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'Bici-Bomba' Pedal Powered Well Purification System

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Date: June 12, 2020

I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

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ENTITLED

'Bici-Bomba' Pedal Powered Well Purification System

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

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‘Bici-Bomba’ Pedal Powered Well Purification System

by

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SENIOR DESIGN FINAL THESIS

Submitted in partial fulfillment of the requirements for the degree of
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School of Engineering
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Abstract

This senior design project consists of designing and building a bike powered well pump that purifies water. The Guatemalan NGO Maya Pedal is the critical customer that requested this project, and will help facilitate implementing it in the San Andrés community. The project addresses these main needs: providing an easier, faster way to retrieve water and to clean water to safe drinking levels. In addition to these primary needs, a major goal is having the project be scalable within the San Andrés community. This means that all of the components are available in Guatemala at reasonable prices, it is durable and no parts need to be replaced regularly, and it is replicable for the local Guatemalans with the equipment currently available. The entire system is designed in Solidworks, with a focus on the flywheel, water tank stand, and bike base which are fully new components that will undergo loading. To help enable a successful project, the team took an initial visit to Guatemala in the Winter to take measurements and gather critical information about the community in order to be better prepared for our Spring Break visit which was unfortunately cancelled because of COVID-19 concerns. The rescoped project goal is to still help Maya Pedal build this machine remotely.

Acknowledgement

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Table of Contents

List of Figures

List of Tables

ix

1. Introduction

Our goal was to make a bike-powered filtration system that pumps water up from a well and filters it into a storage tank for later use. Currently, fairly clean water is available in wells which can be accessed by a hand-pulled rope system. This is an inefficient process and water is not a commodity where "fairly clean" is clean enough. By improving the speed of water access and water quality, we intended to improve the physical health of the people in the community along with their day-to-day quality of life. We planned on using a rope-based withdrawal system, because it can be completely locally sourced and is both durable and maintainable by the community. We believed that implementing a bike powered rope system to a well will present a robust, scalable, and efficient solution.

Our system was designed for a specific well in Montellano, Guatemala. The well is 31 meters (103 feet) deep. Our objective was to pump approximately 18.9 L/min (five gallons/min) from the well and filter the water at a rate of 1.89 Liters/min (0.5 gallons/min). These specifications are goals provided from Maya Pedal, the organization which we are partnering with for the project [1]. This NGO connected us with a community of about 16 people that are dependent on this well for their main source of water. This water will be used for drinking, cooking, cleaning, and bathing. We selected a design to include a dual tank/vat system to separate the dirty and clean water. The first vat is for the well water to be pumped into and from there the water can be slowly filtered through a biosand filter and into a second storage tank that becomes accessible once the holding tank is being refilled.

Each tank will be able to hold around 284 liters of water (75 gallons), meaning the static structure holding the two tanks needs to be able to withstand a downward force of over 3700 N assuming other dynamic forces such as wind, earthquakes or people bumping into the structure will have a minimal impact on the structure breaking. This structure was designed to be a simple table-like structure with trusses to provide additional support. The table was designed to be constructed entirely from locally sourced steel and wood.

A unique component of our project is the community education aspect. We planned to work with the town mayor to partner with local schools and teach them about the system. We also planned on conducting training on biosand filter construction and maintenance with Maya Pedal and the local community. This way any issues that may occur with our system can be handled by the community with confidence and they can ensure that the water is being properly filtered. We are focusing on the community's needs, and making sure our project is made from all local materials, works on a meager budget, and is simple enough to be scalable without needing engineers to build or repair it.

Tabel 1: Team Mission Statement

Mission Statement: Maya Pedal Well Water Filtration/Pump System	
Product Description	• Bike powered pump and filtration system to be used in rural Guatemala
Benefit Proposition	• Pumps water more quickly from the well than can be done by hand and removes dangerous contaminents
Key Business Goals	• Pumps water at 18.9 liters per minute (5 gallons/min) • Removes bacteria and particulate in the water to meet EPA standards using a redesigned biosand filter • Is scalable for other small villages in Guatemala • Implemented in Guatamalan community in Spring of 2020
Primary Market	• Town in Guatemala (speaking with Mayor of city of 40,000 who is selecting town of about 16 families)
Secondary Markets	• Other similarly sized towns under jurisdiction of Mayor • Comunities of similar sizes in other regions of Guatemala and Latin America
Assumptions	• Amount of water needed by town of 16 families • Users are able to bike
Stakeholders	• Users in the community • SCU Student Team • Advisors for the project/ School of Engineering • Frugal Innovation Hub • Maya Pedal

2. Background

Water in Guatemala:

A history of civil wars, government corruption, and drought has created instability which has led to underdeveloped water and sanitation programs in Guatemala. Specifically, rural access to basic water service is only at 44% with access to basic sanitation services being as low as 51% [2].

Figure 1: Image of Guatemala with San Andrés Marked with a red star.

The Department of Economics at Fairfield University explored this issue with a series of interviews with various Guatemalan officials. The problem has built up over the previous few years, ‘‘the last three governments (that account for the last 12 years) did not have a national policy on drinking water and sanitation.’’ An interview discovered ‘‘[the water sector] is chaos at all levels,’’ and another officer commented that ‘‘the functions of actors [in the water sector] is unclear’’ [3]. Clean water in Guatemala is an issue that officials realize is important, but are struggling to fix.

Part of the reason for the confusion is shared blame between municipal and federal authorities. This lack of clear authority over water has led to problems with responsibility. Based on Guatemalan laws, ‘‘there are no guidelines to elaborate municipal budgets and prioritize projects at the municipal level’’[3]. The municipal authorities blame the national ones in the same way, ‘‘managing water resources is quite complicated because we have a problem at the national level that there is no legislation on water issues’’[3]. Complicating the problem further is Guatemala’s financial instability, which creates a lack of consistent funding for water initiatives. This complaint is echoed by many officials including an officer who stated, ‘‘out of the people who use the [water] services, only 25% are on time [in their payments]’’[3]. At the end of the day, local ability to improve water is fairly slow and inefficient. This is due to multiple levels of issues, with two of the most common complaints being a lack of ‘‘economic support to purchase [legal] rights to more water sources’’ and ‘‘economic resources to build a retention tank’’[3]. There is no clear path to success based on government initiatives. The lack of clean water in Guatemala requires smaller scale, affordable, and innovative solutions.

The U.N. Sustainable Development Goal #6 emphasizes the importance of access to clean water and sanitation, which pairs with the goal of this project and is of paramount importance in Guatemala. More than half of the six million people who live in Guatemala live under the poverty line and have no access to sanitation [4]. Research from the Department of Hydrochemistry of the INSIVUMEH (the Guatemalan Science Foundation) found that most river water in Guatemala is contaminated by bacteria with higher rates for those closer to communities [5].

Lack of clean water can result in detrimental health conditions and waterborne illnesses like cholera or diarrhea. This has led to cheap “solutions” for drinking water which pose health risks. Water that is purified with chlorine often leaves a bad taste in the water. Additionally, the cost of clean and purified water is often higher than soda in rural areas. This has forced many Guatemalan individuals to consume beverages like Coca-Cola instead of water, which in turn has led to high rates of diabetes and obesity. According to the US National Library of Medicine, around 25% of the rural population in Guatemala will suffer from diabetes in the near future. Improving the cleanliness of the well water will improve health in the village by preventing waterborne illnesses and reducing rates of soda consumption and diabetes [4].

For our specific project the community has a well containing dirty water that needs to be treated before it can be used. To satisfy our customers needs we are aiming to provide about 250 gallons of clean water per day for the entire village. This water can be used for drinking, cooking, washing, and personal hygiene.

We are working with a community that lacks resources we take for granted in the U.S. such as a wide electrical grid, so our project will need to account for the fact that there may not be a consistent source of electricity around the well. This is one of the constraints that Maya Pedal tries to work around by using bike powered machines instead of having to connect to electrical grids. Our first full interview with Maya Pedal can be seen in the appendix.

Constraints:

The power for the pump is a major constraint that helps determine the design of the system. Due to an inconsistent grid for power, it is ideal to have the pump be powered from an off the grid power source. It would be ideal for the pump to have a flow rate of at least 18.9 L/min. This could be accomplished by powering a pump by pedaling a bike, allowing for flexibility of location.

The filtering of the water for bacterial and fecal matter is an additional important constraint. This limits the types of filters that are reasonable options. It is easy to do the basic purification to make water look clear, but making bacteria filled water potable requires additional levels of filtration. However, this comes at the cost of a slower filtration process and a shorter lifetime for the filters.

The ability of the system to be manufactured locally is an important constraint to consider. In order for the project to be scalable, all of the parts must be able to be purchased and made in Guatemala by locals who are not necessarily expert engineers. This requires a simple enough system that we would be able to make and explain to a community in a reasonable time period (up to 10 days). This means the design should not require any hard to get materials or specific parts unavailable in Guatemala.

The Maya Pedal organization is based around using power that can be generated from bicycles because of their general availability and effectiveness compared to other alternative, non-electric power sources. The power from bicycles is from pedaling, which is generally between 70 and 120 RPM and around 100 Watts for a beginner cyclist, this number is the first major constraint for our project.

For our set of constraints, we need a way to pump water from the bottom of a well to ground level without having to use electricity. Since our main goal detailed by Maya Pedal is to pump water from up to 45 meters underground, the most common pump for that purpose is a centrifugal pump.

Pumps:

Centrifugal Pump:

Centrifugal pumps are best at moving amounts of fluids using centrifugal force, which is a force from rotation such as pedaling a bike. Centrifugal pumps work by transferring rotational mechanical energy from pedaling to the fluid and pushing the fluid radially outward. The fluid enters the impeller vane because of the negative pressure vacuum created by fluid leaving the pump at high pressure and velocity. A general diagram of the main operating principle of the centrifugal pump is shown below in Figure 2. [6]

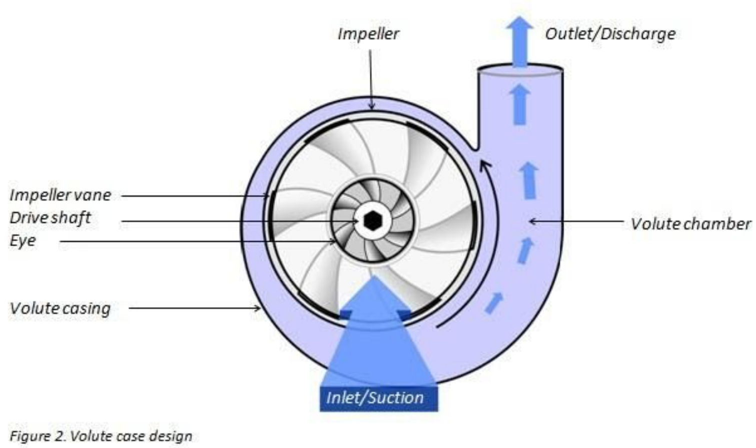

Figure 2: Centrifugal pump diagram [6]. Reproduced without permission

A centrifugal pump would work well for our project because of the simplicity of the pump. The less moving parts our system has the better because we want this project to be long lasting and need as little maintenance as possible. However, the centrifugal pump would need to be submerged inside the well to operate and that comes with a whole set of issues. With impellers moving at high speeds, the system is likely to have some cavitation bubbles along the impellers surfaces which can cause corrosion over time. [7]

Rope Pump:

A Rope pump system is common for use in Central and South American wells. There are 3 typical models of rope pump systems. First, is a wheel pump. A wheel pump typically utilizes car tires that are 14 to 20 inches. The handle for this system is dependent upon the diameter of the wheel and can be calculated with the following equation: ½ wheel diameter +1 inch. The most common material for the pipe is a ¾ inch galvanized pipe. They are also cheap and do not rust or wear out. Low pressure pipes can be used since the main pressure is low. Diameter of the tube depends on the elevation and is based on 50 Watts, which is the power a woman or children can exercise over a long period. The relationship between well depth and pipe/rope diameter can be seen in Table 2 below.

Table 2: Diameter of tube for low powered pumping at different depths. [8]

Elevation	Pipes (inside)	Inches	
0-4 meters	40 mm	1.5 inches	
4-11 meter	30 mm	1 inch	
11-20 meters	23 mm	0.75 inches	
20-35 meters	18 mm	0.5 inches	
35-60 meters	18 mm	0.5 inches	Double handle

The pistons for this system can be made of rubber as can be seen in Figure 3.

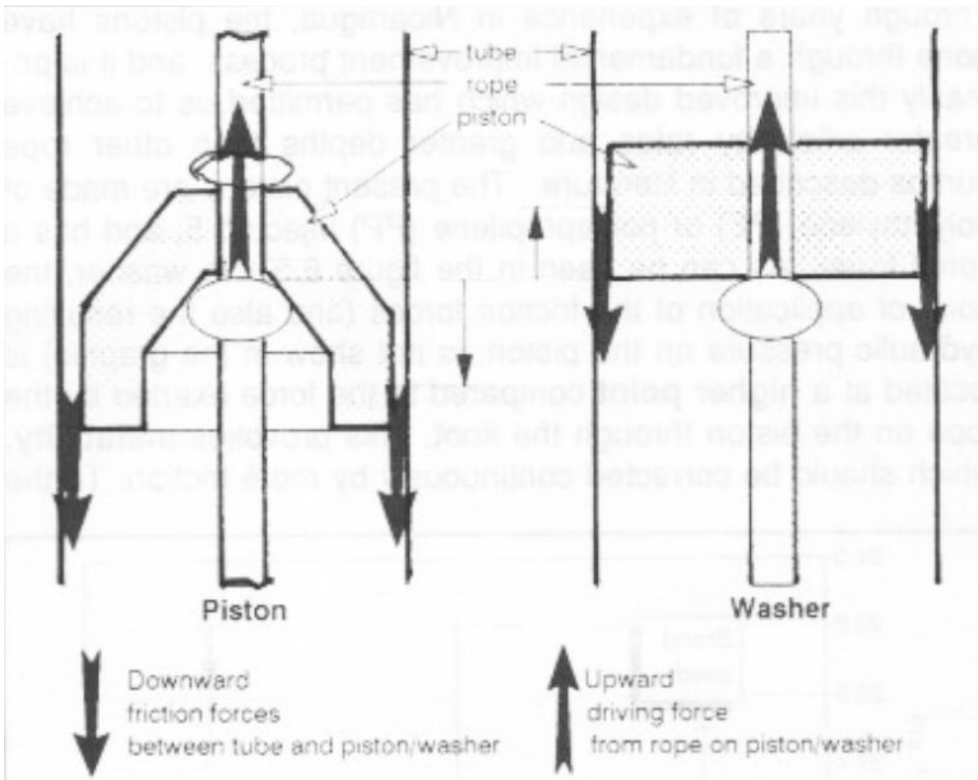

Figure 3: Piston and Washer Force Diagrams. [8]

This is useful and cheap as car tires are already needed for this system. Thousands of rope pumps in Latin-America and Africa use this. Leather and wood can also be used. An efficient piston is made of high-density polyethylene. They are also easy to make to a standard size. They can be made by a motor powered extruder or a hand press. They can be fixed to the rope by knots or melting a piece of rope on both sides of the piston. The rope used should be 5 to 6 mm and

Polypropylene is suggested for the best results. If a well is deeper than 35 meters, a thicker rope should be used. [8]

While this system is a good option, but it was not chosen because, through the use of a bike, human power can be maximized.

Submersible Solar Pump:

Solar pumps work using DC electricity produced by solar panels with energy from the sun. Since the pump is run directly off the DC electricity the need to convert to AC electricity is eliminated. A controller takes the electricity from the panels and sends it to the pump, automatically opening and closing switches and valves to run the system as needed. A system level sketch of the solar panel with a submersible pump system is shown in Figure 4.

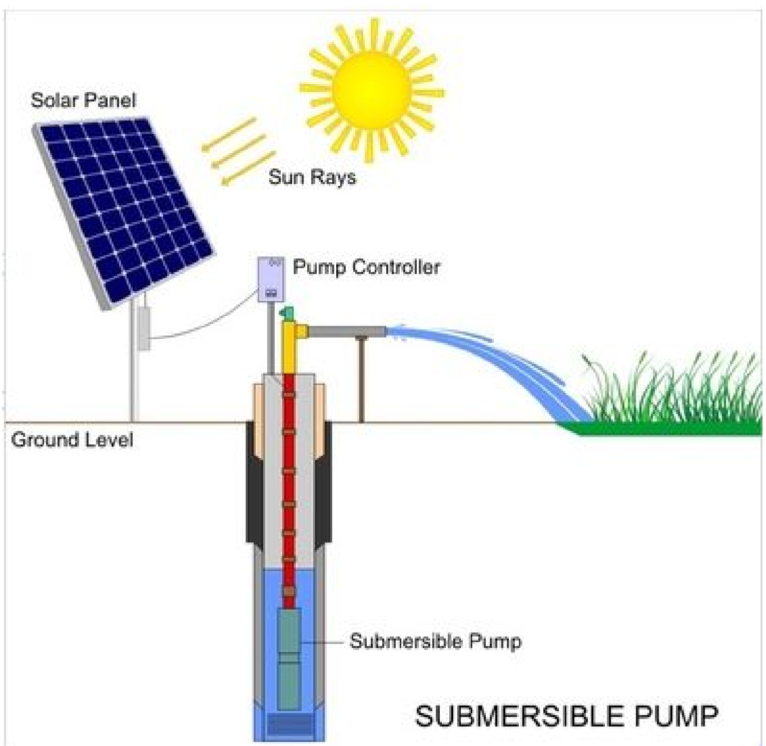

Figure 4: Solar Powered Submersible Pump.[9]

The leader in this technology is Lorentz, a German company. They include an option to use a UV Bulb connected to the main electricity supply to clean the water.[9]

Alternate pump options:

A major alternative is using an electric pump to pump the water. The two main ways to accomplish this would either be by having a solar powered pump with a battery implemented, or a bike powered dynamo to generate electricity. Given the amount of energy required, these solutions are not too realistic between the financial cost and time required. Otherwise, a gas generator is a potential option, but not the most efficient or elegant solution. [10]

Key Feature Comparison:

The pump options are compared more critically in the concept selection section, but the general key features of a centrifugal pump, rope pump, submersible solar pump and alternative submersible pumps are tabulated in Table 3.

Table 3: Tabulated key features of the different pump options. [10]

	Centrifugal	**Rope**	**Submersible Solar**	**Submersible Battery Powered**	**Submersible Gas Generator**
Cost	~$500	~$200	~$2000	~800	~1200
Power Fuel	Electricity or Bike	Hand or Bike	Solar	Electricity	Gas
Lifespan	8 years	15 years	12 years	14 years	11 years
Pump Method	Pressure with rotation	Mechanical	Pressure differential	Pressure differential	Pressure differential
Repairable by:	An engineer	Anyone with tools	A mechanic and electrician	A mechanic	A mechanic
Ability to improve:	It would be difficult to build a better centrifugal pump than currently available models, but it could be adapted to be powered by a bike.	Because this is a purely mechanical system, it can be improved by making it more efficient, improving gearing, and stability.	This could be installed, the main improvements would be buying more expensive models.	Finding an alternative power source could improve this design. We cannot build a better battery than currently available solutions. We could improve the cooling if that is an issue.	Finding an alternative power source could improve this design. We cannot build a better gas generator than currently available solutions. We could improve the cooling if that is an issue.
Guatemalan Supplier	Must be bought in the US	Local hardware stores.	Lorentz	Eijkelkamp Soil & Water	Tanknology Inc.

Natural Filtration systems:

Well water cannot be considered clean and potable without previous testing. According to the EPA(Environmental Protection Agency) there are many potential contaminants in your typical well such as "microorganisms, nitrate and nitrite, heavy metals, organic chemicals, radionuclides and fluoride" [11].

Since our project is being built in Guatemala for people who do not have access to all the resources that are in the United States, we want to try our best to create a system that is long lasting and repairable without parts from the U.S. and that starts with natural filtration systems. We could use an expensive, powerful, efficient filtration system from the U.S., that would be the easiest way to complete our project, but that would put the community in a precarious position if the filter started to break down. There are many different commonly used methods of purifying water. We will give an overview of the main options for our purification system and the challenges or benefits that they would bring while being used in Guatemala.

UV Filter:

A common method for water decontamination is Ultra Violet (UV) light. The light kills 99.99% of microorganisms in the contaminated water. This method is very effective at eliminating bacteria while not having to introduce any chemicals into the water. However, UV light cannot filter out dirt or any other floating particles in the water and would need to be paired with a physical filter unless the well water is clear. Also, the light would need to be powered by an electrical source or battery and conducting maintenance on it would be very difficult if anything were to break. The size or power of the light would need to be large in order to purify enough water for several families per day, meaning it would be an expensive system. The concerns over cost, effectiveness, and availability in Guatemala make UV not feasible for our project. [12]

Reverse Osmosis Filter:

Reverse Osmosis filters are commonly used in the US for treating water. The system works by forcing unclean water through an extremely fine membrane; one with pores 0.0005 microns in size. To pass through the membrane the water needs to be forced through with a pump. The pump will need to pressurize to around 40 psi which leads to large energy costs. This operation is illustrated in Figure 5. The system is also difficult to build and maintain as it usually includes pre- and post-filters and activated carbon in addition to the main membrane. The build difficulty and the fact that it would have to be on grid make reverse osmosis not suitable for our project.

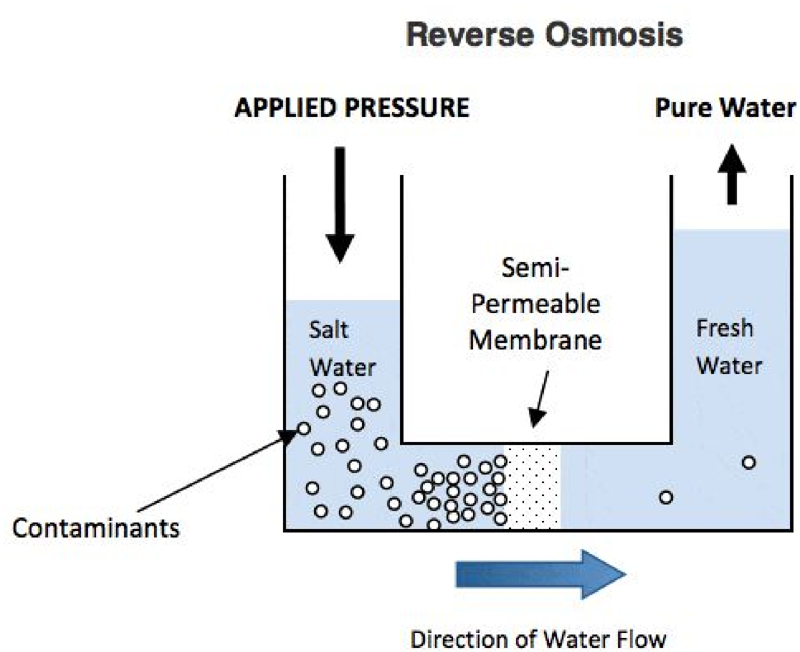

Figure 5: Reverse Osmosis diagram.[13]

Activated Carbon Filter:

Activated Carbon is used to filter water by attracting harmful particles to the carbon as the water is passed through. This method is also commonly used and is the technology behind products like the Brita filter. Regular carbon is activated by heating in an oven to add a positive charge to the carbon causing it to attract more harmful particles. A diagram of an activated carbon filter that outlines the major components is shown below in Figure 6. This process is simple enough that we could possibly conduct it in Guatemala and carbon is a readily available material. The major drawback of carbon filters is that they need to be frequently replaced. The carbon reaches a limit for how many harmful particles they can absorb and then can no longer be reused. Given the scale of our project the filter would need to be changed multiple times per month which also means we would need to continually be sourcing more activated carbon [14].

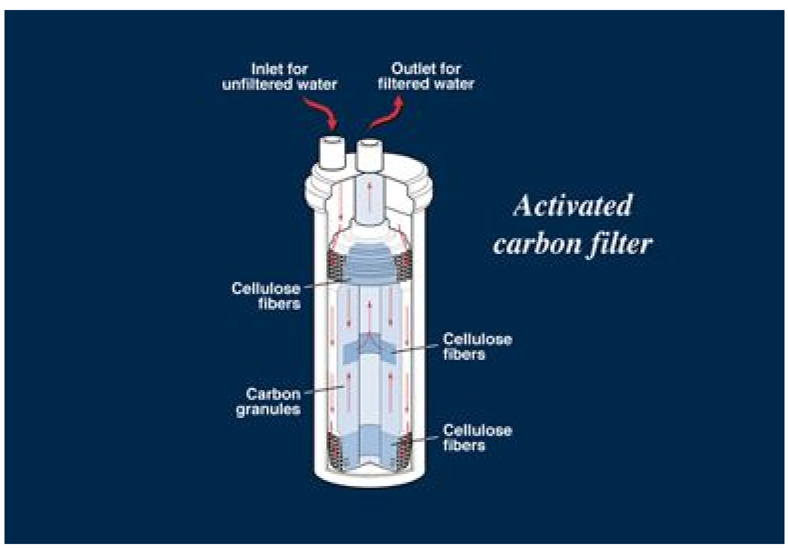

Figure 6: Activated Carbon Filter. [14]

Slow Sand Filter:

A common approach to purifying water with limited materials is slow sand filtration or biosand filtration. Slow sand filtration works by filtering water through a bed of sand that is covered with a mat of algae and microorganisms called “schmutzdecke”. The mat absorbs and metabolizes foriegn particles in the water and clean water flows through the sand layer to be collected. The water does not need to be pressurized to be forced through. The system needs a tank to store the water as gravity filters it through the sand. The general process of filtering water through a slow sand filter is visually represented in Figure 7. Therefore slow sand filtration can be completed off grid with locally sourced, Guatemalan materials. For the system to run efficiently a large tank would need to be used to increase the water weight above the sand layer. The system would not be portable but that is not a constraint for our filter [15].

After speaking with Mario and Dave, two of the directors of Maya Pedal, we have selected this option for our first round of design. Maya Pedal has used slow sand filters or biosand filters in the past to some success. They have built their filter walls and storage tank from mostly concrete and claimed they would like to move to a lighter and easier to manufacture material. We will need to design a tank that can be manufactured with available materials and limited shop equipment to improve on their current filter.

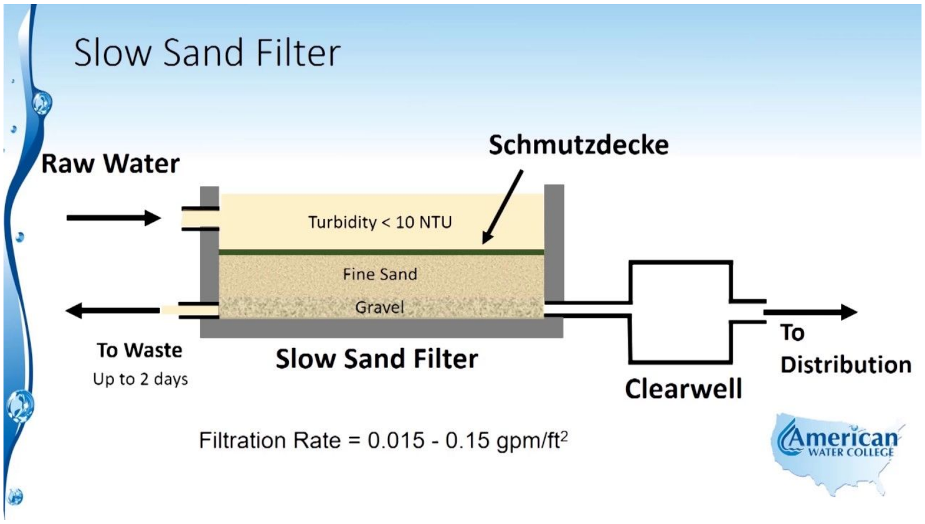

Figure 7: Slow Sand Filter Diagram. [15]

Throughout the preliminary stages of designing the filtration system we have been in continued contact with Maya Pedal. They have provided updates on their filter system. An organization called Pure Water For The World is partnering with Maya Pedal to donate biosand filters to be used in Guatemala. Maya Pedal has requested that we use this biosand filter but pair it with an additional filter in order to remove 100% of pathogens from the filtered water. To gather more information on the Pure Water filter we conducted research on biosand filters to better understand their shortcomings. This research is split into two parts. First, we have conducted a literature review on biosand filter technology through public health journals and the Pure Water website in order to gain more info on the Pure Water filter and its effectiveness. Next, physical tests on the actual filter were conducted in order to measure how successfully it removes different types of pathogens. It is important to verify that the product will perform up to the standard of water purity that it claims.

The first source analyzed to provide a greater understanding of biosand filtration was an article titled "Improved Filtration Technology for Pathogen Reduction in Rural Water Supplies" published in the MPDI journal. This source examined the effectiveness of biosand filters and noted two key issues. First, "the flow rate through the sand decreases with usage" [16]. Second, "purification may be inadequate—especially with virus removal—when high flows or frequent loadings are imposed" [16]. The study attempted two alterations to the filter to combat these issues and found that both were effective and improving the filter performance. The flow rate through the filter can be increased by increasing the grain size of the sand particles, however, pathogen removal effectiveness decreased with larger grain size. By adding a zero valent iron (ZVI) the pathogen removal effectiveness can be increased. ZVI would be available in Guatemala as iron filings and therefore could be locally sourced. Adding a ZVI layer to the bottom sand area of a biosand filter helps to kill pathogens because of iron's biocidal effects [16]. The study found the most effective filter had an increased sand grain size combined with a ZVI layer. These adjustments combat the decreased flow rate over the filter's lifespan and have adequate purification even under frequent or large loads of water. This research can be applied to our modifications of the pure water filter. To improve our filter performance we may be able to simply add a layer of iron filings into the biosand filter instead of having a seperate second filter system for the water to pass through.

In order to better benchmark the expected performance of a biosand filter a market survey was completed on biosand filters that are currently available for purchasing. Table 4 below shows a comparison of these filters. The Hydraid Biosand filter is the filter that is most often used by Pure Water for the world according to their website [17].

Table 4: Biosand filters on the market

	Hydraid BSF [18]	Ohorizons Wood Mold BSF [19]
Effectiveness (Percent of pathogens removed in lab testing)	Bacteria - 98.7% Viruses - 85.9% Giardia - 100% Cryptosporidium - 99.88%	Bacteria - 98.5% Viruses - 70-99% Protozoa - 99.9% Iron - 90-95%
Volume	15 L	11 L
Filter Rate	15 L/Hour	11 L/Hour With a 1 hour pause period required in between loads
Dimensions	Height: 75 cm Diameter: 40 cm	NA
Weight	Empty: 3.5 kg Filled: 55 kg (dry weight)	Filled: 160 kg
Lifespan	10+ Years	NA
Price	$25-50	$25-65
Source	[18]	[19]

3. Customer Needs & Product Specification

Unlike a typical engineering product, our product is not based on the needs of the people paying for it, rather the "customers" are the families that lack access to clean water. There is no incentive at all to make a profit or sell our system, it is only a viable solution for a customer who inherently has no disposable income. Our target "customers" are rural Guatemalan communities that lack clean, potable drinking water along with the non-profit organizations that can take our project, share it with community leaders, and scale it to work for other communities. The "customers" here provide useful resources and insights to our project that help in the manufacturing and designing process, and their unique needs and capabilities shape the project's scope. We are working with a nonprofit organization, called Maya Pedal. They work to produce and repair various bike powered solutions to simplify routine manual tasks in rural Guatemala. Maya Pedal has partnered with Pure Water for the World (another NGO) to provide water filtration systems, such as the one we are designing, to communities in need throughout Guatemala. Additionally, Maya Pedal helped coordinate some of the logistical challenges of an international project, helping provide context for the community, connect us with municipality leaders, and pave the way to scale our project to other communities in need.

To better understand the needs of the Guatemalan community and the Maya Pedal organization, we conducted a series of interviews to gain insight on specifications of our project. The interviews were with groups that worked on projects in a similar area to provide insight on needs that would result from the specific location and the resulting constraints. Additionally, we interviewed people who have worked on similar problems, in order to better understand what unexpected issues we should attempt to anticipate. And most importantly, our group met and interviewed the important groups involved in our senior design project, the different groups that we needed to work with to create a successful project. These interviews are presented fully in the appendix. [A1]

First, we had a video call with the Maya Pedal leaders, establishing contact with the leader of the NGO in Guatemala, Mario, and the liaison that works with groups in the U.S., Dave. We learned about what our general projects goals and scope were—to pump and purify water from a fairly deep well. The exact location of our project was still unknown, however we gained a general idea of how the well currently worked and were informed of various solutions implemented at other wells in Guatemala. We were told what has succeeded in the past, what solutions have failed, and what parts and products are feasible in the rural community. The Maya Pedal leaders were able to tell us the specifications of their current designs, and which areas (subsystems) need the most improvement. These customer needs centered around pumping depth, flow rate, water storage, and water purity.

Additionally, we were able to interview two students who worked on a similar Maya Pedal project last year. Through this interview we were able to learn about the specific needs of the community with which they worked, some of the difficulties they had with the machine shops in Guatemala, and their difficulties transporting materials from the U.S. to Guatemala. Last year's senior design group met all of the specifications given by the Maya Pedal organization and the senior design requirements, but noted that the community really needed the system to be made from locally sourced materials and be easily repairable for it to be considered a success.

We met with Maya Pedal leaders regularly to receive frequent updates on their needs assessment of the community we will be working in. We also established regular contact with last year's Maya Pedal senior design group to try and avoid issues they ran into last year.

Assessment of Customer Needs

Through the interviews conducted with members of Maya Pedal and the Frugal Innovation Hub, we formulated a list of customer needs as shown below in Table 5 to ensure our project meets all of the requirements laid out for us.

Importance of features on a scale of 1 to 5

1. Feature is undesirable. I would not consider a product with this feature.
2. Feature is not important, but I would not mind having it.
3. Feature would be nice to have, but is not necessary.
4. Feature is highly desirable, but I would consider a product without it.
5. Feature is critical. I would not consider a product without this feature.

Table 5: List of customer needs for the community we will be assisting based on a series of interviews with those who have connections with the community involved.

Importance (1-5)	**Customer Needs**
4	Ability to retrieve water from a depth of 45 meters
3	Ability to pump at a fast flow rate
5	Clean water to drinkable levels
3	Bike/pump system is easy and comfortable to operate
5	Ability to scale the project in nearby communities
3	Ability to filter water quicker
4	Filter can be sourced in Guatemala
4	Cheap and affordable system
3	Education system for local students to understand our project and the system

3	The filter tank can store a large volume of water
3	Pump can be purchased or built cheaply
3	Filtration device that will be durable
2	Materials that can handle multi directional stresses
4	System will be durable and easy to maintain

4. Preliminary Guatemala Trip

From January 28th to February 1st, team members Liam Scobey and Matthew Kamimura took a preliminary trip to San Andrés Iztapa, Guatemala to scope out the area the team would be working at in the Spring. The team stayed at the Maya Pedal hostel where they were able to meet the majority of the volunteers and staff including key leaders, Mario Juarez and Dave Renfrow. During this trip, there were five goals. The first was to visit an existing Maya Pedal bike pump system to better understand the design. The next goal was to talk to the community to better understand their needs and cultural norms. Then we needed to find the necessary materials at local hardware stores. Next we had to get to know the Maya Pedal workers. Lastly we went to give a presentation to the mayor of San Andrés Iztapa and his council of community leaders to talk about the community educational program we wanted to implement.

Overall, we were very successful in achieving these goals. At the Maya Pedal hostel, there were a few volunteers that were very knowledgeable about bike gears and biosand filters from their time working at Maya Pedal so we were able to work with them to create our new design for the bike powered pump that improved the existing design by limiting friction in the system, increasing gearing efficiency and keeping dirt and rocks from the well out of the PVCpipes. These ideas were derived from the existing bike pump system in another community in Guatemala. This visit revealed that the current system breaks down very easily because the wooden stoppers rot, the water that did get pumped out was very turbid and contained some small gravel, and the bike chains have too much slack after months of use. This led us to create a guide box for the bottom of the well that is designed to let the water in to be pumped, but is effectively able to keep large clumps of dirt and rocks out of the tubes to prevent clogging as well as reduce the amount of friction from the rope stoppers taking a sharp angle in and out of the PVC tubes. The guide box is illustrated as a CAD model and physical prototype below in Figure 8.

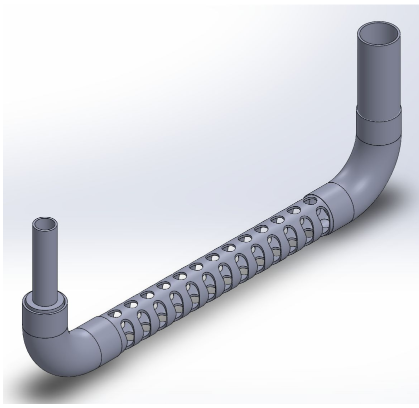

Figure 8: CAD model and actual model of the guide box

After coming up with our final design in Guatemala, we were able to sit down with Dave and Mario, two Maya Pedal leaders, to share with them our vision for our project, how we imagine it being scaled up and down in the future and problems we saw in their existing system. Once we were on the same page, we got ready to present our project to the mayor of San Andrés Itzapa. The purpose was to convince him that the lack of clean potable water in rural Guatemala was a big issue that he and his government should be getting in front of by partnering with Maya Pedal to put a biosand filter in over 200 homes around the San Andrés area. The importance of this project was very clear to us as we visited the family who lives in the community that we are putting the bike pump system in and we learned a lot about their daily lives and water needs. We found out that they can only use their well water for watering crops and washing dishes. If they did have clean potable water, their kids would be able to stop drinking Pepsi everyday and improve the overall health of the community. Also, our geared down bike pump would allow the kids to pump their own water as they would need about 100 liters of water a day for the community. This is important because the fathers are gone for most of the day working. This is all very important context that we needed to know before completing our system design so it actually meets the customers needs. For our project to be successful, the pump system needed to be seamlessly integrated into the community's daily life, and observing the critical customer's routine was essential for defining our project's scope. As mentioned earlier, to ensure this we observed the community members and talked with them about their routine, as shown in Figure 9 below.

Figure 9: Meeting members of the community to better understand the needs of our customer.

We visited local hardware stores in San Andres Itzapa and Chilmatenago (the next closest city) with some experts from Maya Pedal. These visits affected our decisions on parts, and we found out important information about the actual pipe diameters that are commonly available and accurate information about pricing of steel versus wood. Furthermore, we got quotes for labor such as welding and transit, important for the accurate planning of our final trip. We performed water testing at the actual well site and visited setups of various bicimaquinas in rural communities. We spend an afternoon at the well to better understand the community needs that we would be creating a solution for. All of this information was integral to finalizing our design with these rescoped customer needs. Many of our assumptions and design decisions were based on the information that we received during this essential visit. While the phone calls and zoom meetings with Maya Pedal provided some initial estimates, many of these assumptions were changed based on the January trip. For example, the PVC found in Guatemala was considered ½. ¾, or 1 “pelgado” which we translated to inch. However, the measurements did not align with standard PVC piping in the US. Because of this, we purchased some PVC for accurate testing and modeling back at SCU. Figure 10 is Liam bringing some PVC back to Maya Pedal from the local hardware store.

Figure 10: Traveling to different hardware stores around the area to find proper materials.

5. Design Iteration and Analysis

After we translated customer needs into product specifications (see the Appendix for the PDS), we then translated those specifications into various physical concepts that could potentially accomplish the needed specifications. When we were first generating concept designs for our project, we split up the system into subsystems and then generated multiple designs for each subsystem to choose from. These focused on the higher rated needs/specifications and fairly reasonable concepts that do not completely disregard non-targeted needs. Some of the concepts have significant drawbacks for one need or another, but none of the concepts if implemented would inherently signify the failure of our project. We ran these potential solutions through a scoring matrix to help determine which solution would be best for our project and customer needs, with the most benefits and the fewest drawbacks. The subsystems were broken up as follows:

I. Bicycle/pump system
    A. Flywheel with rope
    B. Centrifugal pump
    C. Submersible Electrical Pump
    D. Hydraulic Ram Pump
    E. Deep-well piston hand pump
    F. Deep-well diaphragm pump
II. Storage tank system
    A. Single Tank
        1. Plastic
        2. Cement
    B. Dual Tank
        1. Plastic
        2. Cement
III. Filter
    A. Biosand filter

B. Activated carbon filters with water ionizers
C. UV filters
D. Chlorine filter

Concept Selection

Bicycle/Pump Subsystem

The major types of pumps we considered for this project include deep-well diaphragm pumps, deep-well piston hand pumps, submersible pumps, rope pumps, centrifugal pumps, and hydraulic ram pumps. All of these have been successfully used in different countries with success as hand pumps. These vary in terms of mechanical complexity, cost, and availability in Guatemala. Figure 11 (below) illustrates the hand versions of the pumps that could be adapted to be powered by a bike. These four pumps—deep-well diaphragm pump, deep-well piston hand pump, submersible pump, and hydraulic ram pump—are all mechanical systems that have been implemented in various communities around the world. Our research has shown that none of these have been successfully integrated with a bike, so the functionality rating is a pure estimate. An additional drawing of a submersible pump can be found in the appendix.

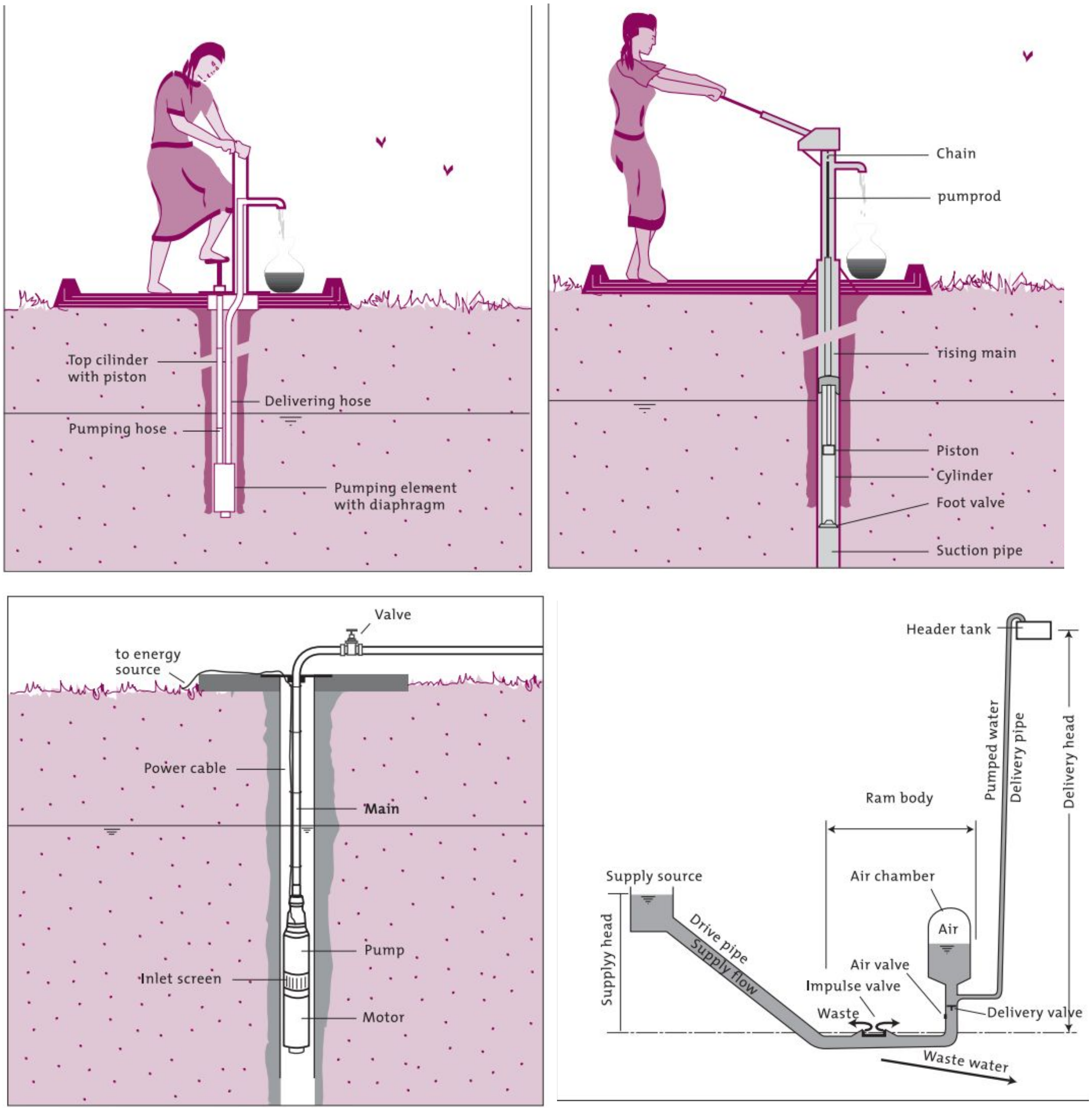

Figure 11: Drawings of deep-well diaphragm pump (top left), deep-well piston hand pump (top right), submersible pump (bottom left), and a hydraulic ram pump (top right) [24, Reproduced without permission].

Below, the rope pump operating principle is depicted in Figure 12. It demonstrates how the stoppers interact with the main pipe to pull up water. Rope pumps have been integrated with bikes before, and Figure 12 depicts the general model that is currently used for well pumps in the San Andrés community, illustrating the general principle that our project relies upon.

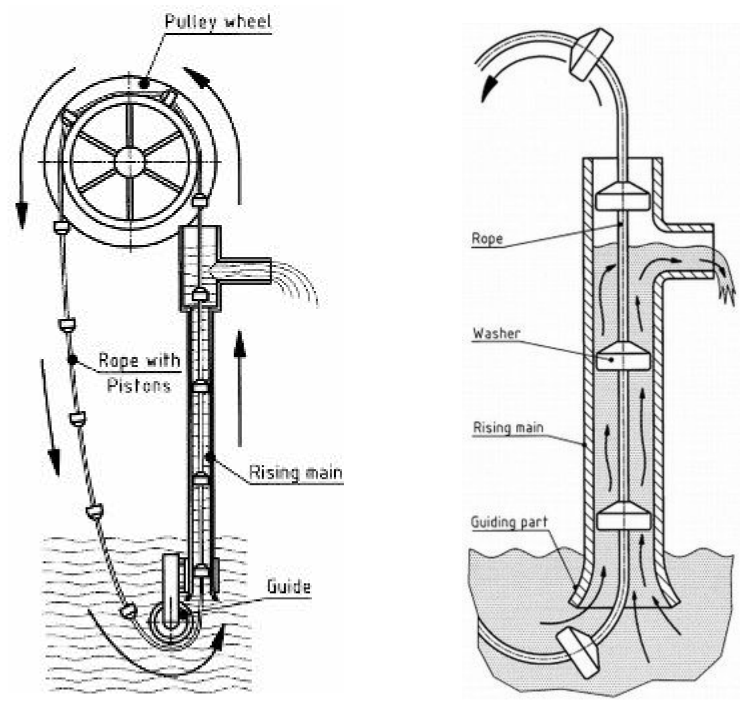

Figure 12: Schematic drawings of the rope flywheel and pump system [25, 26, Reproduced without permission].

The centrifugal design depicted below in Figure 13 is the pumping model that last year's group (and a group of engineers from Great Britain) have integrated with bike systems in Guatemala [27]. This model is traditionally electrically powered, and switching to mechanical bike-power has been found to greatly reduce its ability to pump from a depth [28].This solution is adequate for low depth solutions that require portability, but is less appropriate for a well pump system.

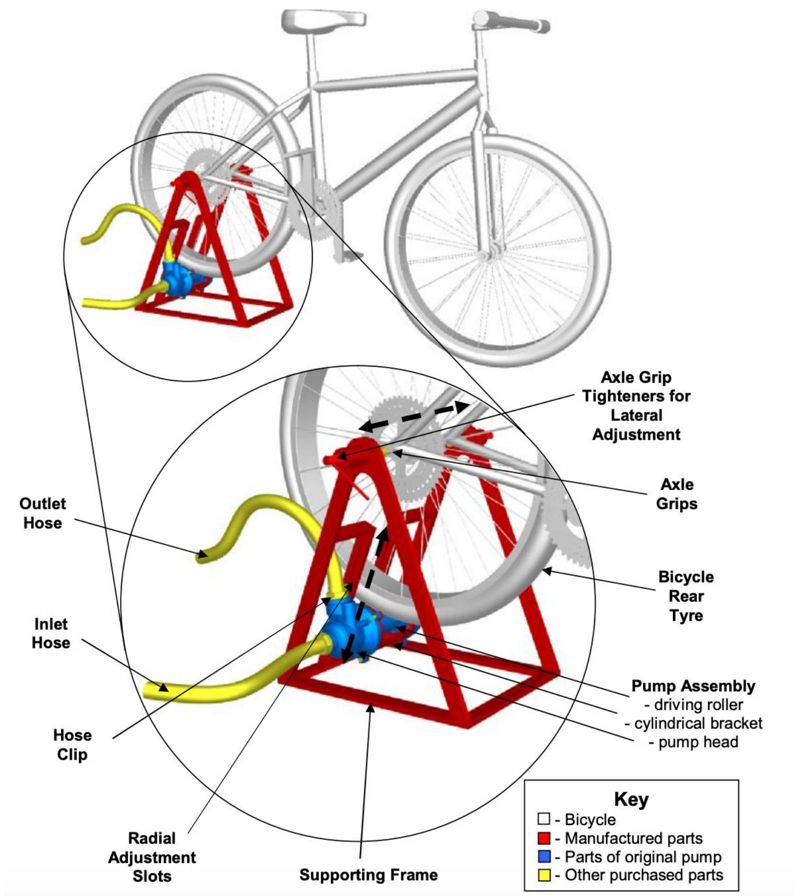

Figure 13: Diagram of a bike wheel to centrifugal pump system [29, Reproduced without permission].

These designs were used to help determine durability, ease to build, usability, and locally sourced categories of the matrix. By looking at how each different pump subsystem works, it was possible to critically evaluate which version would fit within the bounds of customer needs for this project.

While there are not currently available models of bike powered well pumps for all of these pump models, these are all options that are used with either electrical or hand power with wells around the world. Because of this, the above matrix includes statistics from the hand powered or electric powered versions paired with our best estimation of how they would perform if they were adapted to be bike powered. The following statistics for how the following pumps perform without a bike greatly contributed to the Table 10 [30].

Rope Pump:

Range of depth: 0–50 m

Yield: 0.6 litres/s at 10 m, 0.15 litres/s at 50 m

Centrifugal Pump (electrical powered) [28]:

Head range: Typically, 4–50 m per stage, with multiple-stage pumps to 200 m and more.

Yield: Varies widely, according to many options available in the market

Submersible Electrical Pump:

Depth and yield vary with cost of the system

Hydraulic Ram Pump:

Pumping head: 1–100 m (maximum is about 40 times the supply head).

Yields as percent of inflow: 26% for a 2m drop and 6m lift; 5% for 3m drop and 30m lift.

Deep-well piston hand Pump:

Range of depth: 15–45 m, although depths of up to 100 m are possible.

Yield: 0.25–0.36 litres/s at 25 m, and 0.18–0.28 litres/s at 45 m depth

Deep-well Diaphragm:

Range of depth: 10–70 m

Yield: 0.50 litres/s at 10 m depth; 0.32 litres/s at 30 m; and 0.24 litres/s at 45 m

The scoring matrix below (Table 6) makes it easier to understand which elements of the pumps are integral to each system and how they would each function for our project. They were weighted with respect to how essential each factor is to the success of the project from 1 to 2. The weighted scores are in parenthesis, the unweighted score is above.

Table 6: The scoring matrix for the bike/pump system. Each category is scored on a scale of 1 (lowest) to 5 (highest). The weight is given to differentiate between the needs' importance.

Bike / Pump System	**Dura bility**	**Cost**	**Ease to build**	**Ease of use**	**Flow Rate**	**Locally Sourced**	**Stability**	**Depth**	**Total Score**
Weight	X1.2	X1.8	X1	X1	X2	X2	X1	X1.5	
Flywheel with rope	3 (3.6)	5 (9)	5 (5)	3 (3)	3 (6)	5 (10)	4 (4)	4 (6)	**32 (46.6)**
Centrifugal pump	3 (3.6)	3 (5.4)	1 (1)	3 (3)	4 (8)	2 (4)	3 (3)	2 (3)	**21 (31)**
Submersible Electrical Pump	3 (3.6)	1 (1.8)	1 (1)	5 (5)	5 (10)	1 (2)	3 (3)	4 (6)	**23 (33.4)**
Hydraulic Ram Pump	5 (6)	2 (3.6)	2 (2)	2 (2)	3 (6)	3 (3)	4 (4)	3 (4.5)	**24 (31.1)**
Deep-well piston hand pump	2 (2.4)	5 (9)	4 (4)	2 (2)	2 (4)	5 (10)	4 (4)	2 (3)	**26 (38.4)**
Deep-well diaphragm pump	4 (4.8)	3 (5.4)	2 (2)	3 (3)	4 (8)	3 (6)	3 (3)	3 (4.5)	**26 (36.7)**

[24,25,26,27,28,29]

Going through the various designs, it appears that the most effective and applicable solution is the bike powered rope pump. It is the simplest, cheapest design—a scalable solution for the rural Guatemalan community. The biggest drawback of a rope pump is the slow flow rate and possible deterioration over time. While there are risks with a rope getting roughed up over time (especially if there is exposure to sunlight), it is also the most replaceable part of all possible pump systems. It is not realistic to expect a village of Guatemalans who make a few dollars a day to replace a pump from the U.S. that costs a couple hundred dollars, but the community does have access to rope at local hardware stores. By adapting the rope pump system to be bike powered and gearing it down significantly, it is possible to pump water from at least 45 meters at our ideal flow rate of 19 liters/min with relative ease, meeting the specification that anyone from children to the elderly can pump their own water on the bike. Additionally, rope well solutions are used in local communities, so it is something that they are already aware of how to maintain—the primary change is the implementation of a bike. By keeping this as a simple, mechanical solution, it can be completely locally sourced and easy to repair the system as needed.

Storage Tank Subsystem

After the water is pumped, it needs to be filtered and stored, entering the storage tank subsystem. Depending on the setup, the bici-bomba may require one or two storage tanks. Two tanks would allow for any kind of filter, including the biosand filter shown in Figure 14 below. This would allow the water to enter the biosand filter at a different rate than it is pumped from the well. Below is a sketch of the two tank system. We decided to change the tank volumes to be larger in order to better provide for the needs of whole families, the target "customer." We also considered the idea of adding a meter to the top tank to indicate the water level. This would help the community keep the filter running and leave water for the next family to use the system. It would allow people to know if they pumped in a comparable amount of water to what they withdrew.

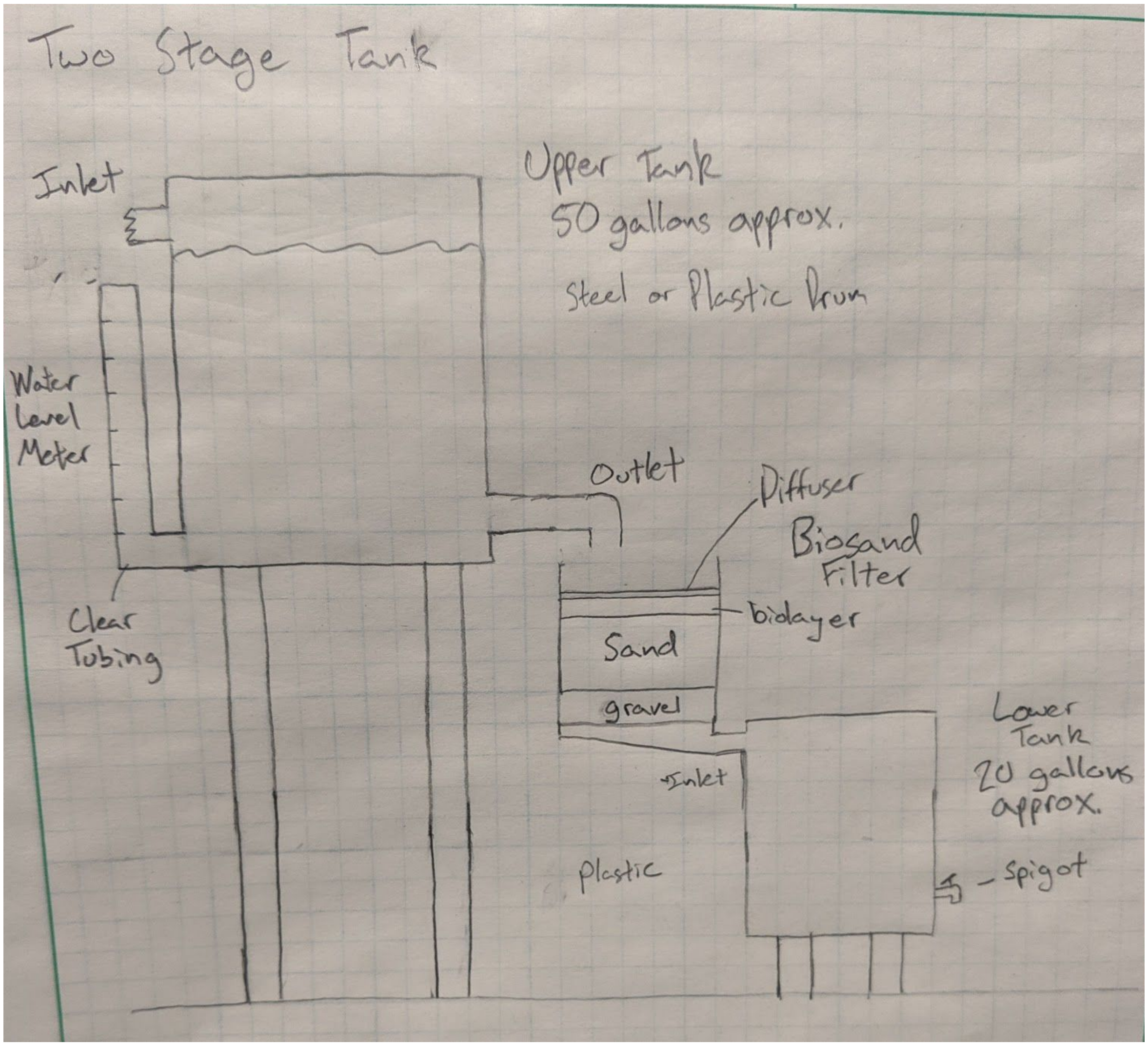

Figure 14: The two tank system with biosand filter for water purification.

In addition to the number of storage tanks, the storage tank material is integral to this subsystem's functionality. The two general options are a hand formed cement storage tank or a purchased plastic storage tank. Market research found some primary characteristics of both styles of tanks [31]. Their functionality was weighted with respect to how essential each factor is to the success of the project from 1 to 3. The weighted scores are in parenthesis, the unweighted score is above.

Table 7: The scoring matrix for the tank system. Each category is scored on a scale of 1 (lowest) to 5 (highest).

Tank System	**Strength**	**Durability**	**Cost**	**Weight**	**Size**	**Safety**	**Effectiveness**	**Total Score**
Weight	X1	X1.5	X2	X1.2	X1	X1.8	X3	
One Plastic Tank	2 (2)	2 (3)	5 (10)	5 (6)	4 (4)	4 (7.2)	1 (3)	**21 (35.4)**
Dual Plastic Tank	2 (2)	2 (3)	4 (8)	4 (4.8)	2 (2)	3 (4.4)	5 (15)	**23 (39.2)**
One Cement Tank	4 (4)	4 (6)	2 (4)	2 (2.4)	4 (4)	3 (4.4)	1 (3)	**23 (27.8)**
Dual Cement Tank	4 (4)	4 (6)	1 (2)	1 (2.4)	2 (2)	2 (3.6)	4 (12)	**21 (32)**

The matrix demonstrates that there are multiple solutions that effectively address the problem. Previous versions of this project have used a cement tank. While it has been a passable solution, a cement tank is very heavy and can be dangerous if the infrastructure is not perfect. It is impossible to repair which was not accounted for on the matix. After discussing the needs for this project with the team and Maya Pedal, the cost of materials, the ability to be locally sourced, and functionality were established as the cardinal elements for the storage system. Maya Pedal's specific comments regarding prioritization of needs are quoted in the interview portion of the appendix, where they mention the importance of cost and being locally sourced. With the weight for these factors given based on customer needs, this led us to the decision to go with a dual plastic tank system.

The effectiveness of dual tanks paired with the weight and cost of the plastic tank make this the best water storage method for this project. The dual tank system allows our system to provide water in a more timely fashion by being able to store approximately 200 liters of water at one time while allowing water to be slowly filtered in 20-40 liter increments.

Filter Subsystem

The purpose of the filter subsystem is to clean the well water to drinkable levels in an efficient, cost effective manner. Our partner, Maya Pedal, received donated biosand filters from a clean water non profit organization called Pure Water for the World. They wanted us to use a biosand filter with our system so it could be a scalable solution. However, they also claimed that the filter can only guarantee removal of up to 98.5% of pathogens from the water. Therefore, we needed to design a solution to remove the remaining 1.5% of pathogens while still using the biosand filter. Below in Figure 15 is a drawing of the biosand filter that is provided by Pure Water for the World [32]. The filter provided will most likely be a CAWST Hydraid filter, one of the most commonly available biosand filters. It is a well known solution backed by documented research as mentioned in the biosand portion of our background section [33].

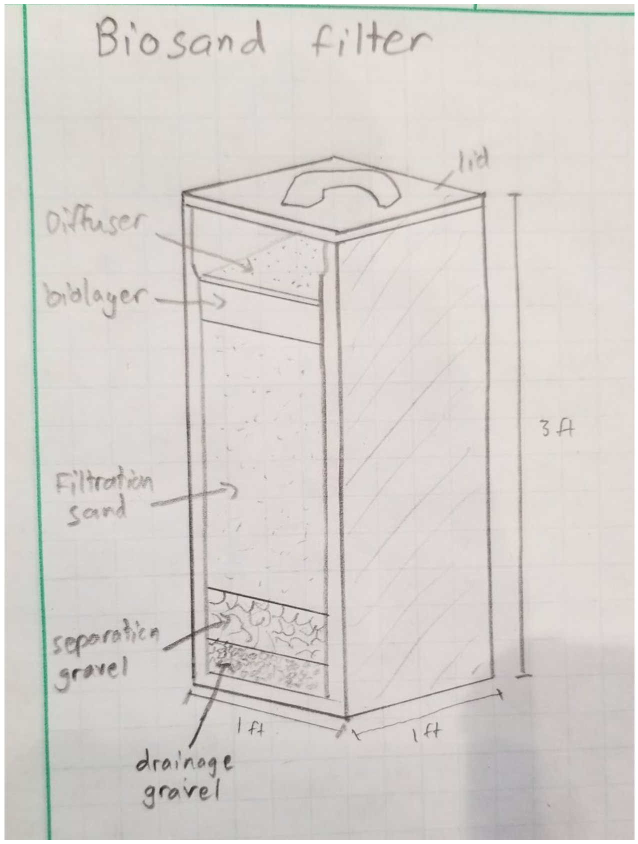

Figure 15: Diagram of the Pure Water for the World Biosand filter [32].

We considered adding a secondary filter after the water leaves the biosand filter in order to remove the remaining pathogens. The first proposed supplementary filter considered was an activated carbon filter. A carbon filter would be cheap and be able to be locally sourced but would require regular maintenance. The carbon would need to be replaced often, as it can no longer absorb pathogens after a limited number of uses [34]. Figure 16 below displays a drawing of a carbon filter. The filter can be paired with water ionizers to increase its effectiveness but this would add greater difficulty to the building and maintaining of the filter. Overall, this is an effective but not ideal solution for our customer.

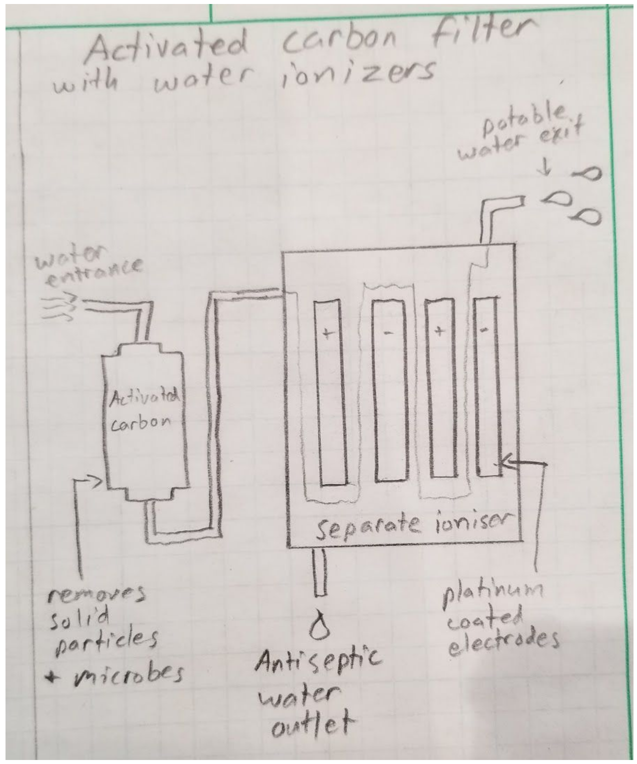

Figure 16: Diagram of an activated carbon filter with water ionizers [34].

We considered implementing a UV filter, as shown in Figure 17 below [35]. The biggest drawback of UV technology is the cost and limited access in Guatemala. The filter would likely need to be purchased in the US and then shipped to Guatemala, which would make conducting maintenance difficult and make our solution far less scalable. Furthermore, it would introduce the need for electricity to our previously purely mechanical solution.

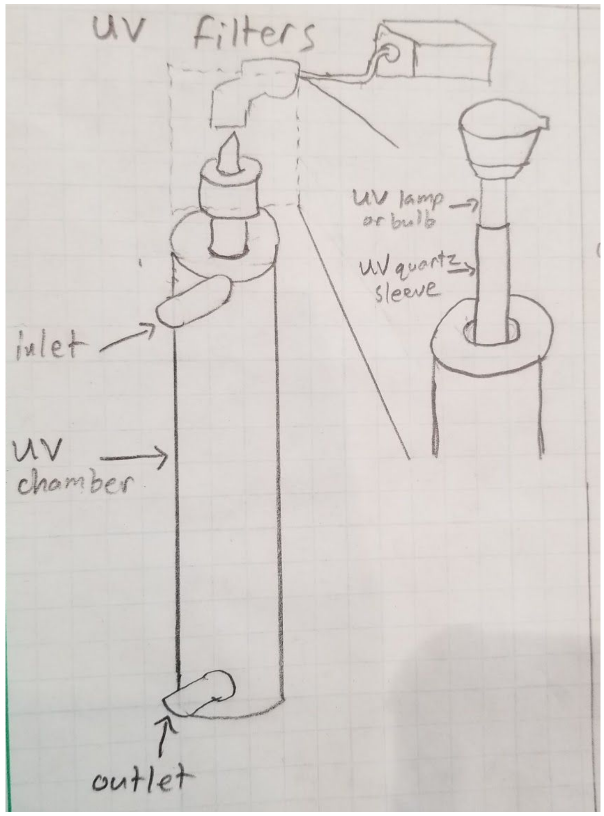

Figure 17: Diagram of a UV water filter [35].

Below, in Figure 18, the subsystem sketch for a chlorine filter is presented. This is a very effective and frugal option, but it has traditionally not been successful in Guatemala due to complaints about water taste. Oftentimes, when the only available option is chlorine filtered water, Mario from Maya Pedal informed us that many Guatemalans have been known to simply drink CocaCola instead. Because of this important consideration, this option would require implementing an additional filter for taste in order to ensure that it would be utilized. Overall, this added complexity and the need to replace the chlorine makes this a less than ideal solution.

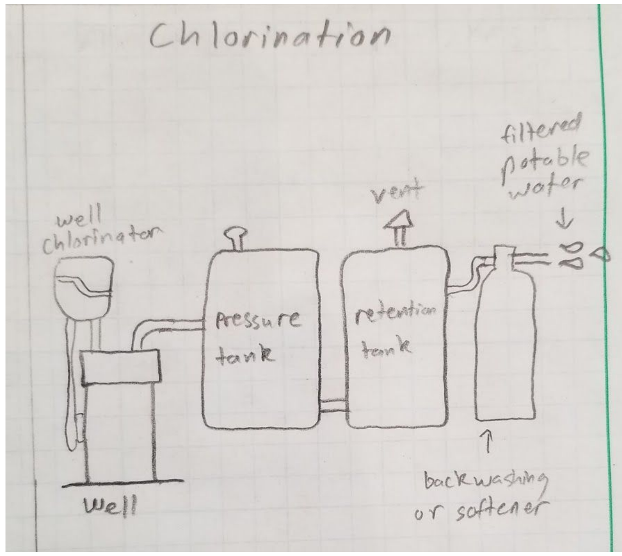

Figure 18: Diagram of a chlorination filter [36].

Another option for removing the remaining pathogens is to improve the donated biosand filter instead of adding an entire second filter system. In order to remove the remaining 1.5% of pathogens, we had to be confident in what the water composition is. Additionally, we conducted research on biosand filters and ways to improve them. This research can be found in the biosand section of the background. The most important takeaway for our research is that a ZVI (Zero-Valent Iron) layer can be added to improve filter performance. This layer is composed of iron filings and is only about 5 cm deep. The iron has a biocidal effect that helps to kill pathogens passing through the filter. The iron is most effective at removing viruses and certain bacteria such as E. Coli, aligning with our need to remove pathogens [37]. Table 8 below lists the percent of pathogens removed for the original filter and the filter after the ZVI layer is added.

Table 8: Percent of Pathogen removal for a Hydraid biosand filter with and without ZVI.

Pathogen Type	Original Hydraid Filter	Improved Hydraid Filter (With ZVI)
Bacteria	98.7%	98.7+%*
Viruses	85.9%	99.99%
Giardia	100%	100%
Cryptosporidium	99.88%	99.88%

*An updated value for percent of bacteria total removed could not be found but data on individual types of bacteria that were removed show improvement, especially for killing E. Coli. [37]

To pick between filter options, we again used a design matrix to rank each option. The matrix, shown below in Table 9, was used to decide on the best option for removing the final 1.5% of pathogens as the biosand filter will be used as the primary filter. Their functionality was weighted with respect to how essential each factor is to the success of the project from 1 to 3. The weighted scores are in parenthesis, the unweighted score is above.

Table 9: The scoring matrix for the filter system. Each category is scored on a scale of 1 (lowest) to 5 (highest).

Filter	**Durability**	**Taste**	**Cost**	**Filter rate**	**Locally Sourced**	**Cleans final 1.5% of pathogens**	**Total Score**
Weight	X2	X2	X3	X1	X3	X2	
Biosand with ZVI layer	5 (10)	4 (8)	4 (12)	2 (2)	4 (12)	3 (6)	**22** **(50)**
Activated Carbon/water ionizer	1 (2)	3 (6)	3 (9)	4 (4)	2 (6)	4 (8)	**17** **(35)**
UV Filter	3 (6)	4 (8)	1 (3)	4 (4)	1 (3)	4 (8)	**17** **(32)**

Chlorine filter	1 (2)	1 (2)	2 (6)	4 (4)	2 (6)	3 (6)	**13** **(36)**

[32, 33, 34, 35, 36, 37]

From our matrix, the biosand filter with an added ZVI layer scored the highest among all the filters across almost every category. This option meets all of the requirements, but testing the actual well water after being filtered is necessary to ensure the filter is purifying water to acceptable, safe levels.

Full System Concept

Beyond the subsystems described below, there are a few other parts needed for the full system to be complete. However, they do not require concept selection, as they are determined by the previous concept selection and simply are parts required to complete the system. These parts—the bike subsystem and the flywheel subsystem in particular—are described in more detail during the FEA and calculation portion of the analysis. Other features, such as the well, platform, guidebox, and stoppers, do not require concept selection but were iterated upon and analyzed during the scope of this project. Below, in Figure 19, the Maya Pedal sketchup of their design is depicted. The stoppers, well, and guidebox are all components that are currently planned on being repeated in some capacity for our design.

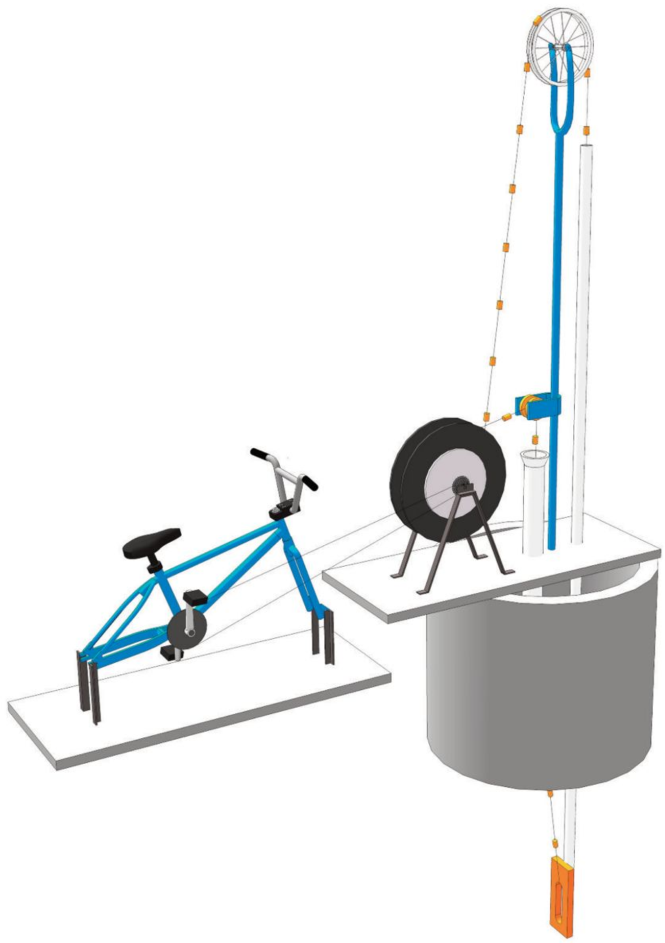

Figure 19: Maya Pedal's current design of a bicycle powered water pump [1, Reproduced with permission].

Below, Figure 20, is a picture of the Pedal 4 Purification team and their centrifugal pump product. Their final design is a good solution when portability is a primary concern and depth is not a factor, but it is not an effective solution to be paired with a well.

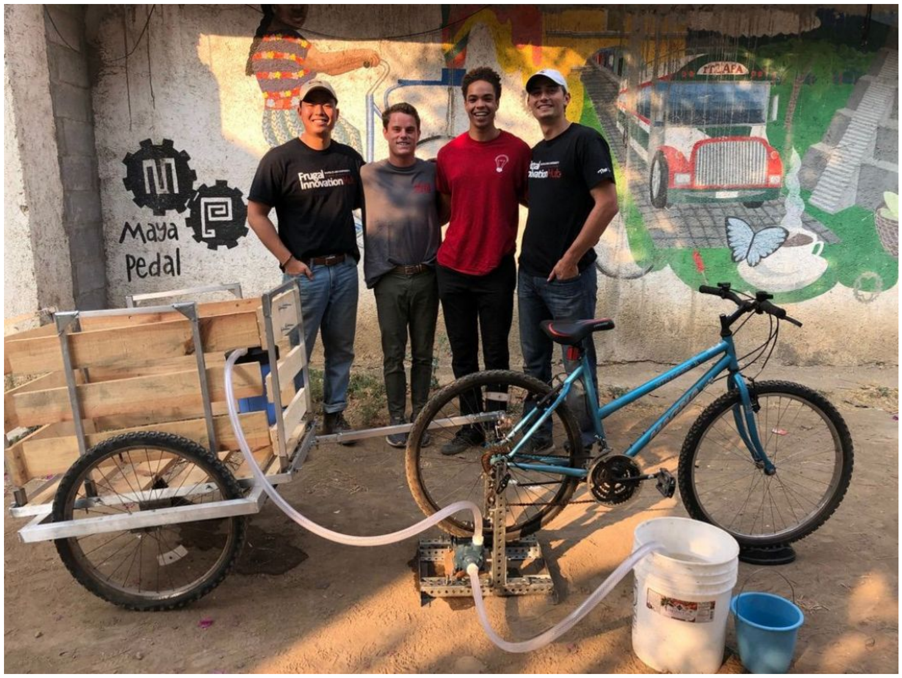

Figure 20: Pedal 4 Purification team with their final design [27, Reproduced with permission].

The sketch in Figure 21 illustrates the initial design regarding gearing for the design. By connecting multiple cassettes, the design is customizable to achieve the ideal combination of gearing to have an appropriate torque and cadence for any well depth and pipe diameter. These calculations are recorded in the power transmission discussion and in Table 16.

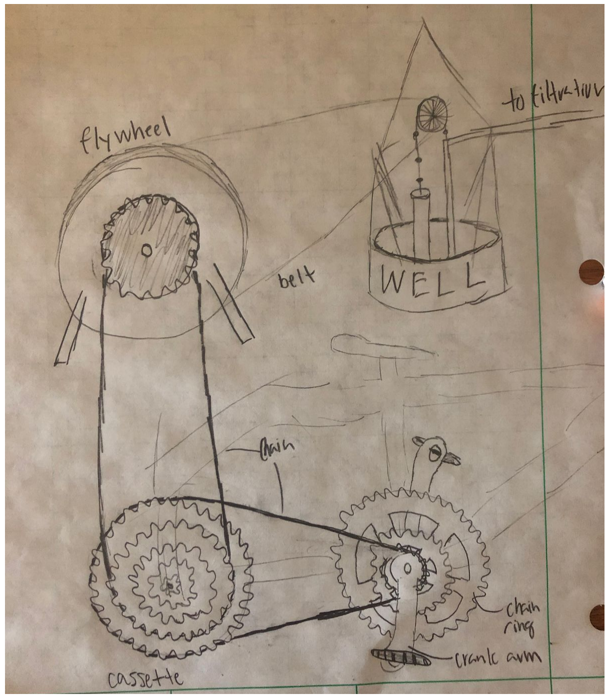

Figure 21: Gearing system for the pump: Utilizing gearing from the chain ring to the cassette along with from the cassette to the flywheel.

Any rope well pump requires stoppers to pull the water up the pipe and a guide box to allow the stoppers to operate correctly and efficiently. In Figure 22, the sketches depict the general stopper (or piston) design currently used by Maya Pedal along with their guidebox. The effectiveness of these components are difficult to test or even estimate without finalized models of dependent components, so it was important to see these stoppers on the preliminary trip and receive a shipment of stoppers from Maya Pedal. After experimenting with the wooden stoppers, recycled rubber stoppers, and store bought rubber stoppers, the wood stoppers turned out to be the most effective solution. Rubber stoppers resulted in the plastic's deterioration, eventually leading to discoloration of the water. Therefore, despite inefficiencies, wood stoppers were our final selection.

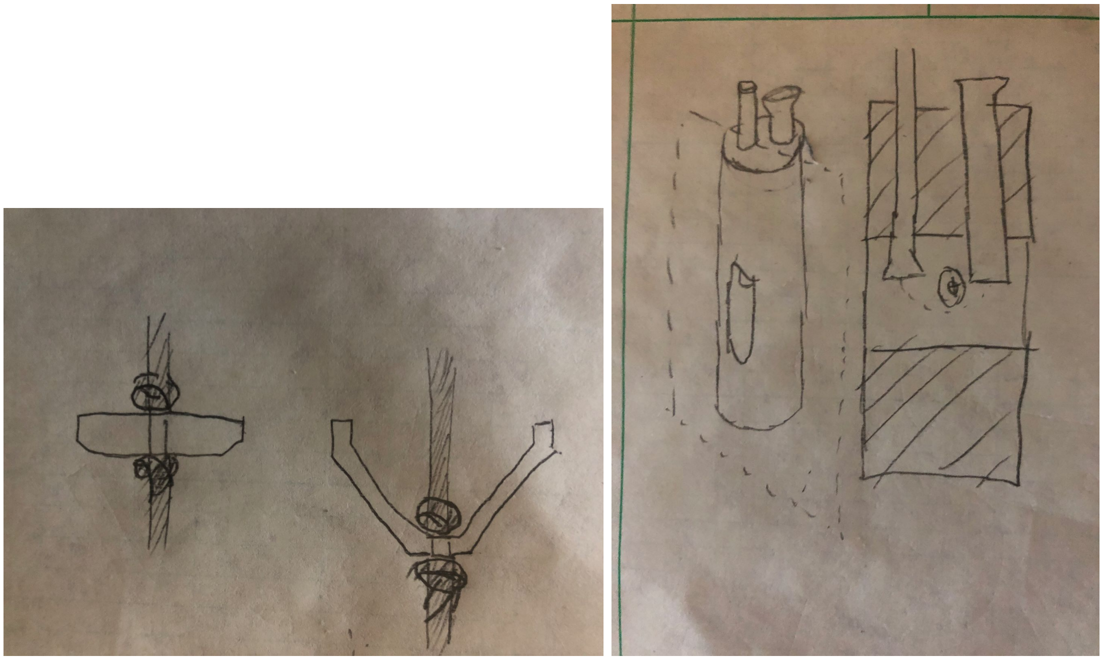

Figure 22: Piston solution and guide box for the rope well: Piston is made out of wood, polyethylene, or rubber. Guidebox made of PVC pipe and cement or PVC pipe and ceramic [39].

System Description

Our system is made up of three subsystems: the bicycle/pump system, the storage tank system, and the filter. The first subsystem, the bicycle/pump system, can be seen below in Figure 23. This system consists of a standard geared bicycle mounted to the ground in a concrete slab. The choice for the mounting process was based on environmental constraints. Since Guatemala has a wet, rainy climate, the ground will often be soft and muddy. This is based on information from the exploratory trip and expertise from Maya Pedal. This requires a sturdy stand that will be able to hold the weight of a person up to 200 lb, a conservative estimate. It is important to note that while the bike seat will be adjustable, the bike will only be suited to adults and older children.

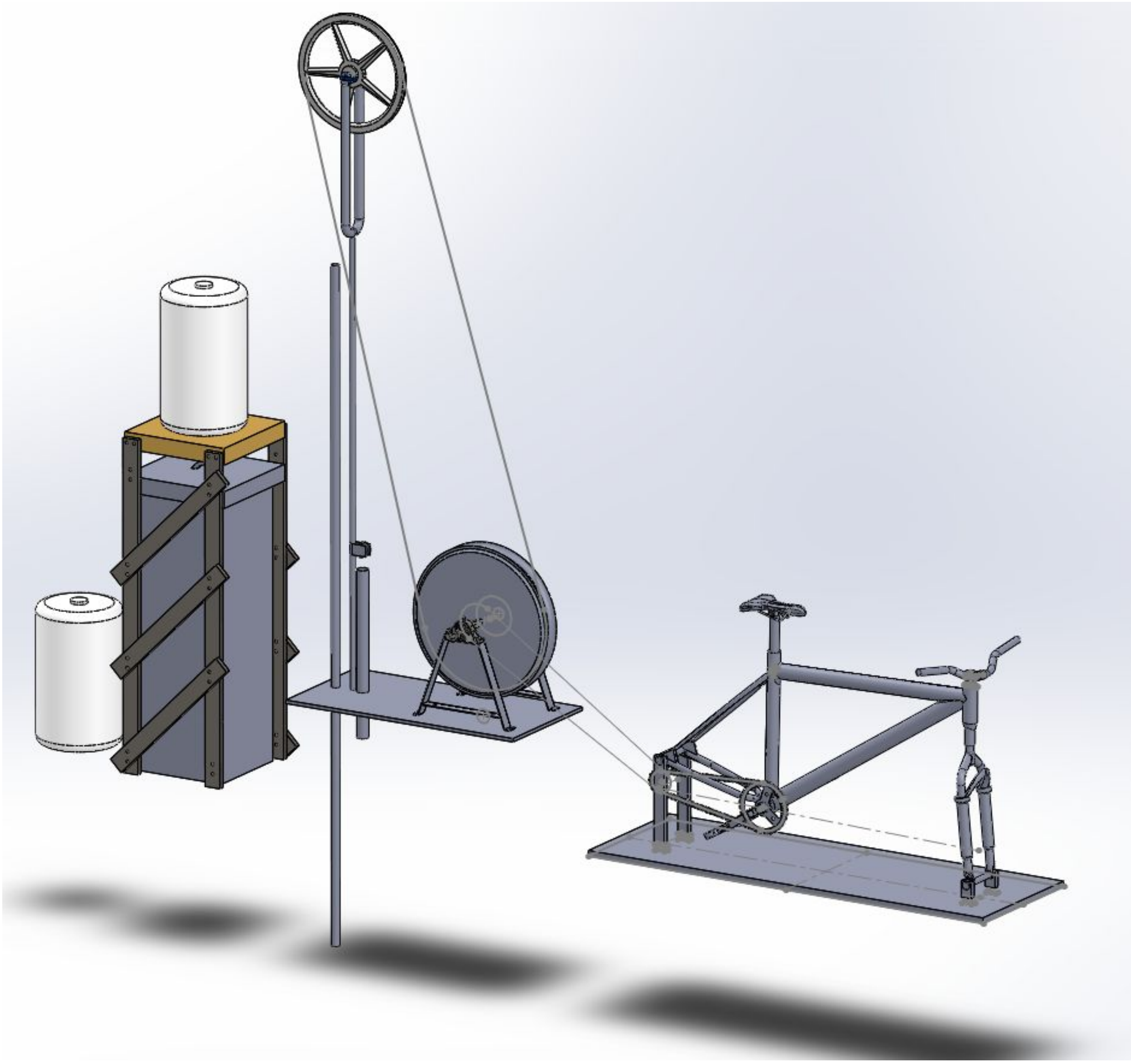

Figure 23: Current assembly design of a bicycle powered water pump filtration system.

The assembly drawing above in Figure 20 depicts the models of the various subsystems working together. The rain barrels are sample tanks that model "barrilitos" that we found are commonly used for milk storage in Guatemala, and are cheaply and readily available. The filter only depicts the outside and does not structurally reflect the filter or account for internal mechanisms. It is only for the visual understanding of the system. The actual filter was built on campus so there was no need to do strength simulation. The power transmission is shown with the side view of the system with subsystems labeled below in Figure 24.

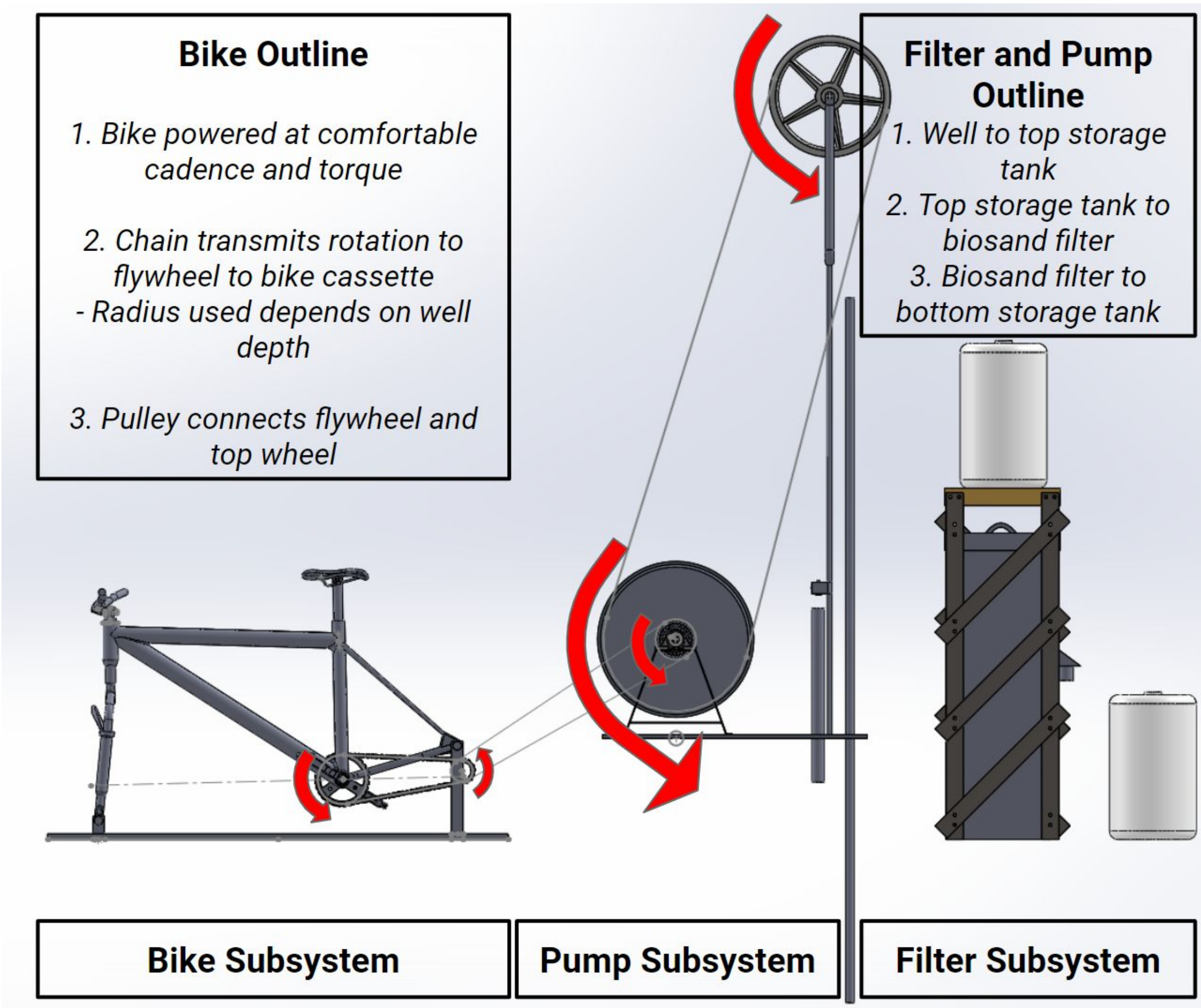

Figure 24: System level sketch with subsystems broken down and power transmission illustrated.

This side view system diagram illustrates the various components and how they transmit motion and power. It also outlines the motion of water through the system. In Figure 25 the basic calculations used for the power transmission are depicted. This is calculated in more detail later in the report.

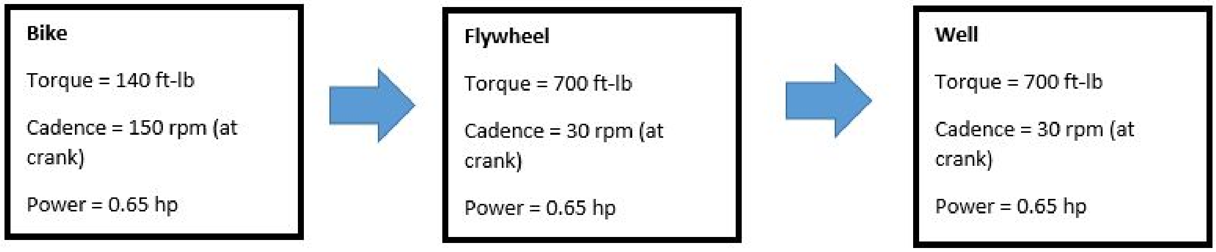

Figure 25: Power transmission block diagram of entire system. The "bike" block is the human input, the "flywheel" block is how the power is distributed at the flywheel and mirrored by the crank, and the "well" block is the power distribution at the top flywheel, which matches the base flywheel.

The power is conserved throughout the system, although it is geared down for the flywheel and well in order to handle the load of water that is being pulled up, characterized by the diameter of the pipe and depth of the well.

$$Water\ Weight = (Pipe\ Volume - Stoppers\ Volume)\rho_{water}g = (Well\ Torque) / (Top\ Wheel\ Radius)$$

The only way to change the weight of the water, the load, is by changing the diameter of the pipe or the depth of the well. Therefore, given a constant radius of the top wheel, the torque is determined by the weight of the water. Because of that, the flywheel and bike should be geared in a way that allows the biker to pedal at a comfortable cadence and lift the water. The well cadence determines the flow rate that the water enters the top storage tank.

Generally, the water enters the first storage tank at the flow rate determined by the calculations above. After that, it enters the biosand filter at a rate characterized by the tube diameter connecting the two components. Finally, the filtered water goes to the storage tank on the bottom where it is ready to be used.

Subsystems

Vertical Rope Pulley Subsystem

The bike is connected to two flywheels, which are used to leverage mechanical energy shown in Figure 26 below. A rope and wood plug system is connected to the top flywheel. This is how water is brought up from the well. One wooden plug enters the PVC tube, then water is allowed to enter and fill the tube until another wooden plug encapsulates the water in a column and then pulls it to the surface. The main assumption about the forces in the system is that the force acting on the top flywheel is completely vertical and no horizontal force is acting on the tallest column of our system. Otherwise, more model analysis would need to be done based on the connection of the column to the base on top of the well, which is information that is not available at this time. Another assumption made while modeling this system is that it will be used by an adult. This allows us to calculate the inputs/power source of the bike system. We accounted for friction by multiplying the force needed by an additional 25% to safely account for the friction in the flywheels, bike, water, and rope stoppers. Lastly, we assumed that water is the only material being pumped up from the well. If other items, such as debris or mud, are present in the well, the weight of what enters the PVC tube and the amount of force needed to pump it up to the surface would be affected, and it could potentially block our opening all together.

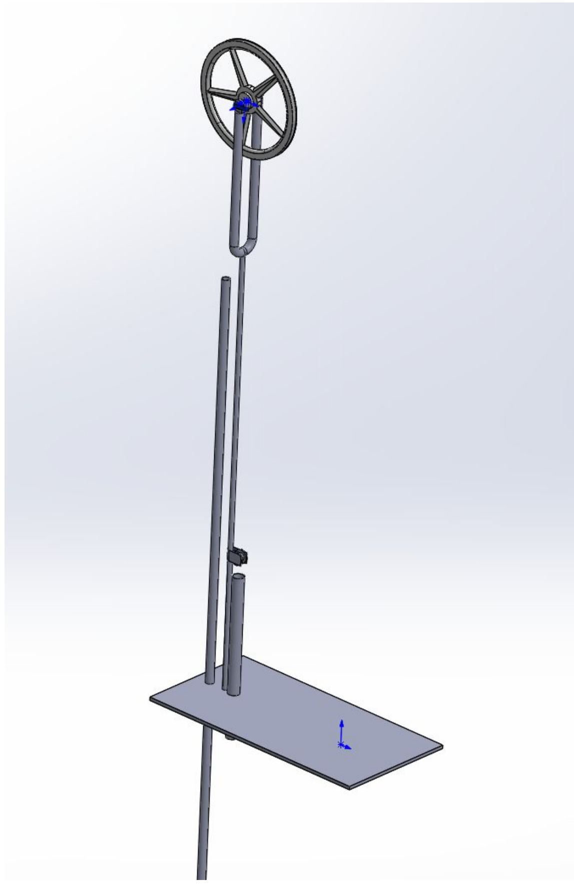

Figure 26: Full CAD view of the vertical rope pulley system.

Water Storage Tanks Subsystem

The second subsystem consists of the storage tanks. For this exercise, the storage tank system was combined with the filter system for the purpose of doing stress analysis. This system can be seen in Figure 27. For this subsystem, the pumped water will enter through the top of a 150 liter barrilito which rests on the stand and holds dirty well water. The water will then move to the filter below the stand and eventually be dispensed into the second barrilito on the ground. Since this system is outside, the system must be made of materials that can withstand typical weather conditions in Guatemala, like heavy wind and rain. This system must also be fully sealed to prevent contamination. One assumption we are making is that the system will only experience internal forces. Our design and calculations do not account for extra weight, or for people bumping into or leaning on our system. Therefore, we designed around a high factor of safety to account for these external forces and variables, but this analysis report focuses on the internal mechanical forces from the system itself.

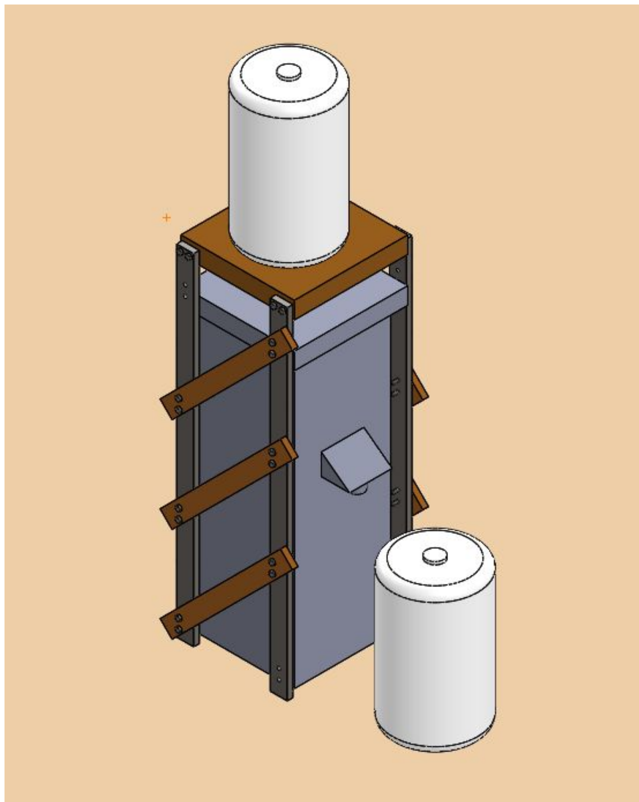

Figure 27: Storage tank and filtration systems produced in SolidWorks.

Materials

Tabel 10: Bicycle/pump system materials and important properties. [40, 41, 42, 43, 44, 45, 46]

Part	Material	Properties
Top Bike wheel	Aluminum	Yield strength: 276 MPa Ultimate tensile strength: 310 MPa Shear Modulus: 26 GPa
Top Flywheel Stand	Steel	Yield strength: 179-207 MPa Ultimate tensile strength: 503-556 MPa Shear modulus: 77-80.9 GPa
Bottom Flywheel	Steel	Yield strength: 179-207 MPa Ultimate tensile strength: 503-556 MPa Shear modulus: 77-80.9 GPa
Bottom Flywheel Stand	Steel	Yield strength: 179-207 MPa Ultimate tensile strength: 503-556 MPa Shear modulus: 77-80.9 GPa
Cassette	Aluminum	Yield strength: 276 MPa Ultimate tensile strength: 310 MPa Shear Modulus: 26 GPa
Rope	Nylon (9mm)	Weight: 5.0 KGS/100M
Water plug	Wood (¾ inch)	Tensile strength: 5.99 MPa Temperature range: -40 C to 70 C
Tube	PVC (Polyvinyl Chloride)	Tensile strength: Rigid PVC: 34 - 62 MPa
Bike	Aluminum	Yield strength: 276 MPa Ultimate tensile strength: 310 MPa Shear Modulus: 26 GPa
Bike Stand	Steel	Yield strength: 179-207 MPa Ultimate tensile strength: 503-556 MPa Shear modulus: 77-80.9 GPa
Concrete	Concrete	Compressive strength: 20-40 MPa Flexural strength:3-5 MPa Tensile strength: 2-5 MPa
Bolts	Mid grade steel	Yield strength: 520 MPa minimum Tensile Strength: 710 MPa minimum

Tabel 11: Storage Tank/Filter/Stand system materials and important properties.

Part	**Material**	**Properties**
Filter	Biosand	Weight: 150 lb
Tanks	Plastic	Dimensions: 24.00 x 19.00 x 34.00 Inches Weight when Full: 470-475 lb
Stand Base	Pine Wood	Modulus of Elasticity: 8000 MPa Poisson's Ratio: 0.31 Mass Density: 340 kg/m^3
Stand Legs	1020 Steel	Modulus of Elasticity: 205,000 MPa Poisson's ratio: 0.29 Yield Strength: 350 MPa
Stand Leg Connections	Pine Wood	Modulus of Elasticity: 8000 MPa Poisson's Ratio: 0.31 Mass Density: 340 kg/m^3
Bolts	Mid grade steel	Yield strength: 520 MPa minimum Tensile Strength: 710 MPa minimum

[40, 41, 42, 43, 44, 45, 46]

Conditions and Expected Results

Water Tank Table Analysis

The first subsystem that we ran finite element analysis (FEA) on was the table top of our tank and filter system. Specifically, we were interested in finding out if the wooden table top and the steel bolts holding it could withstand the force of the water tank above it. An image of the whole system with the tank is shown above in Figure 27 and a close up of the analysis section with bolts and applied force is shown in Figure 28.

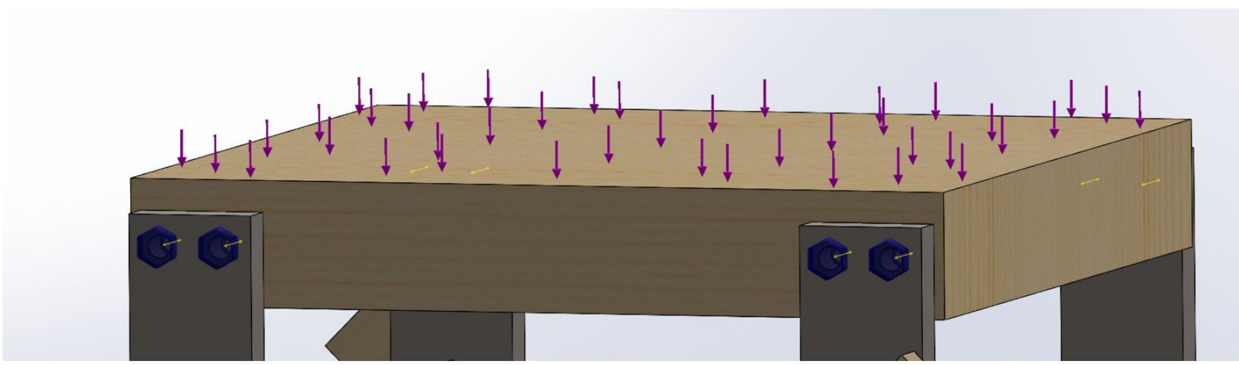

Figure 28: The static loading setup of the table top for FEA analysis. The top block is a 3in by 24in by 24in solid pine block.

There were several parameters that had to be chosen in order to run the study and return useful results. First, we selected pine wood for the table top as pine is a common material available for manufacturing in Guatemala. Based on common types of pine a value of 8000 MPa was chosen for the elastic modulus [5]. The Poisson's ratio is 0.31 and mass density is 340 kg/m^3. The diagonal support trusses were also pine and the vertical table legs are 1020 Steel with an elastic modulus of 205,000 MPa, a Poisson's ratio of 0.29, and a yield strength of 350 MPa. The 75-gallon tank on top of the table weighs 850 lbs when fully filled with water and therefore causes a 3780 N force downward onto the table. This force was distributed evenly onto the top table surface and is represented by the pink arrows in Figure 28. There are eight bolts in the top table, two on each leg. The bolts have a head diameter of 16.9 mm and a radial diameter of 11 mm. We designed the system with 10.9 steel bolts that were axially preloaded to a value of 28,000 N. This may be ambitious, but we've included a high factor of safety ensuring that a lower actual preloaded value will still suffice. Being unable to produce an actual device in Guatemala due to the pandemic signified that we were unable to do actual bolt selection so there was no need to recalculate with a physical bolt preload value.

The expected mode of failure for the table is due to shear force. The critical points of the table and legs will be the holes that the bolts are inserted to. The bolts may also fail due to shear. In order to confirm the accuracy of our FEA model, hand calculations were completed to check against the computer generated result. Figure 29 below also shows the screw and equation.

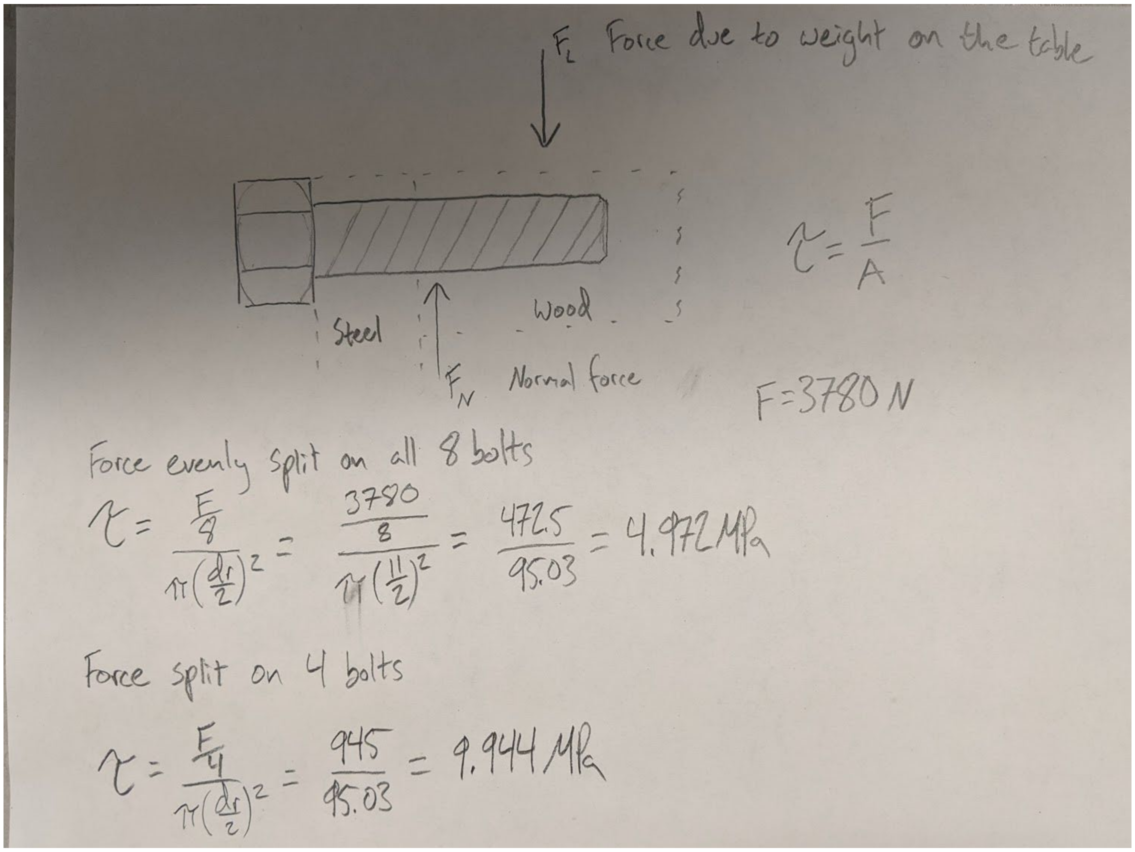

Figure 29: Vertical shear force acting on a screw.

F is the force on the bolt. An assumption that the shear force is evenly split among the eight bolts was made. Dividing the force by eight gives a force of 472.5 N on each bolt. Therefore:

F = 472.5 N

Dr = 11 mm

And:

τ = 4.972 MPa

This calculation was repeated assuming that the load would be taken by only four of the bolts because each pair of bolts will likely have one bolt that takes most of the force. This resulted in a shear stress of:

τ = 9.944 MPa

The FEA analysis returned differing results from our hand calculation. The maximum shear stress value was 221 MPa at the bolt hole edge. The max value is shown in Figure 27 below. This value is below the steel yield strength of 350 MPa. The factor of safety is approximately 1.6 for maximum loading. This value could be higher but given that it is very unlikely the tank will ever be completely full since water should be filtering into the secondary container within an hour of being pumped, the load on the table is going to stay below the values we used. Therefore, it is safe to assume our table legs will not deform from the shear stress.

To analyze the bolts, the force on the connector section was used. The max shear force value on any bolt was 578.3 N. This value is less than the 945 N force we assumed for our hand calculations. Therefore each bolt should experience less than 9.944 MPa of shear stress. This is a very safe range to be in, given that the bolts have a yield strength of 940 MPa.

Problems in the analysis occurred with the mesh failing when bolts were inserted into the hole. To solve this first problem, the bolts were removed and then placed back in as a connector. Then a contact had to be set between the table and legs in order to mesh properly. After these adjustments, the mesh only was successful (did not return an error) when set to the coarsest or lowest settings. These settings could affect the accuracy of our returned result. Additionally, the purpose of the study was to analyze the bolt strength and factor of safety. Because the bolts were connectors in the analysis, shear stress was not analyzed directly on the bolts. Instead, they returned connector force values and these values were checked against the hand calculation values.

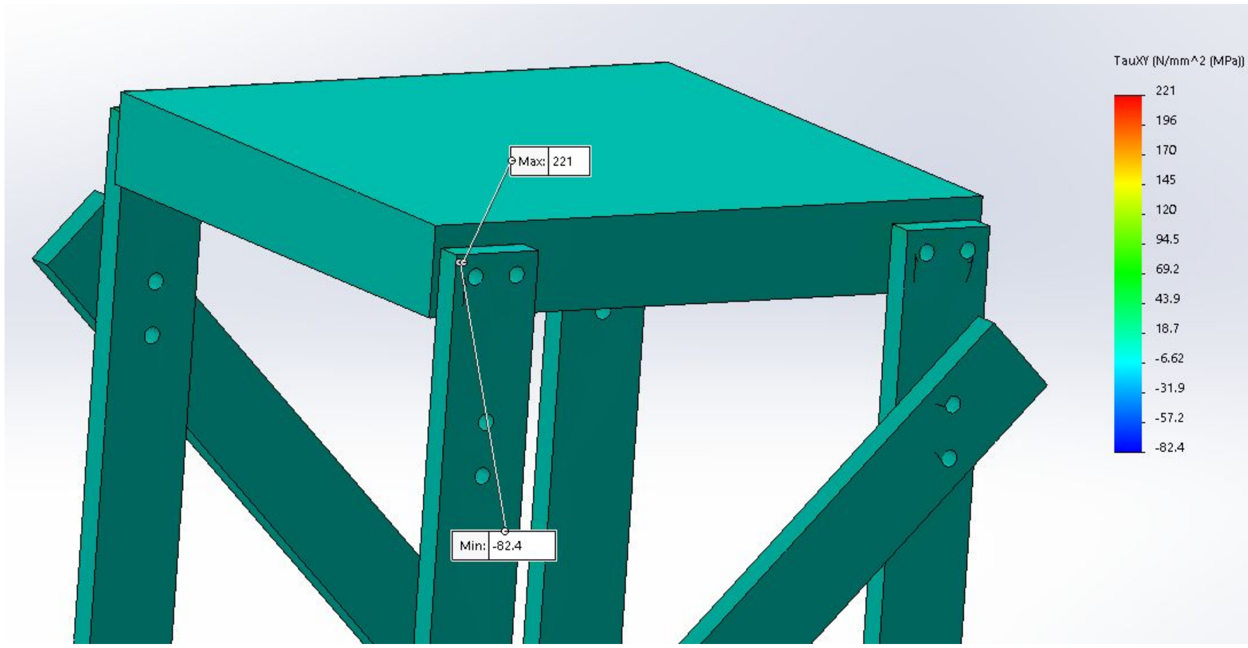

Figure 30: The shear stress analysis of the table top. The max point (221 MPa) is located at the top of the bolt hole right on the edge of the wood and steel.

While the FEA analysis provided some useful results, it is hard to make concrete design decisions from this model, especially considering that it is likely that the material and dimensions will change on the actual build in Guatemala, due to what is available to be sourced in rural Guatemala. However, this analysis does suggest that eight bolts will be sufficiently strong to connect the table to the legs. The trusses do not really provide much added strength to oppose the vertical shear force from the weight of the tank. The trusses were added in order to prevent horizontal forces such as the table being bumped from shifting the position of the legs. Because this force is much smaller than the vertical shear force we likely will only need one support truss on each side instead of three. Further analysis should be done on the vertical and horizontal forces on the table. This will ensure the accuracy of our first result and allow for a more accurate analysis on the need for support trusses.

Flywheel Analysis

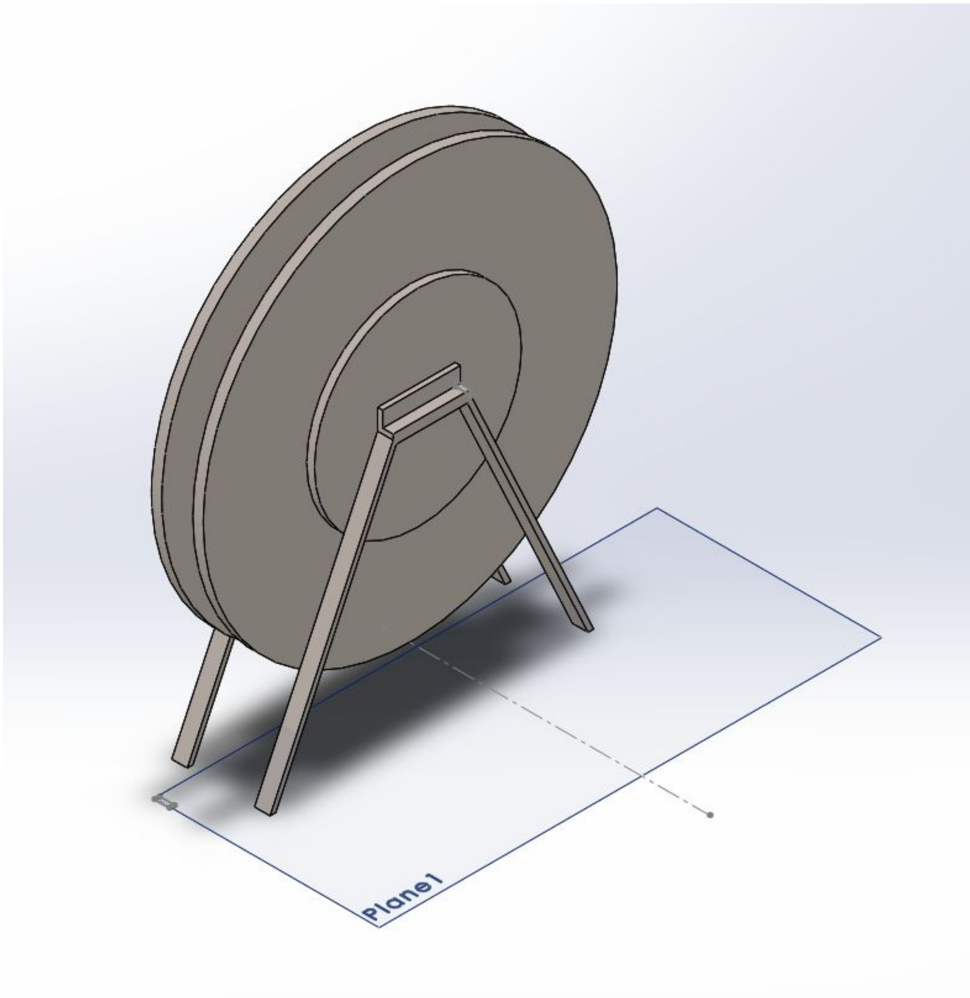

Figure 31: Flywheel subsystem CAD model, initial prototype.

The flywheel in Figure 31 is the subsystem that helps translate the power from the bike to the pump pulley system. Figure 32 below shows the von Mises stress concentrations on the flywheel. The blue areas have lower stress and the red areas have higher stress. The pink arrows are straight down and represent the force of the rope. The legs of the wheel were modeled as being fixed to the ground.

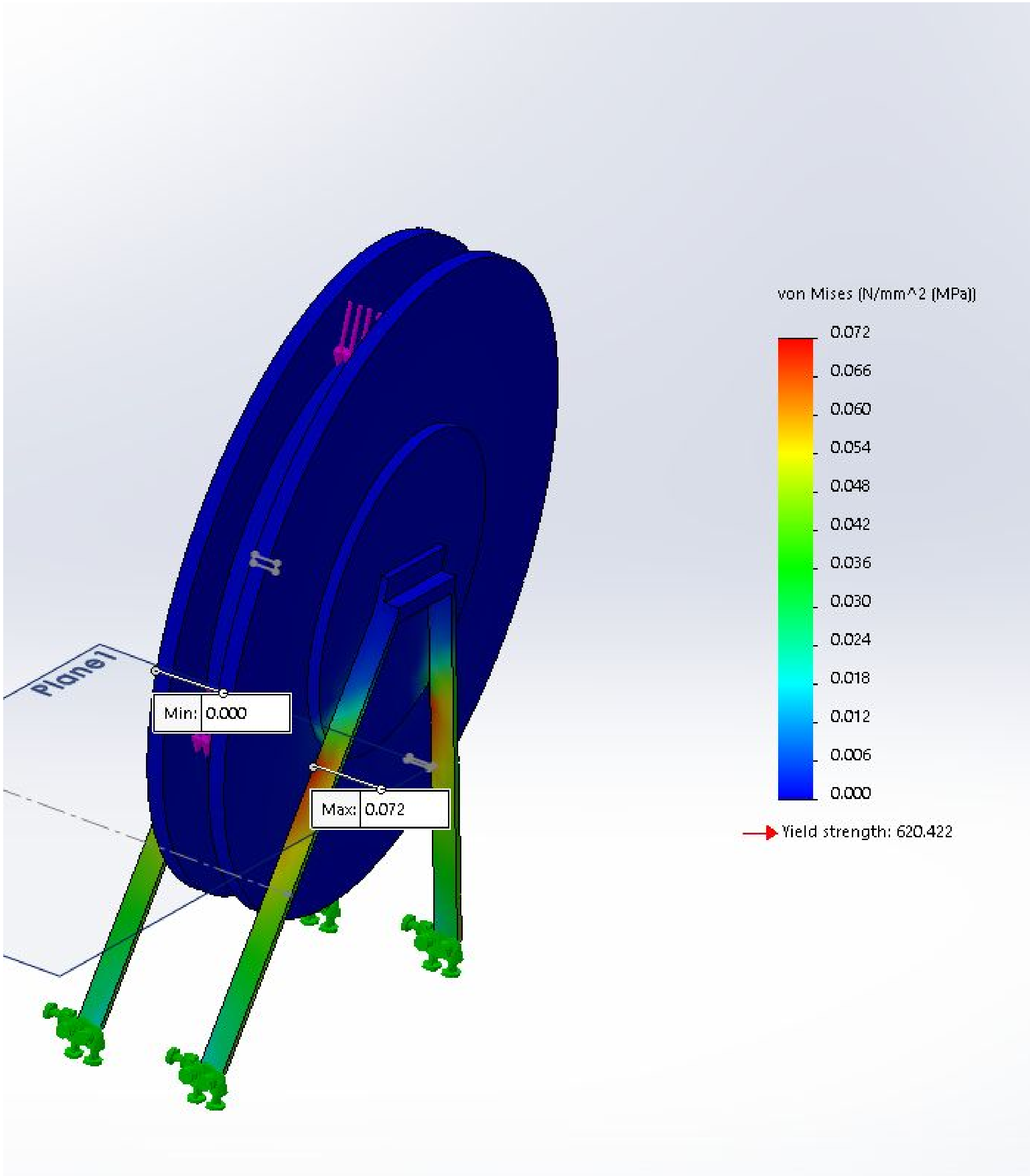

Figure 32: The von Mises stress finite element analysis on the flywheel.

The max stress was 0.072 MPa in the middle of the steel legs, the minimum stress was 0. The yield strength of the alloy steel is 620 MPa, and no deformation is expected in any part of the system. This results in a factor of safety of over 8,000. Based on this preliminary FEA analysis, the system will be strong enough to hold the rope, but several assumptions were made for this analysis that may not be true. First, the rope will have increased weight due to the knots and plugs that will carry the water. The weight of the water being pumped will also contribute. The weight of the rope may also not be directly downward. The rope will likely be strung over two wheels and have force components that act on the wheel in more than just the y-direction. See Figure 33 to see that the flywheel will also need to spin and that the axle was not modeled in this analysis. The axle could be a critical point of stress. The weight of the disc was not considered as it added little to the force on the legs. The connection point between the legs and the disc of the wheel may be a critical point, and further analysis should be done to ensure that welds will be strong enough to hold that connection. By iterating the flywheel, the updated design allows for the wheel to rotate freely and more accurately reflects the system.

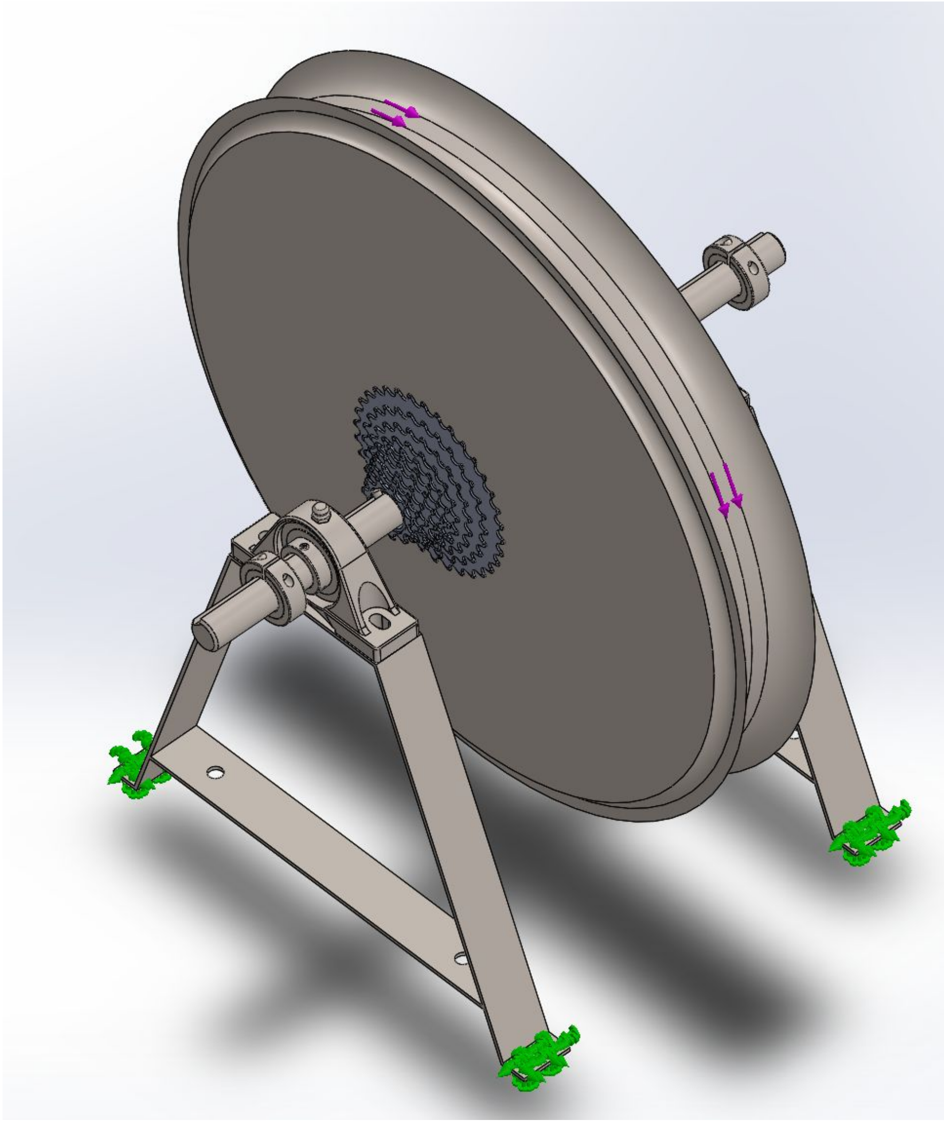

Figure 33: Flywheel subsystem CAD model.

The flywheel, shown in Figure 33 above, is fixed with eight bolts at the bottom to the general frame leading to a completely fixed connection. This supports the bearings, which are fixed with two bolts each to fix the connection and resist any moment. The ball bearings allow the shaft to rotate freely and allow the torque (taking into account the conservation of energy) to be transferred from the cassette to the flywheel rather than creating stress in the system. These parts only encounter stress when the bike cassette and chainring are not aligned with the cassette on the flywheel or the flywheel is not aligned with the wheel above the well. In the current setup where the torque is perpendicular to the flywheel, there would be no stress with the setup of the bearings.

If the system is over tensioned, there would be some axial loading on the bolts attaching the frame to the bearings and attaching the frame to the platform. The class 10.9 steel M10 bolts on the base and class 10.9 steel M4 bolts on the bearings are more than able to withstand these unintended stresses. The other loading could come from misalignment as mentioned earlier. However, these are likely to be able to be absorbed by flexion within the chain or the rope pulley. The aluminum cassette is the weakest link in the system, but since it is being driven by a human biker connecting a chainring or cassette to this cassette, it will be able to withstand the torque shown in Figure 34 below.

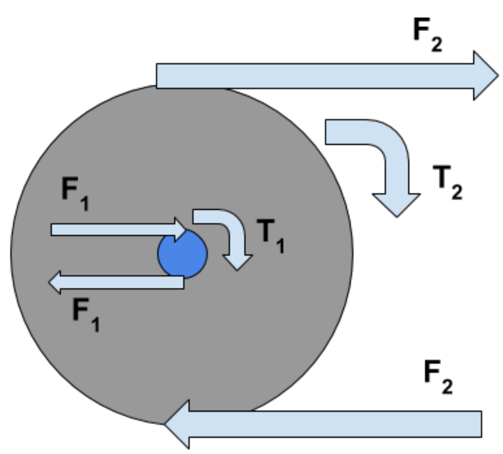

Figure 34: Flywheel Free Body Diagram.

The free body diagram shows the intended forces on the wheel, which would only lead to failure if the bolted/welded connections failed. The only stresses would come from misalignment in the system as the bearing allows the flywheel to rotate. Attempting to perform FEA on the stresses caused by the misalignment was not successful. SolidWorks repeatedly failed to successfully mesh many of the components, despite creating contacts between every connection. Because of this shortcoming, class 10.9 steel bolts are used to ensure a reasonable factor of safety.

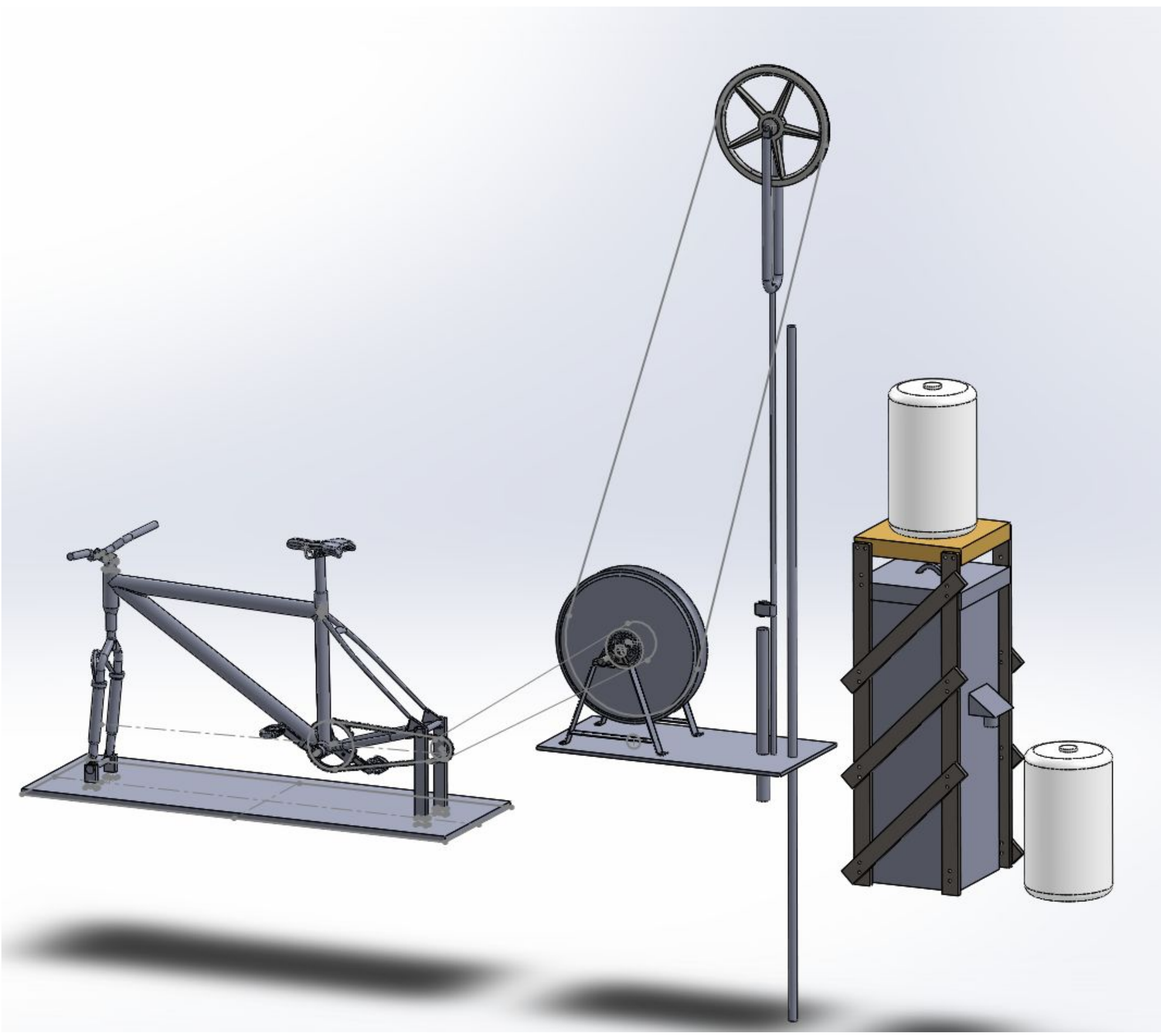

Figure 35: Full CAD assembly with all subsystems. Left view.

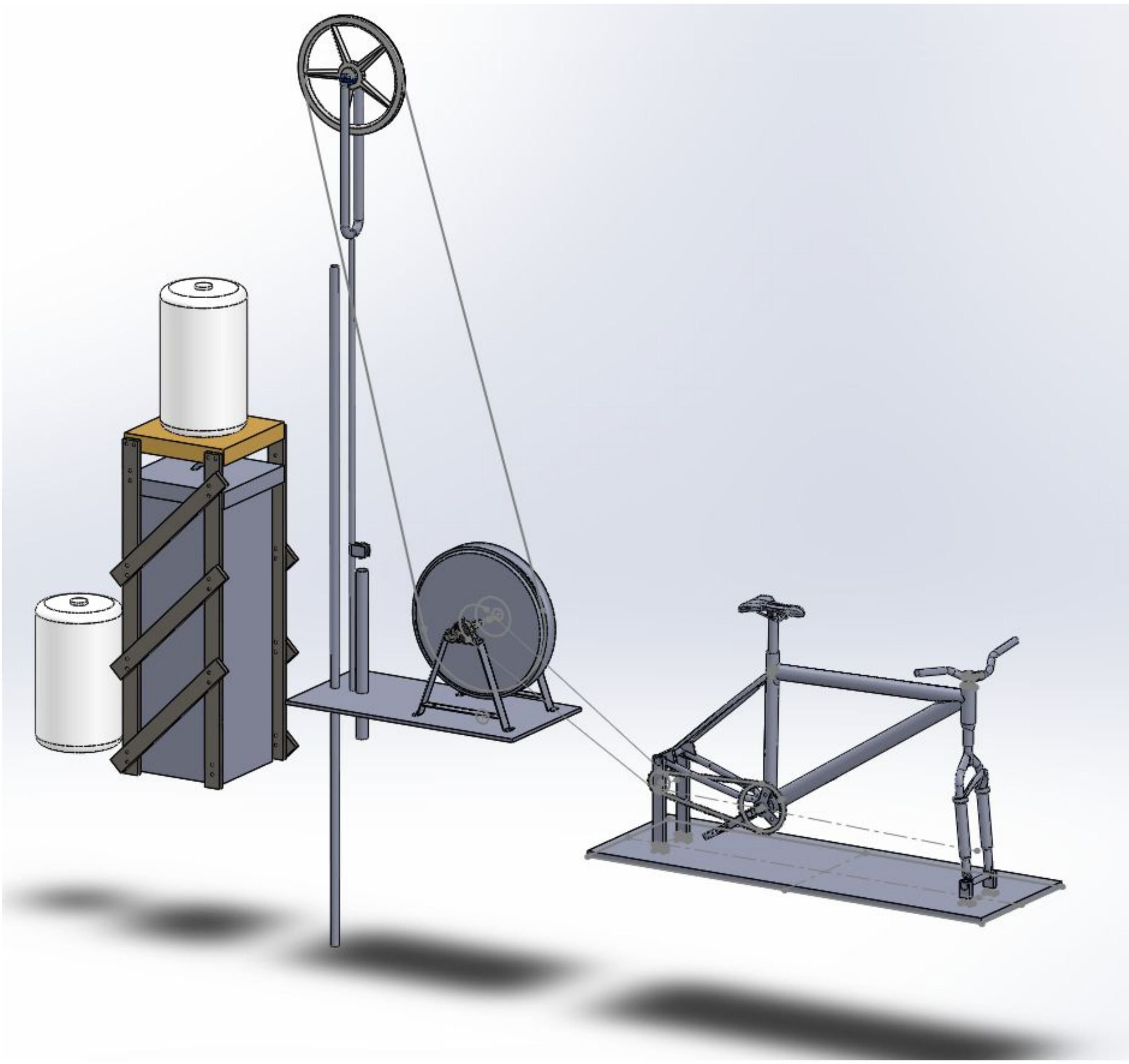

Figure 36: Full CAD assembly with all subsystems. Right view.

Vertical Pulley System Analysis

In the water pump pulley subsystem, there is a major force from the bike that is acting vertically downward on the small bike wheel connected to the bike prong at the highest point of our system. This force will be equal to the horizontal force produced by the user peddling the bike. The pulley wheel axis is two meters above the ground because the water needs to exit at a high enough point so the water can flow into our filter tank, which is a couple of feet off of the ground. The rope goes around the wheel and into each of the tubes attached to the water storage tanks carrying water out. As configured now, the middle column is fixed into the rectangular base and free moving on the other end. With the downward force from the bike pedaling, the only expected failures are from buckling at the point where the bike prong is attached to the rod, or where the rod is attached to the bottom base. These stress areas are shown in detail in Figures 37 and 38 below.

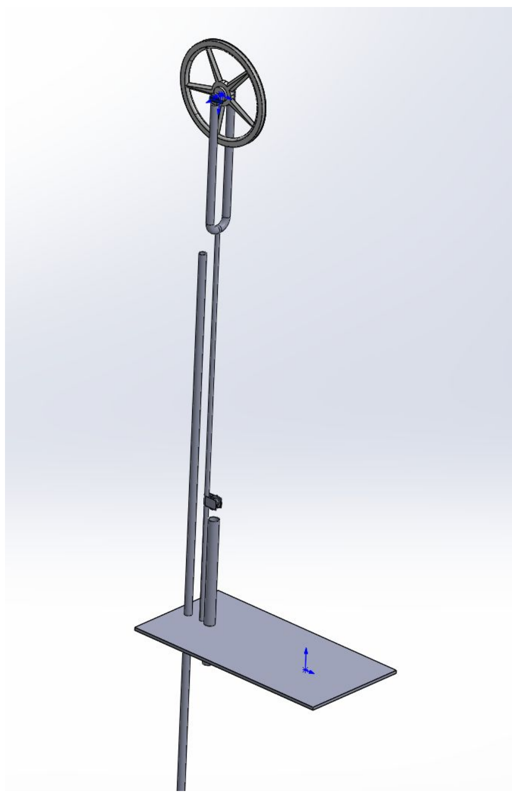

Figure 37: Full CAD of Pulley Rope System.

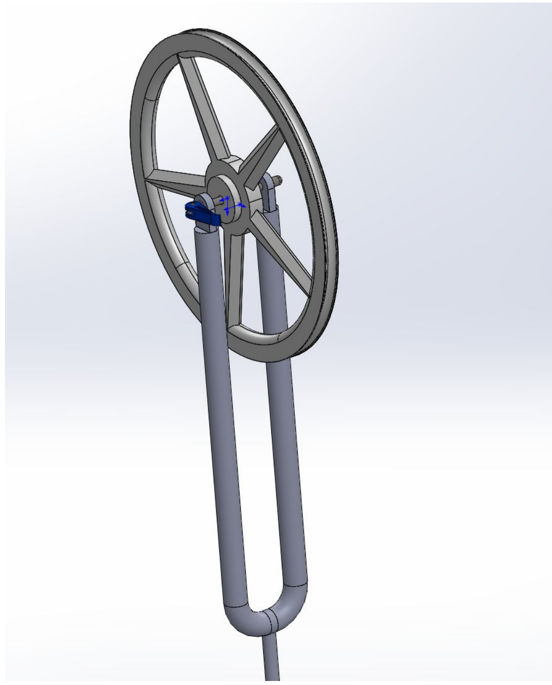

Figure 38: Close up of pulley rope system.

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To find out more about the failure, a finite element analysis was done on the middle column in order to highlight areas of stress. A 500 N of force is acting downwards on each of the two bike prongs. The first image below, Figure 39, shows the stress along the column and prong with a von Mises stress analysis. The two highly stressed areas in the subsystem are along the long alloy steel rod and at the point where the bike prong connects to the rod. According to the FEA, the yield strength of the subsystem made of alloy steel is 620.4 MPa. The von Mises stress along the rod is approximately 4.48 MPa and the highest stress point at the connecting point is 5.97 MPa as gathered from the von Mises diagram in Figure 36 and 37. Neither stress points or ranges reach close to the yield strength of the alloy steel subsystem, and a preliminary factor of safety of approximately 100 was found for this subsystem under typical loading.

The main issue encountered with the finite element analysis was getting the model to mesh because of the contact point between the bike prong and the steel rod. This is a similar problem that may be encountered in the manufacturing of this part since we will need to weld the parts together and that will be a weak point if done incorrectly. This is an issue that needs to be addressed by either becoming very familiar with welding techniques or creating a support at the connecting point to increase the allowable load at that specific point. Further analysis can be conducted on the strength of that weld in order to ensure a reasonable factor of safety. After discussing this with the on site welding expert at Maya Pedal, they showed us various similar solutions that were effective, and were not concerned about implementing this component of the design.

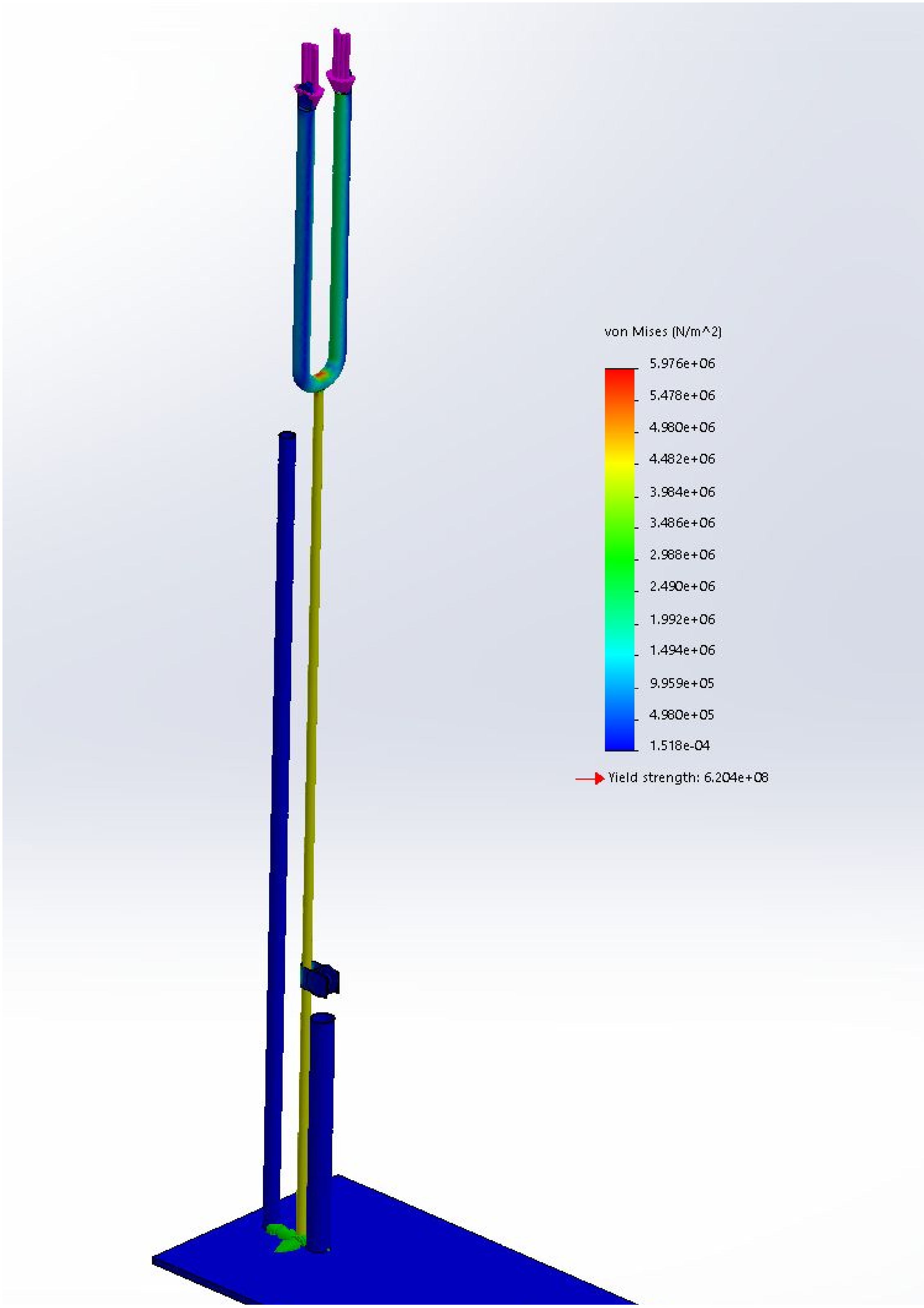

Figure 39: Von Mises stress diagram of the entire water pulley system.

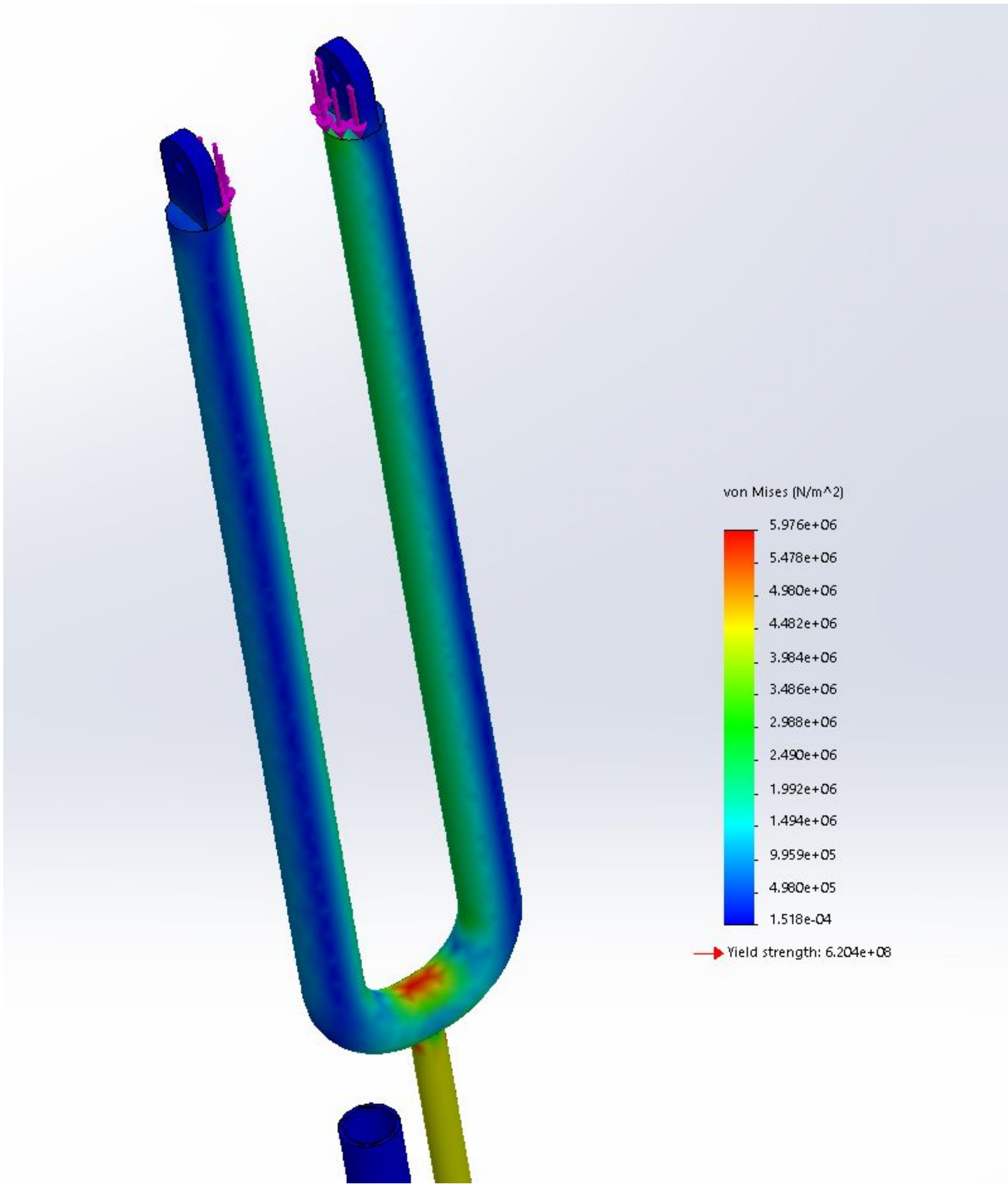

Figure 40: Closeup of the critical point on the bike wheel prong based on the downward force.

To justify the results of the finite element analysis, hand calculations for column buckling were done on the prong system with a downward vertical force of 500 N as shown in Figure 41.

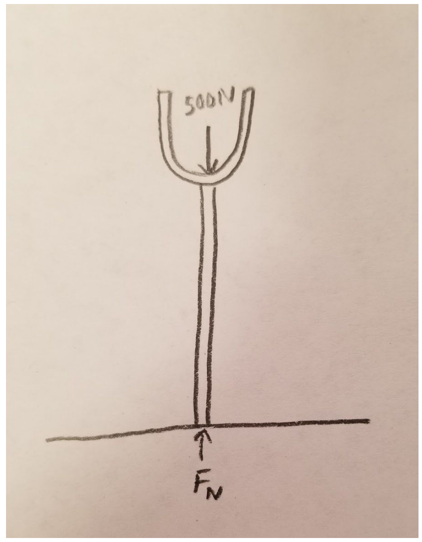

Figure 41: Forces on vertical pulley system accounted for in hand calculations.

Euler's Column Formula for Buckling Columns [46, 47]
$F=n\pi EI/L^2$
Where,
n = factor accounting for the end conditions of the system
E = Modulus of Elasticity
I = Moment of Inertia
L = length of column

For general alloy steel
E = 200 GPa

Moment of inertia equation
$I_y=\pi(d_0^4-d_i^4)/64$

For our CAD design
$d_o = 0.0170$ m
$d_i = 0.0127$ m
t = 0.0043 m
L = 1.65 m
n = 0.25 for a system with one fixed end and one free end
Therefore,
$I_y = \pi(0.0170^4-0.0127^4)/64$
$I_y = 2.84$ E-9 m^4

The final calculation for the allowable load on the column is
$F = (0.25)*\pi*(200E9\ N/m^2)*(2.84E\text{-}9\ m^4) / (1.65)^2$
F = 514.78 N

This hand calculation is done by assuming one vertically downward force on the point where the bike prong and the rod are welded together instead of on top of the two bike prongs as done in the finite element analysis. According to the hand calculations, the rod at its current dimensioning can only withstand 514.78 N before experiencing buckling. This is right around the value that we expect to be produced from the bike, so the allowable load on the column needs to be increased. Fortunately, the thickness of the pipe was selected for the CAD design. The thickness of 0.0043 m, is thinner than the material we expect to be able to find once we build the actual system in Guatemala, so the actual allowable load on the column will be much greater. Both the hand calculations from Euler's equation and the finite element analysis show that the rod thickness or diameter needs to be increased to withstand the load from the bike, even though the force calculations were done with the maximum force that could be exerted by an adult on a bike.

Power Calculations

For this system, there are a few clear boundaries that are outputs and inputs for the system, namely the power in from the biker and the flow rate out from the pump. However, the depth of the well is also a limiting factor, and the pipe diameter along with the top wheel radius determine the torque and cadence that the flywheel should be geared to.

The amount of power produced by a biker greatly changes based upon height, weight, and fitness level. Active humans can produce between 1.5 W/kg (untrained) and 6.6 W/kg (top-class male athletes) [48]. Because of this and other estimations of bike power for a sustained period of time for non-bikers, a power range was established of 75 to 125 W [49]. Another major constraint is flow rate, where the ideal value is 18.9 L/min and the marginal value is 7.5 L/min. The final constraint provided by Maya Pedal is making a system that can work for a well varying in depth from 30 to 45 meters.

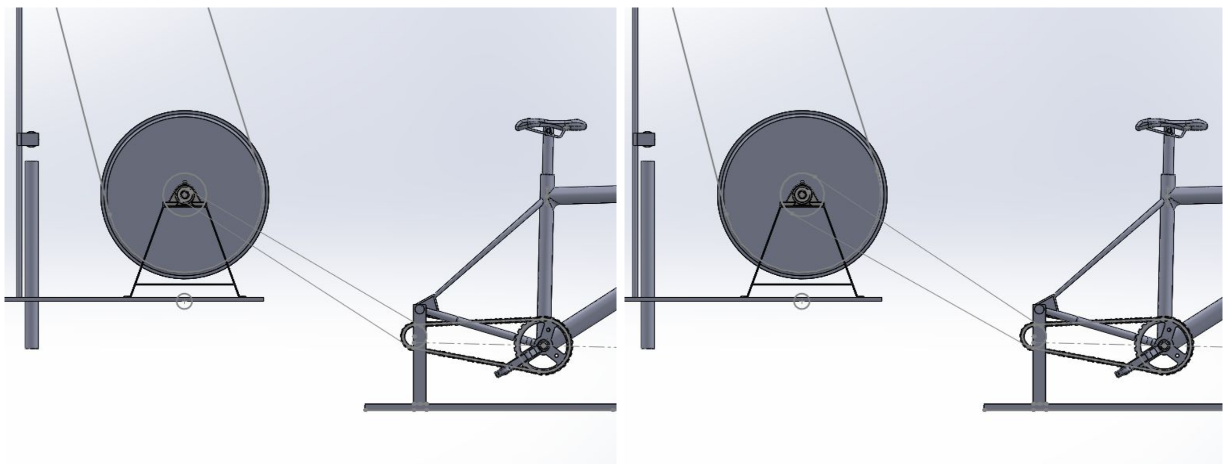

Figure 42: Flywheel configuration for a shallow well (left) and a deep well (right).

These two configurations demonstrate how the torque and cadence of the flywheel can be adjusted based on changing gears on the cassette. By doing so, gearing to a smaller gear on the cassette allows for a faster flow rate at a comfortable torque for shallow wells. This is able to occur without needing a separate entire wheel for deeper wells, which improves the frugality of the solution. The following three equations are used to calculate the power required for the system to meet the goal constraints and the results are provided for different diameters and heights in Table 16 below [26].

1. **Torque** (N.m) = 9.5488 x Power [kW] / **Cadence** (RPM)
2. Water Force [N] * **Top wheel radius** [m] = **Torque** [N.m]
3. Rope velocity [m/s] = **Cadence** [RPM] * **Top wheel radius [m]** * 2π / 60 [s/min]

The following calculations are needed to perform the above calculations successfully. The flywheel is made of cement to increase its momentum, and neglecting the inertia provides a factor of safety for these calculations. The wheel inertia is appropriate to include for steady-state flow calculations, but the system we visited in Guatemala rarely ran so smoothly. Without having physically built our system in Guatemala due to the changed plans caused by the pandemic, we cannot confidently assume the effect of the flywheel's inertia.

Water force [N] = (Volume of Pipe - Volume of Stoppers)$\varrho_{water}g$ = (**Well Torque**) / (**Top Wheel Radius**)
5 [*gal/min*] = 0.000315451 [m^3/s] = *mass flow rate* 0.314504647 [*kg/s*]
Rope velocity [m/s] = Height [m] / (Mass [kg] / *mass flow rate* 0.314504647 [kg/s])
Rope Velocity [m/s] *60 [s/min] / **Top wheel radius [m]** * 2 π = **Cadence** [RPM]
Water Force [N] * **Top wheel radius** [m] = 9.5488 x Power (kW) / **Cadence** (RPM)

Table 12: Calculations for power needed and flywheel torque and cadence. Calculations vary based on pipe diameter and well depth and assume a well top wheel radius of 0.2 m.

Diameter [mm]	Height [m]	Water Mass [kg]	Water Force [N]	Rope Velocity [m/s]	Cadence [RPM]	Torque [N.m]	Power [W]
20	30	9.40	92.2	1.004	95.85	18.44	185
30	30	21.14	207.4	0.446	42.62	41.48	185
40	30	37.59	368.7	0.251	23.97	73.74	185
50	30	58.73	576.1	0.161	15.34	115.22	185
20	45	14.09	138.3	1.004	95.85	27.66	278
30	45	31.71	311.1	0.446	42.62	62.22	278
40	45	56.38	553.1	0.251	23.97	110.62	278
50	45	88.09	864.2	0.161	15.34	172.84	278

The power is conserved throughout the system, although it is geared down for the flywheel and well in order to handle the massive load of water that is being pulled up.

The only way to change the weight of the water, the load, is by changing the diameter of the pipe. Therefore, given a constant radius of the top wheel, the torque is determined by the weight of the water. Because of that, the flywheel and bike should be geared in such a way so that the biker can bike at a comfortable cadence and lift the water. The well cadence determines the flow rate that the water enters the top storage tank.

Table 13: Constants used for calculations in Table 14.

Variable	Amount	Units
Well Depth (Montellano)	31.3944	meters
Well Depth (Minimum)	15	meters
Well Depth (Middle)	25	meters

Well Depth (Maximum)	40	meters
Pedal Power (child)	75	Watts
Pedal Power (adult)	125	Watts
Top Wheel Radius	0.2	meters
Density of Water	997	kg/m^3
Assorted Losses	1.15	(proportion)

Table 14: Theoretical rope velocity and flow rate calculations for various well depths and pipe diameters.

Diameter [mm]	Height [m]	Water Force [N]	Water Force with assorted losses [N]	Torque at top flywheel [N.m]	Top flywheel cadence (child pedaling) [RPM]	Flowrate (child pedaling) [l/min]	Top flywheel cadence (adult pedaling) [RPM]	Flowrate (adult pedaling) [l/min]	Rope velocity (child) [m/s]	Rope velocity (adult) [m/s]
17.8	Montellano	76.4	87.8	17.6	40.8	12.7	67.9	21.25	.854	1.423
17.8	Minimum	36.5	42.0	8.4	85.3	26.7	142.2	44.47	1.787	2.978
17.8	Medium	60.8	69.9	14.0	51.2	16.0	85.3	26.68	1.072	1.787
17.8	Maximum	97.3	111.9	22.4	32.0	10.0	53.3	16.67	.670	1.117
20	Montellano	96.4	110.9	22.2	32.3	12.7	53.8	21.25	.676	1.127
20	Minimum	46.1	53.0	10.6	67.6	26.7	112.6	44.47	1.415	2.359
20	Medium	76.8	88.3	17.7	40.5	16.0	67.6	26.68	.849	1.415
20	Maximum	122.9	141.3	28.3	25.3	10.0	42.2	16.67	.531	0.885
30	Montellano	217.0	249.5	49.9	14.4	12.7	23.9	21.25	.301	0.501
30	Minimum	103.7	119.2	23.8	30.0	26.7	50.1	44.47	.629	1.048
30	Medium	172.8	198.7	39.7	18.0	16.0	30.0	26.68	.377	0.629
30	Maximum	276.4	317.9	63.6	11.3	10.0	18.8	16.67	.236	0.393
40	Montellano	385.7	443.6	88.7	8.1	12.7	13.5	21.25	.169	0.282
40	Minimum	184.3	211.9	42.4	16.9	26.7	28.2	44.47	.354	0.590

40	Medium	307.2	353.2	70.6	10.1	16.0	16.9	26.68	.212	0.354
40	Maximum	491.5	565.2	113.0	6.3	10.0	10.6	16.67	.133	0.221
50	Montellano	602.7	693.1	138.6	5.2	12.7	8.6	21.25	.108	0.180
50	Minimum	288.0	331.2	66.2	10.8	26.7	18.0	44.47	.226	0.377
50	Medium	479.9	551.9	110.4	6.5	16.0	10.8	26.68	.136	0.226
50	Maximum	767.9	883.1	176.6	4.1	10.0	6.8	16.67	.085	0.142

However, these calculations fail to account for the fact that the stoppers are not perfectly sealed. Because they are irregularly shaped wooden stoppers, some of the water leaks through and results in a smaller flow rate than Table 19 indicates. This can be simulated by using the stoppers diameter as 0.8 cm smaller than the pipe diameter, and using Bernouli's principle to calculate the actual flow rate.

Table 15: Constants used for water loss calculations shown below that are used for the flow rates in the graphs of Figure 43 and 44.

Variable	Amount
Length of water segment [m]	0.5
Velocity of water falling [m/s]	3.13
Flow rate [m^3/s]	Q = A * v
Area [m^2]	0.00008745

A= surface area difference between stopper and pipe inner diameter

v = relative velocity between rope and water flow

The velocity of water (3.13 m/s) is found using Bernoulli's equation with the water segment height of 0.5 meters. This is the velocity of the water at the bottom of one segment of water between the stoppers in our pulley system, assuming it's falling undisturbed. The difference between the speed of the falling water and the speed of the rope (v) is used to find the actual flow rate in the area between the stopper and the inner diameter, Q. Finally, this flow rate is subtracted from the flow rate of the water being lifted by the stopper to find the actual flow rate as shown in the graphs below in Figures 43 and 44. This was then converted to liters/minute to make the data easier to interpret. The calculation was focused on one single segment of stoppers because the volume of water in the segment must remain the same as it travels to the top of the well or else the pump will be useless. Of course the leakage from these segments will flow to the segments below, but we don't account for this because if there is leakage the entire time the segment is traveling upwards then there will be little to no water once it reaches the top.

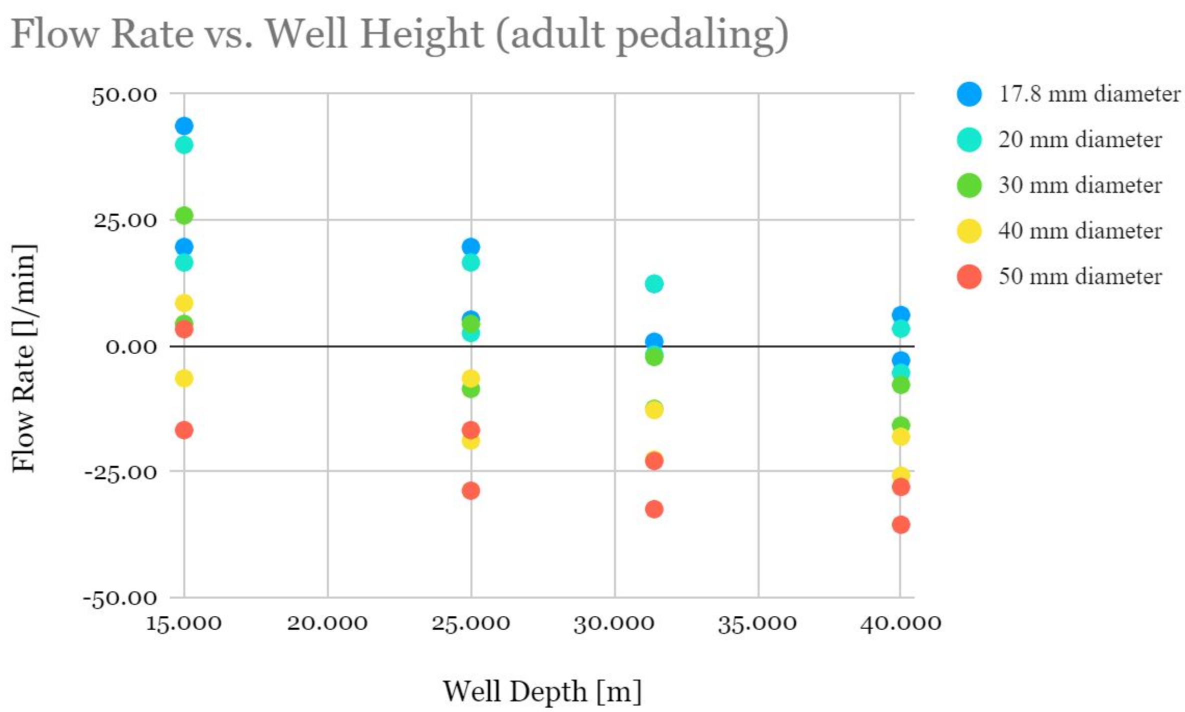

Figure 43: Graph of flow rate versus well depth for various pipe diameters for an adult pedaling, including water loss calculations.

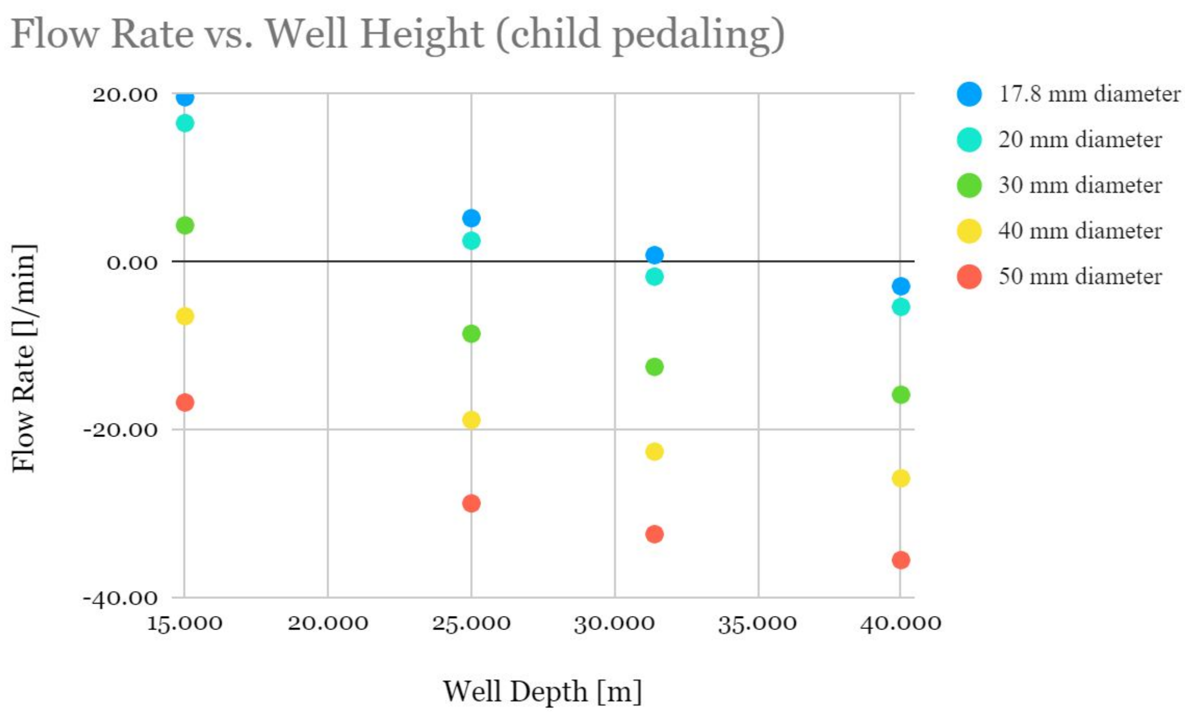

Figure 44: Graph of flow rate versus well depth for various pipe diameters for a child pedaling, including water loss calculations. Full supporting calculations are tabulated in the Appendix.

These graphs indicate the shallower wells have higher flow rates, which makes sense intuitively. Additionally, it indicates that thinner pipe allows water to flow more efficiently. The final graph indicates that a child can successfully pump water from a 31 meter well (100 feet), but no deeper. They won't be able to reach the desired flow rate of 19 L/min, but will still be able to pump water on their own. This aligns with our project goals perfectly, demonstrating the validity of our design for our project constraints. Unfortunately, the design is not efficient enough for a child to pump water from beyond the target depth at 40 meters, that is only doable for an adult.

Analysis Reflection

Computer modeling is a tool that can be utilized to better understand and visualize how a design will function. We used Solidworks to model our system and then analyze the model. This proved to be an effective tool, as we were able to model and assemble our whole system. We did this to develop a full system view in order to better visualize how the sub components of the design fit together, and to be able to more clearly explain the function of our design. We also performed finite element analysis on critical components of some of the sub assemblies. The FEA analysis of the tank table top showed that eight bolts should be sufficient to connect the table top to its legs. However, the hand calculations and FEA analysis returned different results, which lowers the amount of confidence we have in the accuracy of this FEA. The FEA and hand calculations on the vertical pulley system showed that as currently designed, the system can take the expected stress from the force of the bike, but the hand calculations show that buckling may occur when a large force is applied to the small bike wheel column. Therefore, we will be looking for steel pipes in Guatemala that are thicker or have a larger diameter to have a higher allowable force before the system buckles or fails.

This analysis report has shown that there is not always congruence between different stress and strain calculations. So, we need to plan for the worst case scenario provided, and designed a prototype, because that is the best way for us to learn how our system will perform in the real world. Another lesson learned from this analysis report is that our design does not leave much room for error in terms of stress failure for some parts, specifically the vertical rope pulley system. For this subsystem and the project as a whole, we are aiming for a factor of safety of around 2.5-3.5 as a safe range since the community we are working in is not equipped to fix broken components if the situation arises, and we want this system to be operable for years to come.

6. Budget

Maya Pedal: This is an NGO centered in Guatemala which creates 'bicimaquinas' (bike machines) to help provide community members more efficient ways to do everyday tasks such as grinding coffee, stripping wire, or washing clothes. Maya Pedal worked with a senior design group last year and was our primary contact in Guatemala. Maya Pedal is well connected with the mayor of San Andrés Itzapa, the city in which the well site is located. Maya is one of the main resources we are utilizing to establish customer needs and project constraints. In Guatemala, we planned to work with Maya Pedal staff to build the physical system and educate people on how it works so it can be scaled to other communities in the future. Maya Pedal is also working on creating an external funding campaign to purchase more biosand filters from Pure Water for the World.

Frugal Innovation Hub: This organization on campus focuses on serving as a bridge between the School of Engineering and real world organizations. For our project, FIH will be handling many of the non-technical components such as facilitating much of the contact with Maya Pedal, travel logistics, helping to overcome the language and cultural barriers, and providing realistic feedback about our project plans and expectations.

Expenses:

System Costs

Our project is being built for Maya Pedal and the San Andrés community. Through their organization they are providing the bike, and tools for building the system. However, we are responsible for the other components and being able to buy and build those components within our limited time and resources in Guatemala. To make this possible, we prototyped parts of the system while at Santa Clara. By starting with the most general materials, we can create parts of the subsystem we deem very important, but with the COVID-19 pandemic forcing many of us back home we were unable to prototype the bike and the pulley pump systems saving most of our planned expenses. During our first trip to Guatemala, we took many measurements, examined the current system, and visited local hardware stores. We now are more able to categorize components/subsystems with appropriate actionable items and have updated Table 16 below.

Table 16: Categories and action items used for component selection while in Guatemala.

Category	**Action Items**
Currently implemented subsystem. *(i.e. rope, stoppers, and piping is all setup with hand powered well)*	1. Record and measure components. 2. Determine source of components and cost. 3. Buy and bring back small and light parts to SCU for prototype.
Partially implemented subsystem. *(i.e. bike and flywheel are setup for a machine but the gearing is wrong and the stand is not stable)*	1. Record and measure components that are present. 2. Determine source of components and cost. 3. Determine appropriate sizes for the missing components. 4. Buy and bring back small and light parts to SCU for prototype.
Fully unique subsystem. *(i.e. no scalable filter system currently exists)*	1. Look for components that are available that match current CAD prototype. 2. Determine source of components and cost. 3. Record all available components, and document any potentially useful components. 4. Buy and bring back small and light parts to SCU for prototype.

This method will make it possible to have a scalable project and allows the SCU prototype to be a useful model. By buying all of the actual components in the San Andrés region and designing the system based on those materials, the system meets the needs established by Maya Pedal and the mayor of San Andrés. In doing so, we reduce the possibility of making the same mistakes that led to last year's project not being considered an appropriate solution by Maya Pedal because of the inability to replace the parts in Guatemala. Table 17 includes the prices of our parts we needed to prototype a full system in Santa Clara with parts we can buy in the states.

Table 17: Itemized budget with cost estimates for each part in our system

Item	**Cost (USD)**	**Source for Price Estimation**
Pump and Bike Subsystem **Maya Pedal Iteration**		

Bicycle	$0	Donated by Maya Pedal
Metal for frame (Steel)	$200	Disalvi: Major metal supplier in Guatemala, price estimate would be with welding and cutting in the Maya Pedal Shop. [50]
Rope/ stoppers for well	$50	Will use rope used for hand powered rope wells in the area. This way it is easy to replace/repair.
Flywheel	$75	Multimateriales: Major hardware store in Guatemala. Price estimate is half the price of similar wheels at US hardware store. [51]
Flywheel to gear	$30	MSC Industrial Supplier: Another major hardware retailer, this is half the price of similar parts in the US. [52]
Chain ring, cassette, chain, bottom bracket adapter, rear and mid derailers with shifters.	$150	Subsidized by Maya pedal. These are common bike parts that we will need to adapt for our system.
Brackets, bolts and other hardware	$40	Multimateriales [51]
Bike and Pump Cost	**$545**	
Filter and Tank Subsystem Maya Pedal Iteration		
Piping	$50	EPA Guatemala: This is for a flexible pipe that the rope will go through. [53]
Natural Filter Sediment	$35	El Globo: This will be provided through Pure Water for the World [54]
Steel for Filter Case	$100	Online Metals: This price is for the steel bars. We will cut and weld them to size. [55]
Brackets, bolts and other hardware	$40	Multimateriales: Some hardware can be obtained from Maya Pedal; this price is for

		the assorted parts that they may not have such as larger bolts and connector brackets. [56]
Upper holding tank	$75	Multimateriales: Price estimate is half the price of similar sized tanks at US hardware store. [51]
Lower holding tank	$20	Multimateriales: Price estimate is half the price of similar sized tanks at US hardware store. [51]
Biosand filter case/ “Pure Water for the world” filter	$75	Subsidized filter price estimate based on interview with Mario and Dave.
Water quality test meter	$120	Cole-Parmer [56]
Cement Base	$125	Half the price of cement in the US. This supply is available in San Andrés.
Tank filter system cost	**$640**	
Prototype Cost		
Bikes for prototyping	$140	Two used Bikes via craigslist or Facebook Marketplace.
Tanks and piping	$110	Home Depot: Piping and tanks. [57]
Tank reservoir and piping to simulate well	$75	National Tank Outlet: (This is bigger than necessary but the type of tank we will need) [58]
Bolts, brackets and connectors	$35	American Ace Supply: Assorted parts for connecting various components. Not yet included in the design. [59]
Chain rings, cassettes, derailers, shifters, chains, and other bike parts	$225	Bike Exchange: Used bike parts to connect bike with flywheel and reduce the gear ratio. [60]
1.5% Pathogen “Pure water for	$75	Subsidized price, will discuss specific

the world" filter		model with Pure Water for the World and potentially Civil Engineering professors.
Rope	$25	Uline: Actual rope selected will be as similar as possible to rope available in the community. [61]
Biosand filter prototypes	$220	Pond Gardner: We will alter a filter like this to match Pure Water for the World's model [63]
Base (cement, wood or steel)	$100	Home Depot or old umbrella bases on craiglist customized for our project.
Prototype System Cost	**$1,005**	

Table 18: Actual costs of parts to be bought in Guatemala for the system.

System costs						
		Price per ($)	Price per (Q)	quantity	Total cost ($)	Total Cost (Q)
Pump system	6 m 1/2"	2.60	20	18	46.80	360
	6 m 1"	2.60	20	18	46.80	360
	PVC connectors	0.39	3	25	9.75	75
	elbows	0.26	2	6	1.56	12
	rope 1 m of .22"	0.13	1	250	32.50	250
	PVC glue 946 mL	19.50	150	1	19.50	150
	PVC valves	1.56	12	1	1.56	12
	Metal valves	2.73	21	1	2.73	21
	Valve connector	0.26	2	1	0.26	2
	plastic tubing 90 cm	0.52	4	10	5.20	40
	Mesh	1.30	10	2	2.60	20
	Flywheel (weld+cement)	99.71	767	1	99.71	767
	Flywheel cassette + tensioner			1		
Stand	circular metal tube 2m	7.15	55	10	71.50	550

	3/4" wood	3.25	25	1	3.25	25
	Welding labor	97.50	750	1	97.50	750
	Tonel 58 gallons	19.50	150	1	19.50	150
	Barrelito 60L	3.51	27	4	14.04	108
	Tarp 8x10'	2.08	16	1	2.08	16
Biosand filter	Sieves	79.77	613.6	1	79.77	613.6
	Sand/Gravel	99.71	767	1	99.71	767
	Plastic Casing	99.71	767	1	99.71	767
	Cement casing	134.55	1035	1	134.55	1035
	Water testing kit	24.83	191	1	24.83	191
Bike						
	Cement stand	99.71	767	1	99.71	767
	Functioning (18,21,24,27) speed bike	0.00	0	1	0.00	0
	Extra chain	29.90	230	1	29.90	230
	single-speed derailleur	16.90	130	2	33.80	260
	chain tensioner tool	0.00	0		0.00	0
	Bike peg	7.93	61	1	7.93	61
				System Cost	$1,099.95	8359.6Q

Actual budget costs

The cost of our prototype and the one we planned on building in Guatemala were very similar, but for different reasons. The parts from Guatemala were a lot cheaper, but we needed to include the costs of labor from some people at Maya Pedal such as welding and cement pouring so the prices evened out at the end.

Travel Costs

Travel is an integral component of our project because our project is not rooted in Silicon Valley, but rather in rural Guatemala. Our project's foundation is to find a solution to filter well water in the San Andrés, Itzapa region in such a way as it can be expanded to neighboring communities which have similar needs. Because of this community approach, our project involves using local materials within a local budget to meet a local need. The pillars the project is built on are located in Guatemala, and the only true metric to judge the success of our innovation and design is the project's success in Guatemala. The estimated travel budget in Table 19 below is according to Google Flights and assumed buying tickets multiple months before the trip. We were unable to travel to Guatemala due to Covid-19. Therefore, the budget below in Table 19 was only for planned travel. Actual travel costs only included the preliminary January trip resulting in our final travel cost to be $1,790.

Table 19: Travel budget for all aspects for our trips to Guatemala

Travel		
January	*Flight*	$1,320
23rd-27th	*Purchases in Guatemala*	
5 days	*Hotel*	150
	Food	180
	Travel from and to airport	140
	Total	**$1,790**
Spring break	*Flight*	$2,375
March 21st to Ap	*Purchases in Guatemala*	
12 days	*Hotel*	$720
	Food	$1,344
	Travel around Guatemala	$500
	Travel from and to airport	$100
	Total	**$5,039**

Income:

Our funding is updated in Table 20. We were able to secure some additional funding from the FIH bringing our total funding to $7500 and our estimated system, prototype and travel costs totals to $7300. We were barely able to get enough funding for our first trip to Guatemala in January, but it ended up being very informative and gave us a lot of insight to the community we were going to help if our second trip wasn't cancelled. Of course the funding won't be used now to go to Guatemala or build the system anymore.

Table 20: Our proposed sources of income and total system cost

Income Source	**Amount (USD $)**
Xilinx	$1000
Undergraduate Engineering Programs	$2000
Frugal Innovation Hub	$4500
Total Funding	**$7,500**
Total Cost	**$7,230**

7. Business Plan

Goals and Objectives of the Project

The primary goal of the project is to help encourage as many groups as possible to build and implement the bici-bomba system in rural communities. To create a sustainable product, it must be built with local community members who would then be able to maintain, repair, and potentially replicate the bici-bomba system. The strength of the company is engineering expertise and knowledge about the importance of clean water. To be successful, the company would aim to find individuals or small organizations to partner with and have as bici-bomba experts. For example, the team/company has grown close with Maya Pedal in San Andres. There are about 15 to 20 rural communities surrounding the city. By educating and demonstrating a successful bici-bomba in one of these rural communities, the community members could help create more systems in the other local rural communities. In five years, the company would aim to have partnered with groups in 15 to 25 cities in Guatemala and possibly other Central American countries. With this each group would be responsible for 15 to 20 rural community's bici-bomba systems. Altogether, that is a goal of 225 to 500 bici-bomba systems.

This is the most sustainable model for our product and company, frugally using expertise when that is useful and stepping back when that is superior. By allowing the construction to be championed by local individuals, our group could make sure a few people understand the system in each city, and allow them to handle the maintenance and replication in the surrounding rural communities. If a problem arose, we could help troubleshoot, but it is much more sustainable to give the users of the system ownership and responsibility. The biggest challenge to stay sustainable would be receiving donations for the experts to educate the various cities and assist as needed, along with the possibility of subsidising the material cost for the system. We are in this business because it addresses a real need in an effective and frugal manner, and we would hope we could find donors who believed that as well.

Description of the Product

The bici-bomba pedal powered purification system is an excellent investment due to the sustainable and cost effective design. Our system will have a long lasting positive impact on the communities it is implemented in by providing clean drinking water to multiple families for years to come. The longevity of the biosand filter and the low build and maintenance cost make it a superior solution to other water purification systems for implementation in rural Guatemala. The filter operates through a natural process powered by gravity. The biosand filters that we will implement have a ten year lifespan and can be maintained by local community members with no engineering knowledge.

The entire system operates off grid which makes it a more practical solution than any powered pump or UV light purification system in communities without reliable access to electricity. The bicycle pump system offers a faster and easier way to retrieve water than the current hand drawn bucket systems but is still inexpensive and can be locally sourced for implementation in rural Guatemalan communities. We are not seeking patents for our designs as we believe that we should not hold the ability to improve community health as intellectual property. However, we have the experience and technical expertise to implement our designs quickly and cost effectively in order to achieve their full potential.

Potential Market

Everyone buys water, but the closest competition to our system is well and bucket water retrieval systems. These are not sold, but rather built by locals in thousands of rural towns and villages. To start, our product partnered with a NGO in San Andres Itzapa to implement a system in a rural village, Montellango, just outside of the city. We worked with the mayor of the city so the initial market would be the 20 to 30 villages surrounding San Andres Itzapa that primarily rely on well water. Once we successfully begin implementing the system in many of these villages, we would target a city that San Andre Itzapa has many connections to—possibly Chilmantanago—and begin with a village there. We would continue to find cities to center the projects and then implement the system in the surrounding villages.

Competition

There are currently no other companies or organizations that are making well pumps that would be a reasonable solution for rural Guatemala. Part of our mission with the project is to build the entire system out of cheap and locally sourced materials that can be found in local hardware stores. This was a challenge presented to us by the Frugal Innovation Hub and this is what sets us apart from any other similar system. There are other well pump systems that use high powered, pressure differential pumps that cost thousands of U.S. dollars which would be effective, but completely unreasonable for a family that makes a few dollars a day. Not to mention the lack of gas and electricity out in the country. A submersible solar pump would cost $2000, a battery powered pump would be $800 and a submersible gas generator pump would be $1200 compared to the $200 the rope pump would cost. Our project matches the efficiency of these high powered pumps without the need for electricity at a relatively cheap rate and is designed specifically for the geography of the region and the cultural norms of rural Guatemala. So a solution that would make sense for rural Guatemala's water needs realistically only has our project as a plausible solution. The reason there aren't more solutions for this demand is because this isn't a money making endeavour. As mentioned previously, rural Guatemalans earn only a couple of dollars a day and there isn't the typical business to consumer relationship. That being said, our solution is the most practical and has a total system cost of $1100 including labor. Compared to the other possible solutions, our system will be able to provide more families with clean accessible water with the money we are given or donated, which should be the end goal.

Sales and Marketing Strategies

There are two major parties that we need to "sell" our product to. Donors to provide the funding for the company and leaders in the city to help develop local experts and contacts to implement the system. When targeting donors, our method would involve sharing the stories of some of the people who our company has helped along with numbers that demonstrate how far a donation goes. For both groups, social media would be important to document successful projects, highlight the community leaders championing the project, and overall sharing how the product is successful. Beyond that, it would be important to contact foundations that support similar nonprofits and attend conventions that have groups that could be useful partners. Finally, it would be smart to share our story with companies that produce PVC or bikes, to access these essential materials at reduced rates.

We wouldn’t have traditional salespeople of distribution lines, but more of a model of sales engineers. The expert engineer would have to travel to the new cities to make sure a local leader knows the details of how to build and maintain the system. Furthermore, they would have to travel for repairs. In that way it would be disbursed construction with the systems primarily produced near where they are implemented. The local leaders would act as salespeople in some regards. They would receive a lot of our support for the first system, but would gain more responsibility for future systems. Donated materials could help incentivise growth and add more systems as a reward for finding more rural communities to implement bici-bombas in. Overall, it would be a very spread out model of sales and marketing, with the local Guatemalan component and a U.S. donor contingent.

Manufacturing Plan

The plan for our implementation is to begin with building one model in a rural village, Montellango, just outside of the city San Andres Itzapa. The parts will be built and assembled by volunteers and employees at Maya Pedal, the Guatemalan NGO we are partnering with. We are conservatively estimating that assembly of the biosand filter and bicycle pump will take two weeks given that the construction will be done outside and is weather dependent and that the construction will be completed by members of Maya Pedal and the community without the help of engineers or crews from the US. The first system will cost $1,100 for materials.

After implementing the first system we will begin to build new systems at other local communities. We have partnered with the Mayor of San Andres Itzapa in order to identify communities that are in need of clean drinking water. The majority of bike parts needed are sourced through Maya Pedals bike drive donations and the casing for biosand filters will be donated through the organization Pure Water for the World. In the future we hope to be able to source the sand and gravel required through local quarries further reducing our system cost. Each system will take approximately two weeks to build and once in place will last up to ten years.

Product Cost and Price

To ensure accurate pricing of our system, we flew down to Guatemala to visit small and large hardware stores in the San Andres region and found every part we wanted to use on our system and the cost. A couple of interesting things we noticed were that PVC was much cheaper in Guatemala than in the States, but materials like wood and steel were much cheaper in the States than Guatemala. This is something to keep in mind when looking to expand production of systems and the total costs. At a certain point, it would make more sense financially to import wood and steel from the U.S. even though that goes against one of the core premises of our project.

So the total cost of the system with labor and storage space provided by Maya Pedal is $1,100. This price won't change much at all even with an increase in production volume because there are very little overhead costs. Maya Pedal is a non-profit organization that relies on seasonal volunteers to help build and implement the systems so the space, equipment and overhead will be constant. The only place that shows some potential savings is buying expensive materials such as wood and steel in bulk from the States and shipping it to Guatemala. The other systems we mentioned with high powered pumps are not readily available in Guatemala so those would need to be shipped too, but the price of hte pump alone would already surpass what we project to build the entire pump and filter system. The people in rural Guatemala are also not used to technology like centrifugal or electric pumps and when parts malfunction or break they will not be inclined to try and fix it and will go right back to how they were before. Keeping the system to something that looks familiar is actually a key component to the success of the system in this specific area. Given our system can be produced at the same scale as other more technical systems and has a much lower production cost, this gives us a huge advantage in providing clean water to more families for any given budget. This should be a huge selling point to potential investors. To see full details on our systems cost see the budget section of our report above.

Service or Warranties

Our product would be donated so it wouldn’t have traditional service or warranty. If anything went wrong, the first step would be to see if the user can repair it. If that fails, they would then contact the city leader, the group responsible for building the system in the rural communities in that region. They would have been educated by our company’s engineers so they should be able to address most normal concerns. If that still doesn’t work, that is when our company becomes involved. The local city group would be responsible for purchasing any parts to incentivise making quality products that don’t need regular repair. However, they would be purchasing those parts partially with our company’s donation to make sure they are making any necessary repair.

Our engineer would make sure to explain how they are making any repair or change to the system to make sure the community can take care of it from then on.

Financial Plan

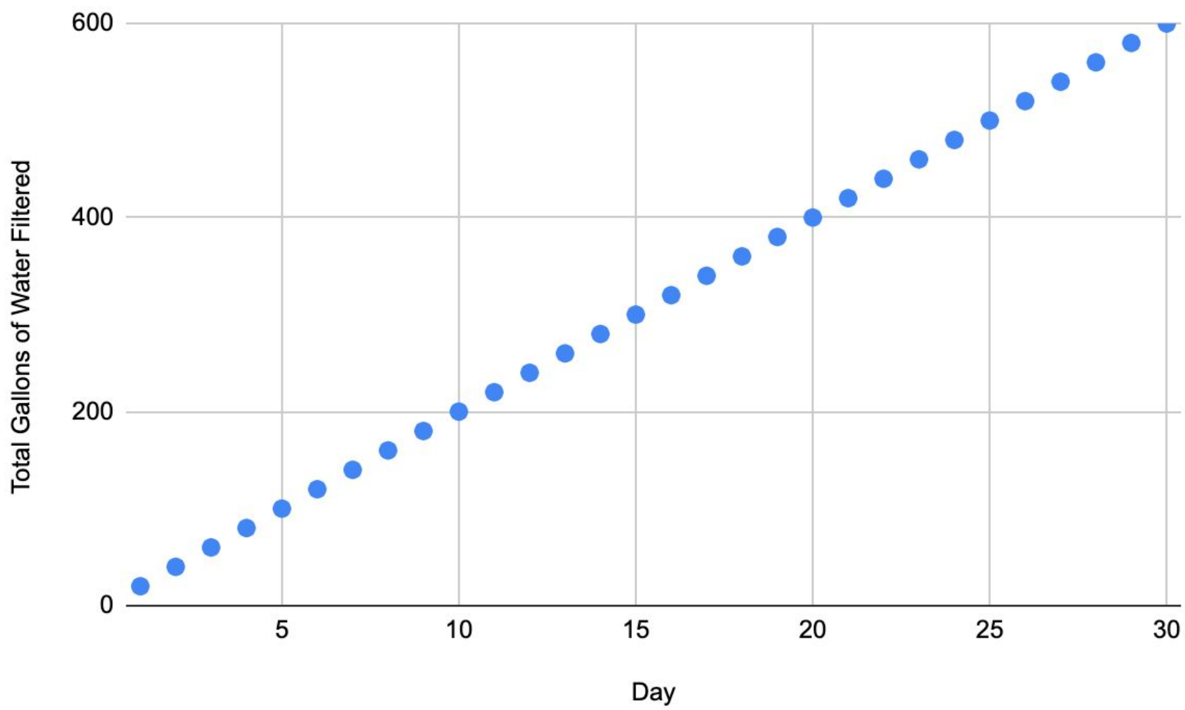

Figure 45: $1,100 donation 30 day timeline, amount of water filtered.

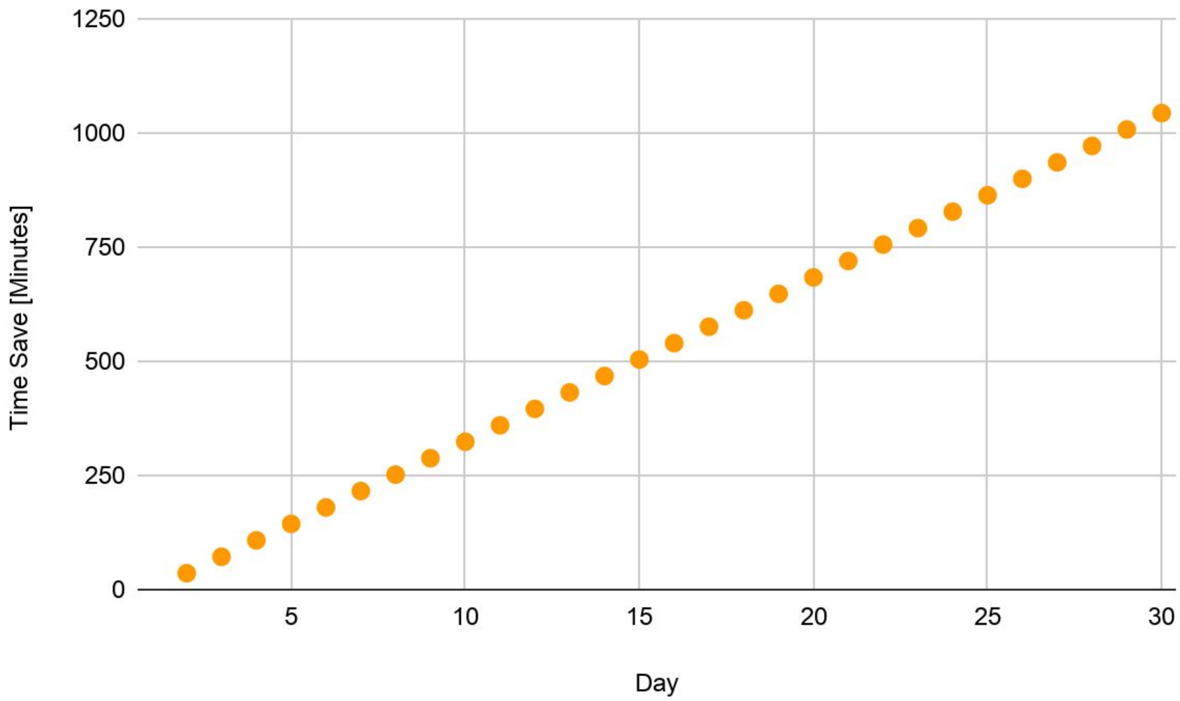

Figure 46: $1,100 donation 30 day timeline, amount of time saved for well users.

Since our company is a nonprofit that aims to donate the product to rural Guatemalan communities, there is not a traditional ROI. Instead we rely on donations, and we aim to get donations based on the effectiveness of our product. Our system costs $1,100 to build and implement. Because of this, the preceding graphs illustrating the 30 day impact of $1,100 worth of donations. While this is not a traditional ROI, within one month a $1,100 donation saves 18 hours worth of time and purifies 600 gallons of water. This does not pay for the system, but can change the lives of numerous people. Hopefully that information about the impact compels donors to keep donating, creating an actual ROI.

We intend to have a mixture of private donors, foundation grants, and local donations of time and materials to fund this nonprofit. The value of a successful project is stories, data, and documentation of the success. That information hopefully leads to more donations which has a lot of value. Some key financial assumptions are that we will be able to find local volunteers to help build the system and donors to continually contribute. Ideally, we can find a consistent foundation grant to improve the stability of the organization. Contingency plans for finding funding includes appealing to local municipality leaders for financial support or asking local companies to support the organization.

Specifically, the cash inflow would be from donors, and the outflow would pay the experts, community centers and material costs. Municipal leaders that shared successful experiences would be eligible to receive more funding because that would help with donations.

8. Societal and Environmental Impacts

The Guatemalan NGO, Maya Pedal, is the critical customer that requested this project, and will help facilitate implementing it in the San Andrés community. Bike powered well water filtration systems will improve the quality of life in rural Guatemalan communities in several ways. First, by providing an easier, faster way to retrieve water. This will allow all members of the community to bring home clean water to their families. By increasing access to clean water community health will improve, rates of waterborne illnesses and diabetes will decrease. In addition to these primary needs, a major goal is having the project be scalable within the San Andrés community. This means that all of the components are available in Guatemala at reasonable prices, it is durable and no parts need to be replaced regularly, and it is replicable for the locals with the equipment currently available. This project has many factors that need to be considered and standards that need to be met and understood before moving forward and the key impacted areas identified are sustainability, ethics, manufacturability, politics and health and safety.

1. Sustainability

Our team worked closely with Maya Pedal and communities in Guatemala to ensure our design would be sustainable. We focused on ensuring that all the parts of the design can be locally sourced in Guatemala. The bike parts needed are gathered through donations and bike drives at Maya Pedal. The sand and gravel for the biosand filter are sourced from quarries in Guatemala. The case for the biosand filter is donated through Pure Water for the World or can be made locally out of concrete depending on availability. New parts do not have to be manufactured or shipped in order for the design to be built. This ensures that the supply chain for our project is ethical and sustainable as we are reusing parts or sourcing material locally.

The design also is sustainable because it provides a long lasting impact. Biosand filters can last up to ten years and the bike pump system will be able to match that lifespan. Our design will need regular maintenance in order to clean the biosand filter and it is possible that parts in the rope pump system will break and need to be replaced. The simplicity of our design offers big advantages for maintenance. Maya Pedal can train members of the community to do biosand filter upkeep which only involves tasks that don't require technical expertise such as filling it with water every day or washing the diffuser plate once a week. The rope pump system is made mostly of standard bike parts that can be easily replaced. Our design can be fully built and sustained by the community without needing engineering help from the US.

2. Ethical

Overall our project is an extremely ethical project as it focuses on uplifting a community by providing them with clean water. Easy access to clean water is a human right. As of now these families and many others spend long hours labouring tirelessly to get minimal amounts of unpurified water. This takes time away that could be spent working, with family, or resting. In many developed areas, access to water is not appreciated or even acknowledged. We are fighting for equality one well at a time. Our ultimate goal is to create a scalable system that will be able to bring clean water to people everywhere. The first fundamental principle of being a good engineer is "using [...] knowledge and skill for the enhancement of human welfare." Our group strives to be good engineers by enhancing human welfare by improving access to clean water.

One of the main reasons we chose the Maya Pedal project is because we believed our efforts throughout the senior design process will have a tangible impact improving lives. An engineer should have an empathetic character and think first about human and societal needs before profit or other selfish motives. An engineer should be a person of integrity who acts in consideration of others.

3. Manufacturability

Our system is split into four different subsystems; the dual tank, the biosand filter, the bike apparatus and the rope pulley pump. The system is designed to be for one community and has to be built on site so this lessens the manufacturability of the system. Many of the sites we are targeting are also in remote areas where vehicles can't reach so for these sites it would be more effective to just take all the materials to the site and build it there. However, a couple of the subsystems are capable of being built in mass quantities and taken to the well sites to be put together such as the biosand filter, the dual tank system and the rope part of the pump. All these subsystems use inexpensive and locally sourced materials we know can be found in the local hardware stores in Guatemala and can be bought in bulk. Materials such as steel beam, wood, sand, gravel, rope and stoppers can be worked on in an assembly line type style to prepare these subsystems. The manufacturing issues occur when putting the systems together at a well site because connecting the bike gears and the pump pulley system requires knowledge of how the system works and has to be done one at a time. There's also variability in the condition or the layout of the site that may require additional systems such as flat platforms for uneven grounds or rain covers in areas that are particularly wet. Considering all of these factors, our system has very low manufacturability as a whole, but we are able to reduce the cost of manufacturing by using inexpensive materials, mass producing certain subsystems and relying on the free labor of the kind volunteers at Maya Pedal.

4. Political

The bici-bomba system was designed specifically for a well in a small town, Montallano, which is on the outskirts of San Andres Itzapa. However, a major goal of our project was to make a product that is scalable to the hundreds of similar towns that rely on wells for their water. In Guatemala, water is meant to be a public resource, and many of the election campaigns over the past 25 years have centered around the goal of bringing clean water. As our project is still needed, those initiatives have not been successful. Despite this, there is a lot of interest for local political leaders to address these concerns. With our project, during the exploratory visit two team members met with the mayor of San Andres Itzapa and his council. After presenting the project, we discussed the scalability aspect and how it would be a viable solution in many of the surrounding villages. While the mayor could not fund the project independently, he mentioned resources to contact for materials and a plan to use social media to help with local support and funding. Overall, working with the political system in place in Guatemala made it possible to access resources and gain local contacts, and avoid any delays or difficulties that could arise if the mayor felt we were not keeping the municipality involved. Permits or permission were not a factor for our project, which we could only be confident about because we were working with local leaders and had their support. Given the goal of scalability, involving the political leaders as early as possible paves the way to the project's expansion in the larger region.

5. Health & Safety

Our goal for our project is to make it as safe as possible for both us to build and for the community to use. One of our goals was to meet the WHO standards for clean water, however this is just a guideline. The people in the community that we would be serving were currently drinking water that is considered unsafe and unclean. The entire goal of our project was to improve health by improving the safety of the drinking water. One of the main issues of health and safety that arose during our project was the standard to which the filter was considered to be effective. The company that donated the filters said that they were considered to be 98.5%. Originally, we worked to find a way to filter out the remaining 1.5% of pathogens however, after doing much research we realized the filter was in fact safe and the 1.5% is just a way from the company to negate defaults. Another health and safety issue we faced was the manufacturing of the well pump system and the risks involved with lowering a person into the well. Our final health and safety issue revolved around young children hurting themselves by trying to touch the system while the system was operating. This issue was solved by putting a protective casing around all moving parts.

The ‘Bici Bomba’ Pedal Powered Well Purification System is aimed at providing water for those who don’t have access to it now. The target market are rural Guatemalan families who make around $1 a day and have no access to clean drinking water. There is no profiting or breaking even in this, not even close. Our team decided to take on this project because we saw the potential to help people in need given the resources for our project. These projects are sustained by generous donations made by people around the world and the time volunteered by the students and workers at Maya Pedal. This means our project has no sustainable model to consistently create systems for different communities, but what we can show possible donors is that their money will go a long way in bringing clean drinking water to families all over rural Guatemala. Working with the Frugal Innovation Hub, we have made our design as inexpensive as possible so that we can make as many systems we can with the resources we receive. Currently, the project is focused on communities in the San Andres region of Guatemala, but we've discussed with the local government to expand to more communities, particularly those in the mountainous regions that have even scarcer access to water.

Our initial system will provide clean water to four families. As this system is replicated it will continue to affect more and more families. At the end of one year of production we can hope to make around 20 systems which could provide water for over 500 people. Every year after that we should see a sharp increase in the amount of people gaining access to clean water as our project scales to larger and larger communities. Every year, more than 5 million people die from unclean drinking water, especially in poor countries so this issue is pressing.

The way that these communities get their water currently is by lowering a bucket down into a well and then turning a hand crank to bring the water to the top. This whole process takes about five mins to get about 3-4 gallons of dirty water. Our system on the other hand has a pump rate of 5 gallons per min and can filter that in about 40 mins. Biosand filters can filter five gallons loads, three to four times a day therefore producing around 15-20 gallons of clean drinking water. Along with all the health benefits of having access to clean drinking water, it would also save these families a lot of time and energy when it comes to getting their water.

Our system, that costs just over $1000, can change lives in communities for years to come. With more donors and communities to work with, the cost of our system could come down, but the effect we are having on the people around us is immeasurable.

Our systems greatest impact is in the health of the people directly impacted by its installation. The families at Montellano, and any future sites, will save hours each week and have fewer health concerns. Beyond that, it will limit the need for single use plastics such as water bottles and soda bottles to be used for everyday drinking, making a significant sustainable impact. The project's sustainable impact is exaggerated by the fact that the project is made from local parts with a well documented design, meaning it can be repaired rather than replaced. If successful, the project's political impact can extend to the entire region because the team and Maya Pedal are working with municipality leaders (including the mayor) to extend the scope of the project. Finally, the project's tangible impact is a strong example of the need for ethical engineers. By creating this project and sharing the results with the San Andres community and Santa Clara, this project has the potential to extend its impact around the world by inspiring mechanically minded people to pursue similar projects.

9. Rescoped Project Goals

By the end of Fall Quarter, our team had developed a strong relationship with Maya Pedal, a clear idea of project objectives and constraints, and the first few iterations of potential system designs. In Winter Quarter, two members of our team went on a five day exploratory trip to Guatemala and we were able to spend some time with the community where we were able to better clarify what their specific needs were. Talking with the Maya Pedal leaders, municipality leaders, and visiting local hardware stores, we were able to get a better grasp of what the project constraints actually were and how to make a truly scalable project. Finally, speaking with local bike mechanics and bike engineers back at Santa Clara, we continued to iterate the design to fully meet these clarified requirements.

At the completion of Winter Quarter, we had a fully designed bike pump system made out of local Guatemalan parts designed for the well in San Andres Itzapa. Furthermore, we had completed testing and the design of how we would implement a sustainable biosand filter to the pump system that would allow the water to remain purified after going through the filter. We had created a fully structured timeline of our planned ten day trip to Guatemala over Spring Break and the first few days of Spring Quarter. This was a plan to buy all of the materials, build the system, and implement the filter. Furthermore, we planned time to educate a group of community “champions” to be experts on how to maintain, repair, and replicate the system. Lastly, we had planned on meeting again with the Mayor of the city and his municipal council to discuss our project and help spark interest in expanding the project throughout the region. With all of this in mind, we created a budget based on funding from four different major sources.

In order to make sure all of the different components of the project were valid, we verified the engineering components with professional engineers and bike experts. The filtration aspects were discussed with Dr. Doyle from Civil Engineering/Environmental Engineering, and the educational components with Allan Baez from the Frugal Innovation Hub and Professor Ribas from the Spanish Department. We were confident and prepared to complete our Senior Design project with all of the necessary components and testing during our trip. However, the trip was canceled, requiring us to take a new look at our project.

Our project is centered on the goal of creating a project to retrieve water from a 103 foot deep well and purify it in such a way that used local materials, was affordable enough to be scaled, and was simple enough to be repaired by the people in Guatemala. Because of this, we avoided designs that were reliant on something like a centrifugal pump or building a big pressure differential which would require advanced simulation. Instead, our "pump" only relied on the principal technology the community has always used to retrieve water from the well. Our improvements came from making the gearing more effective, alignment more precise, and limiting slack in the chain. Because of all of this, a simulation would not be an effective way to demonstrate or indicate whether or not we successfully achieved our project goals. We intended to limit inefficiencies in the system wherever possible, but a simulation would not successfully indicate that. A simulation would be able to show our system with no inefficiencies, but our project only makes sense with the inefficiencies involved. Many of the issues with the current system in Guatemala came from sloppy engineering, and the only way to address that in a simulation would be to artificially introduce and then remove error. Because of all of that, the best way to demonstrate meeting our original goals is by creating clear instructions of how to build the system with some calculations to validate the effectiveness.

New Project Goals

1. Create a detailed manual illustrating our system and how it can be built for the Maya Pedal organization.

2. Indicate how the system improves about existing ‘bicimaquinas’ and how those improvements work.
3. Share the results of our work with the biosand filter and important takeaways from our progress with that subsystem.
4. Send the manuals, brochures, and critical components to Maya Pedal in Guatemala to help kickstart their progress in creating a system for themselves.

The first objective—the creation and distribution of the manual— required a revamping of designs in SolidWorks, especially detailed drawings of different components, in order to create a clear and detailed description of how to build the system. A critical analysis of theoretical troubleshooting was conducted to make a clear guide. This is especially important in determining alignment of the system and working with the power transmission components.

The second objective—validating improvements—consists of a mix of calculations and descriptions of product functionality. The calculations demonstrate the strength of the system along with sufficient power generation for a variety of bike riders despite the depth of the well. They also prove the system can sustain a sufficiently high flow rate. It will be difficult to know the validity of these calculations without the physical system, but the calculations prove the system works with some buffer for inefficiencies.

The third task—biosand filter takeaways—was completed using the knowledge gained while building and testing the biosand filter in Santa Clara. This knowledge was added to the manual in the biosand section as tips and additional information for construction and maintenance.

The fourth task—distributing educational materials—required the whole team and a translator to discuss with Maya Pedal what we learned and designed. Then the manual and any remaining parts in Santa Clara, such as the biosand filter casing can be shipped to Maya Pedal in Guatemala.

10. Timeline & Management

Before our Spring Break trip to Guatemala was cancelled we had a comprehensive Gantt chart to keep our project on track and completed on time. This plan was interrupted by the Covid-19 pandemic and so all these plans were rendered useless. However, it still is important to show our timeline for future projects taken on by other senior design groups or Maya Pedal if they decide to build our system. We set finite deadlines for each stage of the design process to facilitate achieving our goals. These components include: initial design, final drawings, procurement, fabrication, assembly, testing, senior design conference and senior thesis.

See the Gantt Chart on the following page for information on specific deadlines in the fall quarter. The Fall quarter work focused on establishing customer needs and converting those needs into a project scope. Additional major goals are beginning the design process, securing funding, and establishing a relationship with the community. The Gantt Chart, in Figure 40, also shows dependencies, which are represented by blue arrows. Finally, it shows the critical path which is represented by red arrows. This path includes objects that are critical to our end date, so these tasks are the mains ones we considering when trying to stay on schedule, The path includes the following: brainstorming subsystems/concept development, picking preliminary subsystems, and a FEA an analysis report on the selected subsystems.

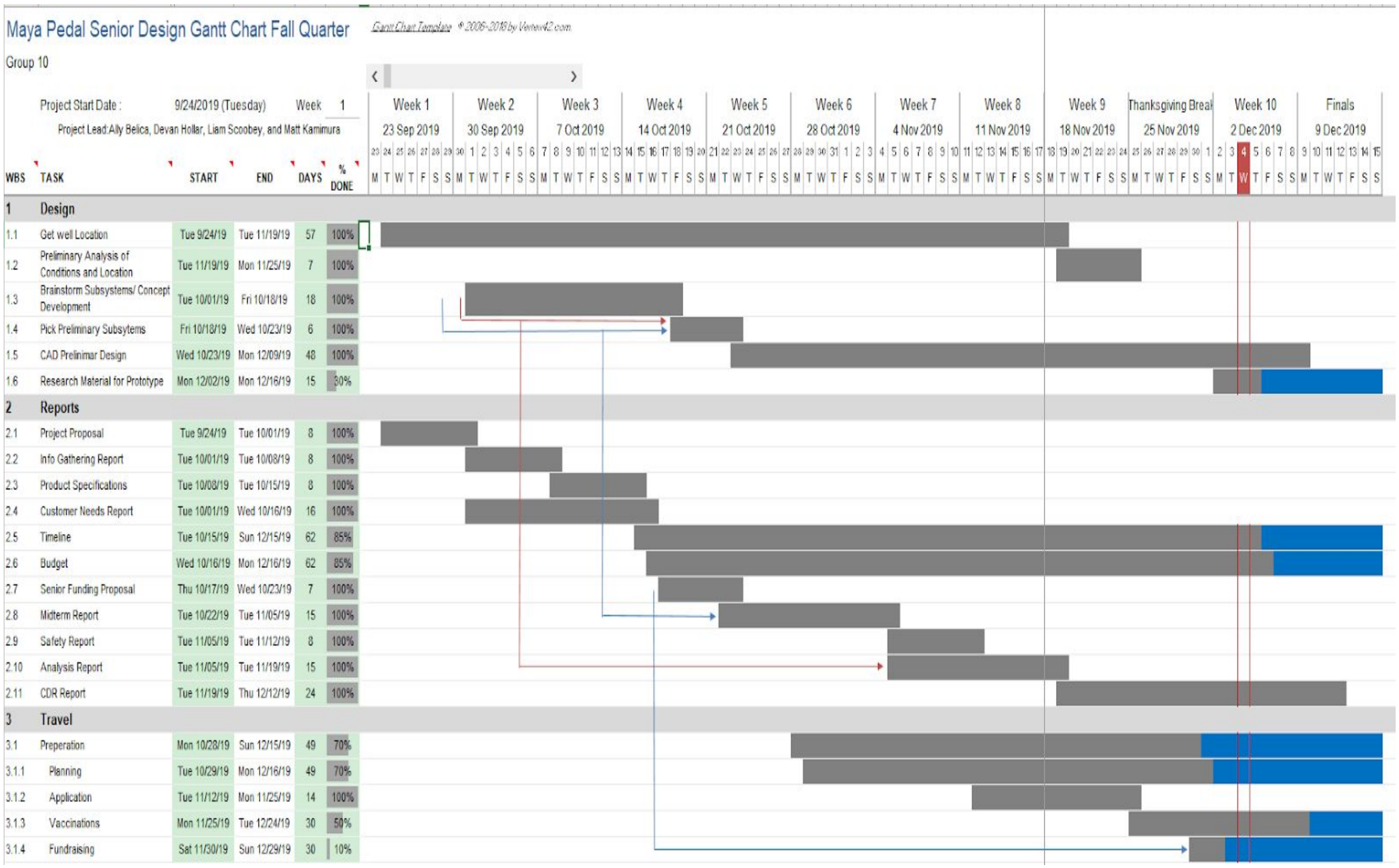

Figure 47: Fall quarter Gantt chart.

The winter quarter work begins with the initial trip to Guatemala to finalize the information gathering and customer needs aspect of the project. Additionally, that involves knowing the project restraints, and material options. This approach allows us to use the majority of Winter quarter to finalize design with iterative prototyping in order to have a final design by the end of Winter quarter. One important date for the Winter Quarter is the senior design conference registration form deadline (2/7). Please see the Winter Quarter Gantt chart in Figure 48.

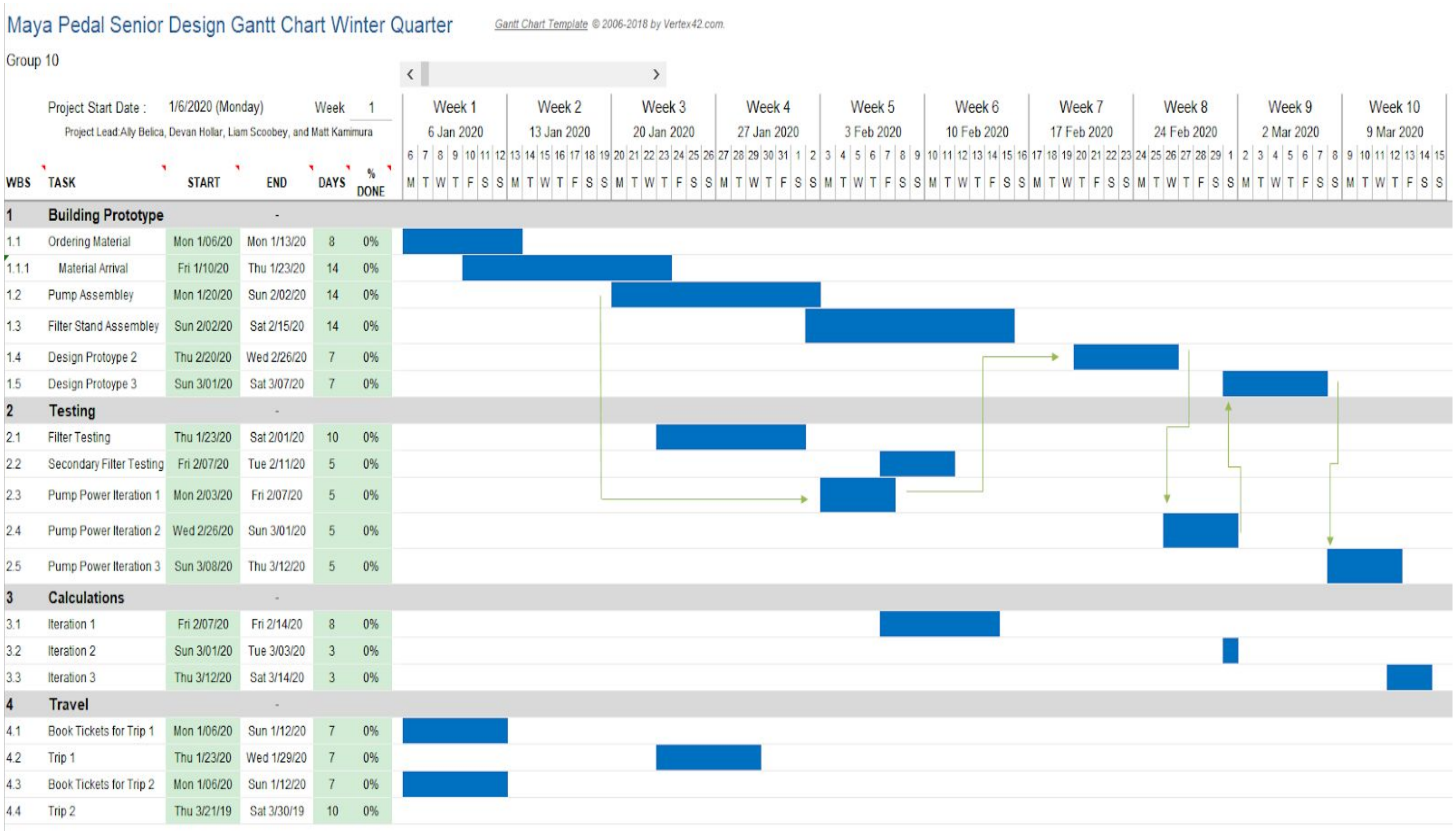

Figure 48: Winter quarter Gantt chart.

Spring quarter begins with our trip to Guatemala to implement the final design and perform the educational outreach. After these steps, we will conclude the project by presenting at the Senior Design Conference and with our final report. Importants dates and events for Spring Quarter include: the Senior Design Ethics Prize Submissions (4/10), the Senior Design Conference (5/14), and the Senior Awards & Honors Ceremony (6/12).

11. Conclusion

This senior design project was part of a bigger goal to help people in disadvantaged places. Through our schooling and resources we thought we could make a difference, but unfortunately none of this could come together because of the COVID-19 pandemic. Although we were unable to travel to Guatemala to implement our newly improved bici-bomba and build the relationship between Maya Pedal and Santa Clara University, we have still provided Maya Pedal with all the research and models we came up with to improve upon the idea they had of helping poor rural communities gain access to water through bike power. While our project was completely based on our ability to build our system and take data on the features, we were still able to pivot our project to be more theoretically focused. Our intentions were to provide meaningful proof to Maya Pedal and anyone else interested in this project that our design would work as a real model and meet all of the needs of the customer we were serving. Through our work, we believe that it is very evident that we've created a better well water bike powered filtration system that can be scaled to different communities and help hundreds of people in rural Guatemala by giving them cheap access to clean water.

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Appendix B: Customer Needs Interviews

Interview with Mario and Dave from Maya Pedal
Telephone Interview, 10/7/19, Interviewed by all members of the group.

Question/Prompt	**Customer Statement**	**Interpreted Need**
What projects are Maya Pedal currently working on that they need our help with?	● Education in Guatemala about welding, manufacturing, and water purification ● More efficient cookstoves to conserve resources ● Water purification bike pump systems to be attached to wells in Guatemalan villages	We can only work on one project for them so our project and product will be a bike pedal purification system
Is there an existing model for the bike pedal purification system?	Yes, they have bike pumps and water filters but they want to improve their design	We need to optimize the pump to improve ease of use, ease of manufacturing, and flow rate
What flow rate is desired?	They can currently pump 5-6 gallons per minute	Our pump must be able to do at least 5-6 gallons per minute, preferably more
How deep are the wells?	Deepest wells are 45 m. Current system can only go 30 m deep and it becomes difficult to pedal at that depth.	Ideally we can reach 45 m deep, at least 35 m minimum. Need to optimize the ease of pedaling to amount of water pumped
Is there a working model for a purification filter?	Yes, they have used bio sand filters in the past. They built the storage tank out of concrete and had issues with weight and ease of manufacturing.	Need to iterate to improve their filter design. We want a lighter design that is easy to manufacture for multiple different villages.
Will the build be stationary?	Yes, the bike and filter will be fixed to one well.	Portability is not an important need for our design.
Can the system have an attached tank to use with the bio sand filter	Yes	We need to design a tank out of materials available in Guatemala

Interview with Matt Lograsso, former student who worked with Maya Pedal Organization. Telephone Interview, 10/7/19, Interviewed by all members of the group.

Question/Prompt	**Customer Statement**	**Interpreted Need**
What kind of resources are available in Guatemala for us to build our project?	Tools and shops in Guatemala were second rate which makes assembling difficult and must fly all resources with us to Guatemala. Limited number of basic tools.	Will need to learn how to assemble our project in unconventional ways and ensure we have all the materials we need before we fly to Guatemala.
Will we need to learn new skills like welding for our project?	Essentially yes. The SCU shop does not give its students the necessary skills to carry out the project, but also third party, local vendors like Blue Light Welding is expensive.	We should figure out a way to build our project without welding so mainly screws and nails because we having an outside vendor weld our parts will be outside of our budget.
What were some logistical issues from flying to Guatemala and working there?	The hardware store is about a half mile walk from the chosen area of need and all of the materials brought from school had to be put into a box and shipped which cost about $200.	We must have a full needs assessment of the place we will be working
What was your timeline for building your project in Guatemala?	Give yourself 5-6 days for building the project, at least a day for implementation and then a few days to integrate with the community and workers.	We are planning to travel to Guatemala over Spring Break and it sounds as if we may need to stay there into week one of Spring quarter.

Interview with Jonathan Keyes, a former student who worked with Maya Pedal Organization
Telephone Interview, 10/7/19, Interviewed by all members of the group

Question/Prompt	Customer Statement	Interpreted Need
What is the best way to guarantee that our project stays focused on the customer needs in Guatemala?	The best contact for the project is Mario and Dave from Maya Pedal. A difficulty that we ran into was establishing what the situation was in Guatemala and what they needed. At times we thought we established aspects of the project and then had either Dave or Mario disagree about what we established during interviews. I would recommend meeting with them regularly and sharing notes with Maya Pedal.	We should make sure to set up regular interviews with Maya pedal and make sure to verify any details with both Mario and Dave to make sure everyone is on the same page. Also, we should make sure to run by our design with them regularly throughout the process.
What are good resources to help make this project successful?	Alan and Pedro from the Frugal Innovation Hub were very invested with our project and very useful throughout the process. It would have been a good idea to start requesting travel earlier.	We made sure to reach out to both of the people they recommended and build good relationships with them. Additionally, we are going to make sure to follow their advice regarding travel.
Did you have any difficulties with the manufacturing aspects of the project?	The hardware store had a very limited supply of parts, and they were only in metric. Additionally, it was like half an hour away and needing to take multiple trips slowed down the manufacturing process. Lastly, we could have done a more thorough job prototyping.	We need to have a detailed list of parts needed ahead of time along with multiple options to account for complications. Furthermore, we should delegate tasks efficiently while we are there. Lastly, we should plan on prototypes with our funding.

Interview with Pedro Hernandez-Ramos, Chaperon on last year's senior design group's Guatemala trip.
In-Person Interview, 10/11/19, Interviewed by all members of the group

Question/Prompt	**Customer Statement**	**Interpreted Need**
What kind of difficulties did you encounter in Guatemala?	The Maya Pedal shop in Guatemala is only half covered and leads to lots of wet tools and equipment,	We will need to communicate with the owners of the shop to ensure we have all the tools we need or adjust our project to fit the shop capabilities.
What were the logistics of obtaining raw material in Guatemala?	The only readily available material in the town last years group worked in was steel. Most materials need to be bought from larger cities like Guatemala City.	We must plan to stop in Guatemala City or a different big city with a lot of stores and resources before we get to the village.
Would you be interested in coming with us to Guatemala this year?	Pedro has multiple commitments to other projects this year and won't be able to accompany us this year.	We will need to find someone to be our travel guide as soon as possible. We will set up a meeting with Allan first to gauge his interest.
What can you tell us about the village you guys went to last year?	Pedro shared with us a file with a bunch of photos of their project being built in Guatemala.	The pictures showed us the reality of the Guatemalans living situation and how bad the quality of water is from the well.

Appendix C: Additional Calculations

The following calculations are used to relate the ideal values. By graphing the relationships in MatLab and iterating, we can find the appropriate values.

Water Force [N] * **Top wheel radius** [m] = 9.5488 x Power (kW) / **Cadence** (RPM)
Water Force [N] * **Top wheel radius** [m] = 9.5488 x Power (kW) / (Rope Velocity [m/s] *60 [s/min] / **Top wheel radius** [m] * 2 π)
Water Force [N] * **Top wheel radius** [m] = 9.5488 x Power (kW) * **Top wheel radius** [m] * 2 π/ (Rope Velocity [m/s] $* 60$ [*s/min*])
Mass flow rate 0.314504647 [kg/s] = **Cadence** [rpm] * **Top wheel radius** [m] * 2 π / 60 [s/min]

X = Torque
Y = Cadence
Z = Top wheel radius
C_1 = 9.5488 x Power [kW]
C_2 = Water Force [N]
C_3 = Rope velocity [m/s] * 3600 [s/min] / 2π

$XY = C_1$
$X=ZC_2$
$YZ = C_3$
$C_1=C_2C_3$

If P = 1/Y

$X = PC_1$
$X = ZC_2$
$Z = PC_3$
$C_1=C_2C_3$

$X = C_1/Y$
$X = ZC_2$
$XY = YZC_2 = C_1= C_3/C_2$

$Y = C_1/X$
$Y = C_3/Z$

$Z = X/C_2$
$Z = C_3/Y$

$X/C_2 = C_3/Y = (C_1/Y)/C_2$

$X/C_2 = C_3/(C_1/X)$

$$C_1 = C_2 C_3$$
$$X/C_2 = C_3/Y = (ZC_2)/C_2$$

$Z = C_3/Y$
$Z = C_3/Y$

Pumping Force and Flow Rate Calculations

Variable	Amount	Units
Well Depth (Montellano)	31.3944	meters
Well Depth (Minimum)	15	meters
Well Depth (Middle)	25	meters
Well Depth (Maximum)	40	meters
Pedal Power (child)	75	Watts
Pedal Power (adult)	125	Watts
Top Wheel Radius	0.2	meters
Density of Water	997	kg/m^3
Assorted Losses	1.15	(proportion)

Diameter [mm]	Height [m]	Water Force [N]	Water Force with assorted losses [N]	Torque at top flywheel [N.m]	Top flywheel cadence (child pedaling) [RPM]	Flowrate (child pedaling) [l/min]	Top flywheel cadence (adult pedaling) [RPM]	Flowrate (adult pedaling) [l/min]	Rope velocity (child) [m/s]	Rope velocity (adult) [m/s]
17.8	Montellano	76.4	87.8	17.6	40.8	12.7	67.9	21.25	.854	1.423
17.8	Minimum	36.5	42.0	8.4	85.3	26.7	142.2	44.47	1.787	2.978
17.8	Medium	60.8	69.9	14.0	51.2	16.0	85.3	26.68	1.072	1.787
17.8	Maximum	97.3	111.9	22.4	32.0	10.0	53.3	16.67	.670	1.117
20	Montellano	96.4	110.9	22.2	32.3	12.7	53.8	21.25	.676	1.127
20	Minimum	46.1	53.0	10.6	67.6	26.7	112.6	44.47	1.415	2.359
20	Medium	76.8	88.3	17.7	40.5	16.0	67.6	26.68	.849	1.415
20	Maximum	122.9	141.3	28.3	25.3	10.0	42.2	16.67	.531	0.885
30	Montellano	217.0	249.5	49.9	14.4	12.7	23.9	21.25	.301	0.501
30	Minimum	103.7	119.2	23.8	30.0	26.7	50.1	44.47	.629	1.048
30	Medium	172.8	198.7	39.7	18.0	16.0	30.0	26.68	.377	0.629
30	Maximum	276.4	317.9	63.6	11.3	10.0	18.8	16.67	.236	0.393
40	Montellano	385.7	443.6	88.7	8.1	12.7	13.5	21.25	.169	0.282

40	Minimum	184.3	211.9	42.4	16.9	26.7	28.2	44.47	.354	0.590
40	Medium	307.2	353.2	70.6	10.1	16.0	16.9	26.68	.212	0.354
40	Maximum	491.5	565.2	113.0	6.3	10.0	10.6	16.67	.133	0.221
50	Montellano	602.7	693.1	138.6	5.2	12.7	8.6	21.25	.108	0.180
50	Minimum	288.0	331.2	66.2	10.8	26.7	18.0	44.47	.226	0.377
50	Medium	479.9	551.9	110.4	6.5	16.0	10.8	26.68	.136	0.226
50	Maximum	767.9	883.1	176.6	4.1	10.0	6.8	16.67	.085	0.142

Diameter [mm]	**Flowrate (child pedaling) [m^3/s]**	**Rope velocity (child) [m/s]**	**Flowrate (adult pedaling) [m^3/s]**	**Rope velocity (adult) [m/s]**	**Speed of Rope [m/s]**	**Relative Speed [m/s]**	**Flow Rate of exposed area [m^3/s]**	**Interpolated flow rate (adult) [m^3/s]**	**Interpolated flow rate (child) [m^3/s]**	**Total flow rate (adult) [l/min]**	**Total flow rate (child) [l/min]**
17.8	0.000212	0.854	0.000354	1.423	0.5	2.63	0.0002300249008	0.0001493	0.0001991	12.29	0.80
17.8	0.000445	1.787	0.000741	2.978	1	2.13	0.0001862939311	0.0000133	0.0001175	**43.67**	**19.63**
17.8	0.000267	1.072	0.000445	1.787	1.5	1.63	0.0001425629613	0.0001175	0.0001800	19.63	5.21
17.8	0.000167	0.670	0.000278	1.117	2	1.13	0.00009883199161	0.0001761	0.0002151	6.11	-2.90
					2.5	0.63	0.00005510102187				
					3	0.13	0.00001137005213				
20	0.000212	0.676	0.000354	1.127	0	3.13	0.0003083686818	0.0001481	0.0002417	12.36	-1.76
20	0.000445	1.415	0.000741	2.359	0.5	2.63	0.000259108509	0.0000760	0.0001689	**39.91**	**16.54**
20	0.000267	0.849	0.000445	1.415	1	2.13	0.0002098483362	0.0001689	0.0002247	16.54	2.53
20	0.000167	0.531	0.000278	0.885	1.5	1.63	0.0001605881634	0.0002212	0.0002561	3.40	-5.36
					2	1.13	0.0001113279905				
					2.5	0.63	0.00006206781774				
30	0.000212	0.301	0.000354	0.501	0	3.13	0.0004656996419	0.0003912	0.0004210	-2.22	-12.51
30	0.000445	0.629	0.000741	1.048	0.5	2.63	0.0003913067278	0.0003097	0.0003721	25.88	4.35
30	0.000267	0.377	0.000445	0.629	1	2.13	0.0003169138138	0.0003721	0.0004095	4.35	-8.56
30	0.000167	0.236	0.000278	0.393	1.5	1.63	0.0002425208998	0.0004072	0.0004306	-7.76	-15.83
40	0.000212	0.169	0.000354	0.282	0	3.13	0.000623030602	0.0005669	0.0005894	-12.77	-22.62
40	0.000445	0.354	0.000741	0.590	0.5	2.63	0.0005235049467	0.0005996	0.0005526	8.49	-6.48

40	0.000267	0.212	0.000445	0.354	1	2.13	0.0004239792914	0.0005526	0.0005808	-6.48	-18.84
40	0.000167	0.133	0.000278	0.221	1.5	1.63	0.0003244536362	0.0005790	0.0005966	-18.07	-25.79
50	0.000212	0.108	0.000354	0.180	0	3.13	0.0007803615621	0.0007354	0.0007534	-22.88	-32.46
50	0.000445	0.226	0.000741	0.377	0.5	2.63	0.0006557031656	0.0006863	0.0007239	3.29	-16.75
50	0.000267	0.136	0.000445	0.226	1	2.13	0.0005310447691	0.0007239	0.0007465	-16.75	-28.78
50	0.000167	0.085	0.000278	0.142	1.5	1.63	0.0004063863726	0.0007453	0.0007592	-28.04	-35.55

Appendix D: Drawing Credits

Part Drawing	Main Contributor
Flywheel assembly	Liam Scobey
Shaft part	Ally Belica
Cassette part	Liam Scobey
Bearing part	Liam Scobey
Flywheel part	Liam Scobey
Bike stand	Devan Hollar
Water pump	Matthew Kamimura

Appendix E: Product Specifications and Benchmarking

Our product is not going to be sold for a profit, but needs to be compared to other existing products on the market to recognize how effective our system will be to how effective it could be. All of the products that will be benchmarked against our own system metrics are made to turn a profit. Tables E1, E2, and E3 show how our necessary metrics compare to already existing products and how it will still compare favorably even though our project has much more restrictive constraints such as costs and resources.

Table E1: Competitive benchmarking chart for the pump based on the metrics.

Metric #	Needs #	Project Specifications	Marginal Metric	Ideal Metric	Unit	Importance	Water-Powered Sump Pump [20]	Pedrollo Centrifugal Water Pump [21]
1	4	Pumpable Depth	30	30-45	Meters	4	6.7	18.5
2	2	Pump Flow Rate	7.5	18.9	Liter/min	2	25	317
13	2	Power required	75	125	Watts	2	NA	NA
17	5	Cost of pump	100	10-50	$	3	259	489
19	2	Efficiency of pump	30	60	%	3	NA	NA

Table E2: Competitive benchmarking chart for the filter based on the metrics.

Metric #	Needs #	Project Specifications	Marginal Metric	Ideal Metric	Unit	Importance	Hydraid BSF [18]	Ohorizons Wood Mold BSF [19]
4	13	Rate of Filtration	2	10-15	L/hour	1	15	11
7	1	Water Cleanliness	Bacteria - 98% Viruses - 98% Protozoa - 99%	Bacteria - 100% Viruses - 100% Protozoa - 100%	% percent of pathogens removed	5	Bacteria - 98.7% Viruses - 85.9% Protozoa - 99.9%	Bacteria - 98.5% Viruses - 70-99% Protozoa - 99.9%
16	5, 6, 7	Cost of filter	150	100	$	3	25-50	25-65

Table E3: Competitive benchmarking chart for the tank based on the metrics.

Metric #	Needs #	Project Specifications	Marginal Metric	Ideal Metric	Unit	Importance	Romo Tech [22]	KoolScapes [23]
5	11, 13, 9	Volume of Upper Tank	50	75	Gallons	2	50	75
6	11, 9	Volume of Lower Tank	30	50	Gallons	2	50	75
9	11	Force on structure holding water tank	1000	2500	Newtons	4	1900	2780

Table E4: The final product specifications with the ideal metrics and importance of each metric. This table reflects on our customer needs and product specification updating process so every need is fulfilled by a system metric.

Metric #	Need #s	Project Specifications	Metric	Unit	Importance
1	4	Pumpable Depth	30 - 45	Meters	4
2	2	Pump Flow Rate	5	Gallons/min	2
3	2	Ease of Pedaling	100	Watts	3
4	13	Rate of Filtration	10-15	L/hour	1
5	11, 9	Volume of Upper Tank	75	Gallons	1
6	11, 9	Volume of Lower Tank	50	Gallons	1
7	1	Water Cleanliness	Bacteria - 98-100% Viruses - 95-100% Protozoa - 99-100%	% percent of pathogens removed	5
8	5,7	Total Cost	1185	$	5
9	11	Force on structure holding water tank	2500	Newtons	4
10	3, 7	Adaptability		N/A	2
11	8, 12	Durability		N/A	4
12	12	Strength of flywheel connector	200	Newtons	4
13	4,13	Power required	125	Watts	2
14	6, 8	Ease of Maintenance		N/A	2
15	5, 7	Scalability to other sites		N/A	5
16	5, 6, 7	Cost of filter	200	$	3
17	5	Cost of pump	50	$	3
18	2	Roughness of pipe		N/A	1
19	2	Efficiency of pump	60	%	3
20	10	Explainable	5	minutes	2
21	5	Reproducible	4	days	3

From our customer needs, we created a “product specification” list in Table E7 to discern how every subsystem should be designed to meet the customer needs in the table prior. Then, we updated the table with the customer needs and metrics for each of the subsystems seen in Table E5.

Importance of features on a scale of 1 to 5

1. Feature is undesirable. I would not consider a product with this feature.
2. Feature is not important, but I would not mind having it.
3. Feature would be nice to have, but is not necessary.
4. Feature is highly desirable, but I would consider a product without it.
5. Feature is critical. I would not consider a product without this feature.

Table E5: Product specifications broken up by subsystem to meet all of the customer needs laid out in Table 3.

No.	Subsystem	Need	Importance
1	Bike	Can be easily pedaled by anyone	4
2	Bike	Can be placed on uneven/dirt surfaces	2
3	Bike	Has ability to change gears/make pedaling easier or harder	4
4	Bike	Does not tilt or fall over	3
5	Bike	Adjustable for different heights	2
6	Bike	Easy replacement of worn parts	2
7	Bike	Long enough chain to connect to pulley system	3
8	Bike	Easy and comfortable to operate	2
9	Pump	Does not clog	4
10	Pump	Maintains a pump rate of 5 gal/min	4
11	Pump	Is made of local materials	4
12	Pump	Reaches necessary depth of well	5
13	Pump	Adjustable range for different well depths	2
14	Pump	Easy replacement of worn parts	3
15	Pump	Made of sturdy material	4
16	Pump	Rope does not deteriorate in water	3
17	Filter	Made of easily replaceable materials	2

18	Filter	Locally sourced materials	4
19	Filter	Can continuously filter water	4
20	Filter	Long lasting	4
21	Filter	Filters out 100% of pathogens in water	5
22	Filter	Filter rate of 0.5 gal/min	3
23	Tank	Separates filtered and unfiltered water	5
24	Tank	Holds enough water for multiple families	3
25	Tank	Ability to release water to filter in batches	3
26	Tank	Structurally sound	5
27	Tank	Made from locally sourced materials	4
28	Tank	Protects stored water from outside contaminants	5

The various customer needs presented in Table E6 are paired with the metrics used to quantify the system to form the matrix in Figure E1. This is useful as a first step in identifying the most relevant and least relevant metrics and needs, and if either of these are not being appropriately addressed.

Table E6: List of metrics for the system as a whole with the updated customer needs ranked on a 1 (lowest) to 5 (highest) scale with units included.

Need #	**Need**	**Importance**	**Units**
1	Clean water to drink or cook with	5	ppm
2	A pump that is easy to power by pedalling	4	Newtons
3	System can be put on the wet, squishy ground	1	NA
4	A pump that can go from 20 meters to 45 meters deep	3	m
5	A solution that makes sense for people who make <$5 a day	5	$
6	A filtration device that will last a while	3	time
7	A filtration system that can be replaced locally	3	$
8	A pump that can be fixed with ease	2	time
9	Filtered water for a whole family	2	Liters
10	An education system for the local students to understand our project	3	NA
11	Vat holding system being able to hold weight of water	2	Newtons
12	Materials that can handle the multi directional stresses	2	Pa
13	Water that can filter in a reasonable time period	1	Liters/min

Needs	Clean water to drink or cook with	A pump that is easy to power by pedalling	Something that can be put on the wet, squishy ground	A pump that can go to 45 meters deep	Cheap and affordable system	A filtration device that will last a while	A filtration system that can be replaced locally	A pump that can be fixed with ease	Filtered water for a whole family	An education system for the local students to understand our project	Vat holding system being able to hold weight of water	Materials that can handle the multidirection stresses	Water that can filter in a reasonable time period
Metrics													
Pumpable Depth				•									
Pump Flow Rate													
Ease of Pedaling		•											
Rate of Filtration									•				•
Volume of Filter Tank									•				
Water Cleanliness	•												
Total Cost					•								
Force on structure holding water tank											•	•	
Adaptability			•				•						
Durability					•	•		•					
Strong connectors (pump to tank to filter to tank)												•	
Amount of pressure difference neccesary for flow rate													
Ease of Maintenance						•		•					
Scalabillity to other sites													
Cost of filter					•								
Cost of pump					•								
Roughness of pipe													
Effeciency of pump													•
Explainable/ reproducable					•		•			•			

Figure E1: Needs metrics-matrix.

Our project is very customer focused, especially since we are working with a non-profit and are just focusing on providing a service to people who have a severe need. The customer needs report and tables clearly identify a set of needs based on the interviews with people who are familiar with the customers we are providing for and this gave us a clear idea of how we needed to improve last year's Maya Pedal project to better meet the needs of the customer. The main focus was making everything locally sourced in Guatemala, making the system pump easier and more efficient, and to filter out all pathogens in the water. The product specifications were very informative for the design and iteration process because it tells us what materials and parts are off limits because they would have to be exported from the U.S. These customer-need based specifications make it possible to begin transitioning from soft goals to physical products to meet these goals. By pairing these goals with concepts and breaking the project into subsystems, it is manageable to identify key components and what can be implemented at later stages in the project.

Appendix F: Drawings

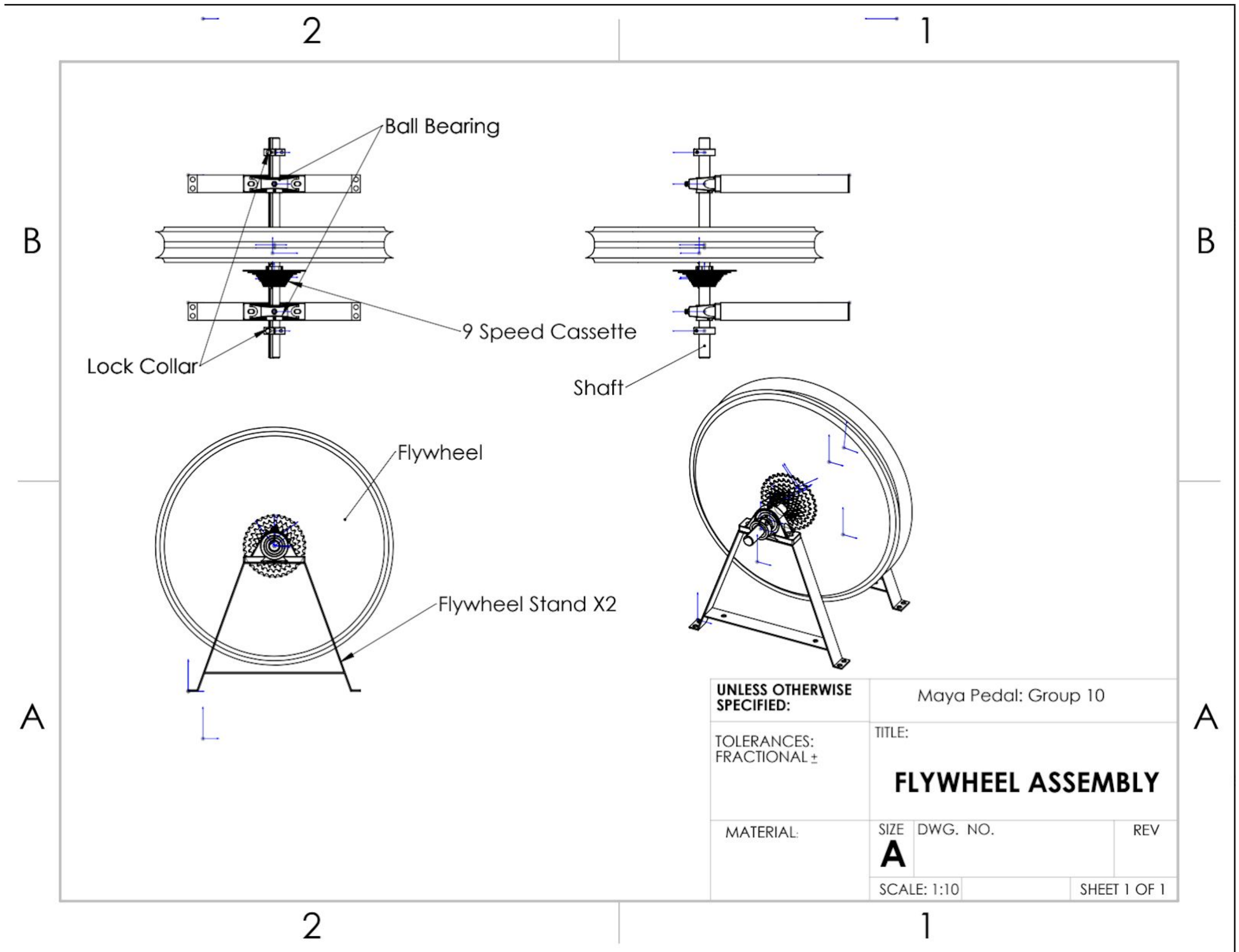

Figure F1: Flywheel Assembly Drawing

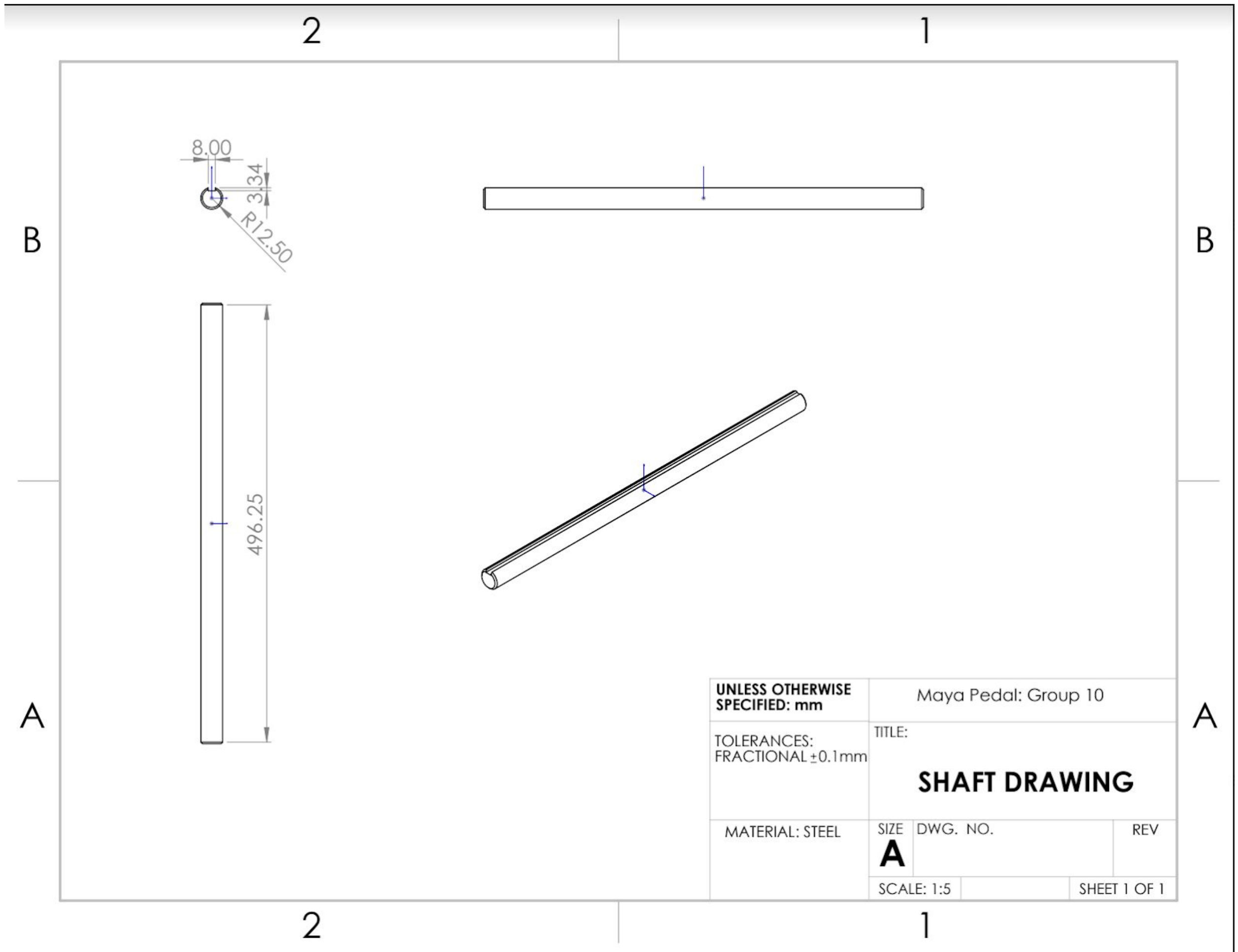

Figure F2: Shaft Drawing

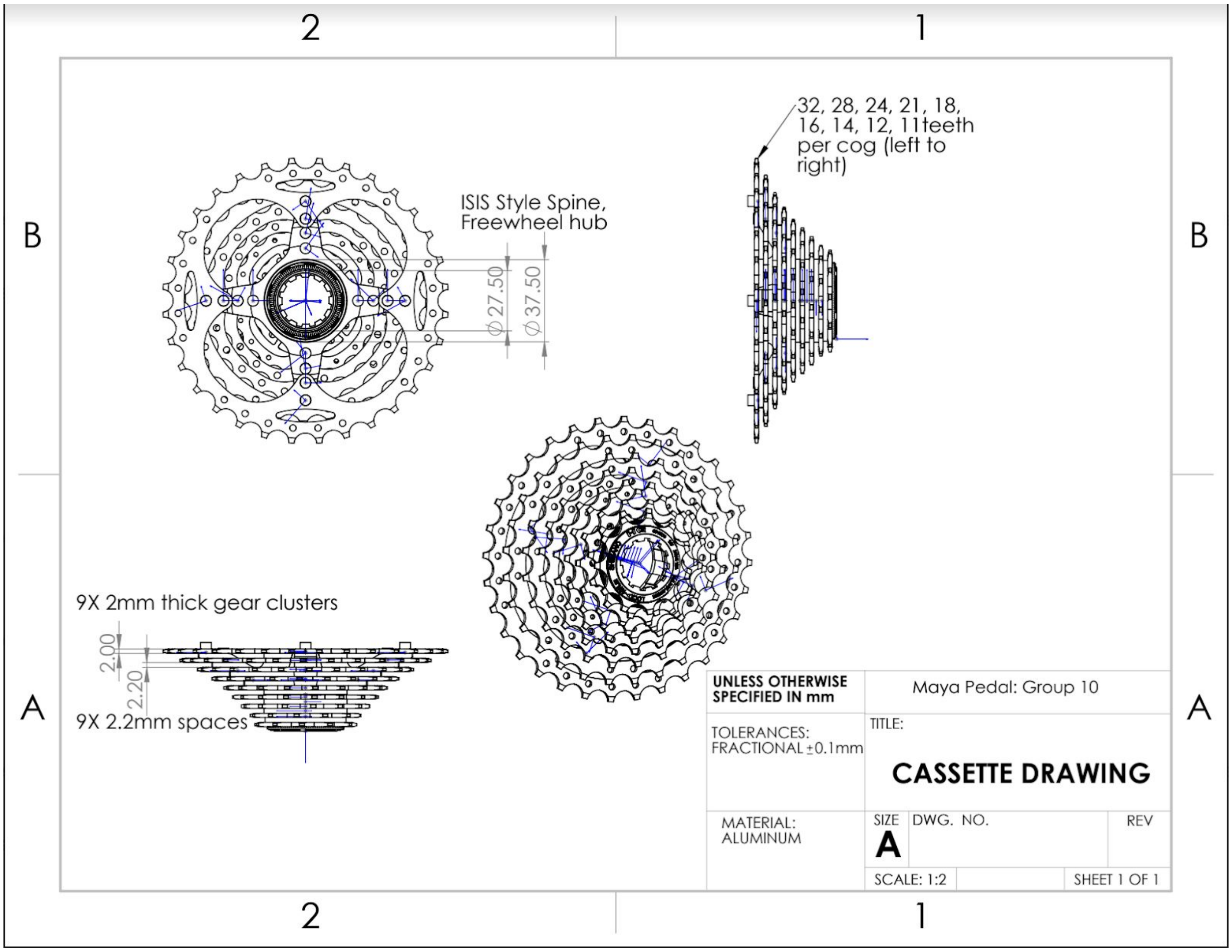

Figure F3: Cassette Drawing

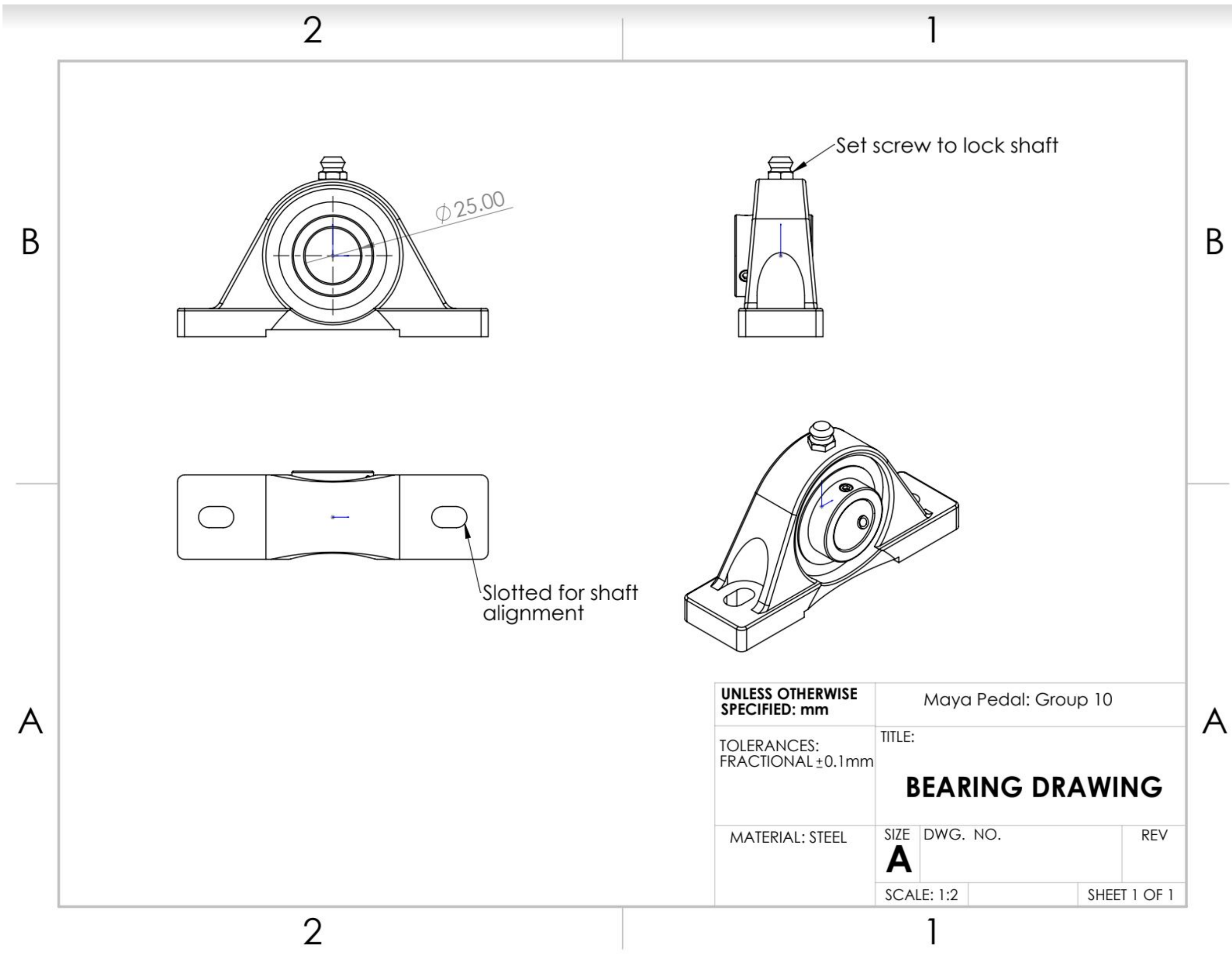

Figure F4: Bearing Drawing

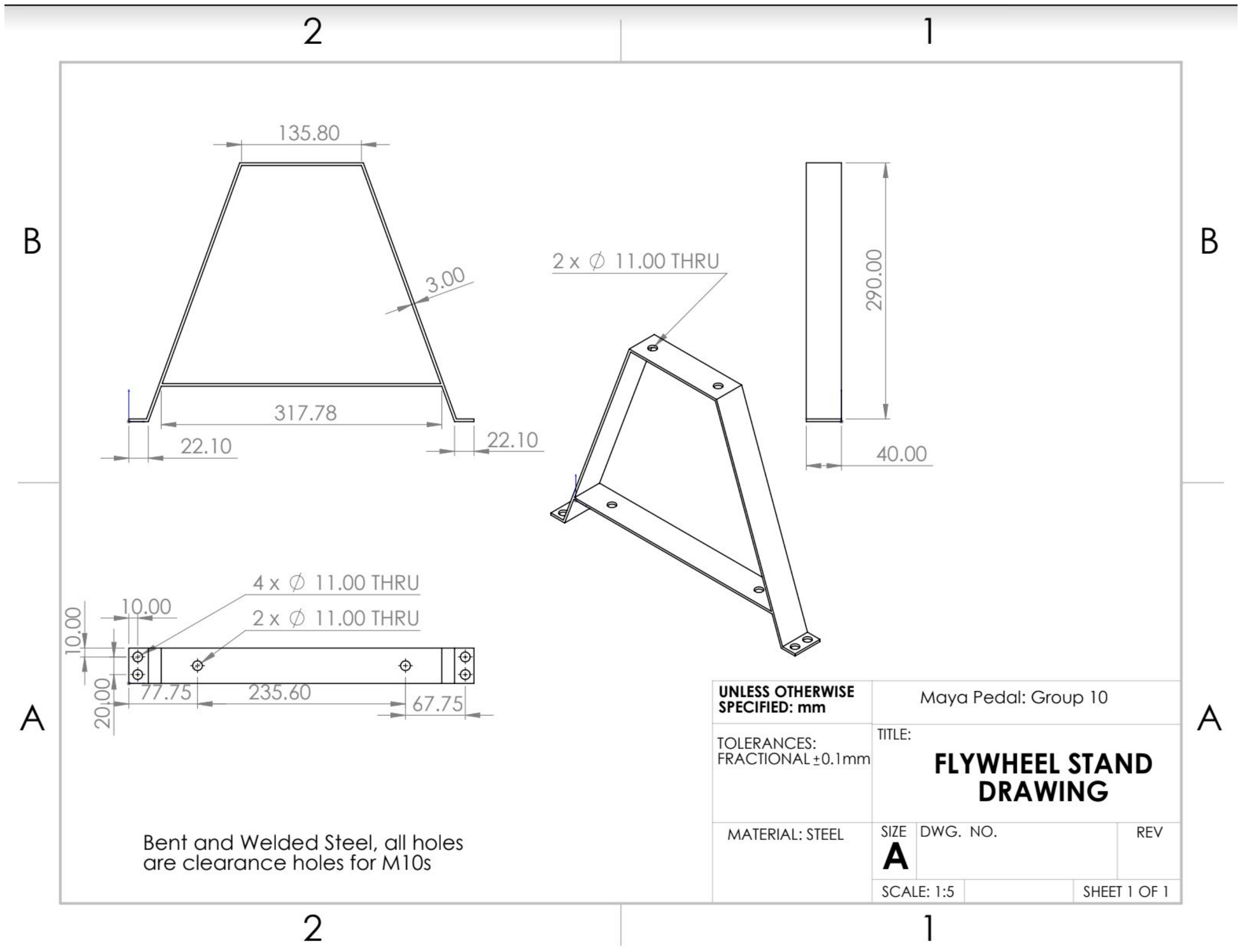

Figure F5: Flywheel Stand Drawing

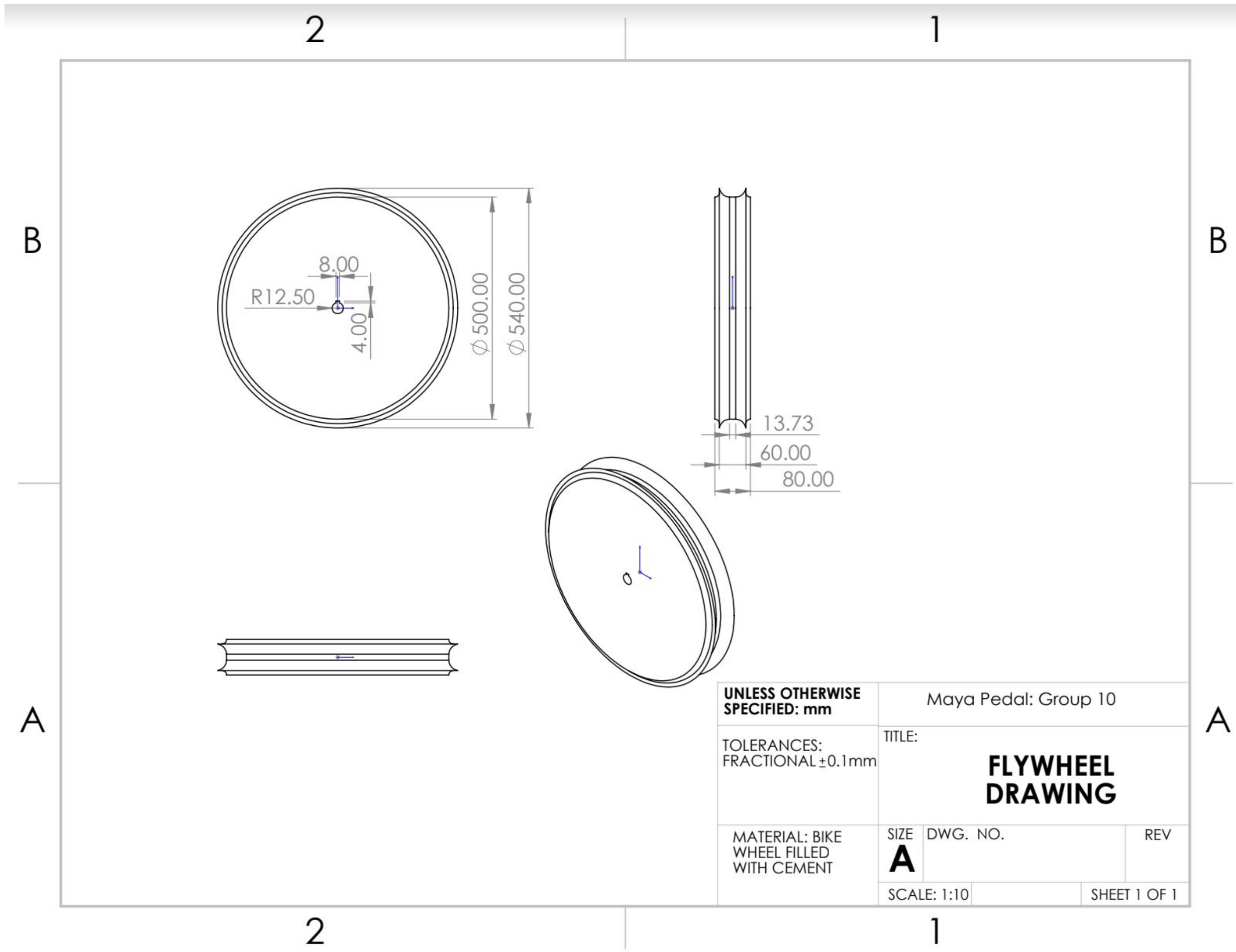

Figure F6: Flywheel Drawing

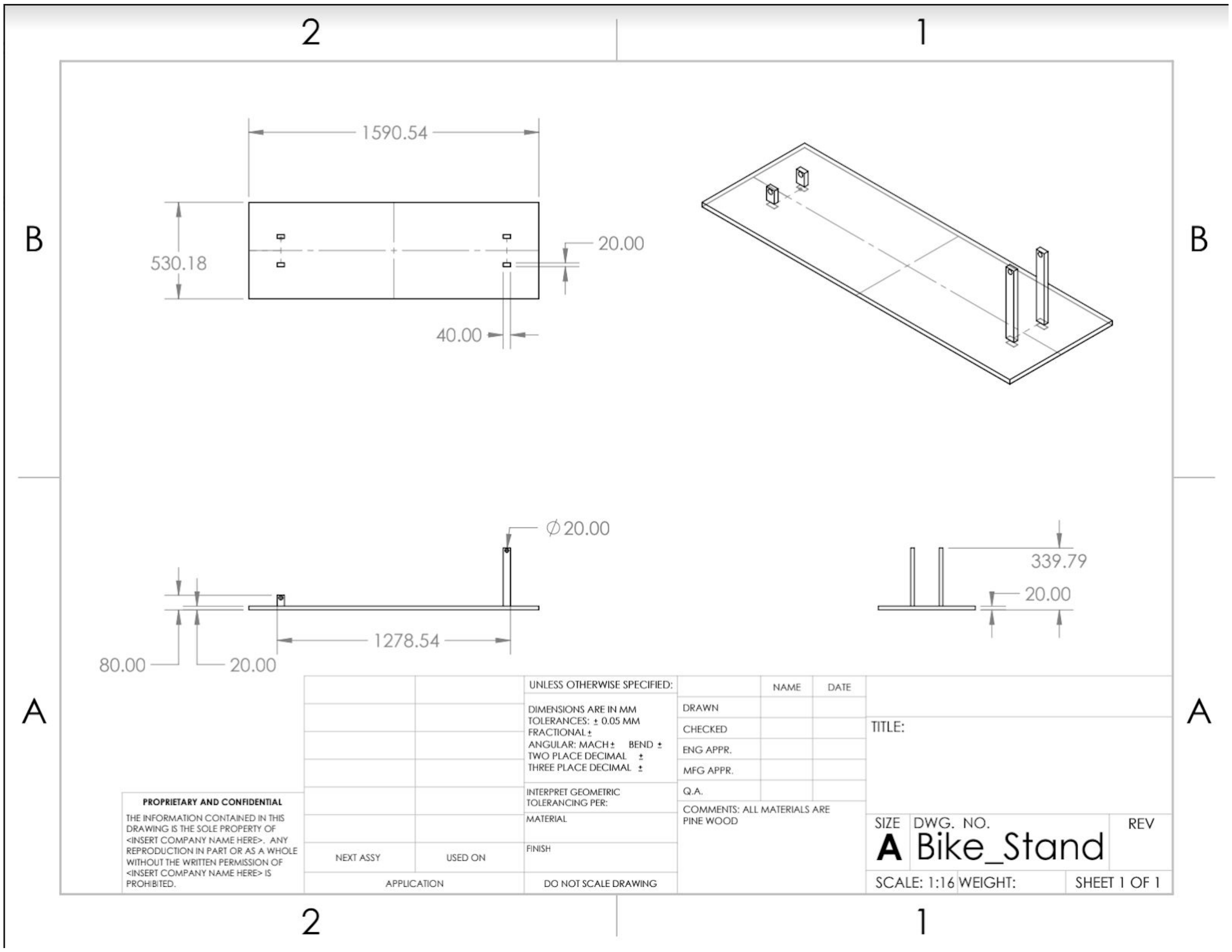

Figure F7: Bike Stand Drawing

3D Models

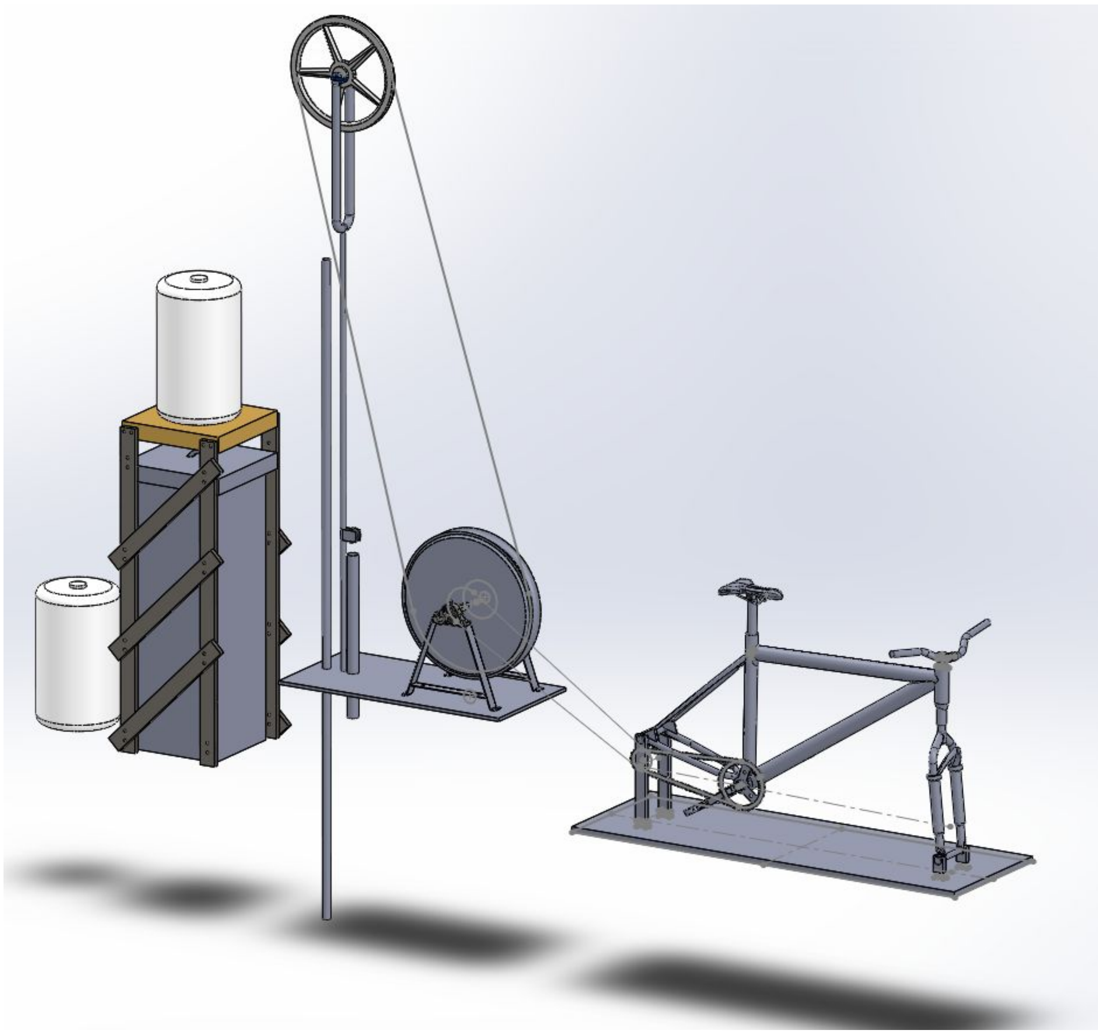

Figure F8: Current assembly design of a bicycle powered water pump filtration system.

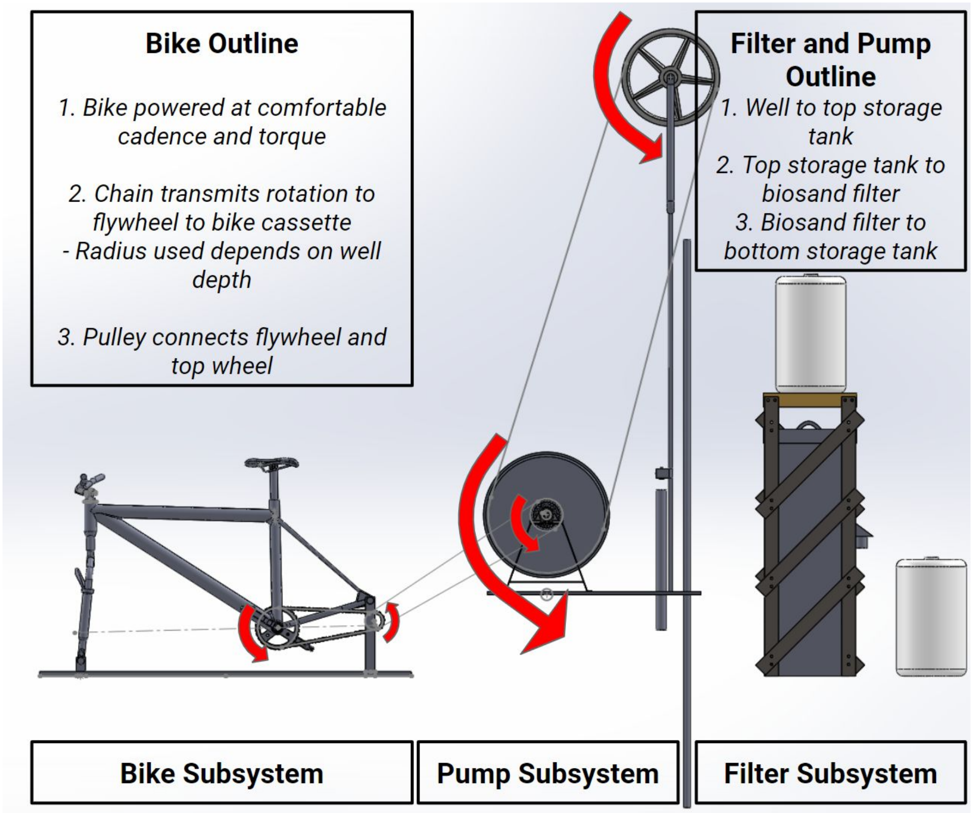

Figure F9: System level sketch with subsystems broken down and power transmission illustrated.

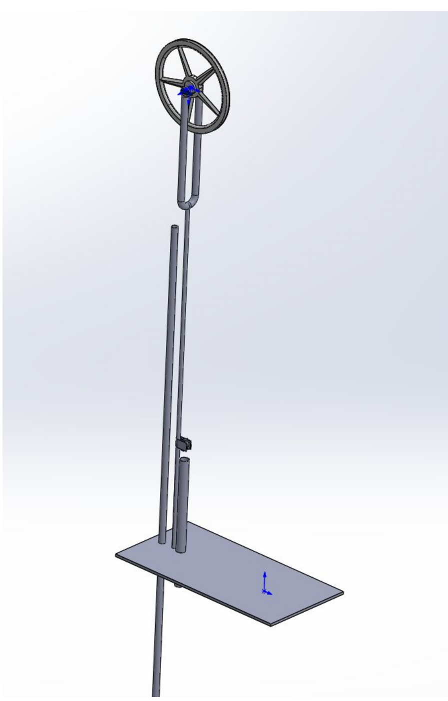

Figure F10: Full CAD view of the vertical rope pulley system.

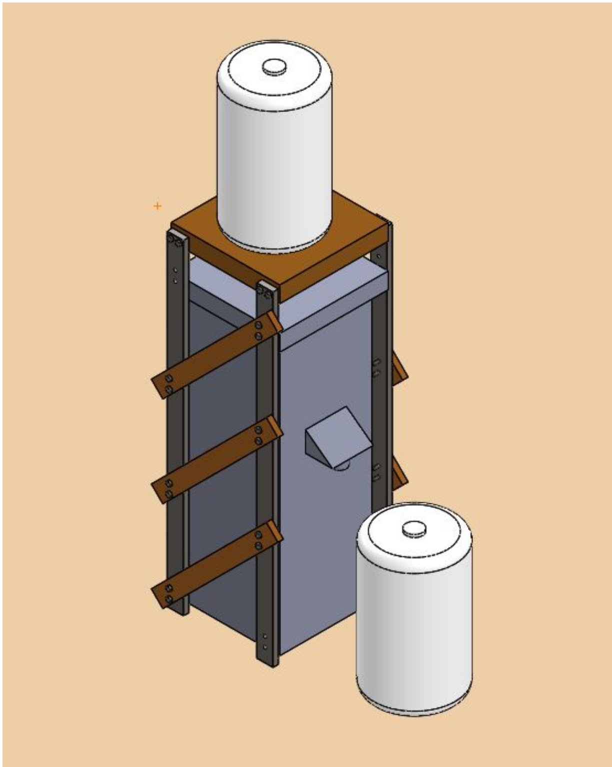

Figure F11: Storage tank and filtration systems produced by team in SolidWorks.

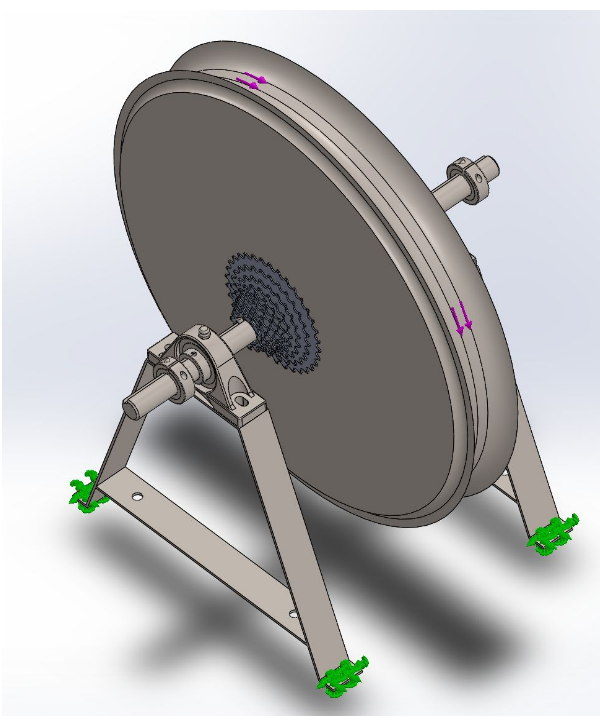

Figure F12: Flywheel subsystem CAD model.

Appendix G: Presentation

MECHANICAL ENGINEERING SESSION 2

BERGIN HALL 214

The Bici Bomba Pedal Powered Well Water Purification System

2:15 – 2:45

Ally Belica, Devan Hollar, Matt Kamimura, Liam Scobey

Advisor: Gaetano Restivo

Our system is a bike-powered pump that pulls water up from a well of up to 100 ft. into a natural biosand filter and into a proper water storage system. All parts of this project are made up of local materials that can be found in rural Guatemala.

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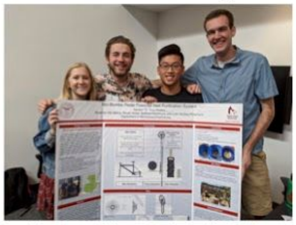
‘Bici Bomba’ Pedal Powered Well Purification System



Group 10: Matthew Kamimura, Liam Scobey, Ally Belica, and Devan Hollar
Advisor: Dr. Tony Restivo

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Background on Project

- Our design will be built in the San Andrés Region of Guatemala
- Only 44% of rural Guatemalans have access to clean water
- Most water available is found underground in wells
- Our Partners
  - Frugal Innovation Hub
  - Maya Pedal
  - Pure Wate

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Introduction and Problem Statement

- Optimize existing well pump system
  - Reach deeper than 30 meters
  - Maintain current pump rate of 19 L/min
  - Improve comfort and easy of peadler
  - Cost effective
  - Scalable and sustainable
  - Locally sourced
  - Culturally appropriate solution
- Provide clean water to three families
- Use a natural filtration system

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Original System

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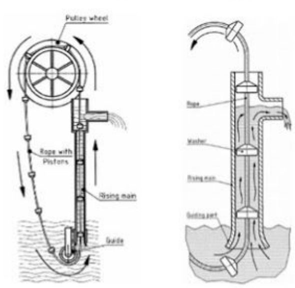
Pump Technology



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Customer Needs

Maya Pedal Guatemala

Importance (1-5)	Customer Needs
5	Clean water to drinkable levels
5	Ability to scale the project in nearby communities
4	Cheap and affordable system
4	Ability to retrieve water from a depth of 45 meters
4	Filter can be sourced in Guatemala
4	System will be durable and easy to maintain
3	Ability to pump at a fast flow rate
3	Bike/pump system is easy and comfortable to operate
3	Ability to filter water quicker
3	Education system for local students to understand our project and the system
3	The filter tank can store a large volume of water

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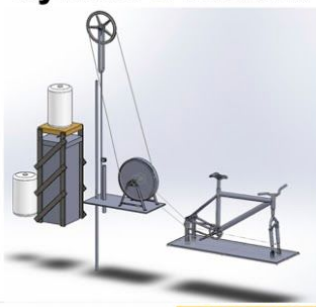
System Overview



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Product Specifications

Need #	Need	Importance	Units
1	Clean water to drink or cook with	5	ppm
2	A pump that is easy to power by pedalling	4	Newtons
3	Something that can be put on the wet, squishy ground	1	NA
4	A pump that can go from 10 meters to 45 meters deep	3	m
5	A solution that makes sense for people who make $5 or less a day	5	$
6	A filtration device that will last a while	3	time
7	A filtration system that can be replaced locally	3	$
8	A pump that can be fixed with ease	2	time
9	Filtered water for a whole family	2	Gallons
10	An education system for the local students to understand our project	3	NA
11	Vat holding system being able to hold weight of water	2	Newtons
12	Materials that can handle the multi directional stresses	2	Pa
13	Water that can filter in a reasonable time period	1	Gal/min

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Preliminary Trip

- Improved understanding of cultural context

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Preliminary Trip

- Clarified customer needs and system requirements
  - Water testing, examined parts, took measurements

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Preliminary Trip

- Prepared and redesigned to ensure scalability
  - Visited local hardware stores, spoke to locals about materials

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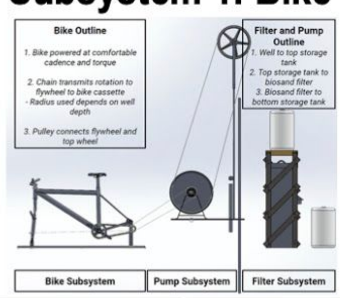
Subsystem 1: Bike



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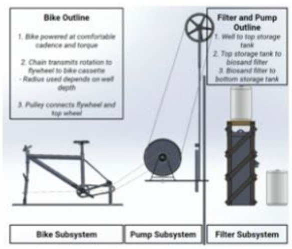
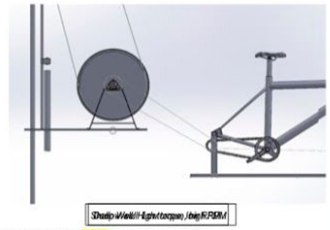
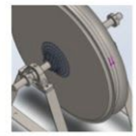
Major Improvements

- Bike Orientation
- Gear Ratio
- Updated bike stand



Power Transmission





1. **Torque** (N.m) = 9.5488 x Power [kW] / **Cadence** (RPM)
2. Water Force [N] * **Top wheel radius** [m] = **Torque** [N.m]
3. Rope velocity [m/s] = **Cadence** [RPM] * **Top wheel radius [m]** * 2π / 60 [s/min]

Based on: top wheel radius of 0.2 m, mass flow rate 0.3145 [kg/s], power of 75 W, flow rate of 5 [gal/min] =0.000315 [m^3/s]

Power Transmission

Diameter [mm]	Height [m]	Water Mass [kg]	Water Force [N]	Rope Velocity [m/s]	Cadence [RPM]	Torque [N.m]
20	30	9	92	1.00	96	18
30	30	21	207	0.45	43	41
40	30	38	369	0.25	24	74
50	30	59	576	0.16	15	115
20	45	14	138	1.00	96	28
30	45	32	311	0.45	43	62
40	45	56	553	0.25	24	111
50	45	88	864	0.16	15	173

Average of 75 to 125 W / hour
0.101 Hp to 0.168 Hp

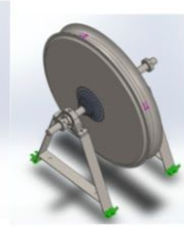
Weight of Water = (Volume of Pipe - Volume of Stoppers)ρ_{water}g = (**Well Torque**) / (**Top Wheel Radius**)
5 [gal/min] =0.000315451 [m3/s]=mass flow rate 0.314504647 [kg/s]
Height [m] / (Mass [kg] / mass flow rate 0.314504647 [kg/s])= rope velocity [m/s]
Rope Velocity [m/s] *60 [s/min] / **Top wheel radius [m]** * 2 π = **Cadence** [RPM]

Subsystem 2: Pump System

Concept Selection

Bike / Pump System	Durability	Cost	Ease to build	Ease of use	Flow Rate	Locally Sourced	Stability	Depth	Total Score
Flywheel with rope	3	5	5	3	3	5	4	4	**32**
Centrifugal pump	3	3	1	3	4	2	3	2	**21**
Submersible Electrical Pump	3	1	1	5	5	1	3	4	**23**
Hydraulic Ram Pump	5	2	2	2	3	3	4	3	**24**
Deep-well piston hand pump	2	5	4	2	2	5	4	2	**26**
Deep-well diaphragm pump	4	3	2	3	4	3	3	3	**26**

Pump Parts



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Guide Box

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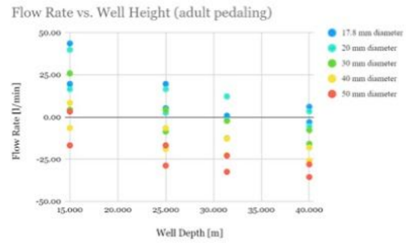
Rationalizing Design



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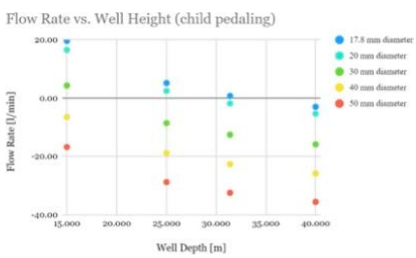

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Subsystem 3: Filtration System

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Concept Selection

Filter	Durability	Taste	Cost	Filter Rate	Locally Sourced	Cleans final 1.5% of pathogens	Total Score
Biosand with ZVI layer	5	4	4	2	4	3	**22**
Activated Carbon/ Water Ionizer	1	3	3	4	2	4	**17**
UV Filter	3	4	1	4	1	4	**17**
Chlorine filter	1	1	2	4	2	3	**13**

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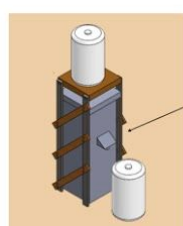
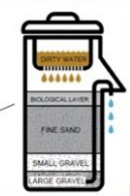
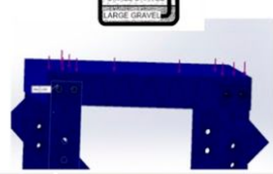
Filter







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Building Process

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Planned Testing

- Flow rate testing
- Coliform bacteria
- Nitrates
- pH
- Sulphate
- Iron
- Manganese
- Hardness

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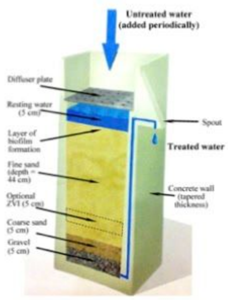
Filter Modifications

- Add Zero Valent Iron layer to improve filter performance

Percent of Pathogen Removal

Pathogen Type	Original Hydraid Filter	Improved Hydraid Filter
Bacteria	98.7%	98.7+%
Viruses	85.9%	99.99%
Giardia	100%	100%
Cryptosporidium	99.88%	99.88%

Source: Tellen, V., Nkeng, G., & Dentel, S. (2010). Improved Filtration Technology for Pathogen Reduction in Rural Water Supplies



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Final Product Specifications

- Remove remaining 1.5% of pathogens from water
- Pump from 30 meters or deeper
- Pump at a rate of 19 L/minute
- Easily and comfortably used by women and children
- Culturally practical solution
- Cost effective, scalable and locally sourced
- Total Cost: $1,100

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Future Impact of Solution

- Provides affordable clean water solution for approximately three families in a sustainable manner
- Scalable solution for other Guatemalan communities
- Education program and career opportunity for children in the village
- Create a long lasting relationship between SCU and Maya Pedal

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Questions?

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[12]"Safe Water System." *Centers for Disease Control and Prevention*, Centers for Disease Control and Prevention, 21 Mar. 2012, www.cdc.gov/safewater/ceramic-filtration.html.

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Additional Slides

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Tank Matrix

Tank System	Strength	Durability	Cost	Weight	Size	Safety	Effectiveness	Total Score
One Tank	3	3	4	4	4	3	2	23
Dual Tank	3	3	2	2	3	5	5	23
Plastic Tank	2	3	4	4	3	4	3	23
Cement	4	4	3	1	3	3	3	21

Going through the matrix demonstrates that there are multiple solutions that effectively address the problem. However, looking at the matrix critically the plastic dual tank solution would be best. The effectiveness of dual tanks paired with the weight and cost of the plastic tank make this the best water storage method for this project.

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Pump Matrix

Bike / Pump System	Durability	Cost	Ease to build	Ease of use	Flow Rate	Locally Sourced	Stability	Depth	Total Score
Flywheel with rope	3	5	5	3	3	5	4	4	**32**
Centrifugal pump	3	3	1	3	4	2	3	2	**21**
Submersible Electrical Pump	3	1	1	5	5	1	3	4	**23**
Hydraulic Ram Pump	5	2	2	2	3	3	4	3	**24**
Deep-well piston hand pump	2	5	4	2	2	5	4	2	**26**
Deep-well diaphragm pump	4	3	2	3	4	3	3	3	**26**

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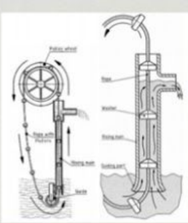
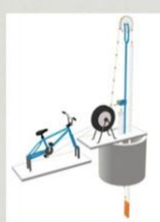
Pump Design





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Filter Matrix

Filter	Durability	Taste	Cost	Filter rate	Locally Sourced	Cleans final 1.5% of pathogens	Total Score
Biosand	5	4	4	2	4	3	22
Activated Carbon/ water ionizer	1	3	3	4	2	4	17
UV Filter	3	4	1	4	1	4	17
Chlorine filter	1	1	2	4	2	3	13

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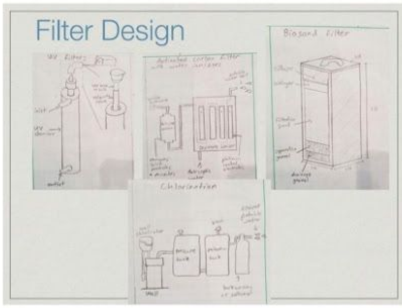

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Budget

Item	Cost (USD)
Pump and Bike Subsystem Maya Pedal Iteration	
Bicycle	$0
Metal for frame (Steel)	$200
Rope/ stoppers for well	$50
Flywheel	$75
Flywheel to gear	$30
Chain ring, cassette, chain, bottom bracket adapter, rear and mid derailers with shifters.	$150
Brackets, bolts and other hardware	$40
Bike and Pump Cost	**$545**

Filter and Tank Subsystem Maya Pedal Iteration	
Piping	$50
Natural Filter Sediment	$35
Steel for Filter Case	$100
Brackets, bolts and other hardware	$40
Upper holding tank	$75
Lower holding tank	$20
UV Filter/ "Pure Water for the world" Filter	$75
Water quality test meter	$120
Cement Base	$125
Tank filter system cost	**$640**

Item	Cost (USD)
Prototype Cost	
Bikes for prototyping	$140
Tanks and piping	$110
Tank reservoir and piping to simulate well	$75
Bolts, brackets and connectors	$35
Chain rings, cassettes, derailers, shifters, chains, and other bike parts	$225
1.5% Pathogen "Pure water for the world" filter	$75
Rope	$25
UV Filter Type	$80
Biosand filter prototypes	$220
Base (cement, wood or steel)	$100
Prototype System Cost	**$1,085**
Total System Cost	**$2,270**

Total Travel Cost	**$4,960**

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Income

Income Source	Amount (USD $)
Xilinx	$6000
Undergraduate Engineering Programs	$2000
Total Funding	**$8000**
Total Cost	**$7,230**

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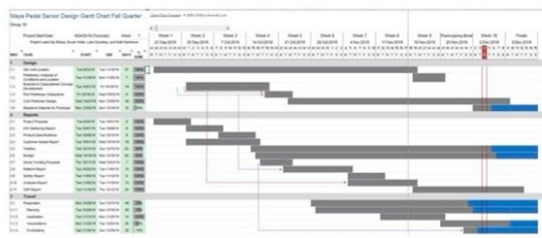
Schedule Look Back



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Schedule Look Ahead

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