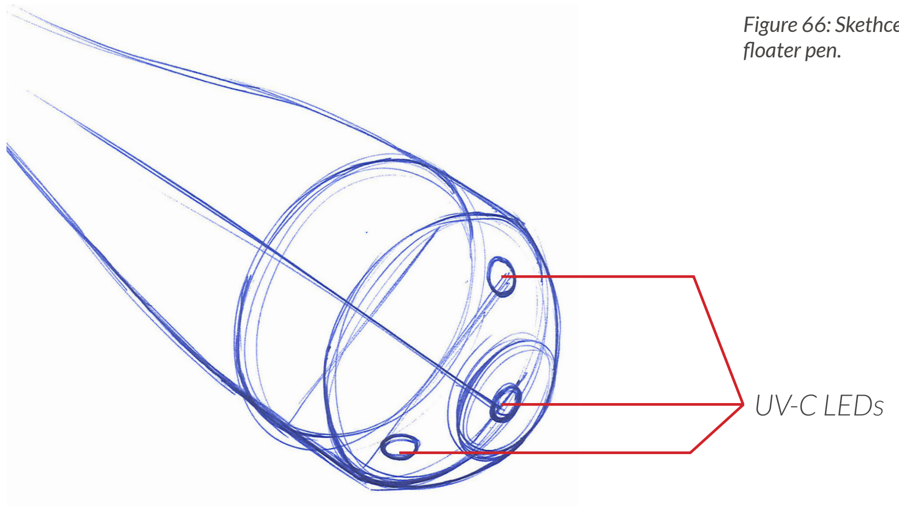


Figure 67: Skethces of application and components palcement of the floater pen.

Envisioned Use

The user will place the Floater Pen in the water, activating it by pressing the on/off button. The Floater Pen will only switch on when the LEDs are submerged, due to the integrated safety sensors (figure 68). These sensors will somewhat guarantee that the user does not expose him selves to the UV-C radiation.

Upon activation the user selects the volume of water that needs to be disinfected, and the LEDs will remain active for the predetermined time necessary to disinfect that volume. Ideally, the user should stir the water with the Floater Pen now and then during this period. This will create a water flow and guarantee a higher degree of disinfection, it allows water that is 'further away' from the LEDs to flow towards the LEDs resulting in a higher UV-C dose. Tests will show whether these actions will have to be mandatory or whether passively floating is sufficient to achieve the log 2 reduction.

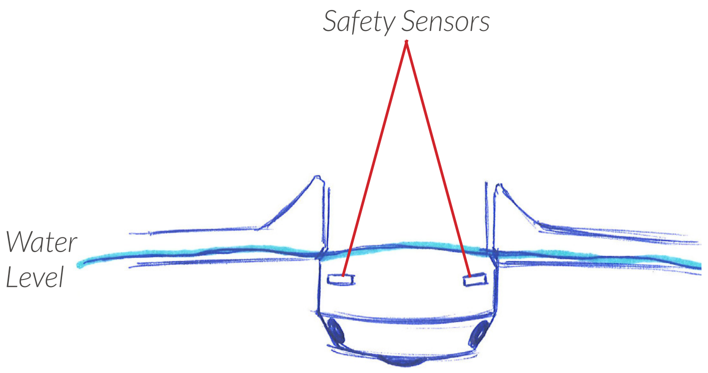
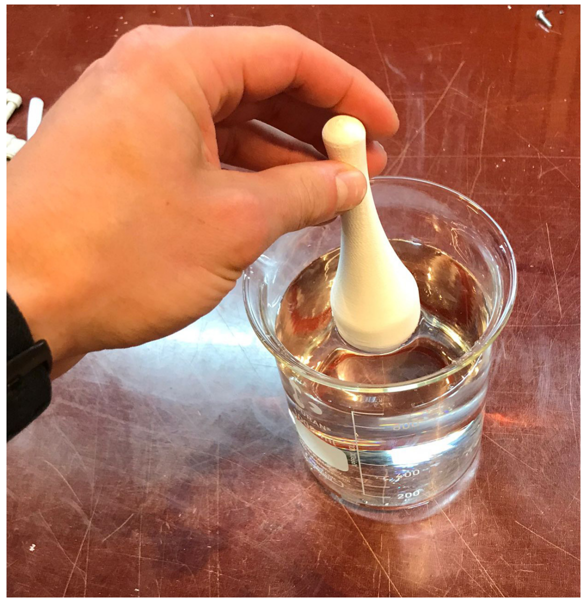


Figure 68: Safety sensors on the Floater Pen.

Mock-Up

To give these insights and ideas a first test run, and to see what the use would feel like, a simple mock-up was made. This mock-up is in fact only a test attribute to get an idea of the look and feel the product would get, and see how it handles.



This first test clearly shows that the current design is not good enough for easy use. Because only a small part of the Floater Pen is underwater, there is too little stability, and it constantly tips over. This would mean that the user would still be required to constantly operate the pen, which is not desirable. Moreover, the current shape also means that the product cannot be used with PET bottles because the neck of the bottle is too narrow for the Floater Pen.

This means that a redesign of the shape is necessary to improve the usability.

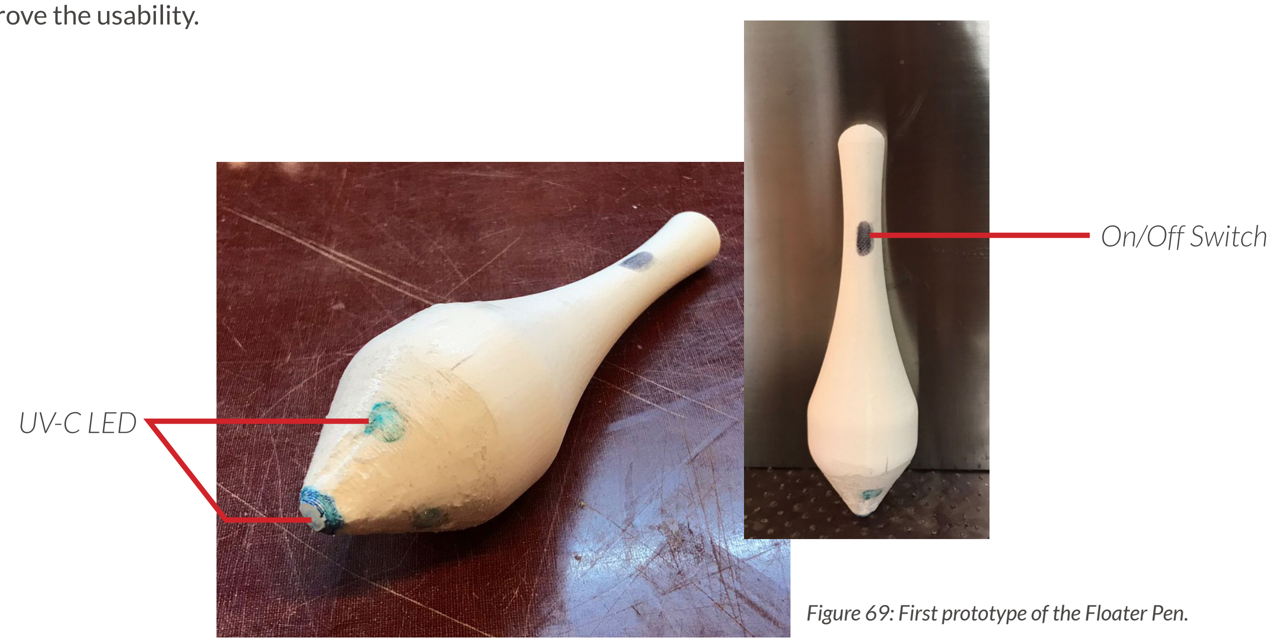


Figure 69: First prototype of the Floater Pen.

Redesign

In order to increase stability, but at the same time maintain the low depth of the LEDs, a different type of design was necessary. In this case, I made use of a wide float that will provide stability while keeping the LEDs at the same depth. This also ensures that the layout of the components will remain virtually the same, and thus the majority of the mass is still close to the water surface.

However, by adding the wide disc, it becomes impossible to use the Floater Pen in a PET bottle. Therefore, I have chosen to design the 'Floater' part in such a way that it can be detached from the 'Pen' part. This leaves a narrow pen that can be placed on a PET bottle and supported by the narrow neck of the bottle. If water needs to be disinfected in a water jug or other container, the 'Floater' can be added. This is illustrated in figure 70.

To ensure that recontamination due to the use of the Floater Pen does not occur more frequently, and to be able to store the Floater Pen safely, a protective cap must also be added. This will protect the LEDs from scratches and dirt when the device is not in use, thus ensuring that the LEDs continue to work optimally. This cap will cover the part that is normally underwater, preventing some of the possible recontamination.

The disinfection cycle of a bottle or jug takes around 30 minutes, but sometimes the user might want to have safe water at his disposal more quickly. Therefore, a secondary disinfection mode should be added, that specifically focuses on this purpose. For the disinfection of a glass for example, a much shorter time is needed because of a reduced distance and volume. Calculations from Appendix M have shown that with the same product design, the water in a glass can be disinfected in approximately 3 minutes. In some situations, this might be preferable. Therefore, the On/Off switch should have 2 functions, one for the treatment of a bottle and one for the treatment of a glass.

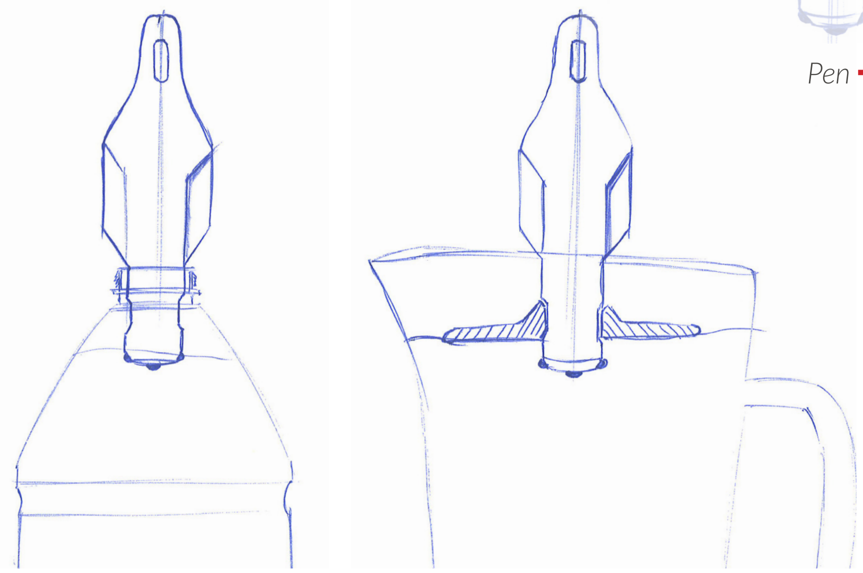
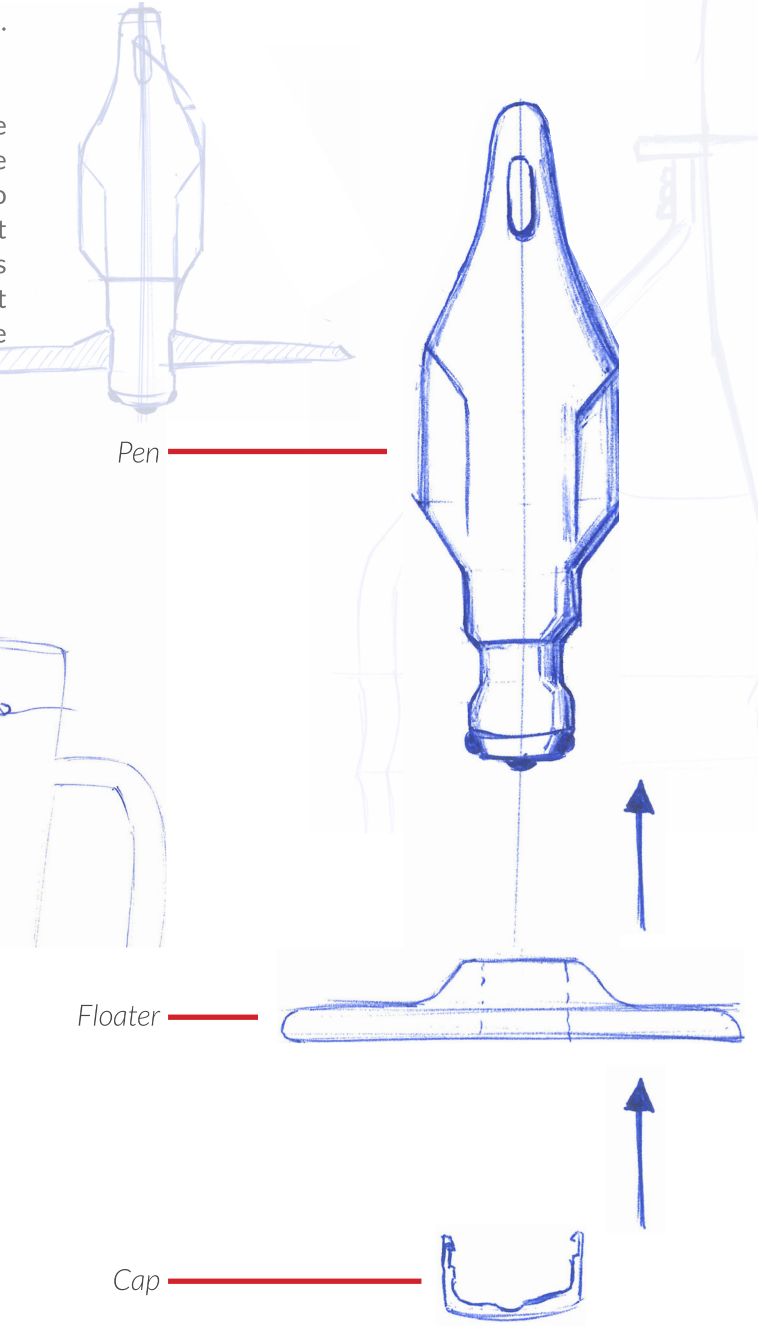


Figure 70: Final design for the Flaoter Pen.



Battery

For simplification of the calculations the assumption is made that the water is disinfected 1L at a time. So, as a requirement the device should be able to treat 48 L on a single battery charge.

One cycle to treat 1L of water with the Floater Pen takes approximately 32 minutes. In total, 48 of these cycles need to be executed. This amount to a total time of operation of approximately 25 hours.

48 L = 48 cycles x 32min = 1536 min = ~25 hours
32 x 35 min = 1120 min = 18.67 h

To achieve the 32 minutes of disinfection time the Floater Pen requires 4 UV-C LEDs. Each of these consumes 150 mA. For the battery to power the Floater Pen for 25 hours it requires a capacity of 15.000 mAh.

150 mA x 4=600 mA
600mA x25 h= 15.000 mAh

A rechargeable battery of this capacity would come to cost around $6.00, and has an overall lifetime between 24.000 L - 48.000L. The component list can be found in Appendix K.

Future Design Considerations

The Floater Pen is a product that is handled by people and comes into contact with water, making the device itself a possible factor in contaminating the water. A crucial aspect in future developments of this concept should be a solution to deal with the recontamination

One of the strong suits of this concept is its versatility, to be used with many types of containers. These containers influence the disinfection rate since these work as a reactor. Understanding how much this influence is and how to deal with it is key in the development of this concept.

Obviously, for this concept as well there are also many user related aspects to consider, very similar to the ones discussed for the UV-Tap.

Costs

Even though the concepts are very different, the costs for components of both are comparable since most components, as well as the amount of units manufactured, are to be the same. The major differences lie in the battery and the amount of LEDs. The same LED as for the Tap concept is used, only more of them.
As for the battery, it needs to power more LEDs for a longer time and thus would require a much higher capacity, increasing the costs.
These two components have the most significant impact on the price, being responsible for almost 90% of the total. See Appendix K for the calculations of the costs

Component	Costs
Casing	*$ 0.56*
UV-C LED	*$ 7.20*
Battery	*$ 6.00*
Quartz	*$ 0.30*
Electronics (PCB)	*$1.00*
Total	*$ 15.06*

Figure 71: First estimate of the costs of the UV-Tap concept.

4.5 CONCEPT CHOICE / CONCLUSION PART 4

The two concepts are very different in terms of use and application. These differences are primarily caused by the working principle of each user, a stagnant water system and a flowing water system. The way both these products supply safe water is what makes them so different.

Figure 72 summarises the comparison of the two concepts, it shows how each has its own (dis)advantages and often fills in for the other concept's weaknesses.

The Floater Pen is a passive system that requires little to no effort from the user once it is activated. After the disinfection cycle the user has a certain volume of water available and can start a new cycle.

The UV-Tap is an active and immediate dispenser of water. It provides disinfected water on demand, and the volume is only determined by the water supply available. The water is dispensed at a low flow rate of 1.5 L/min making it less than ideal for larger volumes.

FLOATER PEN	UV-TAP
Highly versatile, works with many different containers.	*Custom fit to specific size of jerrycans.*
No need for active contribution from user during disinfection.	*The flow rate of 1.5 L/min is not ideal to disinfect large volumes,*
The concept's versatility offers room to optimise the disinfection process.	*Framed and defined process. Little room to adjust the disinfection cycle.*
Does not reduce risk of contamination and probably makes it more likely.	*Reduces the risk of contamination to a minimum and improves the user's interaction with the jerrycan.*
Estimation of costs: ~$ 15.00	*Estimation of costs: ~$ 6.00*

Figure 72: Table summarising the comparison of the two concepts.

Based on the overview of figure 72, I made the decision to proceed with the UV-Tap. This choice is based on three points:
[1] Every household must be able to afford the product. This means that the purchase price should not exceed $10 USD. The costs do not include assembly or transportation costs, but it shows that the UV-Tap will probably be half as expensive as the Floater Pen. In the end, probably the UV-Tap will be over $10, but it will be easier to make up the difference with subsidies or financial models (such as paying in instalments).

[2] Compared to the Floater Pen, the UV-Tap offers a much higher degree of protection against contamination of the water in the jerry can or other container. Furthermore, it makes extracting water from the jerrycan a lot easier, especially for children.

[3] The UV-Tap may have a low flow rate, but with this product the user can drink disinfected water whenever he wants. With the Floater Pen there is the risk of running out of disinfected water, in which case the user would either have to wait for a new disinfection cycle to finish or take a risk and simply drink untreated water.

From this point on, the focus of the project will be fully oriented towards improving and validating the UV-Tap concept and turn it into a working prototype. Working technical aspects out into more detail and also look more into the users' interactions. In the end optimising the design and dealing with the identified future design considerations.

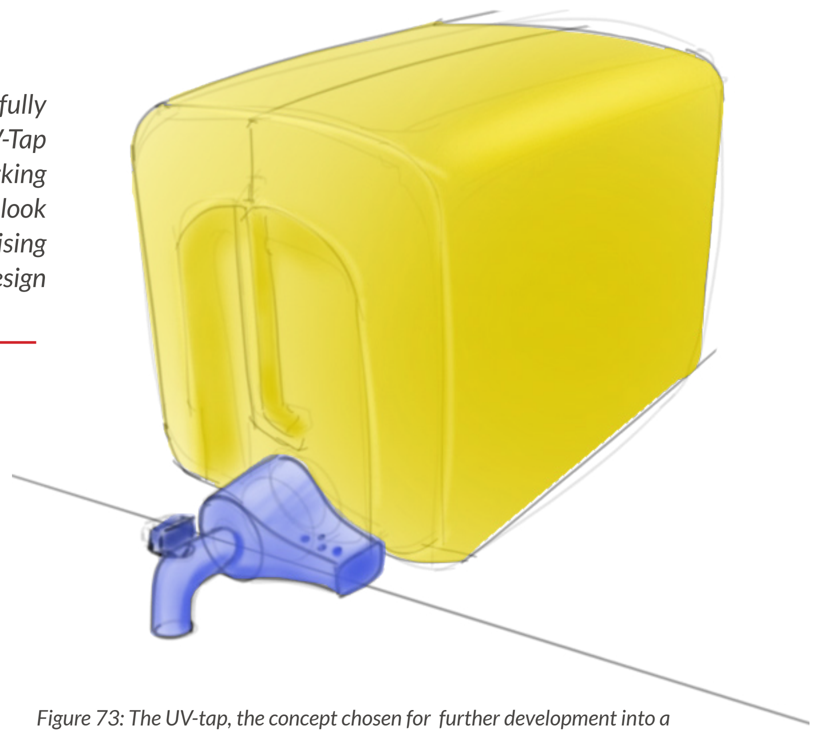


Figure 73: The UV-tap, the concept chosen for further development into a prototype.

PART FIVE

PRODUCT DETAILING AND DEVELOPMENT

With the concept defined, it is now time to work towards a functioning p[prototype to validate the working and integrate all requirements set by the context. Presenting a final design that is ready for user testing and validation in context.

5.1 PROTOTYPING EXPLORATION

The desired end-results of this project is to present Quooker with a functional prototype and recommendation for a future design.
The first step therein is to determine how the set requirements and insights can best be combined to deliver a successful product.

Optimising Disinfection

One of the requirements for the product is to keep a constant 1.5 L/min water flow. At the same time, however, there is also the need to achieve a certain level of disinfection. To achieve that, it is important that each drop of water (and the pathogens it contains) is irradiated with the same dose. Therefore, optimising the irradiation distance and exposure time.

Irradiation distance

I started by designing the most crucial part of the UV-system, the LED holder, without the reactor chamber for now. Trying to combine optimum disinfection with the 1.5 L/min requirement. The first iteration of the design involved a vertically placed LED. The design you see in figure 73 show the placement for the LED on top, shining downwards.

Figure 74: Final sketch of the 'UV-tap' to be further developed into a prototype.

The issue encountered with this design was that the water pressure was too low to eject the water at a speed high enough for it to actually come close to the quartz glass. This is illustrated in figure 74. This was a problem because it did not optimally use the delivered radiation by the LED.

I tried to solve this by adding flow restrictors in different shapes and sizes (figure 75) but unfortunately this did not help enough if the 1.5L/minute requirement is kept in mind.

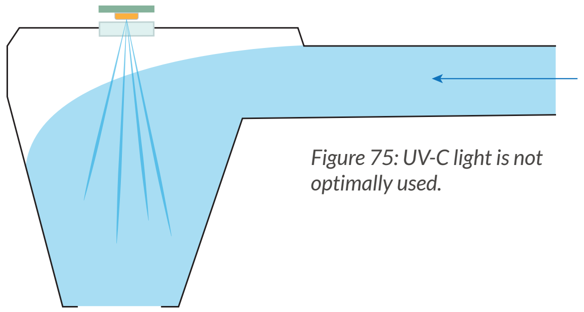


Figure 75: UV-C light is not optimally used.

Therefore, to solve this problem, the model switched to

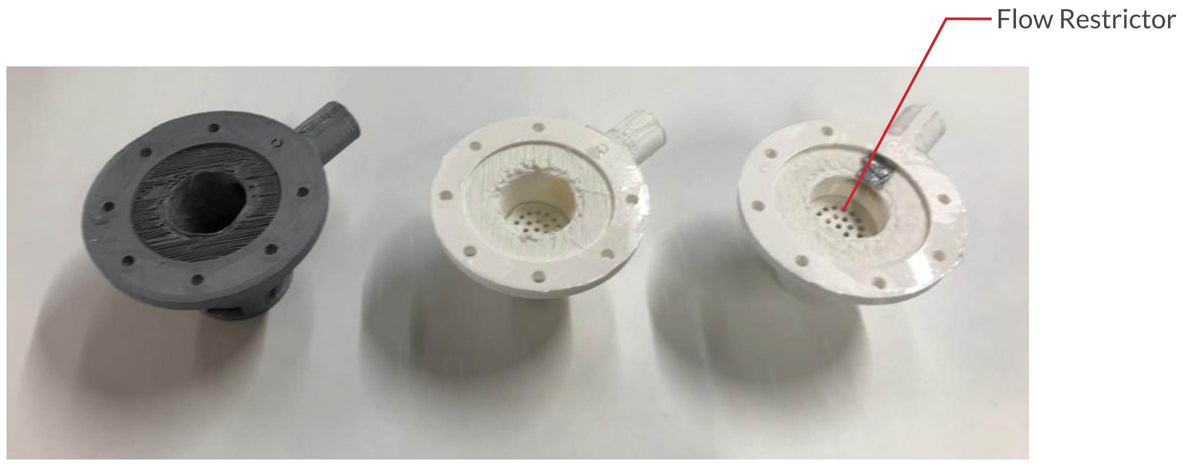


Figure 76: Different flow restrictor and tap designs.

a horizontally placed LED. This allowed the water to be pushed against the quartz glass and effectively use the emitted radiation. Figure 76 shows how the water now does flow correctly.

Although the irradiance is at its highest closely to the LED, the reflection of UV-C by the reactor can increase the UV-C dose and the distance over which it is delivered.

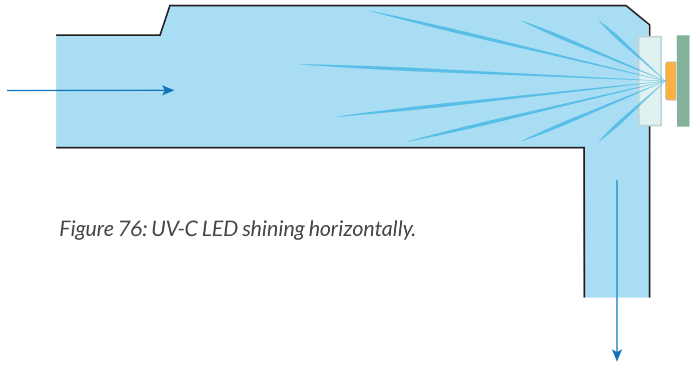


Figure 76: UV-C LED shining horizontally.

Flow Rate

To maximise the exposure time different outlets have been tried to combine both the 1.5 L/min mark, the exposure time and irradiation distance.

This led to a water outlet as designed in figure 77. Going from very narrow to force all the water to closely pass the LED to wider to slow the flow speed down. An important factor was that the outer diameter of the outlet could not surpass the 20 mm in diameter since this would impede it to easily fill PET bottles, which are widely used in households.

This results in an inner diameter of the outlet of 9.4 mm at the bottom, and a diameter of 5 mm at the top.

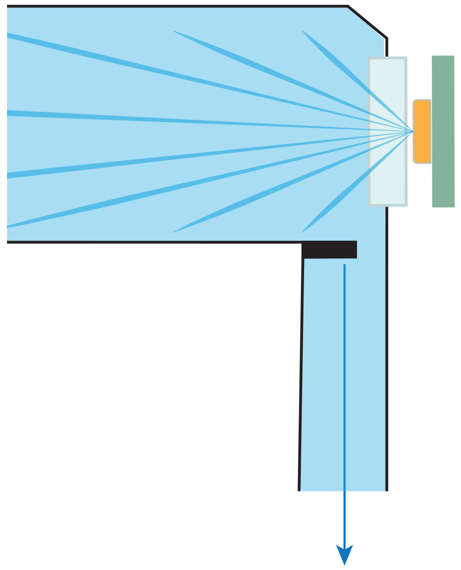


Figure 78: Restricted tap outlet at the top, this forces the water to cpass closely to the LED before leaving the reactor..

Water flow

With the inlet of the reactor, just being a hole would result in water flowing fast in the middle of the reactor and slow on the sides (close to the reactor walls). This would result in different exposure times for different drop of water resulting in an ineffective disinfection.

To ensure equal flow speeds of all the water thought all the parts of the reactor, a flow regulator is necessary. This flow regulator pushes the water coming through the inlet to the sides thereby preventing a faster flow in the middle (figure 78). Results from research executed by Crystal IS that corroborates this can be found in Appendix D.

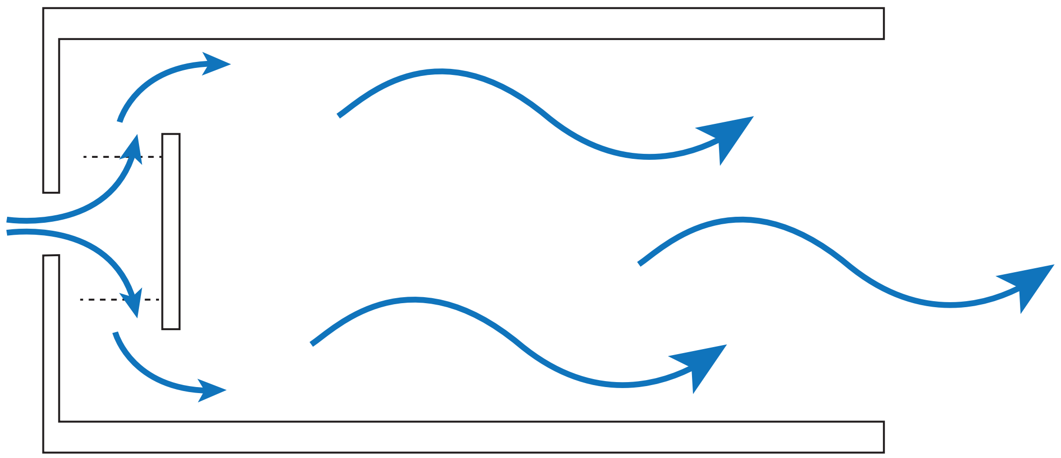


Figure 79: Baffle placed after the water inlet to restrict the water flow, and create and equal flow speed.

Aeriation

A last aspect that that is very important is the aeration. Since the opening of the jerrycan is at the bottom (because it's placed horizontally), no air can get in when tapping water. Over time, this will create a vacuum inside and drastically slow the flow rate, making it unusable. Therefore, it is necessary to add a system that contemporarily with the water flowing out makes it possible to let air flow in.

I tried numerous solutions to solve this problem, from capillary tubing systems, one-way valves and hand pumps (an overview of these solutions can be found in Appendix I). In the end, the most ideal solution to the issue appeared to be a tube that is connected to the outside of the jerrycan. The other end of this tube is inside the jerrycan and is always kept above the water level by a floater. This way air can freely flow in the jerrycan and keep the flow rate constant, figure 80 shows the setup of this system.

The system consists of three parts, the tube, to let the air in. The floater to keep the tube above water level. And a one-way valve on top to prevent water from entering the tube. Figure 79 shows the first prototype, here the floater is still missing, but the functionality remains the same.

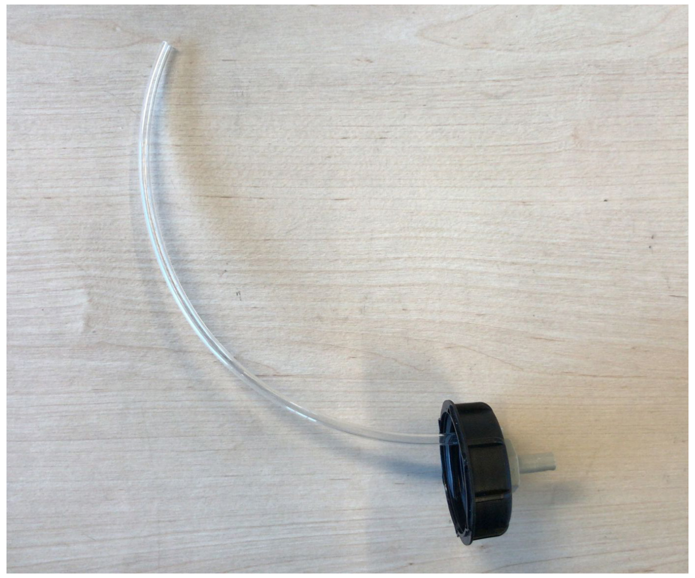


Figure 80: First prototype of the aeration of the jerrycan.

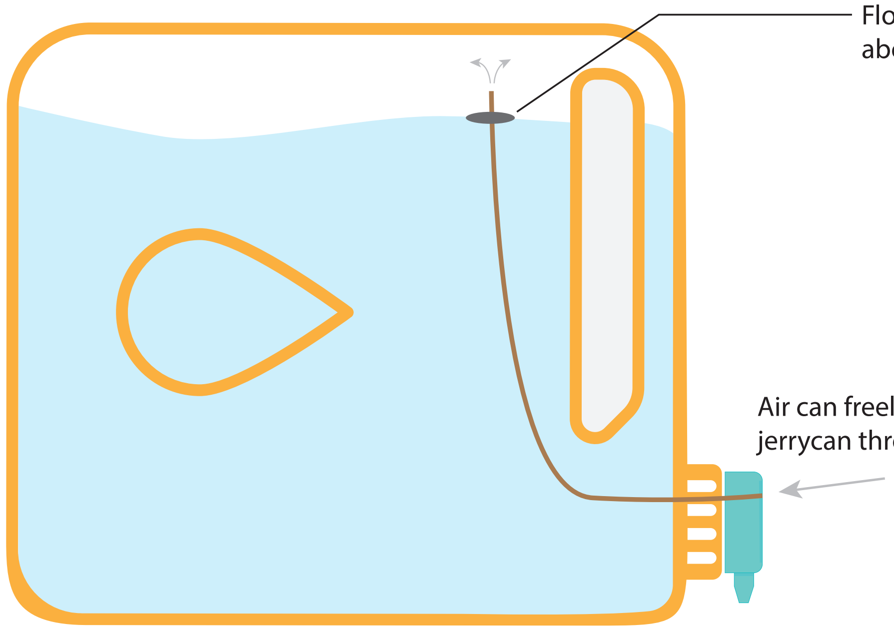


Figure 81: Theoretical design of the aeration.

(De)Activating Tap

A crucial aspect of this product is that the UV-C LEDs must turn on immediately (or just before) the tap opens. This must happen automatically, since otherwise there is the risk that untreated water is dispensed and people get sick.
During the concept detailing, I looked at different operating mechanism for the opening and closing of the tap. During the prototyping however it became clear that these options were not really feasible or too complex to work. The problem I was struggling with was the fact that the UV-C LEDs are placed after the opening and closing mechanism. Therefore, this mechanism cannot obstruct the UV-C light because otherwise the water is not disinfected.

During the development of the UV-Tap concept I already analysed a standard jerrycan cap with integrated tap. From this I learned that it was possible to achieve a water tight seal by just having the diameter of the inner and outer cylinder identical. This insight led to the design visualised in figure 83. This is a very simple mechanism that relies on a limited amount of components while ensuring product longevity.

The rotation of the tap should be limited between 0 and 90 degrees. 90 degrees being ON and the spout pointing downwards, 0 being OFF and pointing sideways. This interaction is easy and clear to understand as the direction of the spout informs the users (figure 82).

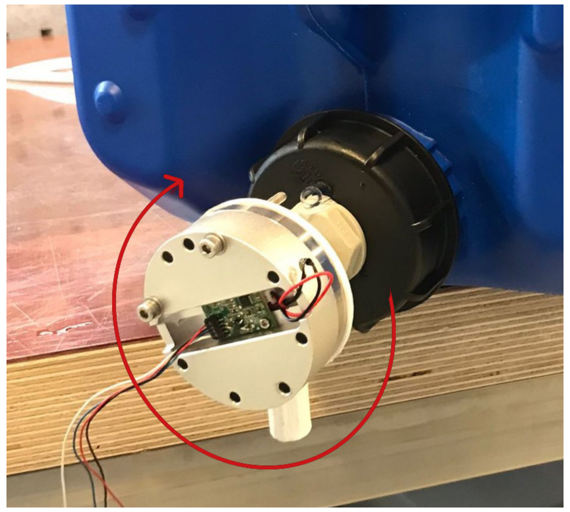


Figure 82: Prototype of the tap, in the 90 degree postion.

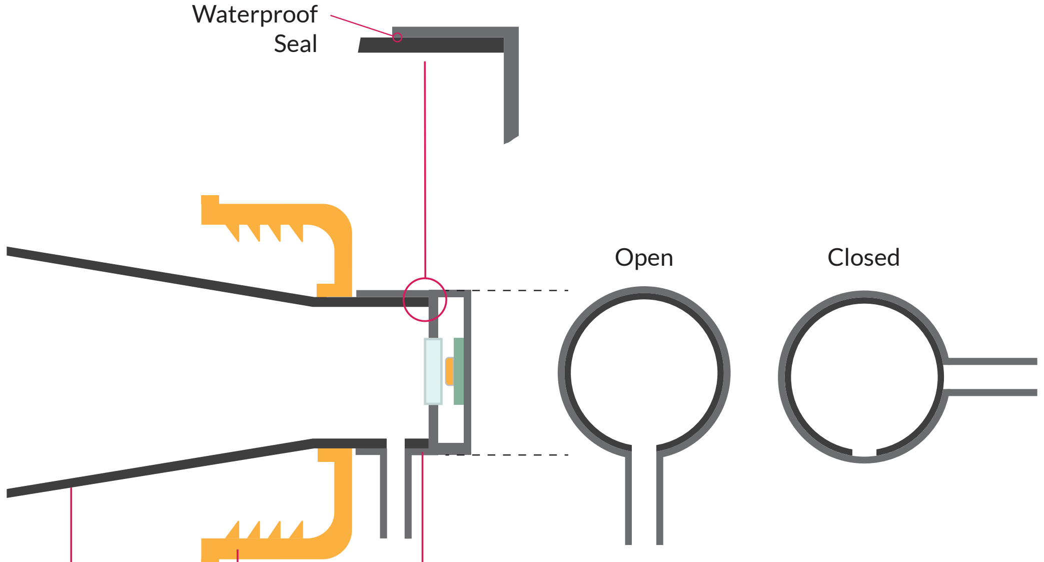


Figure 83: Sketch of how the UV-tap should be desinged to prevent obstruction of the UV-C ligth from reaching the water in the reactor.

5.2 FUNCTIONAL PROTOTYPE

The insights and knowledge gathered during the previous phases and the iterative prototyping process have led to a prototype that fulfils the basic requirements set for the function. This prototype is developed to test the disinfection capabilities The basic layout of the prototype will be discussed by looking at all components and their functionality for the disinfection.

The functionality of this prototype is limited to disinfection of the dispensed water. The main goal with this prototype was to see how well it performs in a later test (chapter 5.3) focused on making water safe and killing pathogens present.

Due to this specific focus, it is not possible to use the prototype for user testing. The tap cannot be opened or closed. With this prototype it is only possible to make assumptions on what the experience is like for the user. These learnings will then be applied in a subsequent iteration.

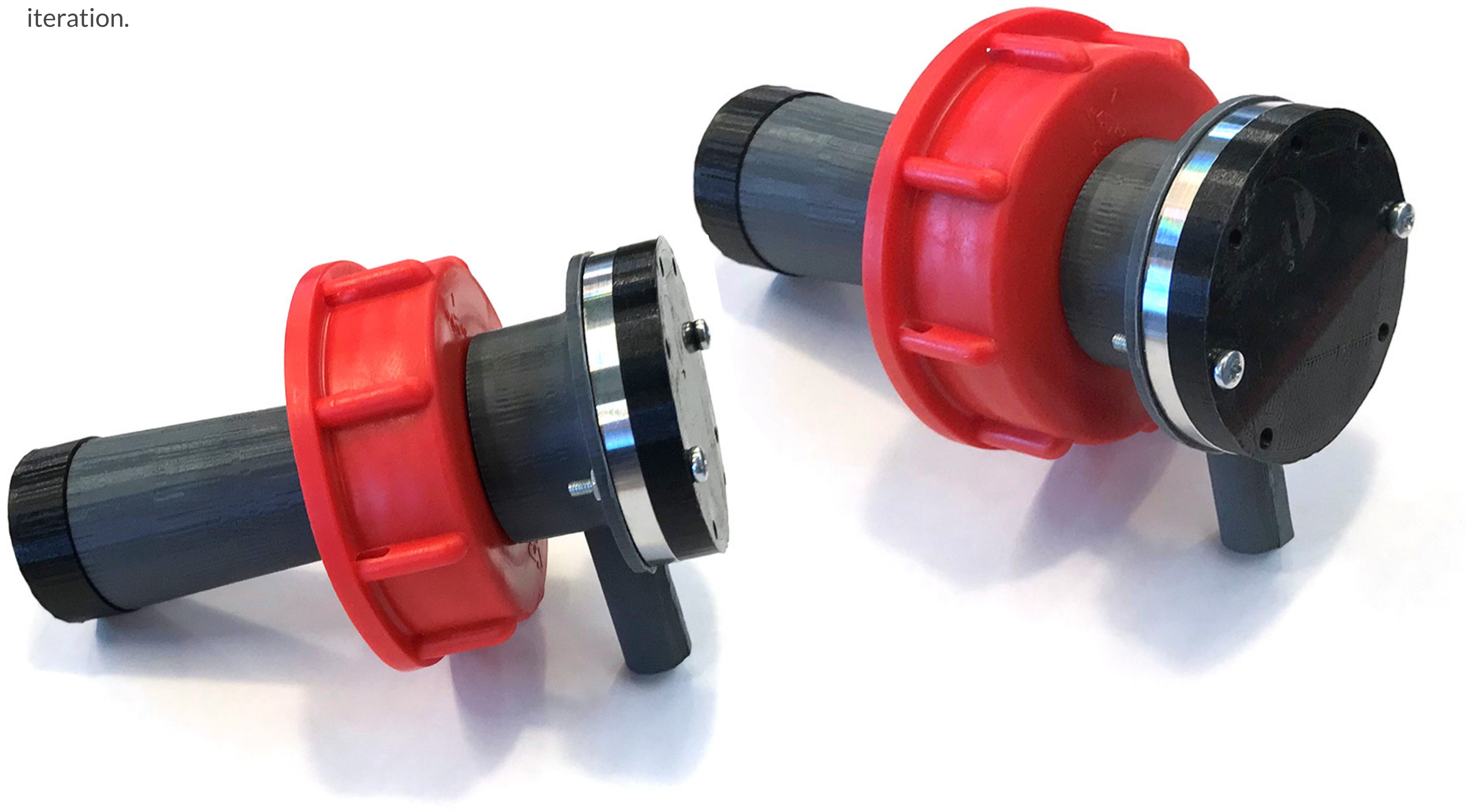


Figure 84: Assembly of the functional prototype.

Figure 85: UV-Tap mounted to a jerrycan.

Component Overview

All the components are part of this prototype are listed on this page in the exploded view of figure 85. In the following pages, each of these components will be explained within its own sub-assembly, and it's role for the water treatment.

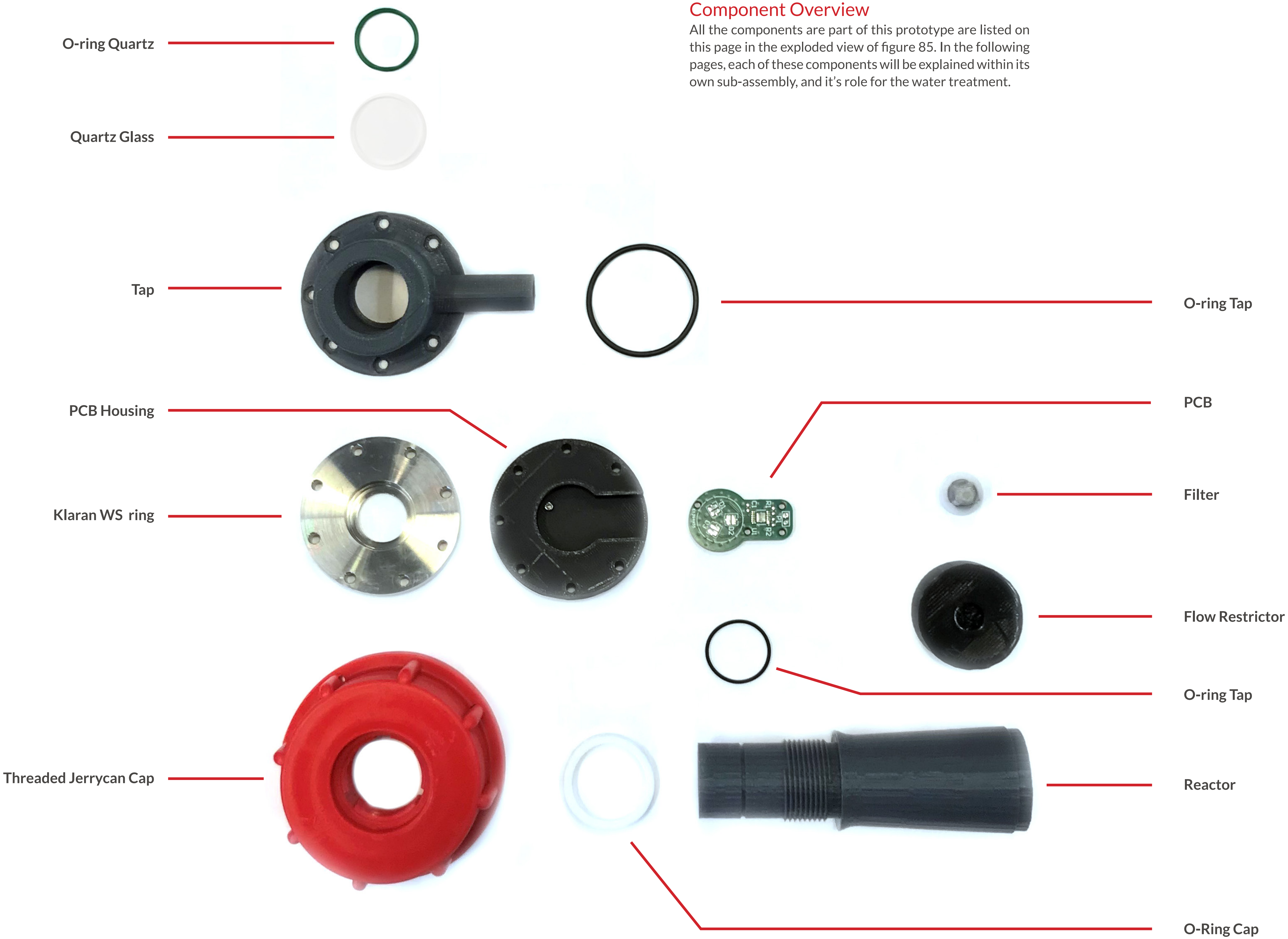


Figure 86: Overview of all the components for the functional prototype.

LED Module

Unfortunately, it proved too difficult to integrate the opening and closing of the tap as envisioned in this prototype. Achieving waterproof seals while maintaining a range of motion was not possible within a certain time limit and the prototyping possibilities at disposal. Therefore, in this current prototype, there is no method to open and close the tap.
To reduce the complexity of the prototype at this stage there is no battery placed, the LEDs will be powered by an external power source.

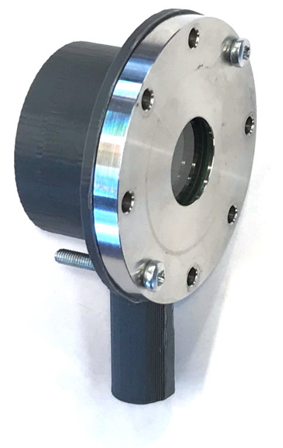


Figure 88: Waterproof connection between the tap and Klaran WS ring.

Klaran WS RIng

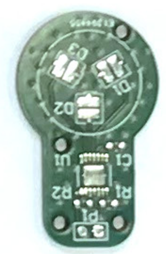
To make the development of the prototype easier, this component, combined with the O-rings of this picture, are taken from the Klaran WS device. This made it easier to develop a product with watertight seals and focus only on improving the product instead of water leaks. This ring contains the quartz glass and provides the waterproof connection between the electronics and the water.

PCB Holder

The PCB holder is designed to be mounted to the Klaran WS Ring, and its main function is to keep the PCB in place and position the LEDs optimally.

PCB

The PCB operates the LEDs and ensures that these do not overheat. To be able to vary the UV-C output in-between test, the PCB is designed to fit up to 3 LEDs.



Tap

The tap does not only dispense the water, but is also the connecting piece between all other components. It makes a waterproof seal with the reactor and connects it to the LEDs.

Quartz Glass

Quartz is one of the few materials that lets most of the UV-C light through. Here it is necessary to protect the LEDs and other electronics from the water while at the same still making it possible to disinfect the water.

O-ring Quartz

This o-ring provides the watertight seal between the quart glass and the Klaran WS ring.

O-ring Tap

This o-ring provides a watertight seal between the tap and the Klaran WS ring.

Figure 87: OVerview of the LED module components.

Reactor Chamber

The reactor chamber is the tube in which the water is disinfected. It is designed so that all the water will be illuminated and there are no blind spots where pathogens might be obscured from the UV-C light. At the extremity of the reactor there is a flow regulator mounted as a cap. The flow speed regulator was designed based upon the research of Crystal IS (see Appendix F). In fact, it is the water inlet to the reactor and ensures a more equal flow speed throughout the reactor while maintaining the flow rate of 1.5 L/min.

The components have a low complexity, making them unlikely to break or can be easily replaced. This part of the prototype is slightly simplified compared to how the final design should look. For this prototype the aeration was left out of the design of the UV-Tap, it proved to be too complex to integrate at this point and was therefore fixed by drilling a hole in the top of the jerrycan

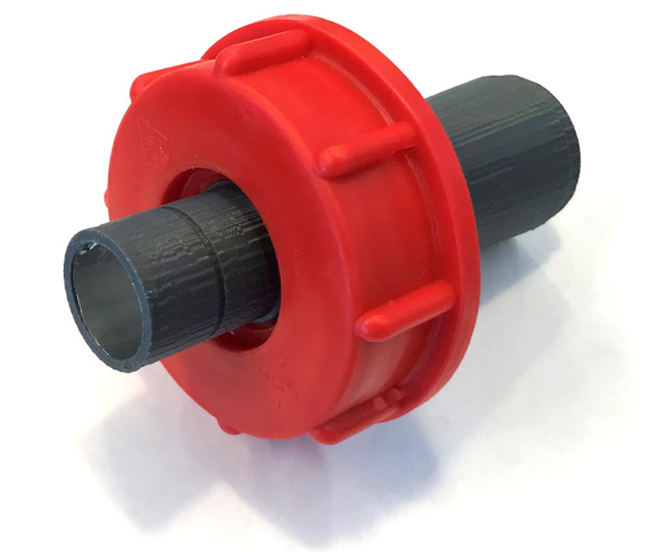
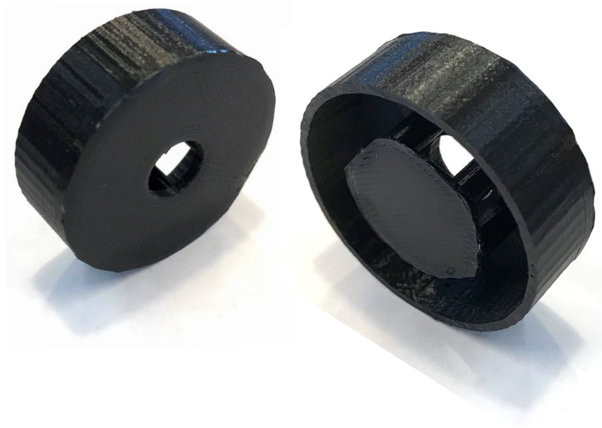


Figure 90: Assembly of the reactor with the jerrycan cap.

Flow Restrictor

The flow restrictor has a single hole through which the water can enter the reactor. On the inside, however, there is a baffle to obstruct the natural flow of the water. It blocks the water in the middle and pushes it outwards towards the reactor's wall. Just as the reactor, this component as well will be covered with aluminium on the insight to reflect as much UV-C light as possible.



Pre-Filter

The pre-filter is in place to protect the inside of the UV-Tap and ensure consistent disinfection. Not all jerrycans might be as clean on the inside, some might contain some sand grains or other particles, and it is undesirable that these enter the UV-Tap. Therefore, at the inlet, a coarse filter is placed to block these larger particles.

Jerrycan Cap

This is a standard issued jerrycan cap with an extra inner thread. This thread, combined with an o-ring, ensures a waterproof connection between the cap and the reactor. At this stage, it was not possible to use the preferred connection type as used by the tap in figure 54, due to lacking material specifications and time. In the end, that connection type will make the product more robust and make it impossible for the user tom disassemble it.

Jerrycan Cap O-ring

This o-ring ensures a watertight seal between the reactor and the cap. The thread make sit possible to put some pressure on the o-ring.

Reactor O-ring

This o-ring is vital to the connection between the reactor and the LED module. The LED module slides over the reactor, and this o-ring makes sure that that connection is waterproof.

Reactor

The shape of the reactor is determined by two standard components, the jerrycan, and the jerrycan cap. The diameter of the reactor cannot exceed the maximum dimensions of the opening in the jerrycan, and at the same time it needs to leave room in the cap for an or-ring that seals the cap and jerrycan.

The reactor has its length to provide more exposure time of the water to the UV-C. The inside of the reactor is covered with aluminium to reflect most of the UV-C radiation and make optimal use of the exposure time.

Figure 91: Overview of components of the reactor chamber.

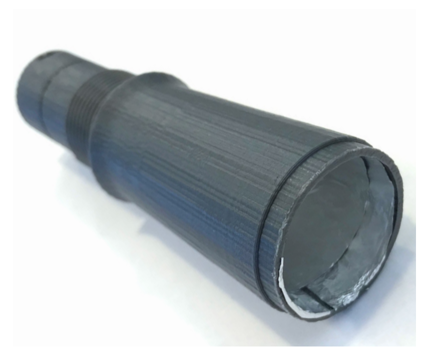


Figure 92: Inisde of reactor walls is covered with aluminium.

5.3 PROTOTYPE VALIDATION

The validation focuses on finding out how well the prototype disinfects water and find possible ways to improve the design of the UV-Tap.

Up until this point, this disinfecting capabilities of the UV-Tap have only been validated in theory, with the help of the Klaran calculator tool. This test will try to validate whether or not the water that leaves the UV-Tap actually is disinfected. Secondarily, this test should also provide learnings on how to further improve the design and possibly make the device more effective.
Besides the UV-Tap, this test will also validate the Steripen and the Klaran WS. As a check to see if the products actually deliver what they promise and see what learnings from these devices can be derived for further improvement of my own design.

Executing this test is also of value to Quooker's R&D department, as they often have to perform bacterial tests themselves. Now, these tests are outsourced to external labs, which costs a lot of time and money. Therefore, it is of interest to Quooker, to see if it is possible to execute these types of test in-house.

Test Setup

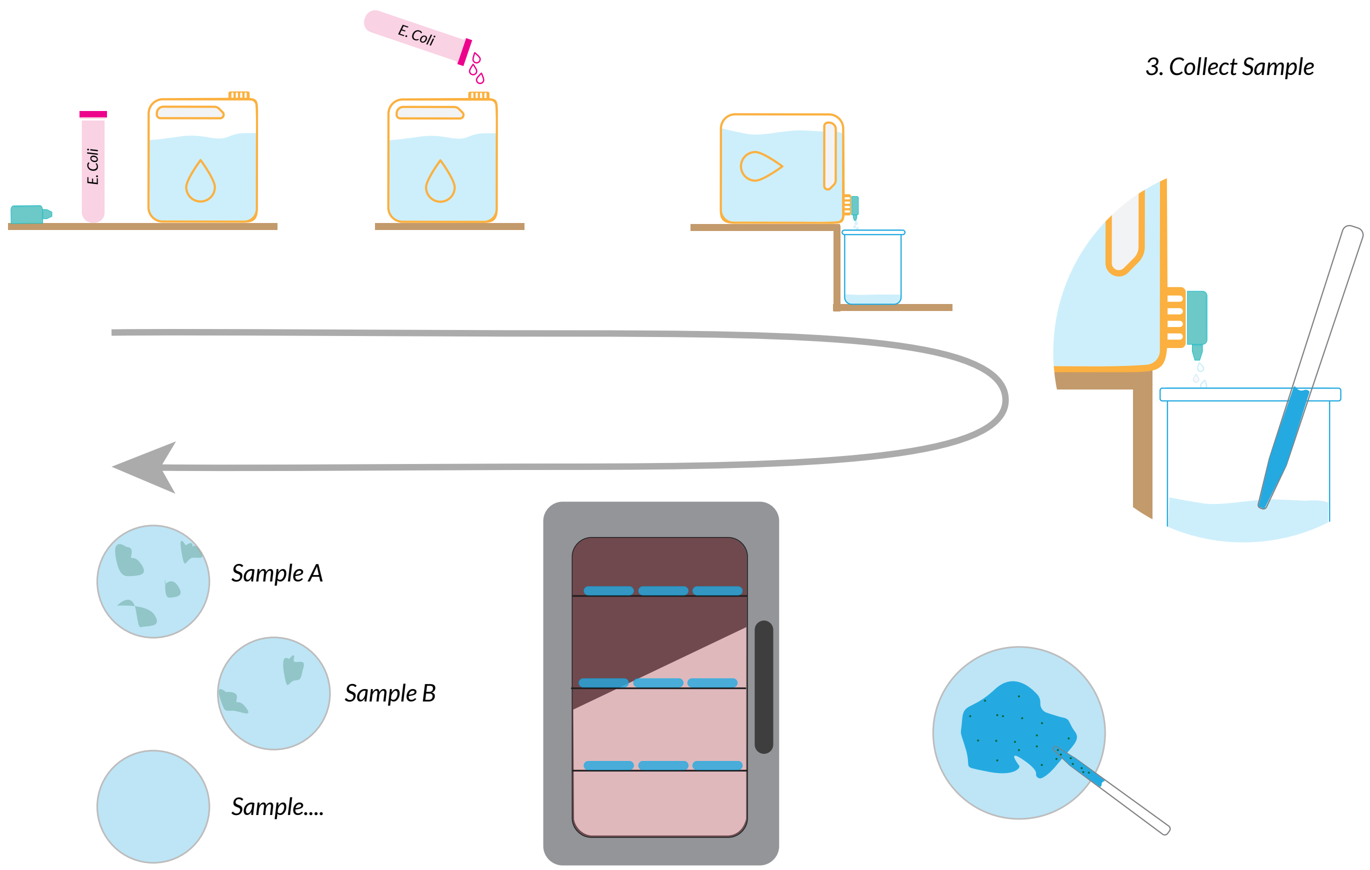
The test will try to mimic the envisioned use in a peri-urban household. Therefore, the UV-Tap will be installed on a standard UN-Jerrycan, which contains contaminated water (figure 93). The test was set up in collaboration with the KWR, a water research institute. They helped in developing the setup of the test and provided the E.coli sample used to contaminate the tap water. Ideally, as explained in chapter 4.1, to validate the Log 2 reduction the test should have been executed with the streptococci bacteria. However, these bacteria are not that easy to get access to and E.coli proved to be the best next thing, as it has a similar required UV-dose for a Log 2 reduction (8.8 mJ/cm^2 vs 8 mJ/Cm^2 respectively).
In figure 94 a simplified version of the test process is visualised, for a more detailed description see Appendix J.

Figure 93: Overview of all the products used for the test. From LTR: power source, Petrifilm, jerrycan, water treatment products, disinfection wipes, gloves, UV-C protection glasses, E.coli sample, measuring cup.

[1] Contaminate the tap water in the jerrycan with the E.coli sample provided by the KWR. The test was executed twice. Once with water that had a concentration of 150 CFU/100 mL and once with a concentration of 300 CFU/100 mL .
[2] Collect different samples:
- Tap water (untreated)
- Jerrycan water (untreated)
- Treated with UV-Tap
- Treated with Klaran WS
- Treated with Steripen Aqua

[3] The collected water was placed on different Petrifilms for bacterial growth.
[4] Place Petrifilm in incubator to speed up the bacterial growth. Wait for 24 h – 30 h.
[5] Compare the results of the different water samples.

Figure 94: Simplied visualisation of the test process.



Results

The tests as described on the previous page did not go according to plan. For both concentrations of E.coli (150 CFU/100 mL and 300 CFU/100 mL) the petrifilms yielded negative tests (figure 95). The test most on the left in this figure should have shwon green dots (as an idication of a postive test) since this sample was disisinfected.

As a comparative test, once both previous test proved to be negative, I used a non diluted bacteria sample. This sample had a concentration of approximately 15.000 CFU/mL. One millilitre of this sample was placed on the petrifilm and stored in the incubator to grow the bacteria. The green dots indicate the bacteria colonies.

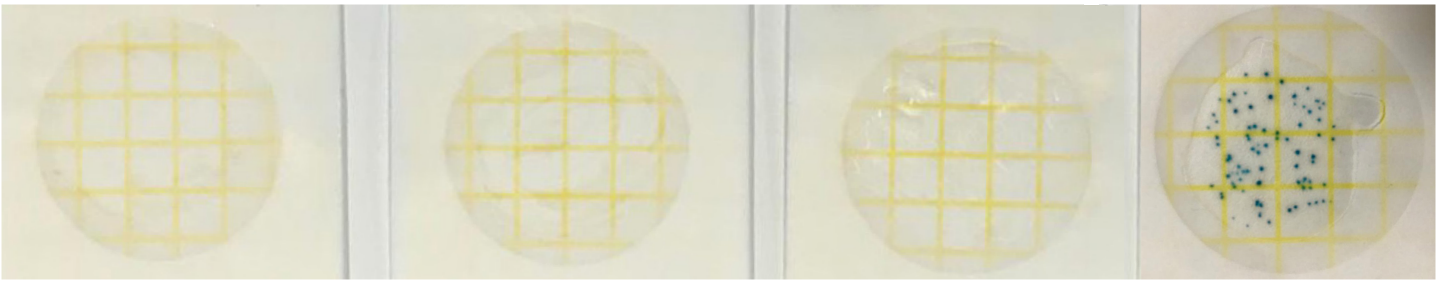


Figure 95: The first three samples present negative results of the test with a concentration of 300 CFU/100 mL, the sample most to the right presents a postive test with a concetration of 15.000 CFU/mL. All samples were collected after 24-30 hours in the incubator.

Discussion

With the diluted samples not showing any results, and the undiluted sample only showing some marginal positive results (at a concentration of 15.000 CFU/mL the whole sample should be green), it becomes clear that some of the materials used for the test are not sufficient.

By reflecting on each of the steps taken and the materials used potential bottlenecks can be identify. The following are found:

- The petrifilm is capable of yielding positive results of 1 CFU/mL. All samples used were above this concentration level and this can therefore not be the issue.
- The pertrifilms do work in combination with E.coli, as we can see from the test with the undiluted sample. However, the test should show more colonies at these concentration levels.
- It is unlikely that the circumstances for the bacterial growth are not good enough. The pertrifilm provides the bacterial with nutrients and the incubator keeps the temperature around 38 degrees (might vary one or two degrees).
- The E.coli strain was not healthy and did therefore not replicate sufficiently.
- The sample collection did not happen correctly and therefore spoil the results of the test with diluted samples.

I discussed the results of this reflection with the KWR to hear what their opinion was on why the test did not work out.
The first thing they did was check the E.coli strain, 2 weeks after the tests the strain was still healthy and could therefore not be an issue.

In the end, the KWR thinks that the results of this test proved inconclusive due to the combination of the afore mentioned factors.

The test wasn't executed in a laboratory, with lab equipment. This makes the collecting of the sample less than ideal, and it does not provide the ideal circumstances for bacterial growth. Those factors combined with the low volume/ concentration of bacteria on the petrifilm are the probable reason for the negative test samples.

For future tests it would be recommended to work with CFU indicators that work with higher volumes of water, making a positive test more likely. Ideally I think it would be best to have these sorts of test executed by professionals in a laboratory for accurate results.

Figure 96: Test is progress with the UV-Tap, the disinfected water is collected in a sterilised measuring cup.

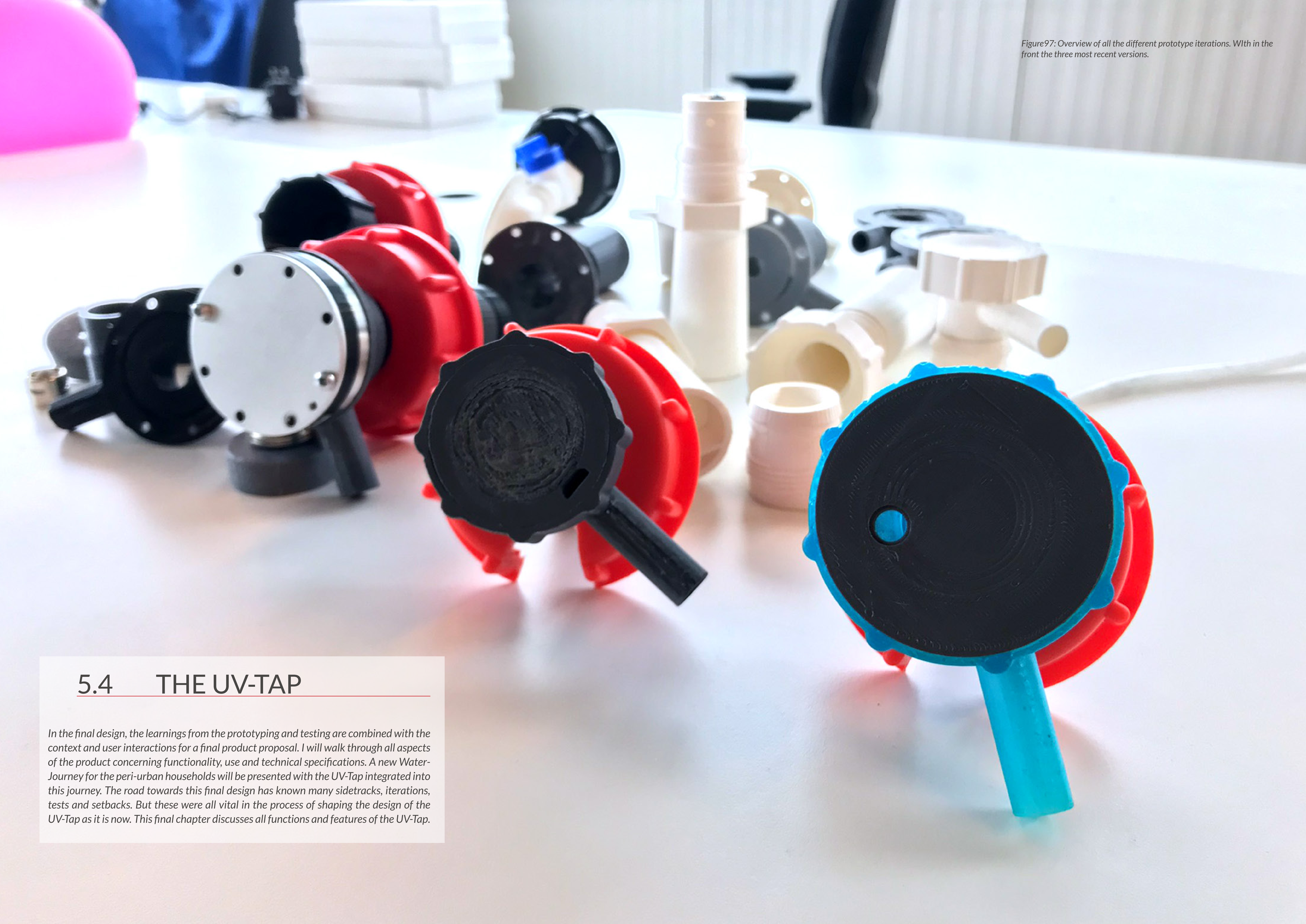


Figure97: Overview of all the different prototype iterations. WIth in the front the three most recent versions.

5.4 THE UV-TAP

In the final design, the learnings from the prototyping and testing are combined with the context and user interactions for a final product proposal. I will walk through all aspects of the product concerning functionality, use and technical specifications. A new Water-Journey for the peri-urban households will be presented with the UV-Tap integrated into this journey. The road towards this final design has known many sidetracks, iterations, tests and setbacks. But these were all vital in the process of shaping the design of the UV-Tap as it is now. This final chapter discusses all functions and features of the UV-Tap.

User functionality

The main functionalities of the device that are crucial to the user are illustrated in the figure below. These are the parts of the design that the user interacts with and are important for the user experience.

On the next page, I will walk through each of these interactions and functionalities in more detail.

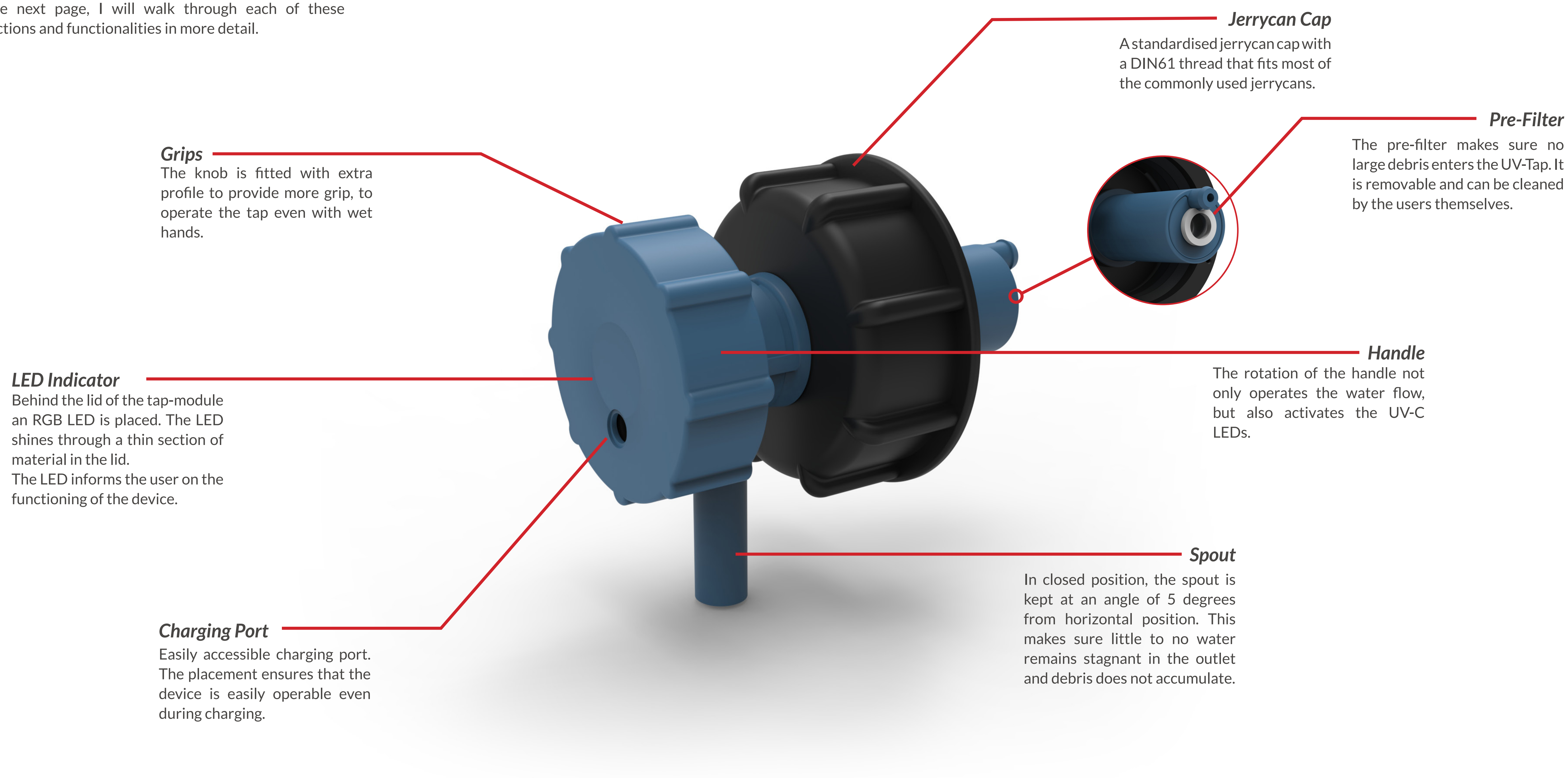


Figure 98: The main functions and parts of the UV-Tap with which the user interacts.

Operating the UV-Tap

The UV-Tap is operated by rotating the handle clockwise. This movement aligns the outlet of the reactor with the Tap-module, see figure 99. The water will only start flowing when these two holes align. At the same time, this rotation activates the UV-C LEDs and the disinfection of the water starts. These LEDs stay on until the tap is closed again. In figure 100 the opening and closing of the UV-Tap is visualised with a prototype.

The spout direction clearly signals to the user whether or not the tap is open. I chose to attach the spout to the handle so that when the tap is closed, and the spout is positioned horizontally, it does not stick out, and it is less likely to get damaged.

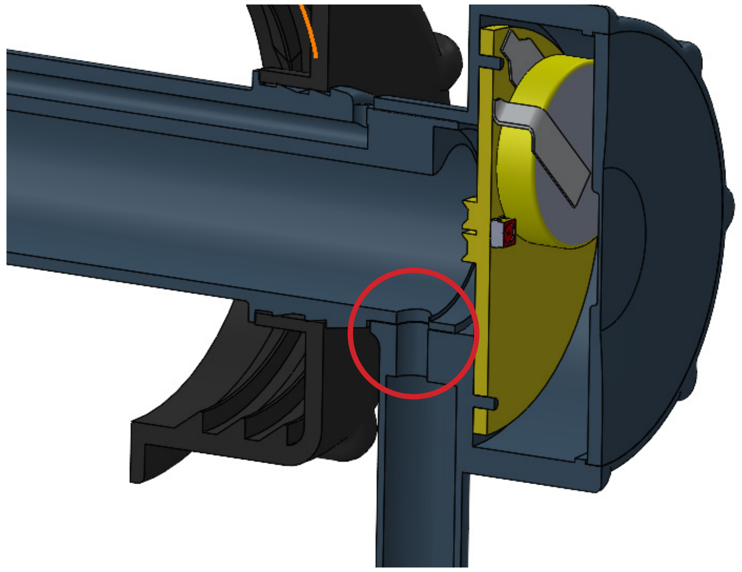


Figure 99: In the red circle the area where the outlet of reactor aligns with the spout. If this is no longer the case the water flow stops.

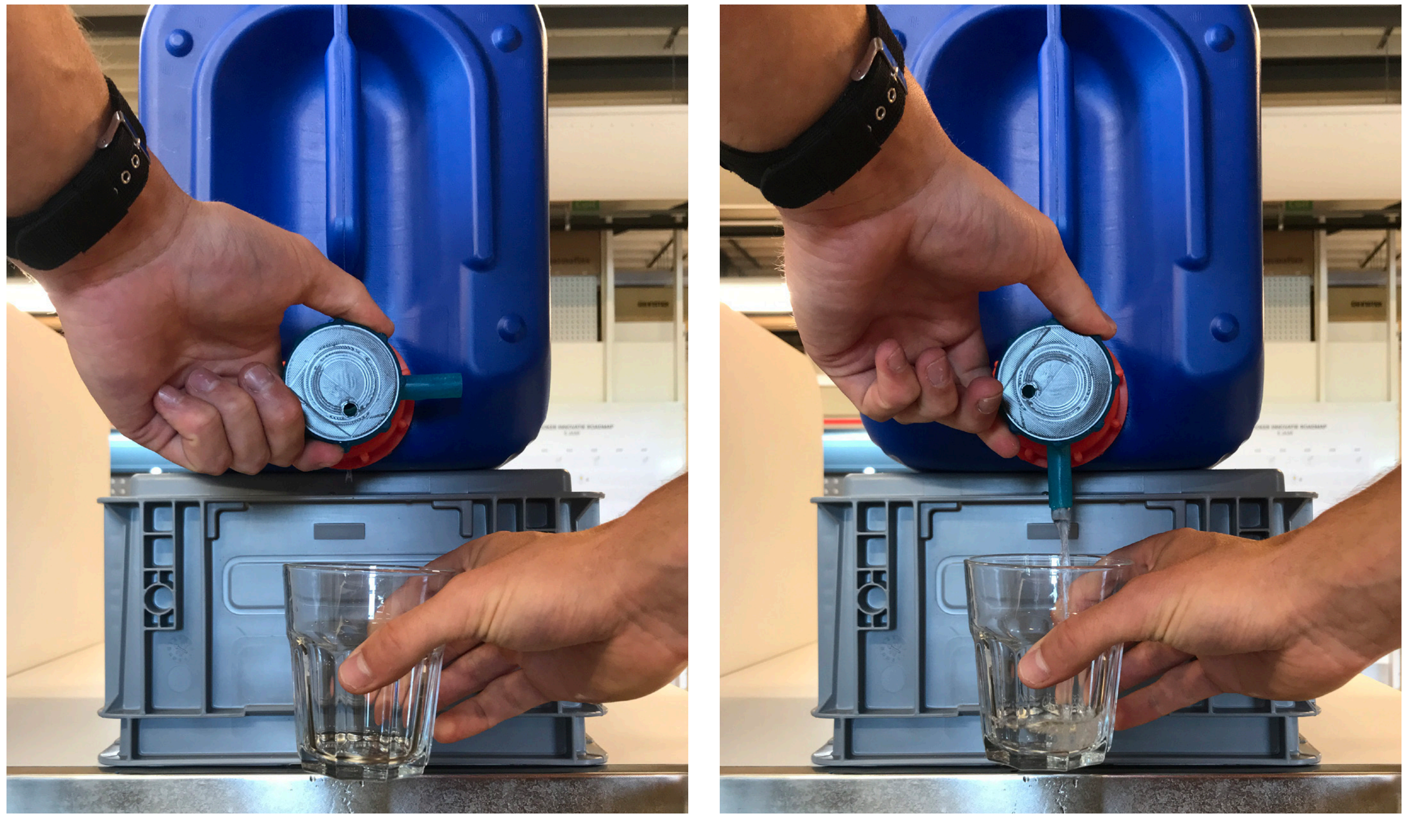


Figure 100: Opening and closing of the UV-Tap demonstrate with a prototype.

Spout Alignement

The first step the user has to take is to screw the cap on the jerrycan once it is filled again. However, different jerrycans have different types of thread designs, even for the same cap size. In reality this means that the spout will not always align correctly (see figure 101).

Figure 101: Two different jerrycans, with the same cap size, having different thread designs and affecting the spout alignment.

To remediate for this problem, the UV-Tap is designed in such a way, that as a whole, it can rotate freely and independently of the cap. This makes it possible to always align the spout correctly. All the user has to do is rotate the tap-module up to the point its movement is limited. If the user then continuous to rotate the reactor inside will start to rotate along, making it possible to align the spout correctly.

Since both the rotation of the handle and the alignment of the spout are along the same axis this could present some difficulty during use as turning the handle would also turn the entire UV-Tap. To make sure the clockwise rotation of the handle does not alter the alignment, the UV-Tap is designed in such a way that the friction between cap and reactor is greater than the friction between the Tap-module and reactor (see figure 102). This difference in friction is caused by a slight difference in diameter dimensions, increasing the force necessary to turn the reactor shell within the cap.

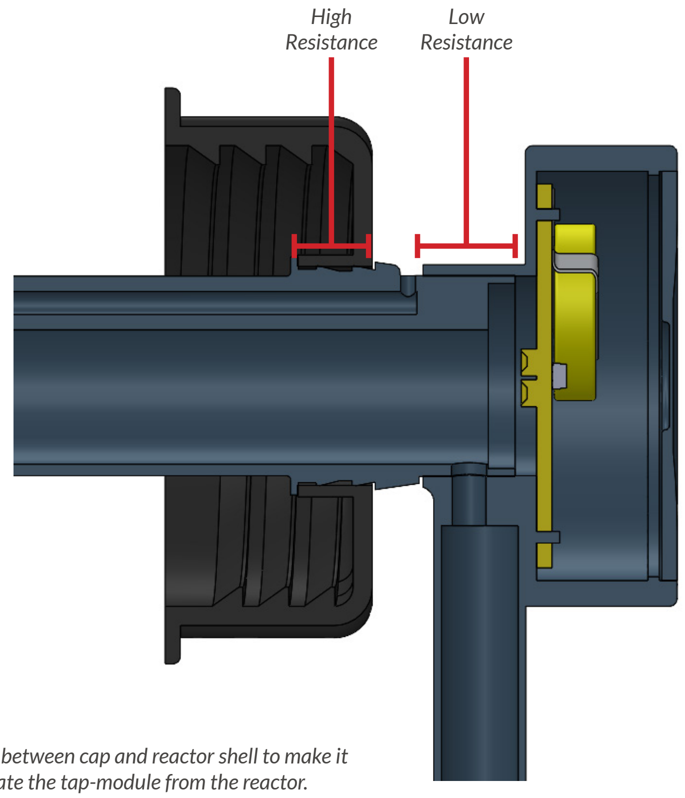


Figure 102: Higher friction between cap and reactor shell to make it possible to independltly rotate the tap-module from the reactor.

Pre-Filter

The pre-filter is used to ensure no debris, such as sand that might be at the bottom of the jerrycan, enters the UV-Tap. This filter is only in place to ensure the UV-C LEDs are used effectively, and is not used to filter pathogens. To make sure this filter lasts a long time and doesn't start to obstruct the water flow, it is removable, and the users can clean it themselves.

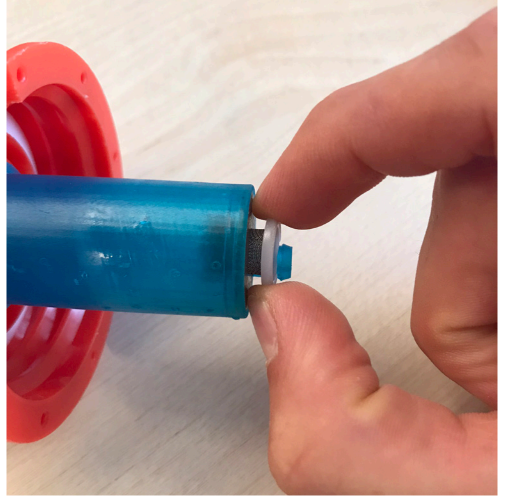


Figure 103: Demonstration of how to remove the pre-filter.

RGB LED

The UV-C LEDs are encapsulated inside the Tap-module it is impossible for the user to tell if they are on or not. Therefore, there is an extra LED that turns on simultaneously with the UV-C LEDs. This LED also functions as a battery indicator, indicating battery level and charging. The LED can emit different colours of light to communicate all these aspects. Figure 104 shows how this is communicated to the user.

- *Blue (steady): UV-C LEDs are on*
- *Blue (blinking): UV-C LEDs are on and battery level is low*
- *Blue (pulsating): UV-C LEDs are on and battery is charging*
- *Green (pulsating): Battery is charging and UV-C LEDs are off*
- *Green (steady): Battery fully charged and UV-C LEDs are off.*
- *Red (blinking): Handle turned to ON position and battery is empty.*

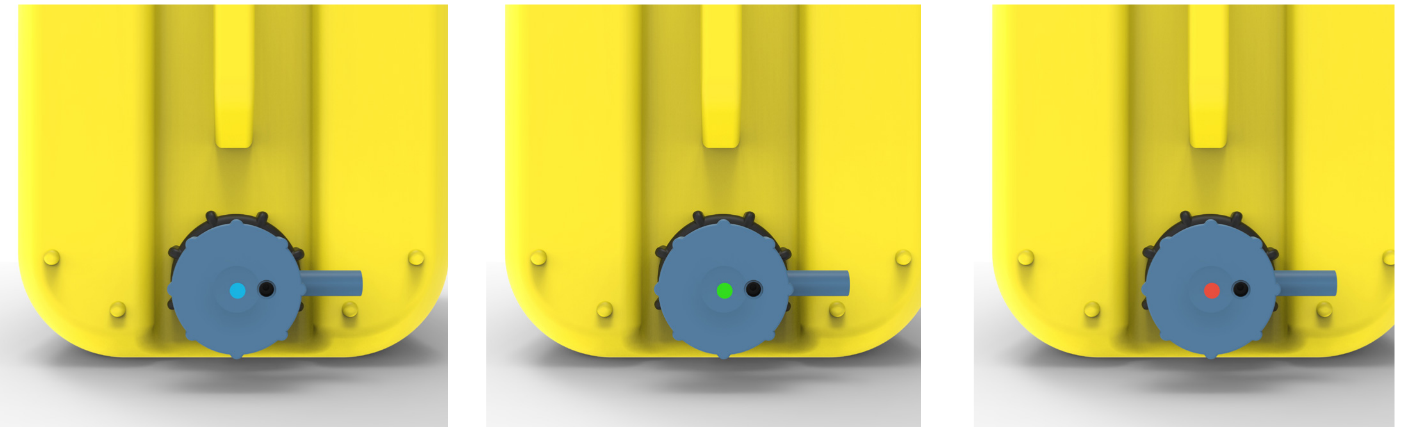


Figure 104: Three different light colours and six different modes to inform the user on the functioning of the UV-Tap.

Power Managment

The UV-Tap can operate independently of the grid. To keep costs down the chosen battery has a low capacity. On one battery charge around 50 L of water can be disinfected, which in practice should suffice for 3 to 4 days for an entire household of 4 people.
In case the device runs empty and water is required it can be plugged in while continuing operation. This makes sure that the households always have access to disinfected water.

Due to the battery's small capacity the charging time is also short. The charger output is around 600mA, and the battery has a capacity of 160mAh. This results in a charging time of around 20 minutes (see calculations on the right).

The formula for the charging time is as follows:

Charging Time = Battery Capacity / Charge Rate Current

The charging cycle is not a 100% efficient, I estimate that it is only for 70% efficient.

160 / (600 x 0.7) = ~20 minutes

To ensure the UV-Tap is comfortable to use even with the charger plugged-in the placement of the adapter was important. The charger should not impede the rotational movement to open or close the tap, nor impede the hand placement. By trying different configurations and placements in the end I decided to place the charger as in figure 105 since this obstructed the use of the device the least, while maintaining easy access to the port and simple component design.

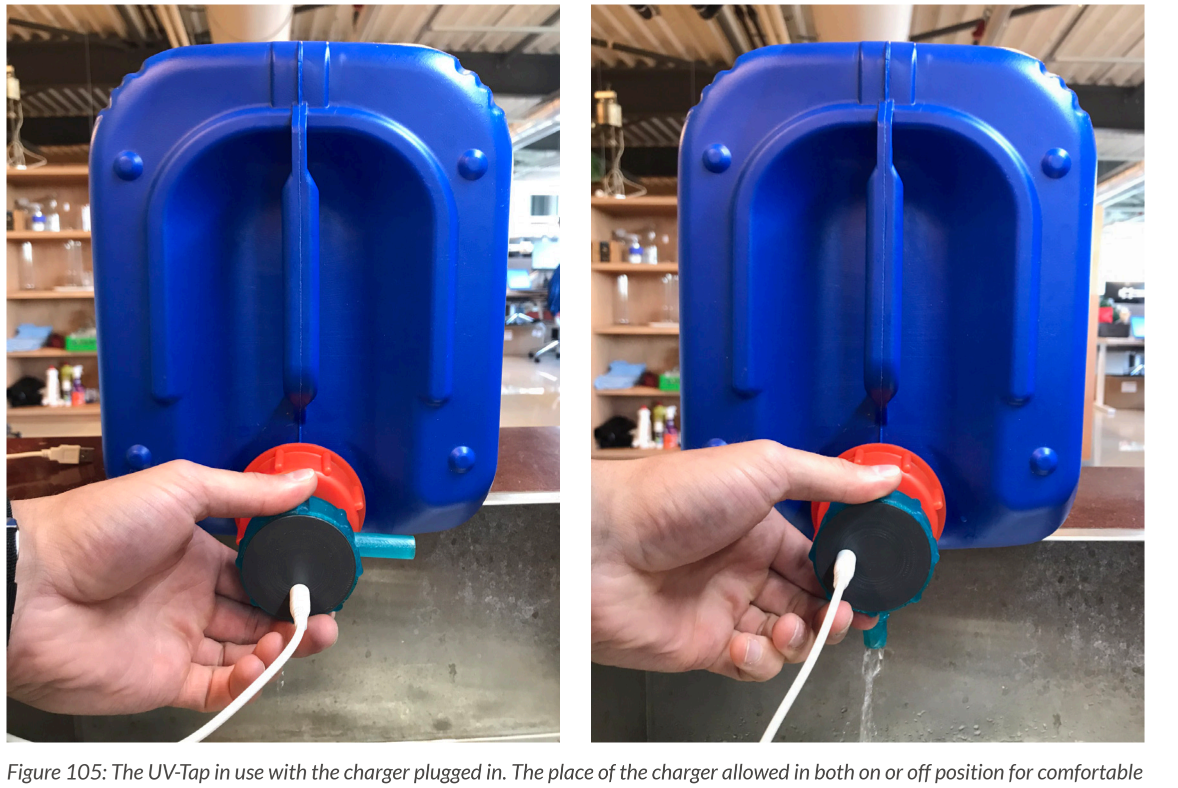


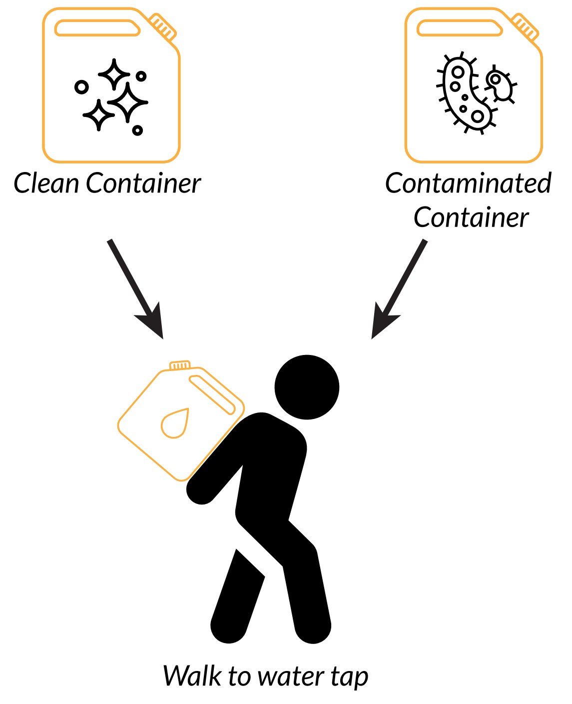
Figure 105: The UV-Tap in use with the charger plugged in. The place of the charger allowed in both on or off position for comfortable use.

The New Water Journey

With the integration of the UV-Tap into the daily lives of people also comes a new Water-Journey. The usage of the UV-Tap does not require a lot of changes in behaviour from the user. The Water-Journey only changes in the few final steps and actually makes these easier. In the final step the water is disinfected and that way the user can be guaranteed to always drink safe water.

Where beforehand people had to pour water from the jerrycan into jugs or bottles before filling a glass, they now just have to open the tap and hold a glass underneath. This also makes it possible for children to access the water more easily and not depend on their parents. Where before it would be impossible for a young child to handle a jerrycan full of water it is now accessible with nothing more than a twist of the tap.

Having the UV-Tap installed also reduces the risk of the user contaminating the water. The tap is installed at when the jerrycan is full and removed when it is empty, reducing the interactions with an open jerrycan to a minimum. Before, every time someone wanted water they had to remove the cap with the risk of contaminating the water.



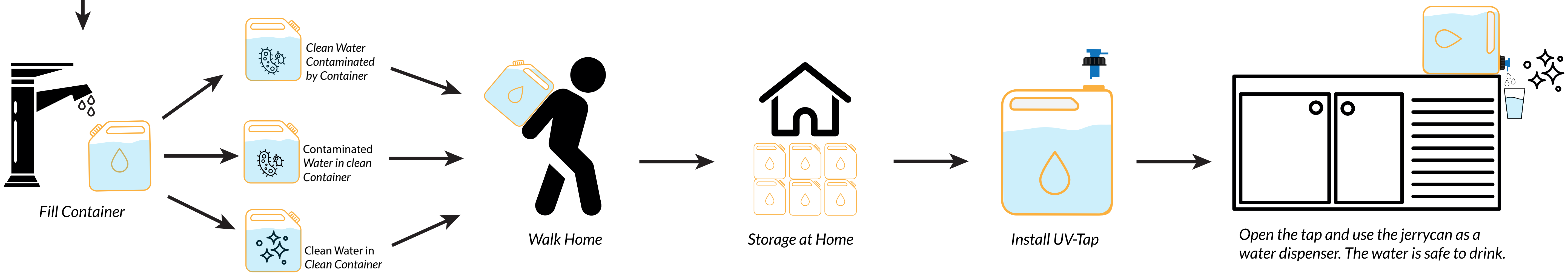


Figure 106: Visualisation of the new Water-Journey with the integration of the UV-Tap.

Technical Aspects & Features

In this section I will walk through the specifics of the design from a more technical perspective and discuss certain design choices in regard to function and feasibility

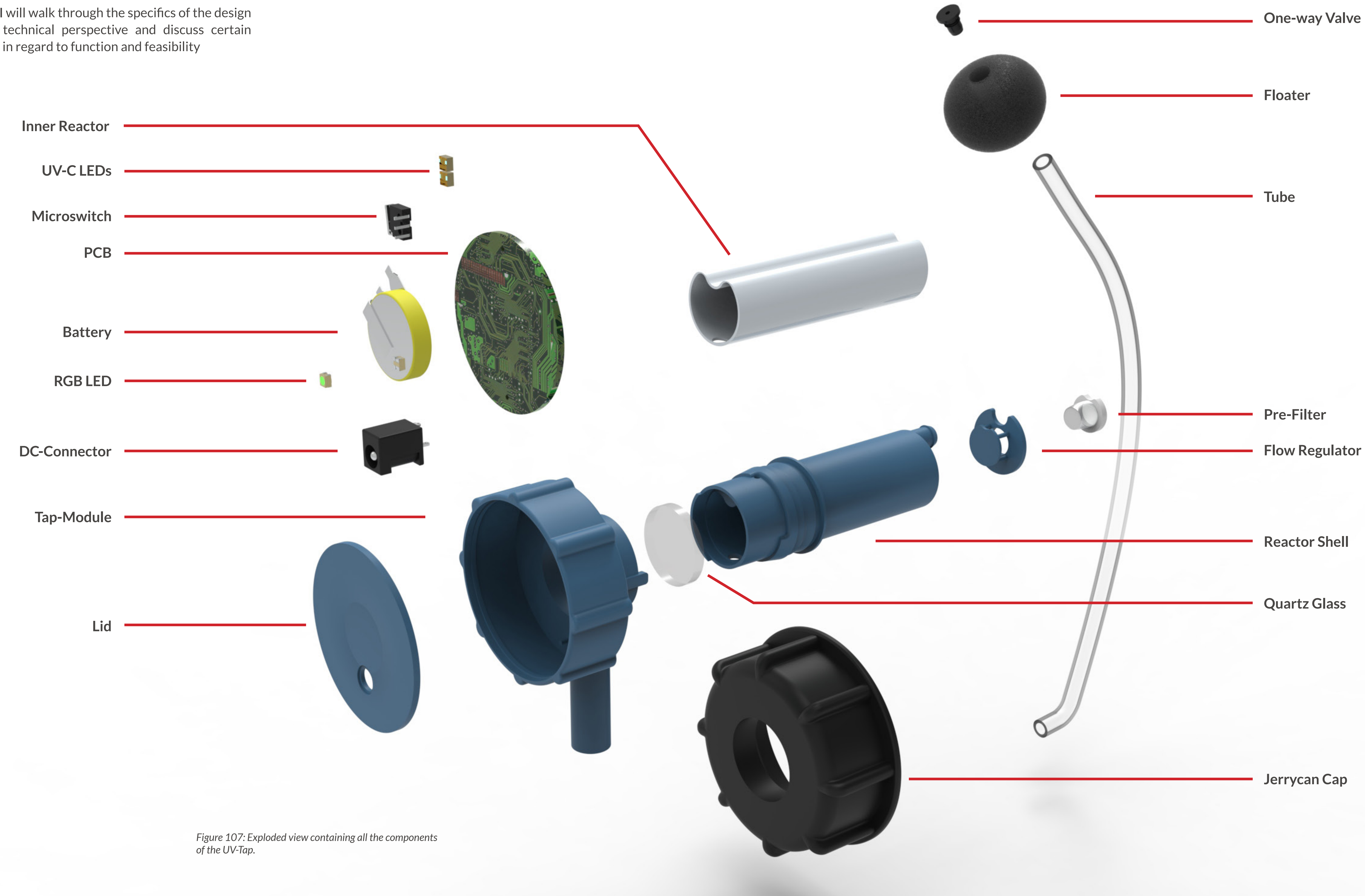


Figure 107: Exploded view containing all the components of the UV-Tap.

Water Tight Assembly

To provide people with a reliable and long-lasting product, it requires a watertight fitting that even after extensive use would continue to work and is not easily damaged.
There are three points in the UV-Tap where a water tight seal is necessary (see figure 109):
- Between the reactor and cap
- Between the reactor and Tap-module
- Between the quartz glass and the reactor

The seal between the quartz glass and the reactor is the simplest to achieve from an engineering perspective. These components are glued together.

The seal between the reactor, cap and tap-module proved to be more challenging. The need for a rotational movement with which the user operates the UV-Tap doesn't lend itself for a water tight seal. Usually o-ring seals are used, however, in this case that is not possible. Over time, the rotational movement of the housing will damage the o-rings due to the friction and the water tight seal will be broken.
Therefore, the water type seal as discussed on page 64 and 81 is used for this product.

The UV-Tap is fixed to the cap by the reactor. The fitting and waterproof seal is provided by the diameter of the reactor being slightly larger than that of the cap. The cap, being a harder material, will slightly squeeze the reactor, which in that way creates a waterproof seal. For this a special cap is necessary, which however is still a standard component (figure 108). This type of seal that allows the UV-tap to spin freely (without opening/closing the tap), and that makes it possible to find the right alignment of the tap.

The same principle is used for the fit between the reactor and Tap-module. The section view of the model in figure 109 shows where the water tight seal is provided.

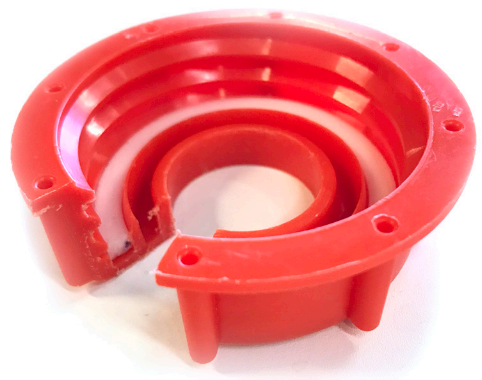


Figure 108: Special jerrycan cap with a hole and border in the middle that provides a watertight connection.

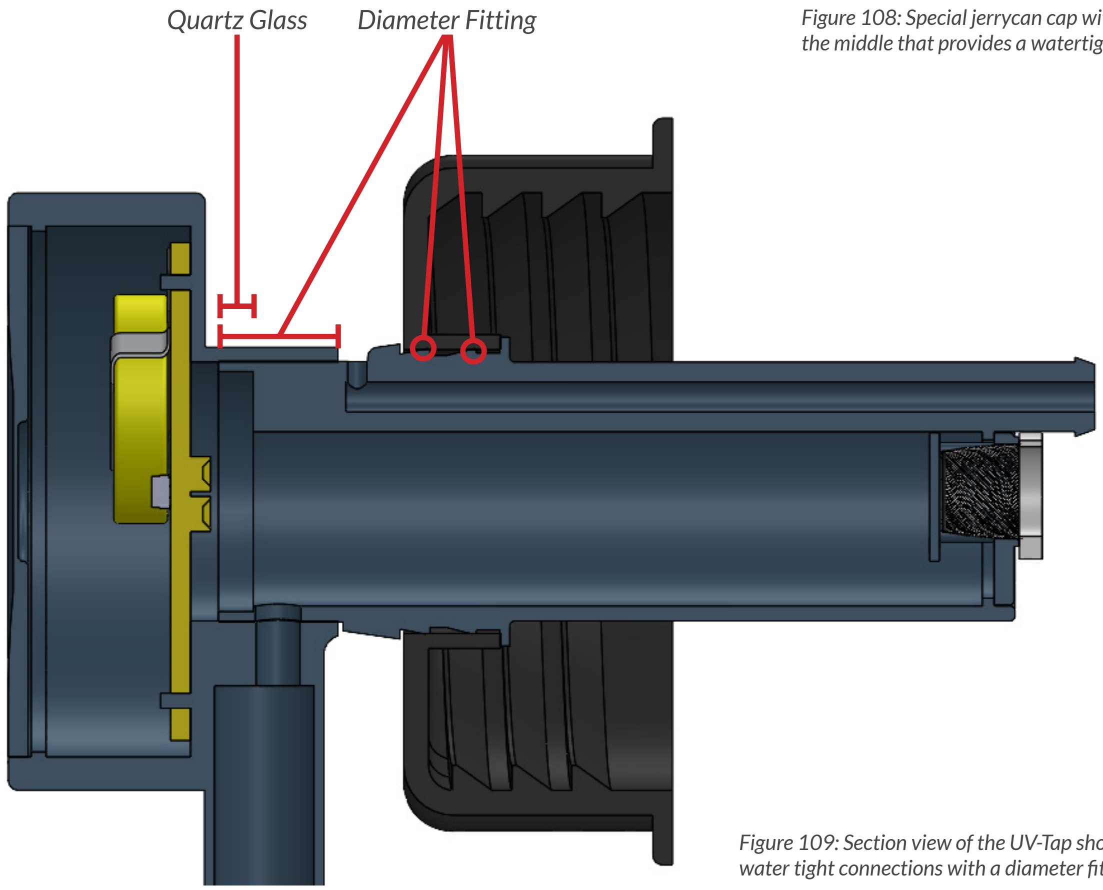


Figure 109: Section view of the UV-Tap showing where the water tight connections with a diameter fitting are made.

Aeration

Aeration is necessary to prevent creating a vacuum in the jerrycan as the water comes out. The aeration system consists of a channel in the reactor shell and a tube with a floater and valve. The channel functions as the connection between the interior and exterior of the jerrycan, whereas the tube ensures the air can get in above the water level.

The one-way valve ensures no water enters the tube to maintain a free flow of air, while the floater ensures the tube is always above the water level. For more details about the thoughts behind the design of the aeration please look at chapter 5.1 and Appendix I.

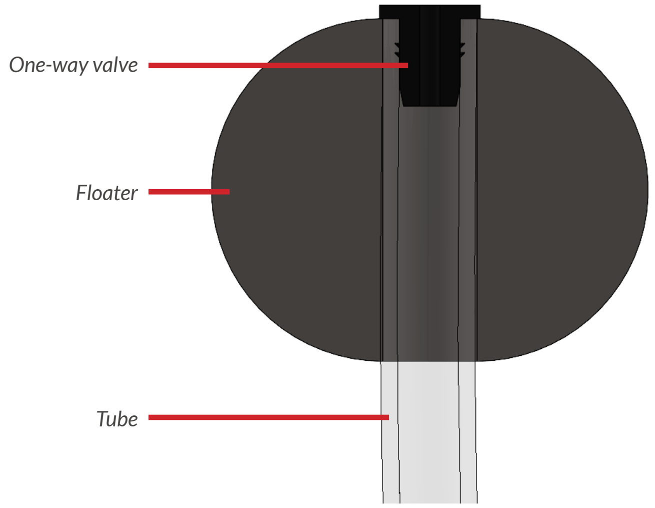


Figure 111: At the end of the tube there is a floater to keep the tube above the water level, and a one-way valve to prvent water from entering the tube.

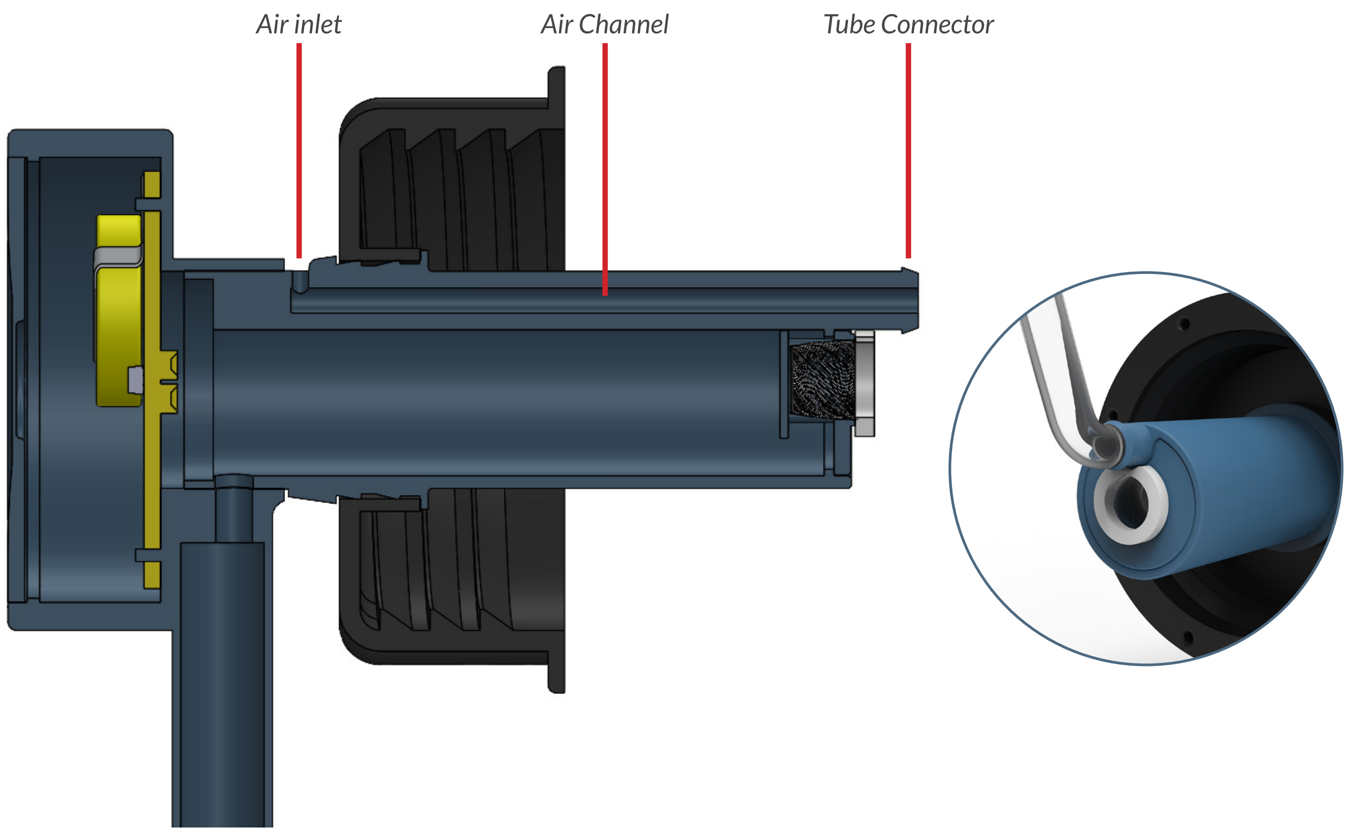


Figure 110:The reactor functions as the connection between the interior and exterior of the jerrycan. The tube connects to the reactor above the filter.

Water Flow

The water flow is regulated by two parts in the design, one is the outlet and the other the flow regulator. Both influence the water flow, but on different aspects.

The diameter of the outlet controls the flow rate. It makes sure that the flow rate does not exceed 1.5 L/min. This is determined by the hole at the start of the outlet (see figure 112).

The flow regulator is the inlet of the water into the reactor, it controls the flow speed inside the reactor. It makes sure that the water in the reactor has an equal flow speed, and thus an equal exposure time to the UV-C light (figure 113). For a more detailed explanation of how this works look at chapter 5.1 and Appendix F.

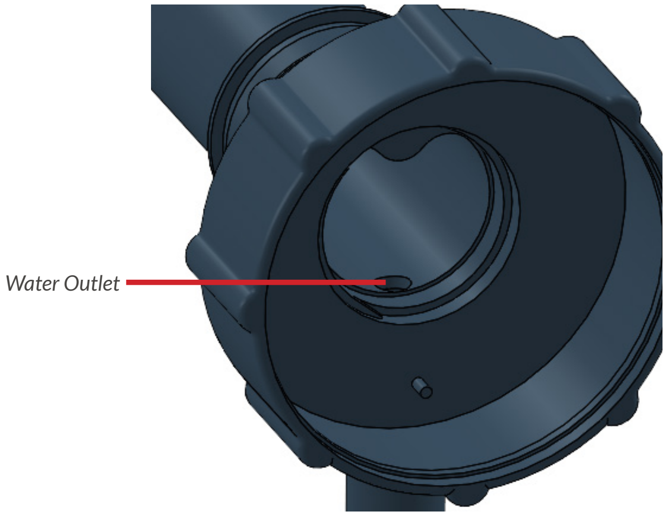


Figure 112: Position of the water outlet that controls the flow rate.

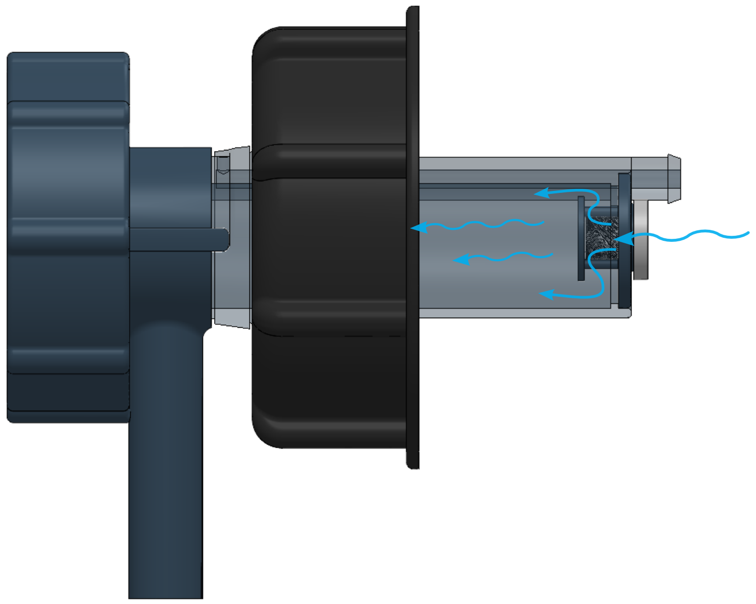


Figure 113: The flow regulator pushes the water coming in outward towards the walls of the reactor to create an equal exposuire time.

UV-C

Inside the tap-module there are two UV-C LEDs that provide the necessary dosage for disinfection. The LEDs are placed in the middle of the reactor to optimally use the dispersion of the UV-C radiation from the LED.

On the inside of the reactor there is an inner layer of PTFE, a material that reflects up to 90% of the UV-C radiation. By reflecting the UV-C, the device becomes effective even with a low UV-C output. The reflection of UV-C is talked about in more detail in Appendix F.

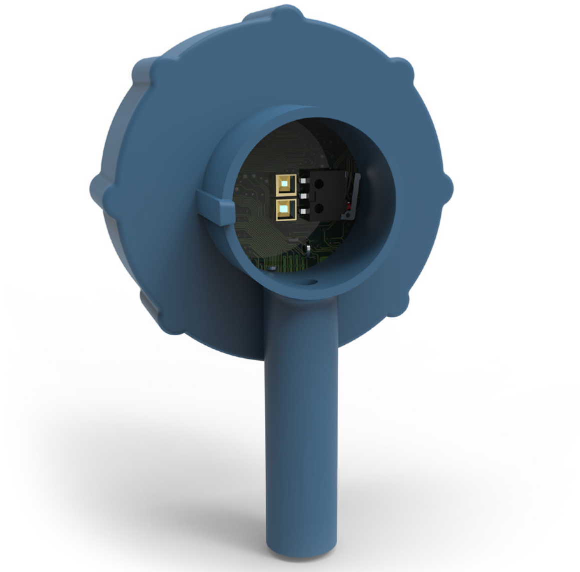


Figure 114: Placement of the UV-C LEDs in the tap-module.

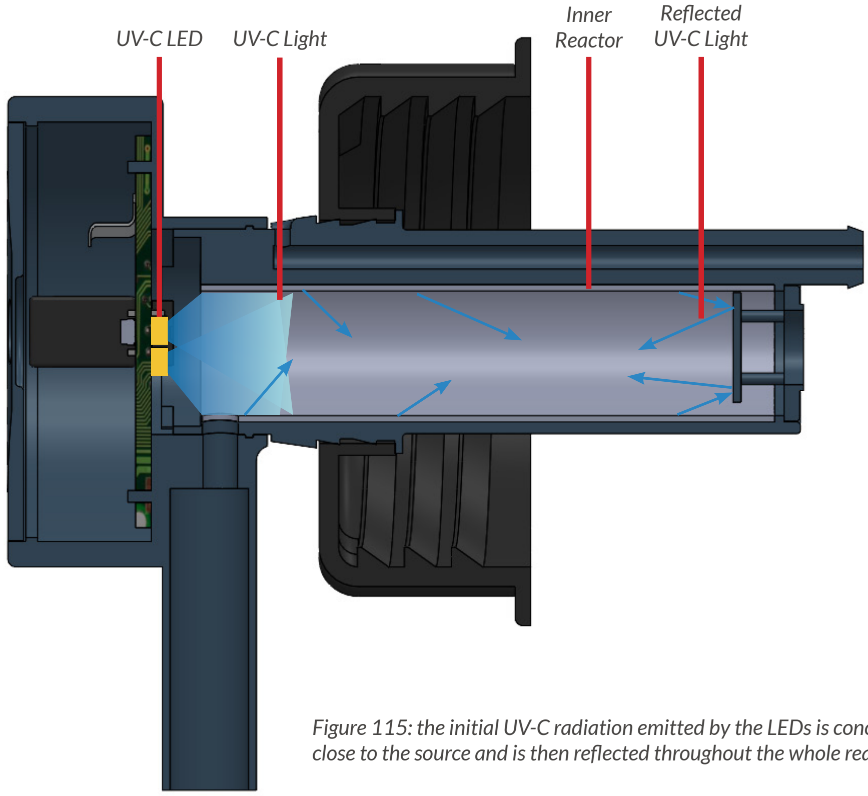


Figure 115: the initial UV-C radiation emitted by the LEDs is concentrated close to the source and is then reflected throughout the whole reactor.

Microswitch

The microswitch is in essence the switch that controls all the electronics, when this switch is pressed the UV-C and RGB LEDs are activated.

The switch is controlled by the rotational movement of the tap-module. When the tap is horizontal the switch is OFF, when the tap is vertical the switch is ON. The switch is pressed by a change in shape of the reactor that compresses the lever, see figure 116 for the activation mechanism.

Having the activation of the LEDs directly linked to the tap-module ensures that the water coming out of the tap is always disinfected.

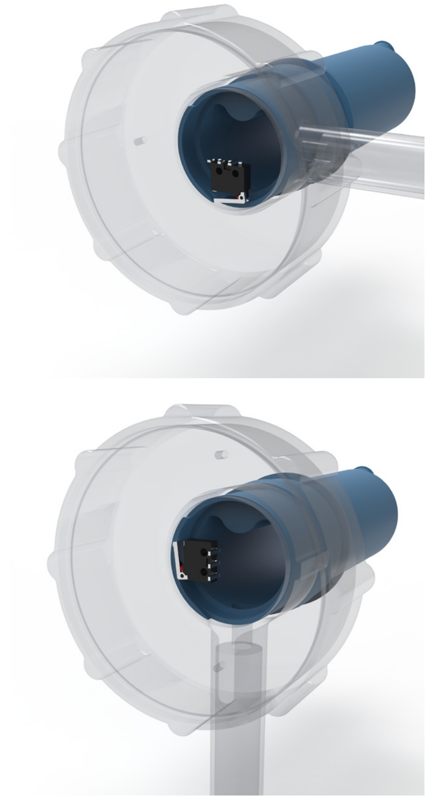


Figure 116: When the tap-module is rotated towards the on position, the lever of the switch is pushed against the reactor which activates the LEDs. In the figure on top the LEDs are off, in the bottom one they are on.

Charging

Rechargeable batteries are a necessity for the context, even if it makes the device more expensive in the end. To make sure the charging of the UV-Tap remains always possible, a sturdy and simple charger is required. A DC-connector (figure 117) is a simple and durable charging port. Its durability comes from the single large connector pin with a large contact point. The large contact point ensures that the device will always charge, even when there is some dirt accumulated inside. If there is too much dirt this can be easily removed since there is a lot of space and there are no delicate connector pins.

Figure 117: A standard DC-Connector

Manufacturing

During the whole process the goal was to make the design as simple as possible, meaning;
- using as few components as possible
- limiting the number of custom components
- keeping the components itself simple, limiting manufacturing or procurement costs

This resulted in a final product with 16 different components, of which 6 are custom. Figure 118 gives an overview of all the components and their origin.
For prototyping I mainly relied on 3D printing, for the final product however, these components will be injection moulded (except for the PCB). Ideally, one mould will be used for multiple components to reduce costs.

This manufacturing process is chosen to provided accurate dimensioning of parts to guarantee watertight fits. In addition to the estimated production quantity of 10.000 units (determined by Made Blue).

For the custom components specific materials have been selected that need to fulfil certain requirements. Foremost it is important that the reactor shell, inner reactor and flow regulator are UV resistant materials. Since these will be exposed to UV regularly and with high dosages it is essential that these materials do not deteriorate over time.

Secondarily, the material choices play a major role in providing the desired watertight connections. The material choices for these have been based upon the jerrycan tap from figure 61. Polyethylene for the 'soft'parts and polypropylene for the 'hard' parts, respectively white and red in the figure.

• Reactor Shell = PE
To make the watertight connections the reactor shell needs to be compressible by both the jerrycan cap and tap-module. Furthermore, PE is UV resistant.
• Inner Reactor = PTFE
To optimise the efficiency of the reactor and make it possible to use fewer LEDs the inner layer is made from PTFE, a material that reflects up to 90% of the UV-C radiation (see Appendix F).
• Tap-Module = PP
The tap-module needs to be of a harder and stiffer material than PE as not to deform and press the reactor into a watertight fit. It does not come into contact with UV-C and therefore does not require any specific resistance to UV-C.
• Lid = PP
The lid is also made from PP to keep the same cosmetic appearances as the tap-module.
• Flow Regulator = PTFE
Just as the 'inner reactor', the flow regulator is made from PTFE as well to reflect any UV-C radiation.

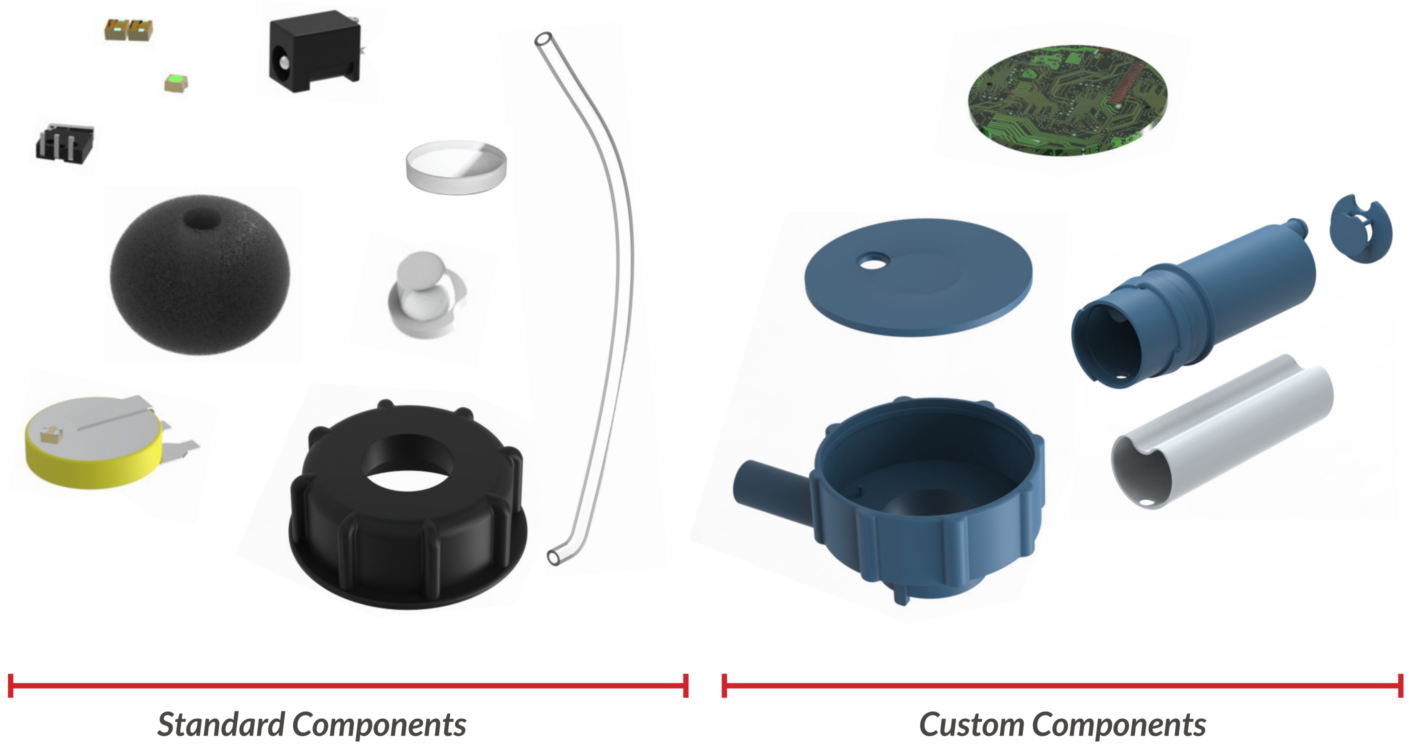
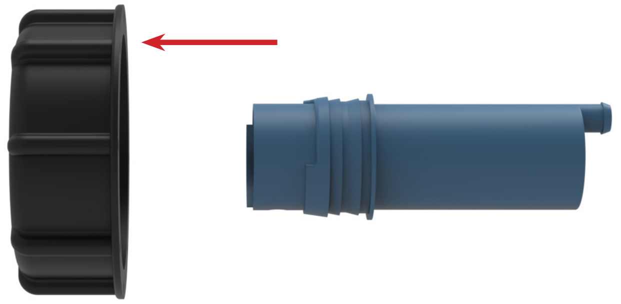


Figure 118: Overview of the components that are standard and the ones that have to be custom manufactured

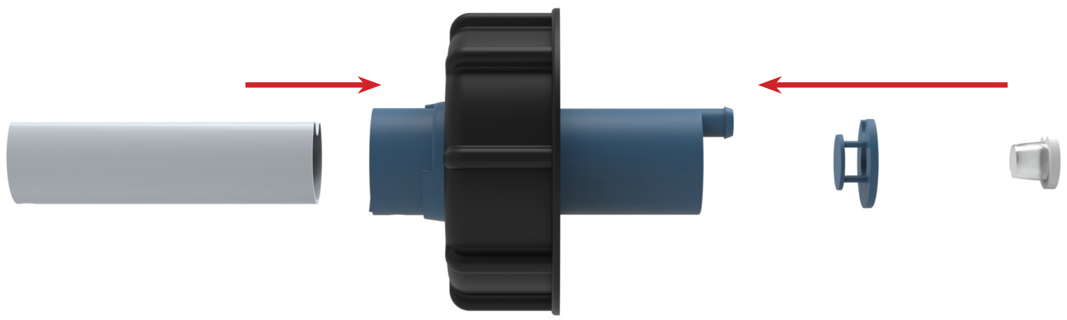
Assembly

The simplicity of the product not only reduces costs of manufacturing, but also makes the assembly process easier. The whole assembly process consist of seven different steps and requires a minimal amount of fasteners, the majority of components are held together with snap fits.
A test to measure the assembly time revealed that the entire assembly process will take between 1.5 and 2 minutes per UV-Tap.

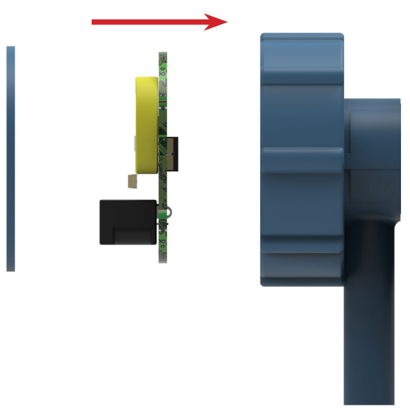
This is the time one person requires to assemble the complete product from start to finish and assuming the PCB is ready to be assembled. If the assembly process were to be subdivided into different stations the process could be faster.



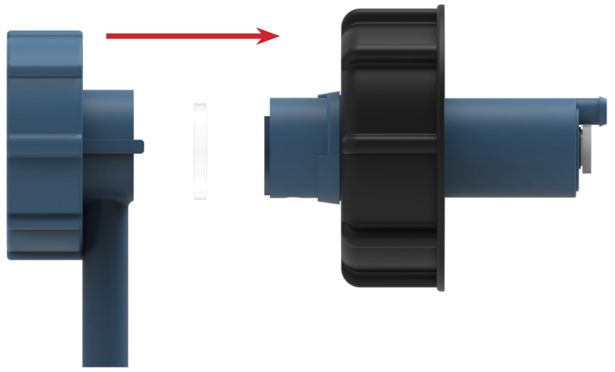
1 *The reactor shell is connected to the jerrycan cap with a snap fit. Fixing it in place while also providing a watertight connection.*



2 *Next the inner reactor and flow regulator are fixed to the reactor shell with glue. These connections preferably provide a water tight seal, but this is not necessary. Then the pre-filter is push fitted in the flow regulator.*

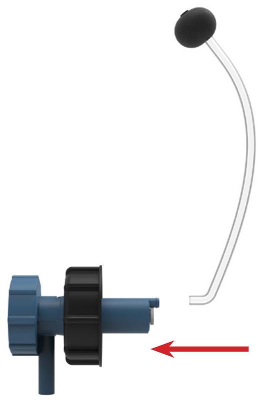


3 *The tap-module is assembled by placing the PCB (which is pre-assembled) on two push pins that hold it in place. This is then covered by the lid which is glued in place.*



4 *The UV-Tap is finished by sealing the reactor off with the quartz, which is glued in place and provides a watertight seal. Then the assembled tap-module is snap fitted into place.*

5 *The aeration system is assembled by glueing the tube, the one-way valve and floater atogether.*



6 *The final step in the assembly is fitting the aeration system to the reactor. It is fixed into place with a push-on fitting and a zip-tie for extra security.*

Product Lifetime & Repair

A crucial part in this design is the lifetime. On the one hand you want to keep the costs of the device as low as possible, but this cannot reduce the product's lifetime too much since frequent replacement makes it more expensive for the user in the long run.

The lifetime of a product depends on the first crucial component to break. In the case of the UV-Tap, this crucial part is likely to be one of the electronic components, since the casing is made from durable plastics that can withstand some impact. Therefore, I have analysed the crucial electronic components and determined their lifespan in litres of water treated, these calculations can be found in Appendix I. In figure 119 the results from these calculations can be found.

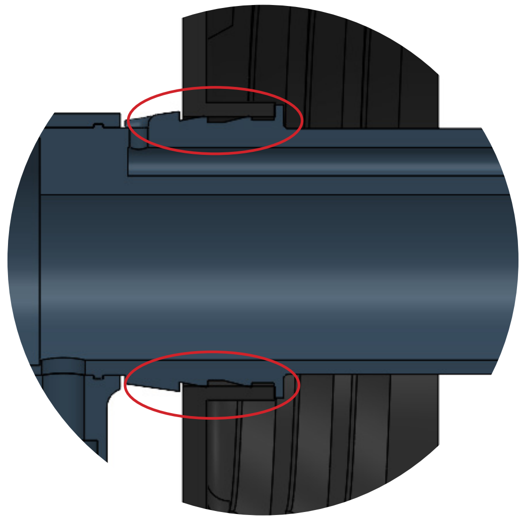
It is clear that the UV-C LEDs (nor the RGB LEDs) are the bottleneck in the lifespan of the device. The currently chosen microswitch will last for a minimum of 50.000 cycles which in reality will result 15.000 L disinfected. Thereby it is probably the first component to break.

Component	Lifetime in L	Lft in years (12 L pdph*)	Lft in years (80 L pdph*)
Battery	25.000	6	1
UV-C LED	900.000	200	30
Microswitch	15.000	3.5	0.5

Figure 119: overview of lifespan of critical components for scenarios in which 12 L and 80 L of water per day is consumed by a single household.
**per day per households*
Lft = Lifetime

If the device is used as intended (requirement: provide 12 L of safe water per household per day) it will probably last for 3.5 years. However, if people were to not only disinfect the drinking water, but also the water used for other purposes, the actual daily consumption would result much higher. In the case people would consume around 20 L per day, as is deemed the minimum necessary by the WHO, this would amount to 80 L per day per household. For those volumes, the UV-Tap is capable of only providing safe water for half a year.

To ensure the maximum lifespan of the device can be achieved, an important requirement is that the device should not be easily disassembled or opened by the user. Since most people in Addis-Ababa lack the knowledge and skills to repair such a device there is no need for people to be able to open the UV-Tap. If it is easy to open or disassemble people would maybe take out parts, or damage the interior electronics making the product useless.



The reactor is fitted to the cap with a snap fit, meaning that once it is assembled it cannot be disassembled (figure 120). The LED module is fixed on the reactor by a protruding ring, which after assembly makes it impossible to dismantle the product manually. This prevents the user from contaminating the inside of the reactor or damage the quartz glass. Furthermore, this is also required for safety measures. UV-C can be dangerous to eyes and skin and therefore the UV-C LEDs should not be removable from the casing. With the product assembled the UV-C light cannot leave the reactor keeping the user perfectly safe.

Only with specific tools disassembly of the tap-module and reactor is possible. In case reparations are needed it can still be disassembled by people with the right skills and knowledge, like employees of maker spaces. These maker spaces would have to be integrated in the supply chain of Quooker to make sure they get spare parts and the knowledge to perform those repairs. Because the components most likely to break are not assembled with any fasteners it becomes quite easy, with the right knowledge and tools to replace parts. For example, with a tool the tap-module can be pulled off the reactor, and a new one can be snapped into place. This repair would require only a few minutes.

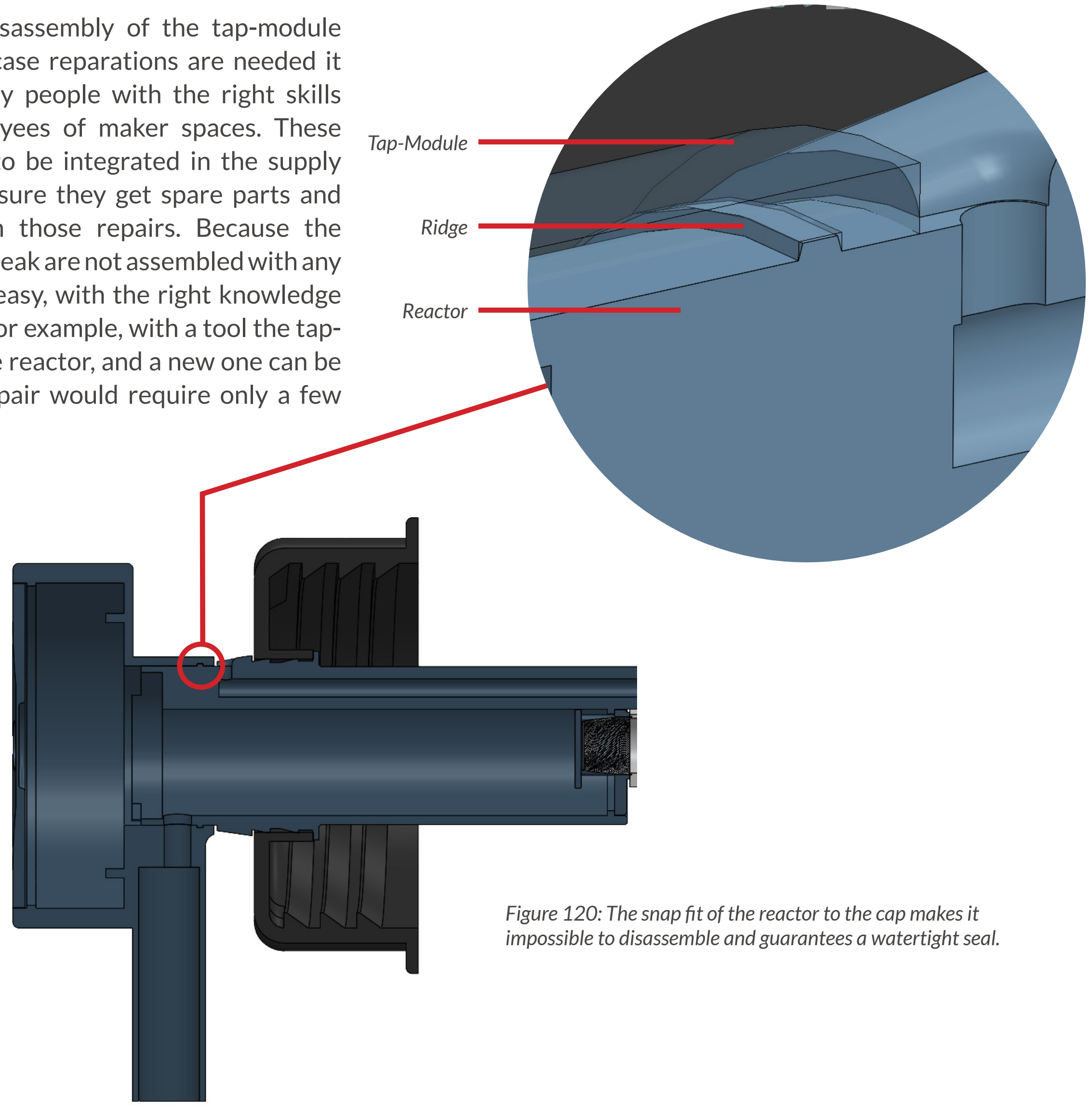


Figure 120: The snap fit of the reactor to the cap makes it impossible to disassemble and guarantees a watertight seal.

Costs

One of the requirements was that the product should not cost the user more than $10.00. From the start it was clear that no matter what the outcome of the project would be, this requirement would be very hard to achieve.

During the design process I have tried to cut down costs and keep things as simple as possible to be able to reach that requirement. This resulted in a price for the product of approximately $15.00 / unit. Figure 121 discusses the different components of this price. The costs for the components themselves have been tried to estimate as accurately as possible by informing with suppliers and estimation of manufacturing costs for the custom parts. The assembly and transportation costs have been estimated based on findings by the company Jerry. For their product, assembly and transport amount to approximately $10.00. The estimation is that, the UV-Tap being smaller and having fewer components, will have lower assembly and transport costs, around $5-$10.

In appendix K the complete bill of materials can be found. This is a preliminary calculation to give an estimate of the costs. In these calculations, the material and procurement part costs are considered. The assembly and transport costs are not.

For Quooker this project was never about making a profit. The goal was to help people improve their living situation and make a step towards the sustainable development goals set by the WHO. Therefore, these calculations do not account for profit margins.

	Component	Costs
Manufacturing	Components Casing	$ 1.55
	Electronic Components	$ 6.07
	Standard Components	$ 1.09
Assembly		$7.50
Transport		
	Total	$ 16.21

Figure 121: Estimation of the price of the UV-Tap

Recommendations for Design Improvements

The UV-Tap as it is now is still far from perfect, throughout the design process there are still many features and improvements I wanted to add but did not have the time for. I will now shortly discuss each of these to help future designers that pick up the project from here improve the UV-Tap.

Aeration

One very important aspect that is vital for the functionality and usability of the design, it aeration. At this moment the designed set-up works, but it feels more like an appendix to the UV-Tap than actually part of the device.
Trying to improve this part many different solutions, have been tried (see Appendix I). In the end the current set-up worked the best and was the simplest.
However, it can easily become dirty and contaminate the water. Finding a way to make the aeration system more compact or less likely to cause recontamination should be one of the main goals in future improvements.

Pre-Filter

For the pre-filter I have now used a standard component from Quooker. This however is a coarse filter, for a UV-C system to function optimally as few particles as possible should be in the water. Therefore, the filter should be as fine as possible while maintaining a 1.5 L/min flow rate, without increasing the water pressure.
The goal is to find the right balance between these two variables.

You could also take it one step further. The pre-filter can also be designated to turn turbid water into clear water that can be disinfected with UV-C. This requires a few changes to the design and probably also a mechanism to push the water through the filter, but it makes it possible to provide clean water to a much larger group of people who need it.

Battery

For the UV-Tap I have focused on finding a rechargeable battery for a low price. During this research I have not taken into account the battery quality and how quickly it might deteriorate over time. Furthermore, I have now chosen for a small-lightweight battery that needs to be recharged quite often. Depending on the context and the availability of electricity through the power network, which differs per region, different types of batteries or no batteries at all could be used.

Acceptability and Trust

The design of the UV-Tap is sort of a black box, contaminated water gets in, and safe water comes out. For the user it is not visible how this works. To increase the acceptability and understanding of the device a secondary RGB LED can be added to illuminate the spout and the water coming out. A blue light illuminating the water can give the user the idea that that is the disinfection taking place increasing the trust in the product.

Disinfection in-between cycles

The UV-C LEDs are only activated when the water flows. The water that is present in the reactor before activation of the LEDs does not get enough exposure time and might therefore not be safe to drink. Especially if the UV-Tap has not been used for some time (during the night for example). This can be solved in different ways, for example by activating the LEDs every couple hours for a short time or activating the LEDs prior to the water starting to flow.

Jerrycan Cap Size

The standard jerrycan cap size is a DIN 61, that is also the cap used in this design. Obviously, this is not the only size and there are many different sizes of caps. The design of the UV-Tap however lends itself perfectly to fit with other dimensions of caps, bigger or smaller. Due to the small diameter of the reactor shell it is possible to fit the UV-Tap with smaller caps as well.

Lifetime

During the lifecycle analysis I came to the conclusion that the microswitch would probably be the first component to fail. This is a fairly cheap component and it is a waste of money and effort to have to repair or throw the whole product away because of it. Therefore, it might be worthwhile to look for a slightly more durable microswitch that outlast the battery life. Possibly this makes the price increase a few cents whiles the UV-Tap's lifetime goes up from 15.000 L to 25.000 L.

Watertight Seals

During the prototyping process I have not had the possibility to really work on the friction difference between the jerrycan cap, reactor and tap-module. The dimensions of the parts for this are so critical that it was not easy to prototype accordingly. Ideally, in future improvement the right balance between friction of tap-module/reactor and reactor/cap will be explored to achieve the best user experience.

Handle Design

Although the handle works fine, the round shape of the handle gives the user the idea that the water flow can be dosed according to preference. In reality, this is not possible, to avoid confusion and make a more intuitive product the shape of the handle should be altered towards something implying two positions, ON or OFF.

UV-resistance

For the plastic components of the UV-Tap I have looked at the resistance of the materials against UV radiation. However, as some parts are glued together it is crucial, to prevent any leaks, to make sure the glue does not deteriorate over time due to UV exposure.

Usability & Contamination

To improve the usability of the UV-Tap, and reduce the chance of contamination a few extra alterations to the design can be made.

One of the most common moments contamination of the water in the jerrycan can happen is when the UV-Tap is removed to refill or replace with a different jerrycan. During these moments the user not only touches the reactor but also has to place the device somewhere, be it on top of the jerrycan, a table, or the ground. These are all surface where the UV-Tap can be contaminated and contaminate the water once it is placed onto a jerrycan. Finding a solution to reduce these risks is recommendable. At the same time this solution could also provide to be an easy way to store the UV-Tap when it is not in use.
Secondarily, to improve the usability and reduce contamination further, the spout can be designed in such a way that a short hose can be attached making it easier for users to fill any container.

5.5 THE UV-TAP IN ADDIS-ABABA / CONCLUSION

Safe drinking water is a basic need for human beings, but it is unfortunately not available in all parts of the world. The lack of access to safe water resources impacts the daily life of almost a billion people worldwide. The scarcity of clean drinking water is also felt in Addis-Ababa, the capital of Ethiopia. Here, especially children and vulnerable people struggle with sanitation and hygiene. With this project, Quooker has tried to take a first step in helping these people in achieving access to safe water.

During this project, the focus was on creating a solution for people living in the peri-urban areas of Addis-Ababa. Developing a concept in these areas provided insights to be used in similar contexts To collect drinking water, peri-urban households in Addis-Ababa use tap points close to their homes. The process of collecting drinking water can be labelled as the 'Water Journey'. The analysis of this journey revealed that 85% of the time the water coming from the tap can be considered safe for consumption. However, by the time people consume it, only 24% of the water is still safe to drink. Due to interruptions in water supply, people must transport and store the water in jerrycans at home. In these containers, water is easily contaminated. This shows that a water treatment solution in the early phases of the water journey is not effective. As most of the contamination takes place at households, this is where an intervention should take place.

The first step to work towards a solution, it to analyse different water treatment methods. Eventually, UV-C was chosen as the designated method. Due to the limited knowledge of the applicability of UV-C in the context of Addis-Ababa, this project provided a first step in the validation of UV-C as a water treatment method in sub-Saharan Africa.

After the research phase, ideas were generated in the so-called ideation phase. This resulted in the UV-tap, a UV-C disinfection device that can be mounted on a jerrican instead of a regular cap. The goal was to develop an affordable and durable product that offers users the possibility to always have access to safe drinking water. To make sure that the UV-Tap would fit in with the habits and needs of the users, it was designed to fit in the Water-Journey. To do so, the concept has to be integrated with a jerrycan and should be able to easily switch between jerrycans. Furthermore, it is designed in such a way that in the future it can easily be adapted to fit different sizes of jerrycans.

Jerrycans can be quite heavy and hard to handle when full of water, especially for children. Therefore, it was also important that the UV-Tap would improve this interaction. As the UV-tap is simple and requires low effort to operate, it can be easily used by children. This is especially important considering that they are one of the largest groups in Ethiopia (over 40% of the population) and at the same time also the group that suffers most from water-related diseases.

In Addis-Ababa, the required knowledge for repairs and maintenance of the UV-Tap is rare, if not non-existent. Therefore, it is essential that the product lasts for a long time and does not require frequent maintenance. The current design of the UV-Tap can disinfect at least 15.000 L of water, which is enough to provide a household with water for 3.5 years. This is approximately three times as long as any filter-based product lasts. A preliminary lifetime analysis of the UV-Tap revealed that by improving the microswitch (the switch that turns the device on and off) the lifetime will improve to at least 25.000 L.

Ideally, the goal would be to have as many people as possible make use of the UV-Tap. In the context of Addis-Ababa and sub-Saharan Africa, the costs of the device is a critical factor to take into consideration. Peri-urban households in Addis-Ababa have limited financial means and are only capable and willing to spend around $10.00 on a water treatment product. This forms an obstacle for most water treatment devices, and the UV-Tap is no exception; the estimated costs of the device are somewhere between $15-$20. This financial discrepancy is one of the major challenges for implementing the UV-Tap. It is up to Quooker to develop a business plan together with Made Blue, and make the UV-Tap affordable for people in Addis-Ababa.

Recommendations

Up to this point in the report the design of the UV-Tap has been extensively discussed. In all the steps and iteration made, to get to the end result I have taken many factors into considerations to make sure it would fit with the context, stakeholders and (potential) future users. However, the design of the UV-Tap is just the first step in the implementation of this device.

There are still areas that require research and exploration for a successful implementation of the UV-Tap and to get it to the people that need it. This section discusses the steps Quooker needs to take to bring the project to the next level.

Validation in Context

Up until now, due to circumstances, the validation of the UV-Tap has mostly been theoretical. However, this is one of the most crucial steps in the design process. Especially considering that UV-C is a novel technology in most of Ethiopia. One of the first steps after the completion of this project should be to start testing the UV-Tap in Addis-Ababa. To learn how the target group experiences the product, what they think of it, how it should be improved, etc..

To make sure the product is adopted and accepted within the peri-urban communities it is important to know the perception on UV-C, the UV-Tap in general and the implementation within the Water-Journey. Because the design process happened thousands of miles from the place of intended use, and my knowledge of the sub-Saharan context is very limited there are definitely going to be improvements on the design that need to be made. Ideally the validation is done in cooperation with Made Blue, they have experience and local contacts that can help set this up properly.

Validation of Disinfection

Another crucial aspect that requires validation is the disinfection. During this project a test to validate the efficacy of the UV-Tap was executed, unfortunately this proved to be inconclusive. Validation of the UV-Tap should be done at a specialised facility such as the KWR, as in house test proved to not be accurate enough.

To make the UV-Tap applicable to a wider scope the disinfection capabilities can be improved. Stronger LEDs or a better designed reactor make it possible to kill a broader range of pathogens making it a wider application possible. In the future this might allow launching the product in places where there are other pathogens present in the water.

Market Placement

Simultaneously with the validation, Quooker should also start to consider how to get the UV-Tap to the places it needs to be. The market placement of the UV-Tap should focus on two things:
- How to make it affordable to the target group?
- How to distribute the product?

Making the UV-Tap affordable to the peri-urban households can be done in multiple ways. Ranging from subsidies, a lease plan to donations. These types of business plans are not my expertise or Quooker's but Made Blue has a lot of experience with these types of projects and should be closely involved in this phase of the project.
Currently, Made Blue works with local entrepreneurs that manage their water projects, and in their experience this works effectively.

Distribution of the UV-Tap, and getting inside the homes of people in Addis-Ababa is a whole new challenge. Research from Jerry (the company) has found that door to door sales and word of mouth prove to be the most effective ways to sell water treatment products. Again, Quooker should closely cooperate with Made Blue and use their local contacts to set a proper distribution system in place.

Implementation in sub-Saharan Africa

From the start, to make this project more manageable, this project scoped down from sub-Saharan Africa towards peri-urban households in Addis-Ababa. Now the question is, what does it take to make the UV-Tap usable in a broader scope? How does implementation in a rural context or other country affect the design?
These are very important questions as they can make the target group much bigger, not only reducing manufacturing cost but also making a bigger impact in the world.

To implement the UV-Tap in other cities, in Ethiopia or abroad, would probably require few adjustments as most people in sub-Saharan Africa rely on the same type of jerrycans.
However, as the UV-Tap is designed to deal with the specific pathogens present in the water in Addis-Ababa, the water in these other cities would require pathogenic tests as well. This to make sure that the delivered UV-dose is also sufficient to kill pathogens that are present in that water. Furthermore, the water will also require a certain clarity to ensure the UV-C light is transmitted sufficiently throughout the water.

For implementation in rural areas the UV-Tap will require one major adjustment. Because the water sources in rural areas often contain heavily turbid water UV-C cannot be effectively used as a disinfectant. To make it work, a filter that removes all the turbidity is required. Future research might determine whether such a setup-up would be preferable over a system that filters both turbidity and bacteria with a single filter.

Manufacturing and Procurement

The design of the UV-Tap is yet to be optimised for manufacturing. Redesigning the custom components of the casing with a focus on making manufacturing will probably make the product cheaper, by simplifying the process itself or even reduce components. This is an area of expertise that Quooker could look into themselves as they have extensive experience and knowledge on manufacturing.

For the standard components, and mostly the electronics I have now been limited by existing suppliers of Quooker. For components such as the battery and especially the UV-C LEDs there might be other supplier with better products. Possibly making the product better but also cheaper, as the LEDs account for 20% of the total costs.

Other target Groups

The design of the UV-Tap does not only lend itself for use in Addis-Ababa or sub-Saharan Africa. Other groups of people, even in developed countries, that require safe drinking water. Example of the groups could be:

- Outdoor or Camping Enthusiasts
- Preppers (people prepared for emergency situations)
- People that are not connected to the main water supply

These are groups of people that might see value in this product as they might need to store water for longer periods of time. For them, affordability is not really an issue since they can easily afford to spend $15-$20 or more on such a product.

In the section on market placement, the affordability of the device has shortly been discussed. For the above-mentioned groups the affordability is not an issue and their purchase can be used as a way to sponsor a UV-Tap for a household in Addis-Ababa. For example, by asking $70.00 for the UV-Tap the profit margin can be used to donate one in Addis-Ababa. This can even work as an incentive for a consumer to buy the UV-Tap as they are supporting a charitable project.

PART SIX

REFERENCES

REFERENCES

• Adane, M., Mengistie, B., Medhin, G., Kloos, H., & Mulat, W. (2017). Piped water supply interruptions and acute diarrhea among under-five children in Addis Ababa slums, Ethiopia: A matched case-control study. PLOS ONE, 12(7), e0181516. https://doi.org/10.1371/journal.pone.0181516
• Addis Ababa, Ethiopia Population (2022) - Population Stat. (2022, February). PopulationStat. Retrieved 3 February 2022, from https://populationstat.com/ethiopia/addis-ababa
• Atnafu, B., Desta, A., & Assefa, F. (2021). Microbial Community Structure and Diversity in Drinking Water Supply, Distribution Systems as well as Household Point of Use Sites in Addis Ababa City, Ethiopia. Microbial Ecology. https://doi.org/10.1007/s00248-021-01819-3
• Bilton, P., & Kahn, K. (2018, June 5–6). Designing with UVC LEDs [Presentation]. Kaplan University
• Bipin Dangol (ENPHO) & Dorothee Spuhler (GMBH). (n.d.). Household Water Treatment and Safe Storage (HWTS). SSWM - Find Tools for Sustainable Sanitation and Water Management! Retrieved October 15, 2021, from https://sswm.info/sswm-solutions-bop-markets/affordable-wash-services-and-products/affordable-water-supply/household-water-treatment-and-safe-storage-%28hwts%29
• Brandt, M. J., Johnson, K. M., Elphinston, A. J., & Ratnayaka, D. D. (2017). Disinfection of Water. Twort's Water Supply, 475–511. https://doi.org/10.1016/b978-0-08-100025-0.00011-9
• Bureau of Finance and Economic Development. (2013, May). Socio-Economic Profile of Addis Ababa. ity Government of Addis Ababa Bureau of Finance and Economic Development. https://www.aabof.gov.et/Documents/Addis%20Ababa%20Profile%20%202004%20E.pdf
• Campbell, B. (2021, June 16). Activated Carbon Water Filters. WaterFilterGuru.Com. Retrieved October 22, 2021, from https://waterfilterguru.com/activated-carbon-water-filters/
• CDC. (2012, October 10). Solar Disinfection | The Safe Water System | CDC. Center for Disease Control and Prevention. Retrieved October 20, 2021, from https://www.cdc.gov/safewater/solardisinfection.html
• CDC. (2020, August 4). Technical Information on Home Water Treatment Technologies | CDC. Center for Disease Control and Prevention. Retrieved October 21, 2021, from https://www.cdc.gov/healthywater/drinking/home-water-treatment/household_water_treatment.html
• Clasen, T., Schmidt, W. P., Rabie, T., Roberts, I., & Cairncross, S. (2007). Interventions to improve water quality for preventing diarrhoea: systematic review and meta-analysis. BMJ, 334(7597), 782. https://doi.org/10.1136/bmj.39118.489931.be
• Crystal IS. (2016, August). UVC LEDs for Disinfection. https://cisuvc.com
• CSA. (2017, December). Drinking Water Quality in Ethiopia. Central Statistical Agency of Ethiopia. https://washdata.org/sites/default/files/documents/reports/2018-07/Drinking-water-quality-ethiopia-ESS-2016.pdf
• The Difference Between Granular Activated Carbon and Activated Carbon Block Water Filters. (2018, April 11). Coconut-Shell Carbon Water Filters - Rajah Filter Technics. Retrieved October 22, 2021, from https://rajahfiltertechnics.com/water-filtration/granular-activated-carbon-vs-activated-carbon-block-water-filters/
• Dollar Street - Gachino. (2019). GapMinder. Retrieved 22 November 2021, from https://www.gapminder.org/dollar-street?countries=et&active=5ec4f9d1f0611d7ddd741a9e&topic=toilet-paper
• Doocy, S., & Burnham, G. (2006). Point-of-use water treatment and diarrhoea reduction in the emergency context: an effectiveness trial in Liberia. Tropical Medicine and International Health, 11(10), 1542–1552. https://doi.org/10.1111/j.1365-3156.2006.01704.x
• dos Santos, S., Adams, E., Neville, G., Wada, Y., de Sherbinin, A., Mullin Bernhardt, E., & Adamo, S. (2017). Urban growth and water access in sub-Saharan Africa: Progress, challenges, and emerging research directions. Science of The Total Environment, 607–608, 497–508. https://doi.org/10.1016/j.scitotenv.2017.06.157
• Economic and Social Commission for Western Asia (ESCWA). (2016, January 17). peri-urban areas. United Nations Economic and Social Commission for Western Asia. Retrieved November 10, 2021, from https://archive.unescwa.org/peri-urban-areas
• Effectiveness on Pathogens | The Safe Water System | CDC. (2021, March 21). CDC. Retrieved October 26, 2020, from https://www.cdc.gov/safewater/effectiveness-on-pathogens.html
• Electrochemistry Encyclopedia -- Brine electrolysis. (2015, August). The Electrochemical Society. Retrieved October 25, 2020, from https://knowledge.electrochem.org/encycl/art-b01-brine.htm
• Ethiopia - The World Factbook. (2021, October 19). The World Factbook. Retrieved October 29, 2021, from https://www.cia.gov/the-world-factbook/countries/ethiopia/#introduction
• Ethiopia Federal Ministry of Health. (2016, January). GUIDELINES FOR THE PREVENTION AND CONTROL OF MICRONUTRIENT DEFICIENCIES. https://e-library.moh.gov.et/library/wp-content/uploads/2021/06/Micronutrient-Guideling.pdf
• Gärtner, N., Germann, L., Wanyama, K., Ouma, H., & Meierhofer, R. (2021). Keeping water from kiosks clean: Strategies for reducing recontamination during transport and storage in Eastern Uganda. Water Research X, 10, 100079. https://doi.org/10.1016/j.wroa.2020.100079
• Gebre-Egziabher, T. (2019, July). The effects of rapid urbanization and rural to urban migration on affordable housing and homelessness in Ethiopia. Addis Ababa University. https://www.un.org/development/desa/dspd/wp-content/uploads/sites/22/2019/07/GEBRE-EGZIABHER_Tegegne_Presentation_2.pdf
• Grönwall, J., & Danert, K. (2020). Regarding Groundwater and Drinking Water Access through A Human Rights Lens: Self-Supply as A Norm. Water, 12(2), 419. https://doi.org/10.3390/w12020419
• Ing, R. (2021, September 28). Hollow Fiber Ultrafiltration Membranes. Water Quality Products. Retrieved October 22, 2021, from https://www.wqpmag.com/hollow-fiber-ultrafiltration-membranes
• Issa, E. H. (2021). Life in a slum neighborhood of Addis Ababa, Ethiopia: morphological facts and their dysfunctions. Heliyon, 7(5), e07139. https://doi.org/10.1016/j.heliyon.2021.e07139
• Jenkins, M. W., & Tiwari, S. (2010, January). Health and Non-Health Impacts of the BioSand Filter for Rural Kenya. Global livestock collaborative research support proGram.
• Kaplan University & Crystal IS. (2016, June). Using UV Reflective Materials to Maximize Disinfection. https://klaran.com/images/kb/application-notes/Using-UV-Reflective-Materials-to-Maximize-Disinfection---Application-Note---AN011.pdf
• Kasa, L., Alemu, D., Zeleke, G., & Hagos, F. G. (2011, February). IMPACT OF URBANIZATION OF ADDIS ABEBA CITY ON PERI-URBAN ENVIRONMENT AND LIVELIHOODS. http://www.efdinitiative.org/sites/default/files/leulsegged_kasa_paper_presented_for_10th_international_conference_on_ethiopian_economy.pdf
• Keffa, S. (2014). Integrated Housing Development Program (IHDP) As Instrument to Alleviate Urban Poverty. Intersocial Consulting. http://fig.net/resources/proceedings/fig_proceedings/fig2014/papers/ts07k/TS07K_keffa_7359.pdf
• Kidane Mekonnen, D. (2015). The Effect Of Distribution Systems On Household Drinking Water Quality In Addis Ababa, Ethiopia, and Christchurch, New Zealand. University of Canterbury. https://ir.canterbury.ac.nz/bitstream/handle/10092/10692/thesis_fulltextpdf.pdf?sequence=1
• Layton, R. (2022, May 7). Iodine crystals for water purification. Ron's Primitive Skills. Retrieved 16 December 2021, from https://ronsprimitiveskills.blogspot.com/2011/08/iodine-crystals-for-water-purification.html
• Mazloum, S. K. (2004, March). Hollow Fiber vs. Flat Sheet Technology. WETICO. http://sawea.org/pdf/2004/March-21-2004/HollowFiberVsFlatSheetTechnology.pdf
• Melesse, H. (2020). Factors Determining the Continuous Price Appreciation of Condominium Units in Addis Ababa. World Journal of Civil Engineering and Construction Technology, 4(1), 64–78. https://www.premierpublishers.org/wjcect/230320203685.pdf?view-type=inline
• Mukherjee, N. (2018, January 3). Why Powdered Activated Carbon (PAC) solid block pre-filter is a preferred choice over Granulated Activated Carbon (GAC) pre-filter in Drinking Water. LinkedIn. Retrieved October 22, 2021, from https://www.linkedin.com/pulse/20140614112057-105135096-why-powdered-activated-carbon-pac-solid-block-pre-filter-is-a-preferred-choice-over-granulated-activated-carbon-gac-pre-filter-in-drinking-water/
• NDSU. (1991). Treatment Systems for Household Water Supplies: Reverse Osmosis. Water Review: Residential Reverse Osmosis, Water Quality Research Council, 9(2). https://library.ndsu.edu/ir/bitstream/handle/10365/9378/AE1047_1992.pdf?sequence=1
• Norwicki, H. (2016, February 1). The basics of activated carbon adsorption. Water Technology. Retrieved October 22, 2021, from https://www.watertechonline.com/wastewater/article/15549902/the-basics-of-activated-carbon-adsorption
• OpenWASH. (2016). Urban Water Supply. The Open University UK/World Vision Ethiopia/UNICEF. https://www.open.edu/openlearncreate/mod/oucontent/view.php?id=79985
• Outbackwater. (2021). Hollow Fiber Membrane Technology at Work. Retrieved October 25, 2021, from https://www.outbackwater.com/hollow-fiber-membrane-technology-at-work/
• Pooi, C. K., & Ng, H. Y. (2018). Review of low-cost point-of-use water treatment systems for developing communities. Npj Clean Water, 1(1). https://doi.org/10.1038/s41545-018-0011-0
• Preventing Recontamination. (2019, May 14). SSWM - Find Tools for Sustainable Sanitation and Water Management! Retrieved 27 January 2022, from https://sswm.info/sswm-solutions-bop-markets/improving-water-and-sanitation-services-provided-public-institutions-1/preventing-recontamination
• QSIL. (2021). About Fused Quartz - QSIL. Retrieved 22 January 2022, from https://www.qsil.com/en/material/about-fused-quartz/

• Rouf, A. (2015, December 29). Why are filters back-washed? What is backwash frequency? Bayt.Com. Retrieved November 17, 2021, from https://specialties.bayt.com/en/specialties/q/247560/why-are-filters-back-washed-what-is-backwash-frequency/
• Soni, R., Bhardwaj, S., & Shukla, D. P. (2020). Various water-treatment technologies for inorganic contaminants: current status and future aspects. • Inorganic Pollutants in Water, 273–295. https://doi.org/10.1016/b978-0-12-818965-8.00014-7
• Statista. (2021, September 20). GDP of African countries 2021, by country. Retrieved January 3, 2022, from https://www.statista.com/statistics/1120999/gdp-of-african-countries-by-country/
• Templeton, M. R., Antonakaki, M., & Rogers, M. (2009). UV Dose–Response ofAcinetobacter baumanniiin Water. Environmental Engineering Science, 26(3), 697–701. https://doi.org/10.1089/ees.2008.0048
• UNDP. (2006). Human Development Report 2006: Beyond scarcity - Power, poverty and the global water crisis. http://hdr.undp.org/en/content/human-development-report-2006
• UNICEF & WHO. (2019). Progress on household drinking water, sanitation and hygiene | 2000–2017. https://apps.who.int/iris/bitstream/handle/10665/329370/9789241516235-eng.pdf
• United Nations. (n.d.). Goal 6 | Department of Economic and Social Affairs. Sustainable Development Goals. Retrieved September 30, 2021, from https://sdgs.un.org/goals/goal6
• United Nations. (2015, September 27). THE 17 GOALS | Sustainable Development. SDGs. Retrieved October 13, 2021, from https://sdgs.un.org/goals
• United States - Bureau of Radiological Health, Division of Biological Effects. (2022). A review of biological effects and potential risks associated with ultraviolet radiation as used in dentistry / Division of Biological Effects Loren F. Mills . . . [et al.]. 1975 [Leather Bound] (2nd ed.). Generic.
• UVC LEDs vs. Lamps - Klaran. (2022, February 14). Klaran. Retrieved 27 March 2022, from https://klaran.com/intensity-comparison-uvc-leds-vs-lamps
• Vermeulen, N., Keeler, W. J., Nandakumar, K., & Leung, K. T. (2007). The bactericidal effect of ultraviolet and visible light onEscherichia coli. Biotechnology and Bioengineering, 99(3), 550–556. https://doi.org/10.1002/bit.21611
• Water Aid, & Crampton, J. (2005, April). Maintaining clean water: contamination during water collection and storage in Addis Ababa. Water Aid. https://washmatters.wateraid.org/publications/maintaining-clean-water-contamination-during-water-collection-and-storage-in-addis
• Weir, S., & Knight, J. (2004). Externality Effects of Education: Dynamics of the Adoption and Diffusion of an Innovation in Rural Ethiopia. Economic Development and Cultural Change, 53(1), 93–113. https://doi.org/10.1086/423254
• Welch, D., Buonanno, M., Shuryak, I., Randers-Pehrson, G., Spotnitz, H. M., & Brenner, D. J. (2018). Effect of far ultraviolet light emitted from an optical diffuser on methicillin-resistant Staphylococcus aureus in vitro. PLOS ONE, 13(8), e0202275. https://doi.org/10.1371/journal.pone.0202275
• Weldeghebrae, E. H. (2021, June). ADDIS ABABA: CITY SCOPING STUDY. The University of Manchester. https://www.african-cities.org/wp-content/uploads/2021/12/ACRC_Addis-Ababa_City-Scoping-Study.pdf
• WELL. (1999). Household water treatment 2. WELL Technical Briefs, 24(4), 105–108. https://wedc-knowledge.lboro.ac.uk/details.html?id=12388
• Whitby, B. (2020, April 9). How silver ions kill bacteria. ScienceDaily. Retrieved November 11, 2021, from https://www.sciencedaily.com/releases/2020/04/200409140021.htm
• WHO. (2005, January). Turbididty Measurement. World Health Organization. https://www.who.int/water_sanitation_health/hygiene/emergencies/fs2_33.pdf
• WHO. (2007). Combating waterborne diseases at the household elvel. World Health Organization. https://www.who.int/household_water/advocacy/combating_disease.pdf
• WHO. (2018, October). Developing drinking-water quality regulations and standards. https://www.who.int/publications/i/item/9789241513944
• WHO. (2019, June 15). Drinking-water. Worl Health Organization. Retrieved October 13, 2021, from https://www.who.int/news-room/fact-sheets/detail/drinking-water
• WHO. (2021, December). A global overview of national regulations and standards for drinking-water quality. https://www.who.int/publications/i/item/9789240023642
• WHO & UNICEF. (2012, October). Rapid Assesment of Drinking Water QUality. World Health Organization. https://apps.who.int/iris/rest/bitstreams/1272345/retrieve
• WHO & UNICEF. (2015). Progress on Sanitation and Drinking Water: 2015 Update and MDG Assessment. https://apps.who.int/iris/rest/bitstreams/799097/retrieve

• WHO, UNICEF, & JMP. (2021). Progress on household drinking water. sanitation and hygiene. JMP. https://washdata.org/sites/default/files/2021-07/jmp-2021-wash-households.pdf
• Wikipedia contributors. (2021, October 10). Reverse osmosis. Wikipedia. Retrieved October 20, 2021, from https://en.wikipedia.org/wiki/Reverse_osmosis
• WHO, Wester Pacific Region. (2014). Household Water Treatment and Safe Storage: Manual for the Participant. World Health Organization.
• Wikipedia contributors. (2021, October 10). Reverse osmosis. Wikipedia. Retrieved 20 October 2021, from https://en.wikipedia.org/wiki/Reverse_osmosis
• Worldometer. (2020). African Countries by Population (2021) - Worldometer. Worldometer.Com. Retrieved October 29, 2021, from https://www.worldometers.info/population/countries-in-africa-by-population/