Hydraulic Auto-nomous Doser (HAnD)

An affordable prototype for autonomous and remote dosing on AguaClara water treatment plants

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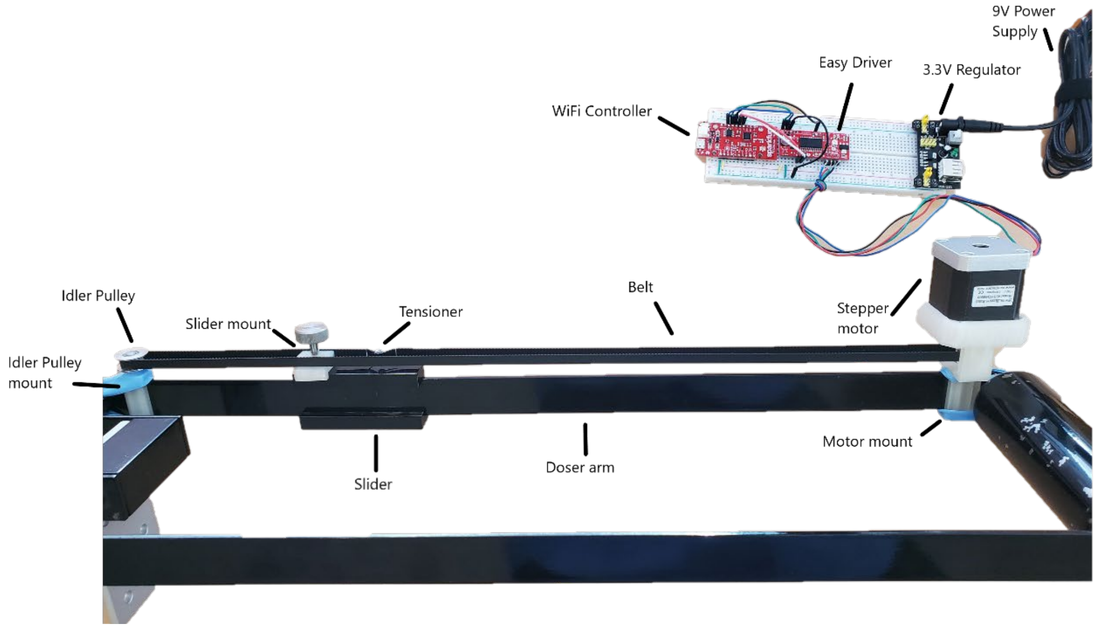
AguaClara Cornell

Diagram of the HAnD



The purpose of this project

The purpose of this project is to further develop the existing solution to the problem of lack of access to safe drinking water on tap. Over 800 million people lack access and as a result one in five children who die before the age of five do so because of treatable water borne illnesses.

This challenge and its potential solutions are very complex and span many disciplines. We aim to focus on developing an additional technical solution that we hope and expect will help communities to implement drinking water treatment and alleviate their pains. This report will contextualize the challenges we currently face, provide a new solution, and then justify its application.

The current state of the solution: AguaClara

For the past 15 years the AguaClara program has been developing a solution to provide access to safe drinking water. They do so by researching the physics behind how water is treated and then based on that physics they create designs that eliminate many of barriers to water treatment.

These are the most important requirements that AguaClara uses to design water treatment plants:

- The plant shall consistently treat water to safe drinking standards.
- The plant shall be able to operate in remote, electricity constraint communities.
- The plant shall be maintained by local community members.
- The plant shall use locally sourced, labor, materials, and parts.
- The plant shall be easy to operate and maintain.

With these requirements in mind, AguaClara has been able to bring access to safe drinking to over 85,000 people through 21 treatment plants in Honduras, India, and Nicaragua. The gravity powered plants consistently provide safe drinking water at a fraction of the cost and as a result of the design requirement, they are more robust, sustainable, and equitable than competing solutions.

However, 85,000 people is five significant figures away from our goal of providing drinking water to the 800,000,000 people who still do not have access. We therefore still have a long way to go and what better place to start than in our own backyard, the United States.

Participation in the NSF I-Corps

In the summer of 2021, AguaClara participated in the National Science Foundation's Innovation Corps (I-Corps program. The purpose of this program is to help academics turn their research into products and businesses by developing a business plan around potential customer. AguaClara used this program in order to determine whether or not current solutions would be applicable, useful, and scalable in the United States drinking water markets.

Over eight weeks the team conducted more than 100 interviews with customers and potential stakeholders ranging from the director of water enforcement at the EPA, to rural operators Montana. Their perspectives and stories helped the team understand the current challenges with the state of drinking water and showed that the United States faces similar challenges with access to safe drinking water as our Central American and Indian counterparts.

Most vocal current problem

Many of the operators, officials, and engineers that the team spoke to highlighted one recurring pain point, namely the lack of operational staff. They attributed this problem to a number of key factors:

- The skills an operator uses at a water treatment plant can be transferred to higher paying industries such as oil and gas.
- Water treatment plant operation is an extremely difficult job to do well because it requires an understanding of chemistry, physics, and mechanical and electrical engineering.
- Water treatment as an industry is often thankless because as a public good it is expected by the consumers. Additionally, it is not rewarded monetarily, or otherwise as other public service industries are such as emergency personnel like law enforcement and firefighters.

In addition to the challenge of lack of qualified operators, the team identify many similar challenges that the AguaClara program already provides solutions for, such as how moving parts is a major cause for failure and often requires expensive and highly specialized maintenance which leaves plants non-operational for extended periods of time. Additionally, access to electricity and other important treatment resources and high costs associated with capital and operational expenditures were found to be challenges that rural US treatment systems shared.

A Report Overview

This report consists of four separate sections each written as separate reports. They are, a how-to guide with justifications and observations, a systems model, a dynamics model, and a failure mode and effect analysis. The first section serves as an instruction manual to duplicate the design and explain the process what went into developing the HAnD. The second section is a systems overview which includes a collection of over 30 tools used to help develop the design. The third selection section is an attempt at systems dynamics model that could be used in the autonomous online portion. The final section is an in-depth failure mode and effect analysis which provides insight into why certain design decisions were made.

How to make a Hydraulic Autonomous Doser (HAnD)

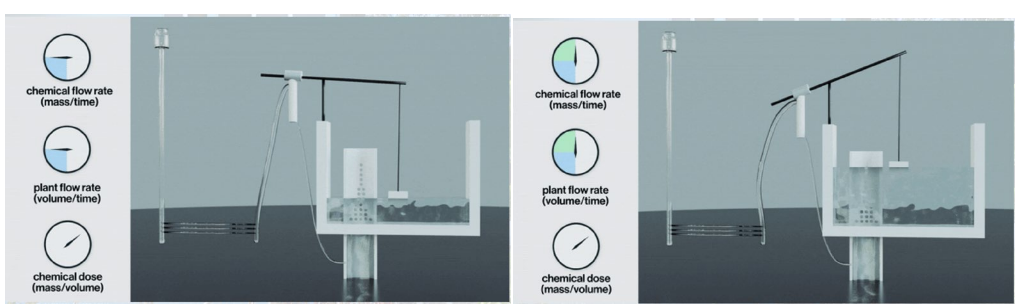
New Requirements (as compared to the requirements in section 2)

The purpose of developing new requirements is a result of reevaluating what physical components and systems we are going to be using and developing new requirements based on their systems. This is within the iterative process in the system design framework. Our new approach does not use any pumps and instead continues to use the AguaClara doser by attaching to it a motor pulley system which moves the slider wirelessly. This new design is very different than the initial concept sketches and as a result requires new set of guiding requirements.

The purpose of this redesign is result of the many failures associated with using a pumping system that is discussed in the extensive AguaClara documentation as well as in section 4. It also works as more modular system where current of AguaClara plants can now add the HAnD to their existing doser and so it does not require any significant modification to the existing plants. Lastly it also takes advantage of the dosers already existing unique flow-based properties and so it adapts very well into the current AguaClara gravity-based design process.

The HAnD shall be able to maintain the same dose in the highest and lowest possible flow rates

The purpose of this requirement is to ensure that the HAnD works across all dosing scenarios. This is important because at different flow rates the incline of the dosing arm changes (see figures below). With this incline change comes a difference in force acting on the slider component. Ensuring that all circumstances and all inclines associated flow rates are accounted for in the design minimizes the chance of failure in extreme conditions.



Left: depict near horizontal position of doser arm during low flow rates. Right: inclined doser arm during high flow rates.

The HAnD shall be able to be controlled via a wireless connection

This requirement is in essence the basis of this project. It is important that the HAnD be controllable via a wireless connection so that the operator is not needed to be physically present at the plant during the time of dosing. This requirement manifests itself in the appropriate selection of wireless controllers.

The HAnD shall be able to track its position on the doser

This requirement is to ensure that the operator understands where the slider is positioned on the dosing arm. This is important because sliders position corresponds to the dose that is being administered to the plant and that dosing process is essentially what the operators most important job.

The HAnD shall be able to reset zero its position within 30 secs

This requirement is to ensure that if the slider on the doser arm needs to be reset either as a result of power outage or intentional sleep to reduce power consumption, then the HAnD is able to self-zero its position and ensure that it is dosing correctly. An alternative solution would be to create a sense of memory so that in the event of a power outage or sleep the position of the slider is immediately known. However, if that fails then the ability to zero and reset accordingly is still an important requirement.

The HAnD shall be able to dose to within 5% precision

This requirement sets the standard for what correct dosing looks like. The number of 5% was chosen arbitrarily and this can be included in further work to determine what is an appropriate error threshold. Part of that future work might include an analysis of what is the effect of a percent difference on the actual dose. However, with a current standard of 5% precision this ensures that the HAnD set dose is at least comparable to human error occurring during physical dosing.

The HAnD shall be able to be controlled autonomously

This requirement ensures the ability for the HAnD to be controlled without an operator at all. This can be important if an operator is needed to manage multiple plants but is unavailable for either maintenance or other extenuating circumstance. This requirement also highlights the need for the development of the dosing model (attempt at that model was made in section 3). Additionally, it can be used to provide insight as to what is an appropriate initial dose for the operator and serve as suggestion.

The HAnD shall be corrosion resistant

As the HAnD is going to be operating in environment with exposure to chlorine and various coagulation and buffering solutions, the HAnD needs to be able to resist the negative effects of those chemicals for at least a certain period of time. This requirement will influence the component selection as well as the housing for the various components.

The HAnD shall be water resistant

This requirement ensures that the electric components such as the motor and controller are designed to be water resistant or at least housed in water resistant container. This ensures that circuits will not short and reduces the chances of electrically induced failure.

The HAnD shall be cheaper than a 100$

This requirement is to maintain the autonomous dozing addition as an affordable solution particularly as it relates to financially challenged communities. The $100 price point was chosen arbitrarily, however, it is a number that is easy to wrap one's head around its value and it is often well below the cost of a single chemical pump. Additionally, its low costs ensures that various components can be replaced with very little difficulty.

The HAnD shall be made of parts that can be replaced within one week

This requirement is to ensure that all various components can be easily maintained and replaced in the event that a failure ensues. It ensures that operators are able to maintain the HAnD within a reasonable timeframe and allows them to return to normal operations promptly.

The HAnD shall be made of components with large online troubleshooting communities

This requirement is to ensure that new difficulties and unforeseen circumstances can be accounted for with the help of large online communities. This reduces the barrier to adoption and implementation as it corresponds to lower level of expertise needed to understand the system and troubleshoot. It in turn insures longer working time and shorter maintenance time for each of the various components.

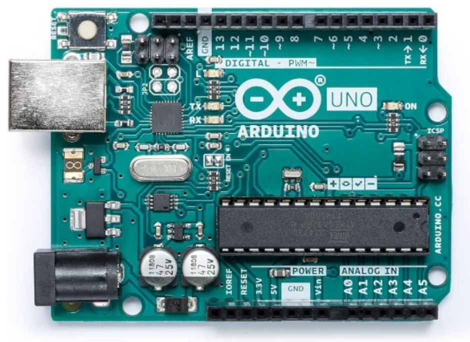
Product Selection

We developed a series of potential solutions that satisfy each of the requirements specified above. We then compared those solutions with a simple pro and cons list as well as an expected effort category that incorporates the effort needed to implement and troubleshoot each of those elements by the operator themselves. The table below is an example of the type of research that went into each design decision.

1		Requirement	Item	Cost	Effort	Pro	Con	Alternatives 1	Cost 1	Effort 1	Pro 1	Con 1	Alternative 2	Cost 2	Effort 2	Pro 2	Con 2	Notes
2	The CFDS shall	send operational commands	Arduino	2	2	Cheap and simple, best for single task, can be easily battery powered !!	No OS	Rasberry Pi	3	3	OS, best for multiple tasks	Didicated OS requires work to program	Custom board	1	5	Cheapest	Most difficult to learn and build	
3	The CFDS shall	recieve operational commands wirelessly	Arduino	2	2	indepedant and replaceable = easy maintence	requires dedicated system and external hardware	Rasberry Pi	3	3	has internal dedicated systems	maintence will require replacement	Custom board	1	5	Cheapest	Most difficult to learn and build	
4	The CFDS shall	change the dose within x sigma DoE	Screw Actuator	??	??	Faster, higher load, more accurate,	Friction wear, needs lubrication,	Belt Actuator	??	??	more intuitive and eaiser to fix with less resources, replace belt vs new bolt,Longer	belt wear, timming (accuracy) less,	Stepper vs servo vs integrated			servo is more precise continual and controlloed, stepper is easier, integrated is less work and be default protected	servo = constant tourque, stepper =	
5	The CFDS shall	be resistent to corrosion	Possible					Possible				think car	Possible					Corresponding
6	The CFDS shall	send sensor data	Arduino	2	2			Rasberry Pi	3	3			Custom board	1	5			
7	The CFDS shall	know current position dose	Servo	2	2	internal position tracker	no integrated with actuator	Stepper					DC					

Arduino

An Arduino was initially selected as the controller for the overall process control because it is it satisfies the requirement of having a large online troubleshooting community. There is an extensive documentation and a wide online network of hobbyists and DIYers who use Arduinos in various systems and as such it makes for a very good controller. Additionally, it is relatively inexpensive and there exists entire back-end user interface called Arduino IDE which makes learning and using in Arduino vary easy and seamless.

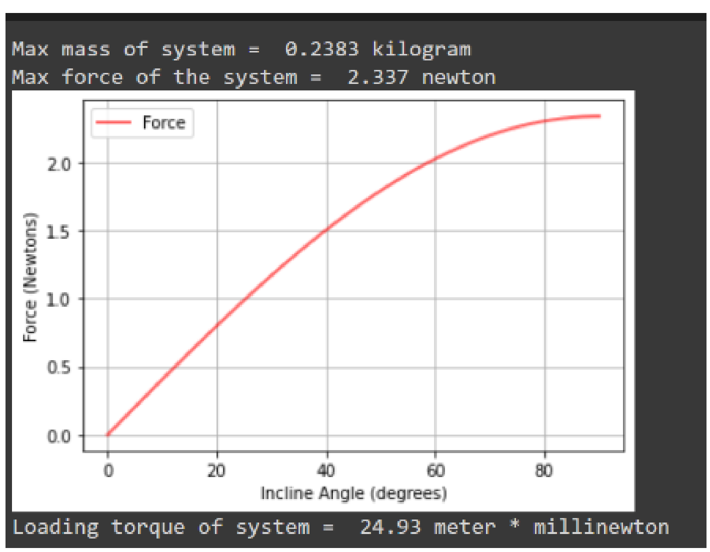


Link: https://www.amazon.com/Arduino-A000066-ARDUINO-UNO-R3/dp/B008GRTSV6

Motor Sizing

The primary driver for selecting which motors where the appropriate ones are mostly based on the requirement of will it be able to dose consistently at the extreme flow rates. To properly analyze this, we created a graph showing the force is it varies with respect to the angle of the dosing arm (see figure below). As the angle increases force of the weight acting on the spider increases as well, therefore. We then took the Max force experienced and solve for the loading torque on which was used to determine the debt and force. The getting force is the force that the stepper motor exhibits when it is in the power off stage. This force is as a result of the magnetized holes inside the stepper motor still retaining some of its magnetism even after the power off stage. We used this parameter as the major deciding factor and looked specifically for stepper motors that included deadly force in its spec sheets.

We determined that the loading maximum loading torque and our system feel experience was X and we then found a motor whose does not force was applied.



Equations used

$$Torque_{loading} = \frac{F_{Total} \times Diameter_{Pulley}}{2 \times \mu \times i_{gear\ ratio}}$$

$$F_{Total} = F_{external} + Mass_{Total} \times g \times (\sin\theta + \mu\cos\theta)$$

$$Mass_{Total} = Mass_{slider} + Mass_{pvc} + Mass_{tubing} + Mass_{coagulant\ dose}$$

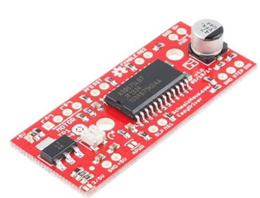
For detailed equations see code in appendix.

Links: https://www.digikey.com/en/products/detail/sparkfun-electronics/ROB-10846/5318748

http://cdn.sparkfun.com/datasheets/Robotics/42BYGHM809.PDF

Sparkfun Easy Driver

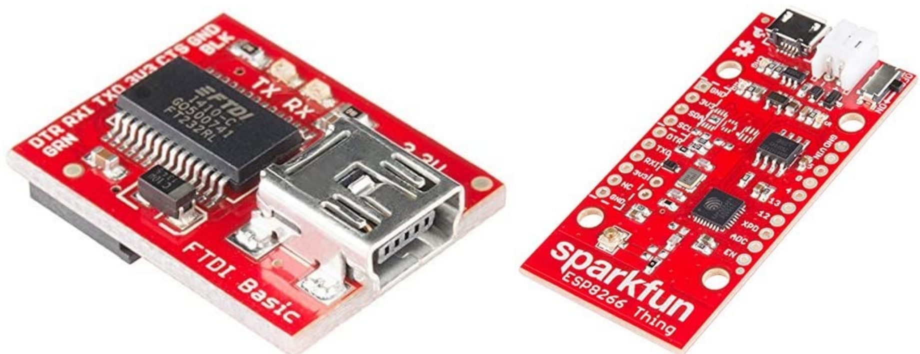
The driver we chose was the SparkFun Easy Driver due to its high level of documentation and its overall low cost. Though it worked well, there are considerations that future iterations of this system should take into account. It is a known problem that Easy Driver can get very hot. This is problem because as the temperature of any driver increases the performance decreases so it might be worth considering a substitute with a more consistent temperature for sake of reliability and uniform performance.



Link: https://www.digikey.com/en/products/detail/ROB-12779/1568-1108-ND/5318750

Sparkfun ESP8266 Wi-Fi Controller and Adapter

The ESP8266 Wi-Fi Controller was selected similarly to the easy driver because of its wealth online resources. Additionally, and this was later found out during execution, that this controller can act as its own microcontroller. In our final schematic it entirely replaced the Arduino, thus reducing the costs by almost half. It also works into the Blynk online community and has considerable documentation as well as verification of its parts of authenticity unlike other ESP8266's. Lastly, it can be programmed using the Arduino IDE interface making it easy to use and develop.



Link: https://www.amazon.com/gp/product/B079M4F7W5/ & https://www.amazon.com/SparkFun-WRL-13231-ESP8266-Thing/dp/B00YUU4AMK/

GT2 belt and pulleys

The GT2 belt and pulley system was selected because of its ubiquity and low cost. It is often the belt and pulley system of choice for 3D printers and as such it has an extensive online community as well as readily available replacement parts. For future iterations and maintenance documentation it is important to find a belt that is more corrosion resistant than rubber and who's internals are made of a fiberglass or other inert material rather than steel. Similarly, the pulley, bearings, and their screws should be made of an inert substance. Bearings are often made of steel and an expected failure point is their balls rusting.

Link: https://www.amazon.com/gp/product/B07JKT5BZQ/

Switches

The searches were selected based on recommendation of the schematic software there was very little research or decision-making process and in future the switches will be selected on how resilient and reliable they are especially in caustic wet environments. The switches and zeroing capacity were not tested in this iteration.

Power Supply

The initial power supply and step-down system was chosen based on the maximum voltage accepted by the various components such as Wi-Fi controller, the Easy Driver, and the motor. All of the systems run on 3V and so a voltage regulator from the breadboard kit was used. Additionally, this voltage was selected to work with a standard 12-volt system so that in the event of an emergency a car battery could be hooked up and used as a replacement. This makes for a much more resilient system given the accessibility of car batteries. Additionally, the Wi-Fi controller and through it the driver and motor can be powered via a lithium battery. This connection is already incorporated into the controller design making it a very adaptable and easy to use and charge.

Link: https://www.amazon.com/gp/product/B06Y1LF8T5/

Breadboard and tools

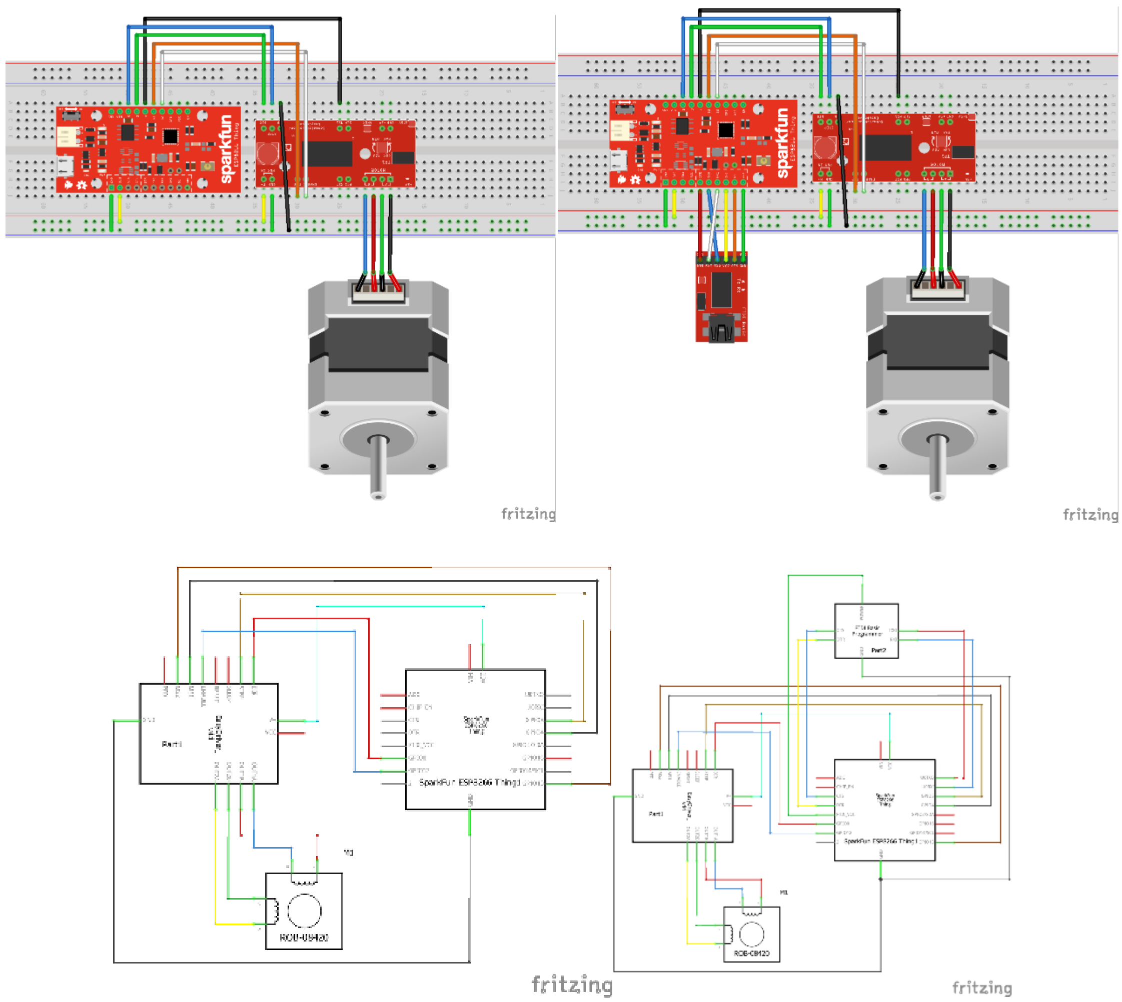
To connect all of the components a breadboard, jumper cables, and soldering iron was used. Future designs should include the development of a housing system or potentially even a dedicated PCB. This may prevent failures due to exposed circuitry. However, the replicability and modularity of the system should be taken into consideration.

Link: https://www.amazon.com/gp/product/B073ZC68QG/

Schematics

The open-source circuitry tool Fritzing was used to develop the schematics. A link to a download file can be found below. In the google drive there an upload of the Fritzing files

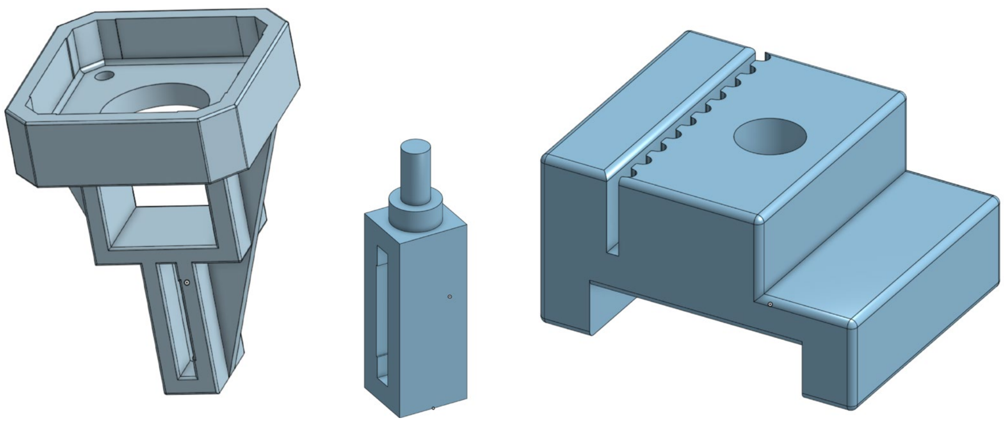
https://onedrive.live.com/?authkey=%21AJ4yupk5PGV2vs0&cid=56559D033B70DDA3&id=56559D033B70DDA3%21929397&parId=56559D033B70DDA3%211006996&action=locate



Left: Schematic without the FTDI adapter. Right: Schematic with the FTDI adapter.

3D Prints

The 3D printing process required many iterations, and the final designs can be seen below. For the motor mount it became important to provide truss-like support as the 90-degree position of the motor has high leverage and creates an easy break point. The pulley and motor mount were designed to fit onto the slider itself and to have the pulleys be centered on the slider. This make the GT2 belt off center allows for the same screw used to hold the slider initially be reused. The slider connector was designed to serve as a clasp for the belt and to be easy to detach. It was also designed to allow for the return side of the belt to move freely and not cause any damage to the belt due to friction. The slider mount sits snugly on top the slider and so it can be removed with very little effort making the system easy to return to normal operation in the event of electrical failures. The idler pulley mount was designed to the securable via threaded screw on the bottom similar to the motor mount and was designed to have a tight tolerance for the inner middle layer of the bearing of the idler pulley.



Left to right: Motor mount, Idler Pulley mount, and Slider mount

Link:https://cad.onshape.com/documents/9fece2ddf68dd54c344c3a1b/w/c25aa388d0e9a895ed77d61e/e/581227e74c1a916146499014

Set up and Running Tutorial

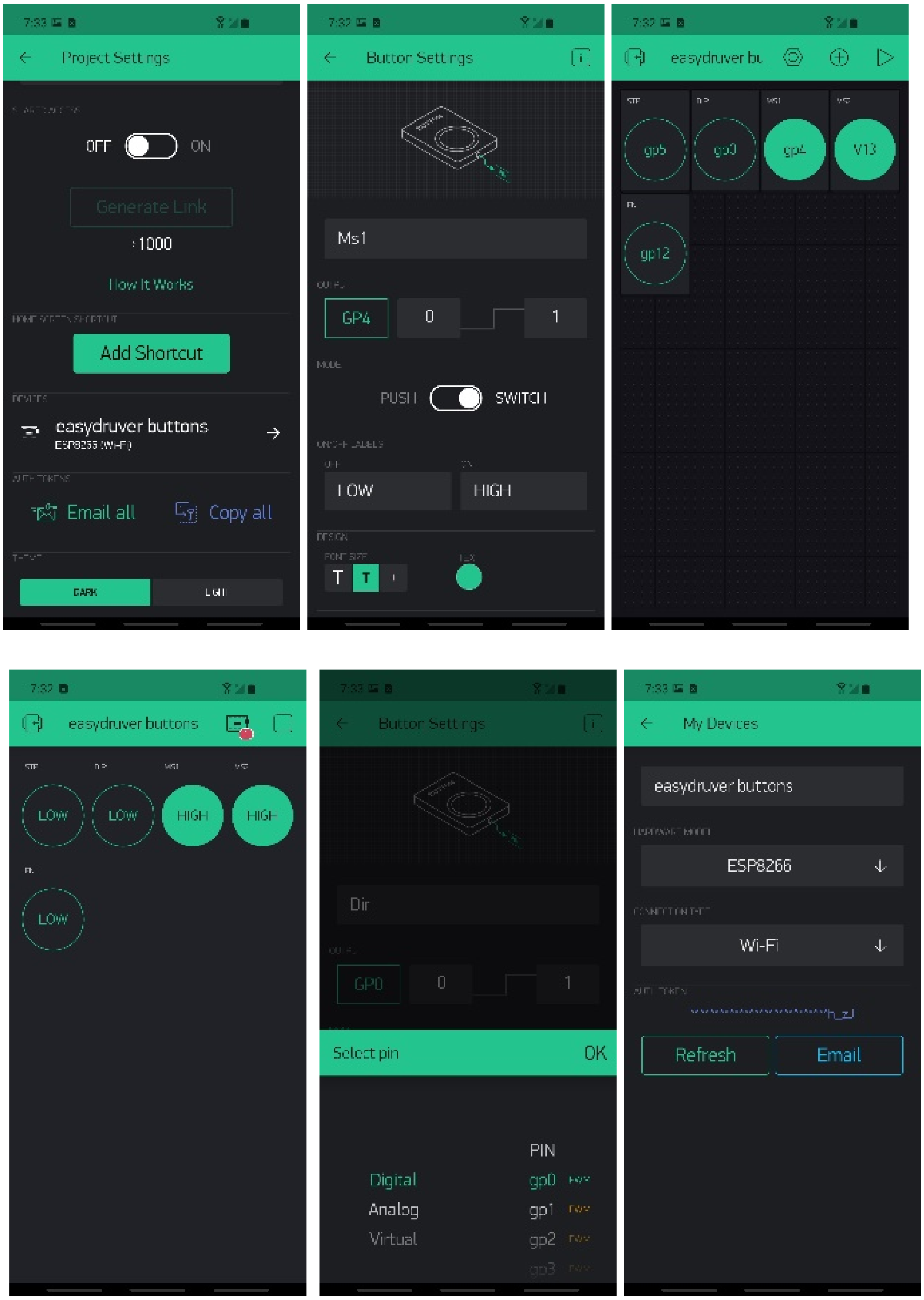
In order to connect the ESP8266 Wi-Fi controller to Arduino IDE and upload the correct code. You first have to follow each step in this tutorial.

Link:https://learn.sparkfun.com/tutorials/how-to-install-ftdi-drivers/windows---in-depth

https://learn.sparkfun.com/tutorials/esp8266-thing-hookup-guide/installing-the-esp8266-arduino-addon

Using Blynk

The pictures below demonstrate the appropriate setup setting in Blynk for connecting to the Thing.



The YouTube link below demonstrates the HAnD being used in action.

Link: https://www.youtube.com/watch?v=nQSnWTDhNq0

Observations

Cheap

Item	Cost ($)
Motor	17
Wi-Fi Controller	15
Easy Driver	15
3D printed parts	3
Total	**50**

As we can see by the table above the total cost for developing this autonomous doser is approximately $50. These costs do not include the initial setup costs or tools as those costs get reincorporated and reused for the development of each HAnD. Nor does this include the miscellaneous costs of the actual development itself however those costs are negligible and can be ignored.

It is apparent that this solution is a very scalable and a good minimal viable product to demonstrate our goal. With the intention of replacing the need for continual operators to be physically present at plants by providing an option to autonomously control, this approach is clearly a very cost-effective method.

Easy to build

While there is some learning curve to setting up the system and getting it working, it is not too great so it can be implemented in a majority world context. For example, just in the development of this solution alone I have had to learn all of the skills necessary to create this product such as coding, the app development, 3D printing, 3D modelling, motor sizing, soldering, troubleshooting, electrical engineering etc. However, that said most of those skills are not going to be necessary once a final option is offered to AguaClara clients. Similarly given that there is only a single connection point to the existing doser arm, in the event that this system is no longer wanted or does not work the operator can very easily dismantle it within a few seconds. This adaptability allows for the system to be tested cheaply and easily and designed with specific plants needs in mind.

Easy to fix

Given that all of these parts are readily available DIY electronics parts and are extremely inexpensive this system is one that can be very easily fixed just by replacing the parts. Additionally, it is not a complex system that requires a deep understanding of engineering disciplines and so any hobbyist with very basic tinkering understanding should be able to troubleshoot and fix the system in the event of a failure.

Future Work

Independent user Interface

Currently our system uses the Blynk app and their online web servers to connect a smart phone to the HAnD. While this is a good temporary solution it is not ideal as sensitive information regarding the dosing of a water treatment plant is now flowing through a third-party software. In the future, our system should have its own dedicated user interface for the operator that is end to end encrypted and protected from software security breaches. This can be created in collaboration with the POST team and their data collection and troubleshooting efforts. Additionally, through the development of an independent user interface for the operator we can provide a useful means of continual communication of the performance and quality control with the operator.

Part of the development of the user interface should incorporate not just monitoring the existing plant conditions, but various elements of the electrical components and the environmental conditions as well such as ambient temperature and humidity.

Modeling

In order to truly have an autonomous doser a dosing model needs to be created. Outputs for this dosing model will include suggested dosages and those suggested doses can move the slider arm using the HAnD. This will ensure an optimal dosing of the water given its current initial conditions and its current performance. This model will incorporate various elements of physics as well as empirical data. An attempt at developing this model is created in Section 3 of this report.

Field Testing

To truly demonstrate whether or not the HAnD is an appropriate solution we need to conduct thorough testing of each element. Testing procedures can be created using the tool specified in Section 2 of this report. Specific elements of the hand to test include demonstration with actual weighted dosing and dosing across various flows to test motor strength.

Waterproofing

As the system stands, it is extremely vulnerable to water induced failures and for it to work in water treatment plant it obviously needs to be waterproof. It is therefore important that at the very minimum enclosures are designed and developed for all of the electrical components as well as measures taken to protect the mounts. The current printed material is very susceptible to heat and will deform and loose its shape at temperatures above 100 degrees which in warm tropical climates is to be expected.

Self-zeroing

The self-zeroing and incorporation of switches into our design was not implemented for this proof-of-concept stage. The importance of developing this aspect is specified in the requirements mentioned above and the next step should include its development.

Independent Position Tracking

The position of the slider on the dosing arm is essential for appropriate dosing and for true proof of concept. There are a number of ways which position tracking can occur. They include a Rotary encoder which corresponds to turns of the pulleys, a linear encoder which can correspond to linear position tracking of the slider itself and a time-based tracker which can correspond to turns of the motor either via current, steps, or time. All of those options should be explored when developing position tracking for this system and incorporating the tracking into user interface.

Power Sizing

The appropriate powering system for the HAnD should be developed. Consideration can be taken into account to include what it might look like if the system has a sleep mode. Additionally, consideration to using solar, as well as even hydropower through the tubing of a plant should be taken into account. Systems that can incorporate various kinds of power supply such as sure power and battery power to serve as backups in the event of outages should be taken into consideration as well.

Cheap performance sensors

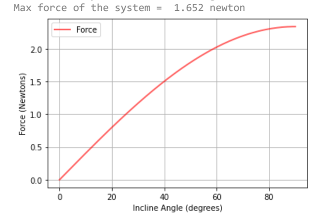
Incorporation of cheap performance sensors to wirelessly communicate the performance of the plant to the operator and to the model which can then dose appropriately should be developed. To truly make the entire plant run autonomously there has to be various measurements of turbidity, color, and pH at various stages of the AguaClara process. If those data points can be obtained and communicated cheaply then the automating of the entire plant can prove to be a truly revolutionary advancement for the water treatment sphere.

```
!pip install aguaclara
```

```
import pandas as pd
import matplotlib.pyplot as plt
import sympy as sp
import numpy as np
import aguaclara as ac
import aguaclara.core.physchem as pc
from aguaclara.core.units import unit_registry as u
import aguaclara.core.constants as con
import aguaclara.research.environmental_processes_analysis as epa
import aguaclara.research.floc_model as fm
```

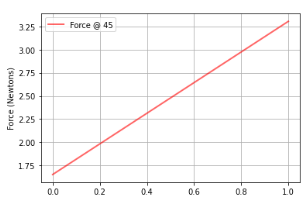
```
def VolCyl(r,h):
  V = np.pi*r**2*h
  return V

def Force(F_a, m, g, mu, theta):
  F = F_a+m*g*(np.sin(theta)+mu*np.cos(theta))
  return F

def LoadTorque(F,D,nu,i):
  T_L = F*D/(2*nu*i)
  return T_L

def TorqueConstant(F_a,r,nu_effic):
  T_constant = F_axial*r/(1000*nu_effic)
  return T_constant

def ForceAxial(m,g,mu_fric):
  F_axial = m*g*mu_fric
  return F_axial

def InertiaTotal(J_motor, J_coupling, J_driver, J_driven, J_load):
  J_total = J_motor+J_coupling+J_driver+J_driven+J_load
  return J_total

def InertiaLoad(m_load, m_belt, r_driver):
  J_load = (m_load+m_belt)*r_driver*10**(-6)
  return J_load

def AccelAngular(N,t_accel):
  alpha = 2*pi*N/(60*t_accel)
  return alpha

def TorqueAccelDecel(J_0,i,J_l,thetas,f_2,f_1,t_1):
  T_a = (J_0*i**2+J_l)*np.pi*thetas/180*(f_2-f_1)/t_1
  return T_a

def TorqueStopStart(J_0,i,J_l,thetas,f_2):
  T_a = (J_0*i**2+J_l)*np.pi*thetas/180*f_2**2
  return T_a

def TorqueRequired(T_L,T_a,Sf):
  T_m = (T_L+T_a)*Sf
  return T_m

#Caulculating the Force applied to the motor of the dosing system
pvc_mass = 97/2 * u.gram

slider_mass = pvc_mass

daim_inner_tubing = 3/8 * u.inch
r_inner_tubing = daim_inner_tubing/2
height_tubing = 1 * u.meter
coag_density = 1138 * u.kgram/u.meter**3
coag_mass = VolCyl(r_inner_tubing,height_tubing)*coag_density

tubing_density = 1.17 * u.gram/u.cm**3
daim_outer_tubing = (3/8 + 1/16) * u.inch
r_outer_tubing = daim_outer_tubing/2
tubing_mass = 2*(VolCyl(r_outer_tubing,height_tubing) - VolCyl(r_inner_tubing,height_tubin


total_mass = (pvc_mass+coag_mass+tubing_mass+slider_mass)
print("Max mass of system = ", total_mass.to_base_units())


F_a = 0 #External forces
g = con.GRAVITY
mu = 0 #friction coeffecient
theta = np.pi/4 #angle
F = Force(F_a,total_mass,g,mu, theta)
print("Max force of the system = ", F.to(u.N))

# plot of force per angle
theta_max = np.pi/2
num = 500
a = np.linspace(0, 1, num)
x = np.zeros_like(a)
y1 = np.zeros_like(a)
y2 = np.zeros_like(a)
x = a * theta_max
for i in range(len(y1)):
  y1[i]=Force(F_a,total_mass,g,mu,x[i]).to(u.newton).magnitude
x = x * 180/np.pi
fig, ax = plt.subplots()
ax.plot(x, y1, 'r-', linewidth=2, label="Force", alpha=0.6)
ax.set(xlabel='Incline Angle (degrees)')
ax.set(ylabel='Force (Newtons)')
ax.set(yscale='linear')
ax.set(xscale='linear')
ax.grid(True)
ax.legend(loc='best')
plt.show()

#Pulley and belt system
# https://www.amazon.com/KeeYees-Timing-Tensioner-Torsion-Printer/dp/B07JKT5BZQ/ref=sr_1_6

teeth = 20
pulley_OD = 16 *u.mm
nu = .75 #efficiency
i = 1 #gear ratio
T_L = LoadTorque(F,pulley_OD,nu,i).to(u.mN*u.m)
print("Loading torque of system = ",T_L)


#product whos holding torque exceed our loading torque
#https://www.digikey.com/en/products/detail/sparkfun-electronics/ROB-09238/5318747

# from above product
spr = 200
motor_current = 330 * u.mamp
motor_resistance = 32.6 * u.ohm
torque_holding = 230 * u.mN*u.m
motor_V = 12 * u.V
motor_step_angel = 1.8
Nema_size = 17
torque_detent = 1/10*torque_holding
```

```
Max mass of system =  0.2383 kilogram
Max force of the system =  1.652 newton
```




```
Loading torque of system =  17.63 meter * millinewton
```

```
# plot of force per angle

F_a = 0 #External forces
g = con.GRAVITY
mu = 1 #friction coeffecient
theta = np.pi/4 #angle
F = Force(F_a,total_mass,g,mu,theta)

num = 500
a = np.linspace(0, 1, num)
x = np.zeros_like(a)
y1 = np.zeros_like(a)
x = a * mu
for i in range(len(y1)):
  y1[i]=Force(F_a,total_mass,g,x[i],np.pi/4).to(u.newton).magnitude

fig, ax = plt.subplots()
ax.plot(x, y1, 'r-', linewidth=2, label="Force @ 45", alpha=0.6)
ax.set(xlabel='Friction Coeeficient')
ax.set(ylabel='Force (Newtons)')
ax.grid(True)
ax.legend(loc='best')
plt.show()
```




```
#List of design variable

len_doser_arm = 50 *u.cm
t_min_dose = 30 *u.sec
spd_op_min = len_doser_arm/t_min_dose #max necessary operating speed (cm/sec)
t_acl_max = 1*u.sec #acceleration/deceleration time
acr_stp = 1*u.mm #stopping accuracy +- 1mm
sf = 1.5 #safety factor
fric = 0.1 #friction coefficient
total_mass = total_mass #total mass of loads and conveyer belt

spr = 400
motor_current = 1.7 * u.amp #I
motor_resistance = 1.8 * u.ohm #L
torque_holding = 480 * u.mN*u.m
torque_detent = 2.2 * u.mN*u.m
motor_V = 3.06 * u.V #V
motor_step_angel = 0.9
Nema_size = 17

print("Minimum speed = ",spd_op_min)

#1 rev = 20 teeth
#1 tooth = 2 mm

spd_motor_max = (motor_V/(motor_resistance*2*motor_current)/spr*10**3).magnitude*20*2*u.mm

print("Motor max speed = ",spd_motor_max.to(u.cm/u.sec))

P_max = (motor_current*motor_V).to(u.watt)

print("Max power = ",P_max)

t_short = 2*len_doser_arm /spd_motor_max

print("Shortest time to relay and back = ",t_short.to(u.sec))
```

```
Minimum speed =  1.667 centimeter / second
Motor max speed =  5 centimeter / second
Max power =  5.202 watt
Shortest time to relay and back =  20 second
```

HAnD_Thing_Code.ino

```
#define BLYNK_PRINT Serial
#define stp 5
#define dir 0
#define MS1 4
#define MS2 13
#define EN 12

int x;

#include
#include
char auth[] = "B4T8cju_0kN-7eiDI1-oHUBN4cI5h_zJ";
char ssid[] = "RedRover";
char pass[] = "";

void setup()
{
pinMode(stp, OUTPUT);
pinMode(dir, OUTPUT);
pinMode(MS1, OUTPUT);
pinMode(MS2, OUTPUT);
pinMode(EN, OUTPUT);
// resetEDPins();
Serial.begin(9600);

Blynk.begin(auth, ssid, pass);
}

void loop()
{
Blynk.run();
}

BLYNK_WRITE(V0) {
if (param.asInt() == 1) {
{
Serial.println("Moving forward at default step mode.");
digitalWrite(dir, LOW); //Pull direction pin low to move "forward"
for(x= 0; x<1000; x++) //Loop the forward stepping enough times for motion to be
visible
{
digitalWrite(stp,HIGH); //Trigger one step forward
delay(1);
digitalWrite(stp,LOW); //Pull step pin low so it can be triggered again
delay(1);
}
Serial.println("Enter new option");
Serial.println();
}

void resetEDPins()
{
digitalWrite(stp, LOW);
digitalWrite(dir, LOW);
digitalWrite(MS1, LOW);
digitalWrite(MS2, LOW);
digitalWrite(EN, HIGH);
}
```

Section 2: A Systems Approach

Incorporation of System Engineering Tools

A Systems Approach

LogLine

A complete water treatment chemical dosing and flow control system that allows for remote performance and quality monitoring; remote dose and component control; and semi-autonomous corrective dosing and operation based on the AguaClara physics derivations.

Customer Value Proposition

This past summer, the AguaClara team participated in the National Science Foundation's Innovation Corps intending to understand a potential entry point for AguaClara into US markets. Over eight weeks, the team interviewed over one hundred stakeholders in the US and Canadian drinking water treatment sector. Through these interviews, the team identified the following needs and pain points for rural drinking water systems: operators are becoming harder to find, retain, and train, systems are too expensive to construct,maintain, and operate given that chemicals and labor are costly. Our system addresses these key pain points in the following ways.

Our system will run semi-autonomously based on the physics from the AguaClara labs. As quality and performance data enter the system, operational instructions will be sent to the chemical feed lines and flow control valves. This automation reduces the need for the operator's time-saving labor cost. This automation reduces the barrier for operator training, as suggested dosing will be based on programmed physics equations. Our system will also be remotely operable, allowing for fewer operators to be present at a given plant on any given day. Operators will instead serve as circuit riders only routinely operating and maintaining plant equipment. Our system's only moving and electronic components will be the inlet pumps, chemical feed pumps, and sensors. All other components will be hydraulically driven; this reduces the cost of electricity and increases the resiliency of the system by reducing the amount of failure points and maintenance costs. Additionally, the chemical feed will be optimally dosed based on the physics equations, and thereby reducing costs of chemical stock.

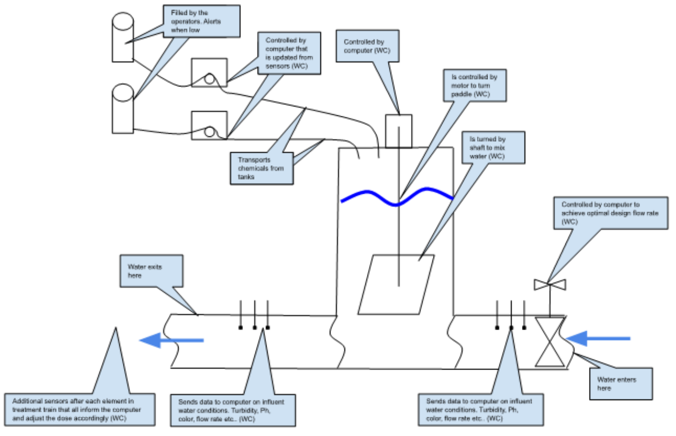
Customer Affinity Process

The customer and their needs are at the center of our model. This is an important tool to begin our analysis and systems modeling because with this tool all of our designs and all our solutions will be based on real needs and not just need the engineer or what the designer thinks their needs are.

The way that we went about understanding what our customers valued was through multiple stages where in each step we looked for commonality and assigned a value to it. With each sequential stage we combined similar segments into overarching categories. We repeated four times we were left with three guiding categories. In the case of our toy they were as the toy relates to the pieces, how the toy is used, and the feeling one feels when it's being used. We could apply this process to any customer discovery system as our team did with AguaClara.

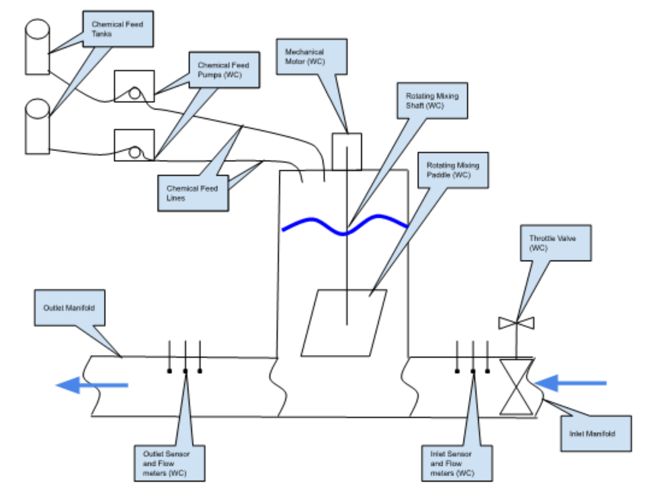
Level 1	Totals	Level 2	Totals	Level 3	Totals	Level 4	Totals
Safety Appereance	1	Safety	7	Deployment	14	Piece	47
Safety Marketed	2						
Safety Piece	2						
Safety Sharp	1						
Safety Weight	1						
Marketed	3	Purchase Process	7				
Affordable	2						
As Advertised	2						
Looks Durable	1						
Peice Dependant	10	Material	20	Construction	33		
Life Span	3						
Durability	6						
Environmental	1						
Feature Auditory	2	Feature	13				
Feature Physical	1						
Feature Visual	8						
Features General	1						
Animals	1						
With Family	3	Players	8	How	20	Use	27
With Fiends	2						
Shareable	1						
Single Player	2						
To Demonstrate	1	Control	12				
Interactive	2						
Controllable	1						
Customizable	2						
Intuitive	1						
Multi Use	5						
Storability	3	Stationairy	5	Where	7		
Location	2						
Active	1	In motion	2				
Transportability	1						
Puzzle	2	Intellectual	9	Engagement	17	Feeling	33
Engaging	2						
Role Play	5						
Voilence	2	Vicseral	12				
Ease of Use	5						
Emotional	1						
Accomplishment	2			Satisfaction	16		
Unique	2						
Development	12	Growth	12				

Annotated Concept Sketches



Functional Concept Sketch

We began with concept sketches that were created to assist in the development of our system. Concept sketches are intentionally very vague and approach the system from a very high point of view. They are like the back of the envelope calculation but for developing an idea. It helps to put thoughts on paper and actually create some sort of visualization of what you expect.

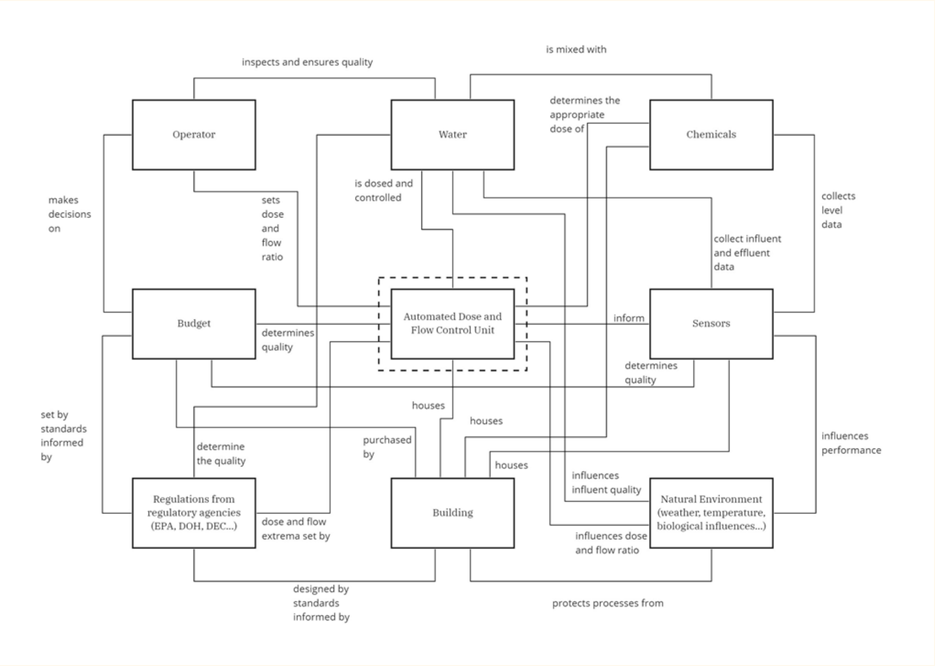


Structural Concept Sketch

We break them down into two separate sketches, the Structural Concept Sketch and the Functional Concept Sketch. The Structural Concept Sketch as its name implies shows how all of the various components are connected to each other physically or otherwise. This is useful and important because it helps the engineer and the designer to recognize connections as they relate to context diagrams. The Functional Concept Sketch as its name implies attaches a functional use to the various components. These uses are defined by what those components need to actually accomplish for the user. In our concept sketch the working components are what our system needs to incorporate as they relate the user. For instance, having working sensors in the right places for turbidity and pH is important and its function is to provide information to the user operator as well as a model you want you want.

Context Diagram

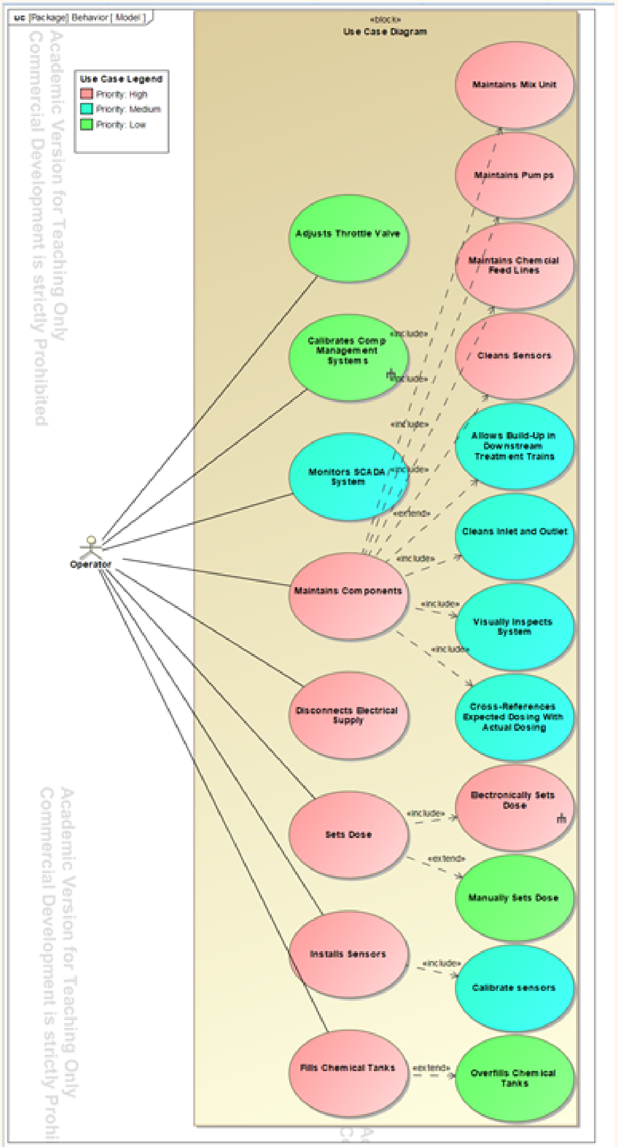
Context diagram is a particularly useful way to understand the relationships that various elements of our system have as they interact with each other. It's centered around our actual system, The Automated Dose and Flow Control Unit, and everything outside of the dotted lines are the influencing elements.



By understanding these relationships you can get a feel and an understanding of how the system interacts with its influences. Through the relationships you can see the impact of an element and design with that impact in mind.

For instance the natural environment strongly influences the majority of the elements that are involved in our system. It obviously has an effect on the water quality coming in, it affects the ratio of dosing, the building, and sensor's degradation and erosion. Another example would be how the regulations actually determine what the dose should be initially even though our program might specify some other optimal system. It also affects the building design standards and importantly the quality control limits. The information in this diagram is used to develop use cases as well as other originating requirements because those influences that we note are often what guide the designers and engineers.

SysML Use Case



Use case diagrams are a way for the systems modeler to put themselves in the shoes of the person who's actually going to be using that system. Based on how the system is being used the designers can then develop an appropriate set of requirements. If those requirements are fulfilled for all of these case diagrams and all of the use cases have relevant requirements then we can say that the system is thorough and complete with respect to its scope.

A good use case is one that is very clear and actionable. It should describe essentially what the system looks like at the end of the use. It's also important to note that many of these use cases can actually be expanded into further use cases. For instance, the use case of maintaining components actually has many other use cases that are derived from it such as maintaining a mix unit and pumps … One should realize that use cases are also not just how the engineer intends the system to be used but how the operator might actually use them even if it's in even if it's the wrong way. Those incorrect usages can sometimes even be more helpful to the designer and engineer. For instance the use case of overfill chemical tank within the use case of fills chemical tanks can alert the engineer to design safety systems to catch overfilled chemicals. You can also prioritize the various use cases so that the engineer can focus on designing what's most important.

Behavioral Use Case Diagrams

Similar to new use cases we have the behavioral use case diagram that leads us through a step by step of what needs to happen in each use case and creates requirements based on those steps. The tool incorporates conclusions and terminals as well as entry conditions exit conditions. In our system it follow the operator as our user and notes how they interact with each segments. Each those steps are then turned into design requirements which act as constraints for the designers. They are requirements because without them that step would be impossible to be completed and so this is perhaps one of the most important diagrams. It enables us as engineers to develop a framework for when we consider our system to be complete and designed according to the customer's needs. You can see that if each use case has a behavioral use case diagram and each behavioral use case diagram has its relevant requirements met then every use case will be designed and accounted for and can therefore consider our system complete.

A	B	C	D
Operator fills chemical tanks			
Initial Conditions			
1. The Control Flow Dosing System (CFDS) chemical tanks are at or near empty			
2. The CFDS chemical pumps are on and running			
Operator	**System (CFDS)**	**Chemical Pumps**	**Chemical Tanks**
The operator is alerted of the chemical level in the chemical			
	The CFDS shall be able to receive data on the level of chemicals in		
	The CFDS shall be able store data		
	The CFDS shall be able to transmit data		
	The CFDS shall be able to alert the operator when chemical tanks		
The operator shuts off the operation of the pump			
	The CFDS shall be able to receive pump operational input		
	The CFDS shall be able to output pump operations		
	The CFDS shall be able to receive pump operational status		
	The CFDS shall alert the operator the operational status of the		
		The chemical pumps are not running	
The operator verifies that the pumps are off			
The operator visually examines the chemical level			
The operator fills the chemical tanks per standards and			
			The tanks are full
	The CFDS shall be able reset current data		
The operator verifies that the CFDS is displaying the correct			
Ending Conditions			
1. The chemical tanks are full			
2. The chemical pumps are off			
Notes			
1. Assumes proper usage			
2. Ends at tanks are full			

Operator monitors SCADA		
Initial Conditions		
1. The Control Flow Dosing System (CFDS) SCADA visiualizing system is off		
2. The CFDS SCADA is collecting data		
Operator	**System (CFDS)**	**SCADA**
The operator turns on the SCADA systems		
	The CFDS shall be able to collect sensors input data	
	The CFDS shall be able to differentiate between various	
	The CFDS shall be able to present differentiated data	
	The CFDS shall be able to store data	
	The CFDS shall be able push and pull select data	
	The CFDS shall be able to accept operator input for historical data	
	The CFDS shall be able to scale data according to format	
	The CFDS shall be able to present selected data	
The operator selects historical data		
The operator selects data format		
		SCADA is presenting data
	The CFDS shall be able to collect real time performance data	
	The CFDS shall be able to present real time performance data	
The operator selects real time data view		
	The CFDS shall be able to collect data while display is off	
The operator turns off SCADA view system		
Ending Conditions		
1. The chemical tanks are full		
2. The chemical pumps are off		
Notes		
1. Assumes proper usage		
2. Ends at tanks are full		

In our model, the behavioral use case of “operator monitors the scada system” we were developed multiple requirements based purely on the sensor input data via collecting, differentiating, storing, pushing, and pulling the data. We were also able to develop requirements based on the timing of the collection of the data and how it's presented. It also prompted the question of what we do when the operator isn't using the system. In other words do we need a requirement for data collection with the display off.

Originating and Derived Requirements

Originating requirements are what set the foundation for the designs. Any design or outcome from a systems model must meet the set forth requirements. We split them up into two kinds of requirements, originating and functional.

The originating requirements are based off of the behavioral use case diagrams. Their foundation is in understanding how the system is going to be used by the user. They are also developed based on additional parameters because even if those requirements don't relate to a use they might enable a use.

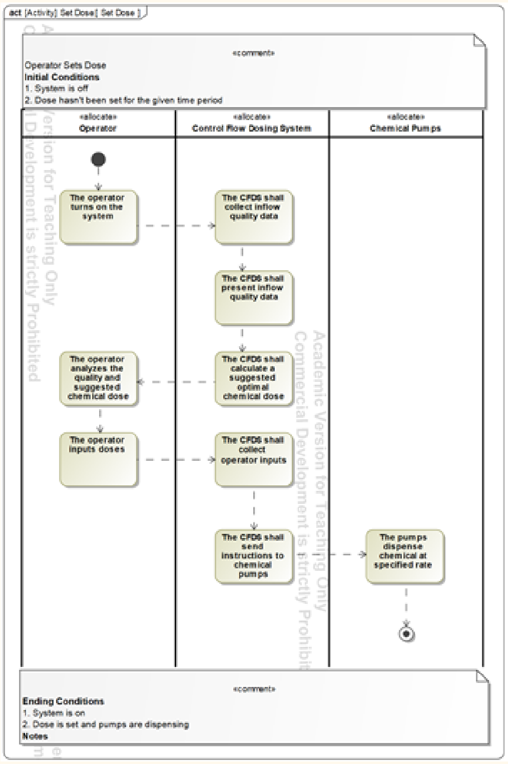
The functional requirements are in essence an interpretation of the originating requirements however they are focused on what function they deliver and what function they satisfy. This is important because an originating requirement by itself doesn't necessarily speak to what it's trying to accomplish however a functional requirement clearly states its goals. Important and related functional requirements for our system are data ones like sensor data presentation, sensor data adjustment and sensor data collection.

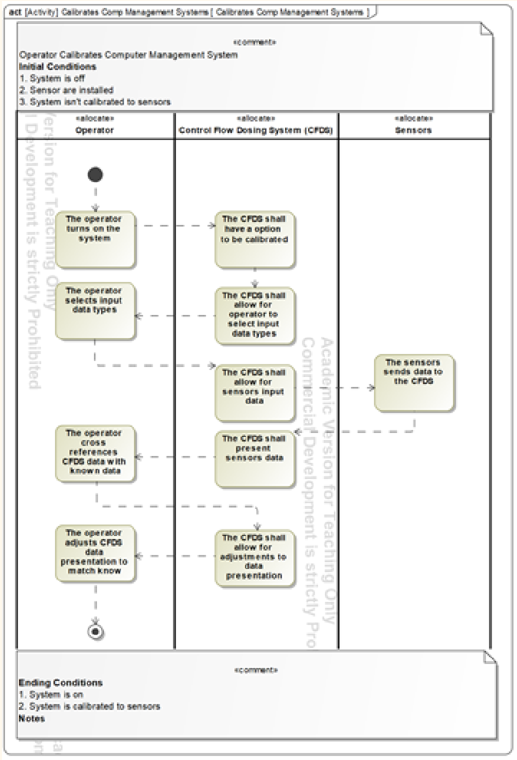
Index	Derived Functional Requirement	Function Name	Source
DR.1	The CFDS shall suggest an optimal dose to the operator	Optimal Dose	OR.3
DR.2	The CFDS shall allow for operator to control dose	Operator Control	OR.4
DR.3	The CFDS shall be able to control the dosing mechanisms	Autonomous Control	OR.5
DR.4	The CFDS shall store information on water quality	Store Data	OR.13
DR.5	The CFDS shall be able to remotely communicate with an operator	Remote Communication	OR.11
DR.6	The CFDS shall be able to communicate via standard channels	Standard Communication Channels	OR.16
DR.7	The CFDS shall be able to communicate with various standard pumps	Standard Pump Communication	OR.17
DR.8	The CFDS shall collect information important water quality parameters	Collect Relevant Data	OR.1
DR.9	The CFDS shall allow for the operator to see water quality data	View Data	OR.2
DR.10	The CFDS shall be able to be calibrated based on operational circumstances	Calibratable	OR.6
DR.11	The CFDS shall be adaptable to various makes of sensors	Adaptable Sensors	OR.8
DR.12	The CFDS shall be able to show specific sensor data	Variable Sensor View	OR.21
DR.13	The CFDS shall be intuitive to the operator	Intuitive Interface	OR.7
DR.14	The CFDS shall allow the operator to change the view format	Data View Control	OR.10
DR.15	The CFDS shall allow for automation based on specifics in performance	Performance Based Automation	OR.26
DR.16	The CFDS shall collect dose performance in real time	Real Time Dose Performance	OR.27
DR.17	The CFDS shall present performance in real time	Real Time Performance Visualization	OR.28
DR.18	The CFDS shall allow the operator to reset view	Reset View	OR.12
DR.19	The CFDS shall be able to send data to multiple sources	Data Distribution	OR.14
DR.20	The CFDS shall communicate chemical feed failures	Chemical Feed Failures	OR.15
DR.21	The CFDS shall communicate dosage failure	Dosage Failures	OR.20
DR.22	The CFDS shall be able to control pumps independently of internal pump control	Independent Pump Control	OR.18
DR.23	The CFDS shall be able to independently monitor chemical dosing	Independent Dose Monitoring	OR.19
DR.24	The CFDS shall express data in format useful to the operator	Useful Data Representation	OR.9
DR.25	The CFDS shall present data in multiple selectable formats	Selectable Data Formats	OR.22
DR.26	The CFDS shall allow the operator to create and send reports	Report Generation	OR.23
DR.27	The CFDS shall store historical data	Historical Data	OR.24
DR.28	The CFDS shall allow for the operator to scale data	Scalable Data	OR.25
DR.29	The CFDS shall be continually collected data	Off-State Data Collection	OR.29
DR.30	The CFDS shall be resilient and maintainable	Reslient and Maintainable	OR.30

Index	Derived Functional Requirement	Function Name
OR.1	The CFDS shall collect inflow quality data	Inflow Data Collection
OR.2	The CFDS shall present inflow quality data	Inflow Data Presentation
OR.3	The CFDS shall calculate a suggested optimal chemical dose	Chemical Dose Calculation
OR.4	The CFDS shall collect operator inputs	Operator Inputs
OR.5	The CFDS shall send instructions to chemical pumps	Pump Commands
OR.6	The CFDS shall have an option to be calibrated	Calibration Option
OR.7	The CFDS shall allow for operator to select input data types	Input Selection
OR.8	The CFDS shall allow for sensors input data	Sensor Data Collection
OR.9	The CFDS shall present sensors data	Sensor Data Presentation
OR.10	The CFDS shall allow for adjustments to data presentation	Sensor Data Adjustment
OR.11	The CFDS shall be able to transmit wirelessly	Wireless Transmission
OR.12	The CFDS shall be able reset current data	Data Presentation Reset
OR.13	The CFDS shall be able store data	Data Storage
OR.14	The CFDS shall be able to transmit data	Data Transmission
OR.15	The CFDS shall be able to alert the operator when chemical tanks are low	Chemical Level Alert
OR.16	The CFDS shall be able to transmit via wifi	Wifi Transmission
OR.17	The CFDS shall be able to receive pump operational input	Receive Pump Operation Input
OR.18	The CFDS shall be able to output pump operations	Output Pump Operation Commands
OR.19	The CFDS shall be able to receive pump operational status	Receive Pump Operational Status
OR.20	The CFDS shall alert the operator the operational status of the pumps	Pump Operation Alert
OR.21	The CFDS shall be able to differentiate between various sensors data	Differentiate Data
OR.22	The CFDS shall be able to present differentiated data	Present Differentiated Data
OR.23	The CFDS shall be able push and pull select data	Push/Pull Select Data
OR.24	The CFDS shall be able to accept operator input for historical data	Accept input for Historical Data
OR.25	The CFDS shall be able to scale data according to format	Scale Data
OR.26	The CFDS shall be able to present selected data	Present "Selected" Data
OR.27	The CFDS shall be able to collect real time performance data	Collect Real Time Data
OR.28	The CFDS shall be able to present real time performance data	Present Real Time Data
OR.29	The CFDS shall be able to collect data while display is off	Collect Data (Display Off)
OR.30	The CFDS shall be constructed of materials that can be replaced within 1 week	Local Materials

In our model we created 30 originating and functional requirements and placed them in a diagram together. We gave them functional names so that they can be easily differentiated. It's also important to write the requirement using the language of "the CFDS shall do x y and z." There shall statements tell the designer that these elements must be met.

Activity Diagram





SysMl activity diagrams are similar to the behavioral use case diagram in that it follows a sequence of events that the user will conduct and requirements are derived based on those steps. This version is a more visual representation unlike the Excel version and so it becomes a little more clear and easy to follow what the sequence of the event is and how those events flow between each other. It also allows for the requirements to be developed within the model itself and the requirements to be used in further modeling activities.

Personally, I like the SysMl model more because it provides a visual understanding of what happens, when it happens and what requirements are being called in at certain moments. This provides a more intuitive approach to when the requirement is being called upon and used and why that requirement is being created at that moment.

Concept Fragment Generation

Concept fragment generation is the first attempt at developing a solution, based on the requirements that we've established. It's similar to the concept sketch, however, it turns the concept sketch into real ideas. It is a very back-of-the-envelope way of solution development and not a thorough or well-designed concept. However, it differs in comparison to the concept sketch in that it's less conceptual and more real where you take the requirements and turn them into concepts and those concepts solve those requirements.

Concept Fragments

The CFDS shall present inflow quality data	The CFDS shall collect operator inputs
Remotely	
Website	Form
Online server	App
App	Online
Video Feed	Physical Actuators
	Computer Control
In-Person	
SCADA	Switch
PLC	Lever
Meters	Button
Jar Tests	Crank
	Handle
	Valve

For instance, in our system, we segmented concepts based on remote solutions versus in-person ones, given that both have very different interactive characteristics. So for the requirement of “The CFDS shall present info quality data” if we were to do that remotely, a potential solution could be having a website, app, or even a live video feed while the in-person version would have manually conducted jar tests. As we can see some of these solutions are not what we would end up designing or even consider to be good, such as the live video feed which at this moment may be considered an unnecessary design. However, it's important in this stage to remain as open-minded as possible because having that open mind might allow you to come up with new ideas and new concepts that could actually change the design substantially. It turns out that the video feed concept is what our clients want as a backup and for security purposes so it's fortuitous that we considered it in this step.

Combination Table

A combination table is a collection of all potential concepts and ideas which allow you to begin to branch them together. As you do so, you begin to see viable ideas or what may be a good starting point for a solution space. Although it depends on the final engineer and the final designer, this tool serves as a good basis for understanding what is within the realm of possibility and what is unnecessary or non-viable. This tool also allows you to see which systems can branch across multiple requirements.

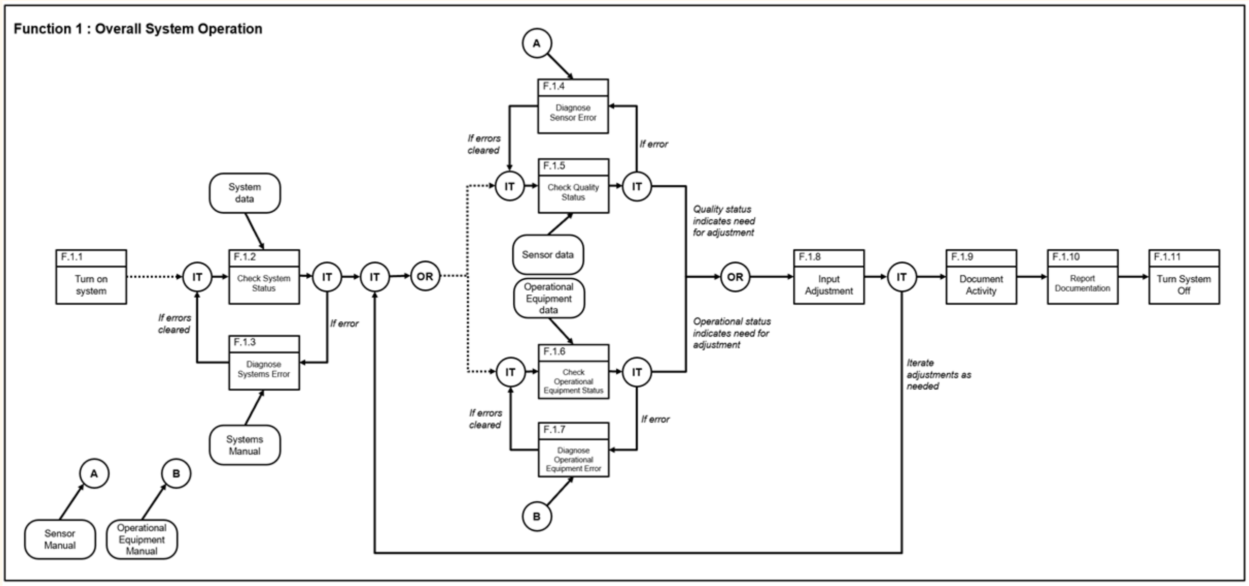
For example, having a website and an app is redundant and unnecessary but having a website and computer control might end up being a solution. Additionally, the ways in which the website and computer solution can solve the two requirements that we've previously specified can be evaluated as follows.

Concept Combination Table

The CFDS shall present inflow quality	The CFDS shall collect operator inputs
Remotely	
Website and form	
Website and app	
Webste and online	
Website and computer control	
Online server and form	
Online server and app	
Online server and online	
Online server and computer control	
App and form	
App and online	
App and computer control	
Video feed and Physical Acturators	
Video feed and computer control	
In-Person	
SCADA and Switch	
SCADA and Lever	
SCADA and Button	
SCADA and Crank	
SCADA and Handle	
SCADA and Valve	
PLC and Switch	
PLC and Lever	
PLC and Button	
PLC and Crank	
PLC and Handle	
PLC and Valve	
Meters and Switch	
Meters and Lever	
Meters and Button	
Meters and Crank	
Meters and Handle	
Meters and Valve	
Jar Tests and Switch	
Jar Tests and Lever	
Jar Tests and Button	
Jar Tests and Crank	
Jar Tests and Handle	
Jar Tests and Valve	

As it relates to our system, the most probable solution right now would be having an online server computer control for the remote aspect as well as having the ability for jar tests and meters to exist, in the event that the online system goes down. This combination table was useful for helping us establish what the overall solution space might eventually look like even before the actual design took place.

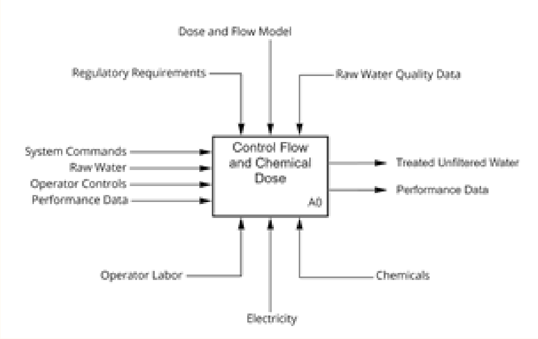
Functional Flow Block Diagram



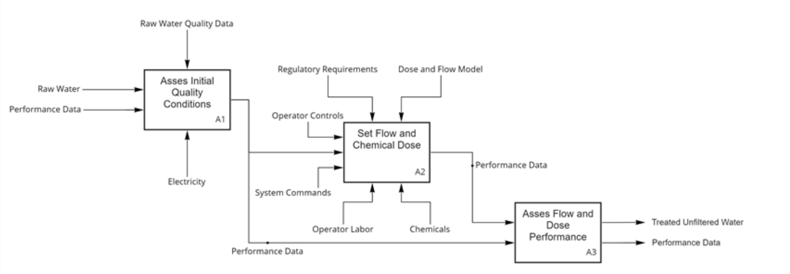
A functional flow block diagram is a tool used to determine how various functions operate within each other. It can give the designer an idea for what happens and when. It's particularly useful because it has the benefit of incorporating logic gates as well as iterative loops. You can attach and document various requirements and elements of what needs to be done to the functional blocks and through it, indicate when and why the transition between the blocks occurs. This can be particularly useful for developing manuals and approaches.

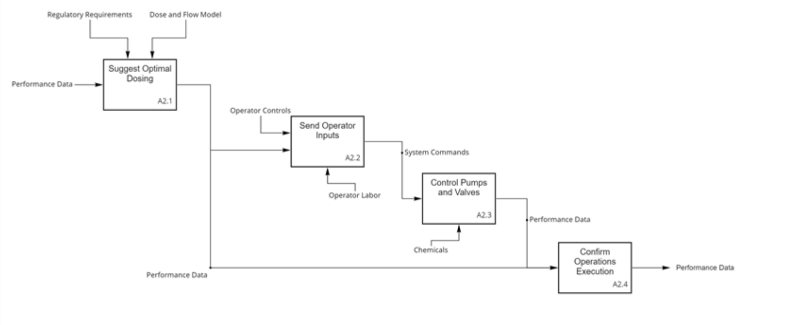
In our system, we benefited from developing a functional flow block diagram by noticing the iterative use of the dosing adjustment system and the variations of steps that could be happening within that loop, in order to properly diagnose and calculate the correct dosage. Our blocks flowed from two separate steps corresponding to two operator possibilities. Each has their own internal iterative loop; one for tracking the status of the operational equipment such as the pumps and the other for the status of the quality of the water. Depending on those statuses you can then do your adjustment, and depending on the quality of adjustment, you could then go back to the loop to do it all again or just document the activity. This flow is essentially what would happen when our system is being used.

IDEF0



The IDEF0 is a tool that tracks information inputs and outputs based on specific action steps. This is particularly useful and important for understanding what needs to go into each step in order to ensure what comes out is the desired outcome. The granularity and specificity you gain as a result, is a function of what level you are approaching modeling the system through.





For instance, at the most macro level, we have all of the inputs such as raw water quality, the system commands and outputs of treated water, and performance data. Those depend on data inflows such as the concentration of the dose, the dosing model, regulatory requirements, electricity chemicals, and operator labor. It shows what it takes to accomplish our output of dosed water. The next level of granularity requires that we go one step further and break it down into "assess initial quality conditions," "set the flow dose," and "assess performance". Based on those you can see that all of the inputs that were in the first level carry over into the second one because within that level you still need all of those elements such as the electricity to run the and chemicals to dose the water. Taking that one step further in the third level, you can determine everything that flows into A.2 as you can see all the information that goes into the step before carries over like operator control, system commands, as well as, the labor and chemicals. This tool and approach can carry on to whatever level of granularity is necessary.

Goal Question Metric

#	Goal	Question	Ideal Metric	Approx. Metric	Data Collection Method	Notes
1	**Make the system user-friendly for the opperator**	Will the operator have to conduct maintainance often?	Components maintence/expected failures on a time scale	# of non-AguaClara components * maintence frequency factor	Maintence/failure mode analysis	Need to define "often"
		Is the expected maintence operator friendly?	A scale of the expected maintence and the user freindliness of each procedure	# of non-AguaClara components * maintence freindliness factor	Maintence type analysis	Will be hard to find EMTF for non-standard components
		Does the system require many steps to operate?	# of steps	No Substitute	Activity diagram	Need to define "operate"
2	**Make the system easily repairable**	How difficult is it to troubleshoot components?	Hours spent troubleshooting	# of non-AguaClara components * maintence frequency factor / sourcing factor	Maintence type analysis	
		How difficult is it to find spare parts?	Hours spent part sourcing	# of non-AguaClara components * maintence frequency factor / troubleshoot factor	Maintence type analysis	
		How difficult is it to replace components?	1-5 scale	Hours required to replace componenet	Maintence type analysis	"difficulty scale" based on some of the following; distance, popularity, specialization,
3	**Make the system run semi-autonomously**	How long can the system run without an operator?	Hours spent before operator input	Hours of reaction time between internal sensors and distribution	Activity diagram	
		What activities require an operators	# operator "touch points"	Hours of operator presence / hours of total operation	Activity diagram	
		How controlable is the system?	# of features that can be internally corrected	Hours of operator presence / hours of total operation	FFBD	

Now that we've created the basis for design and we've started the development of the system itself, we need a way to gauge how successful our approach, design, and model is and will be. To do this we develop the goal question metric where we specify goals that we're going to use in order to evaluate the system.

We begin by setting initial goals like, "to make the system user-friendly for the operator." We then ask questions based on that goal whose answers will allow us to determine success. After this, we set up both an ideal metric and an approximate one because we have not developed a system yet. We also document a way to collect the information on this metric and we add notes to fill in any missing information.

In our system we have the goal of "to make the system user-friendly for the operator" and so within that element we asked ourselves the question of "will the operator have to conduct maintenance often?" How we ideally would measure that would be having lifetime and failure rates for each of the components. Given, however, that our components haven't been created yet we can only use an approximate metric of basing it on components that have been developed. In order to collect information, we would conduct a maintenance failure mode analysis. However, we need to determine what the word "often" in our question means because that can be subjective based on the operators and the regulatory requirements, so we put that insight in the notes section.

Analytical Hierarchy Process

1	Make the system easy to use			Make the system inexpensive			Make the system have low risk		Other (size and upgradeable)	
	0.6			0.15			0.2		0.05	
2				CapEX		OpEX				
				0.7		0.3				
3	Make the system user-friendly for the opperator	Make the system easily repairable	Make the system run semi-autonomously	Make the system last for a long time	Make the system cheap to construct	Make the system utilize minial resources (chemicals / electricty / labor)	Make the system safe	Make the system secure	Make the system compact	Make the system upgradeable
4	0.3	0.3	0.4							
5				0.3	0.7					
6						1				
7							0.6	0.4		
8									0.8	0.2

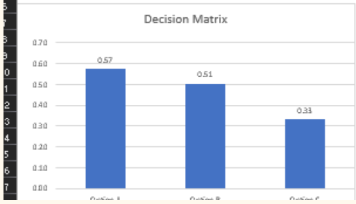
After we've established our goals, we need to determine which ones are most important and thus which should be prioritized. We can do that by making a priority list whose total equals 100% which is divided based on each of those goals. We can add a level of granularity where certain elements that influence those goals can also have assigned percentages of importance. The final imputed percentage can then be what we use to guide the design engineers and the future model for what to focus on first, what to pay attention to the most, and perhaps even what goals to allocate resources to.

For instance, our system goal of “make the system inexpensive” has an overall importance of 15% because water treatment plants themselves are expensive, and our treatment compared to competition is already considerably cheaper, so the the goal of driving costs down for our system is not as significant of a driving factor. Still, we broke that down further by focusing on capital and operational expenditures because when deciding to build our system, the customer is usually the respective city’s Water Systems Manager who pays more attention to capital expenditures because that is the hardest button to push with their stakeholders (i.e the citizens) and so we place 70% importance on capital expenditures and 30% on operational expenditures. Taking one step further we broke down capital expenses into goals of “making the system last for a while” versus “the cost to construct the system” and each got their own percentage of importance. As with all the other tools you can go to whatever granularity level is necessary.

Decision Matrix

Decision Matrix for Control Flow Dosing System

		Values					Normalized Values				Final Scores			
Criteria	Units	Option A	Option B	Option C	Min Value	Max Value	Option A	Option B	Option C	Weight	Option A	Option B	Option C	Notes
Simplicity	1-5	5	3	1			1.00	0.60	0.20	0.10	0.10	0.06	0.02	
OPEX	$/Year	20,000	35000	50000		50,000.00	0.60	0.30	0.00	0.25	0.15	0.08	0.00	Cost for whole sy
CAPEX	$	250000	500000	1000000		1000000	0.75	0.50	0.00	0.15	0.11	0.08	0.00	Cost for whole sy
Repairability	1-5	5	3	1			1.00	0.60	0.20	0.03	0.03	0.02	0.01	Can the operator
Operator Training Level	1-5	5	3	1	1		1.00	0.60	0.20	0.03	0.03	0.02	0.01	As definied by El
Treatment Types	1-5	1	3	5	3		0.20	0.60	1.00	0.10	0.02	0.06	0.10	What can it actua
Treatment Performance	#(sigmas)	2	3	4	3		0.50	0.75	1.00	0.10	0.05	0.08	0.10	Deviations from p
# Components	#	0	2	5		5	1.00	0.60	0.00	0.03	0.03	0.02	0.00	
Operator Hours	#/week	15	6	3		40	0.00	0.60	0.80	0.05	0.00	0.03	0.04	Missing data
Size	1-5	3	3	5		5	0.40	0.40	0.00	0.10	0.04	0.04	0.00	Missing data
Operator Control (Feelir	1-5	1	3	5	2		0.20	0.60	1.00	0.03	0.01	0.02	0.03	"spirit"
Flow Rate Variability	1-5	1	3	5	2		0.20	0.60	1.00	0.03	0.01	0.02	0.03	
									Score Totals	1.00	0.57	0.51	0.33	

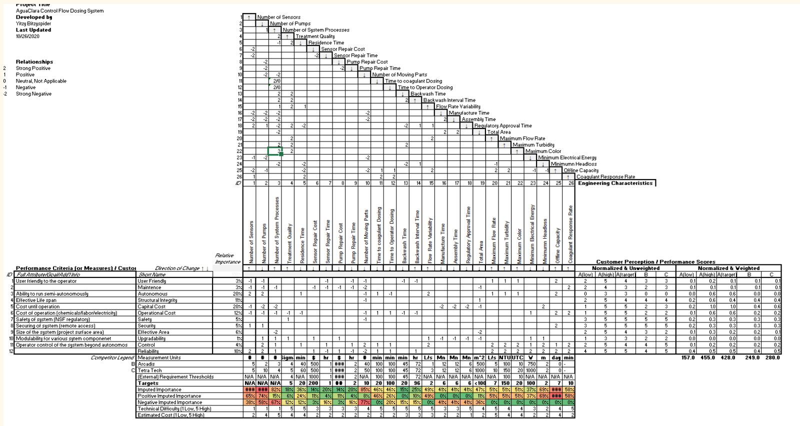


Simplicity	
Score	Evaluation
5	0 moving parts, 0 electrical components, 0 external components, gravity pwered, intuitive design, fluids driven, simple parts
4	<2 moving parts, <2 electrical components, <2 external components, gravity pwered, intuitive design, fluids driven, simple parts
3	<2 moving parts, <2 electrical components, <2 external components
2	>=2 moving parts, >=2 electrical components, >=2 external components, gravity pwered, intuitive design, fluids driven, simple parts
1	>=2 moving parts, >=2 electrical components, >=2 external components

Along the same vein as the goal question metric we have the decision matrix. This is a way to break down how we're going to go about making specific decisions from an objective standpoint so that our decision-making process is not going to be hand wavy and based on a feeling. It's important to have actual numbers and units to compare it to in order for it to be as objective as possible. If you can’t assign a specific number you can design a scale and that scale has to have specific criteria attached to each number or level of scoring. Those criteria should also have some objective numerical way of comparing or binary function.

For instance, in our system, when comparing capital expenditures between AguaClara technology and our competitor’s options we can see that the AguaClara technology is objectively much cheaper. However, for something like repairability how would we determine what is more or less repairable? So we developed a scale from 1 to 5 that focuses on moving parts, electrical components, and external components, where depending on how many of each you have your number on the scale will increase or decrease. After normalizing and weighing all the values, you end up with its final score which can be used to determine how much better your system is versus the competitors and potential areas of improvement to your technology.

QFD House of Quality

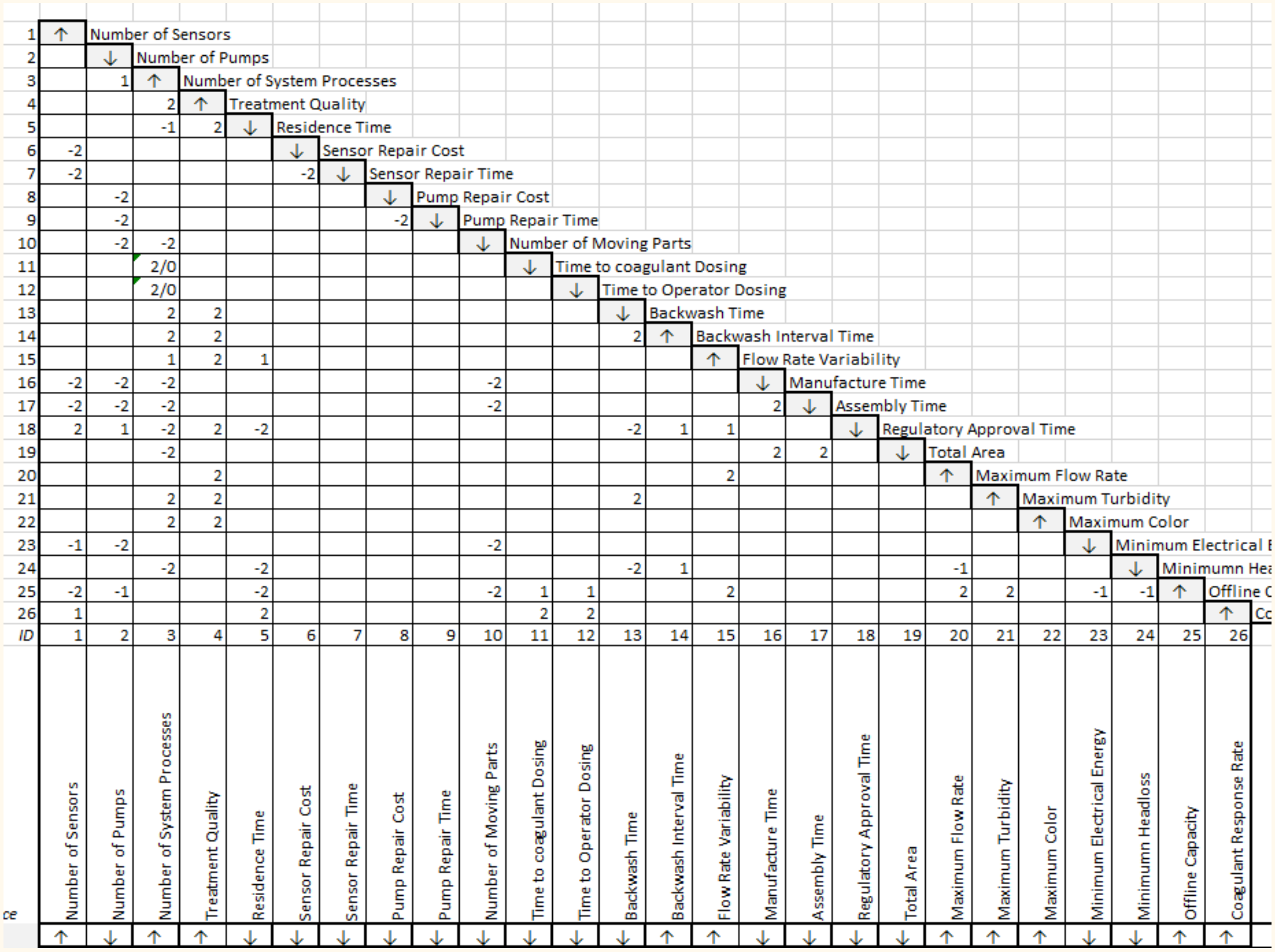


The QFD or the house of quality, is another useful and impactful tool because it allows the model or engineer to compare many different aspects of the overall system to one other in a numerically objective way. With those comparisons we then analyze your solution versus competitors solutions, as well as various elements of your system to each other and understand where “give” is and what levers you can pull to design or improve your solution accordingly.

For instance, the first section of the house is the performance criteria. Here you put in the important factors that matter to your customer. By setting up criteria or measures that can be independent, objective, and are customer focused attributes, you can then assign them weight based importance with an overall percentage of 100%. Essentially, what you are doing is determining what is the most important criteria for your customers and then interfacing what happens in your system given those criteria.

	Performance Criteria (or Measures) / Customer Attributes	Direction of Change ↑ ↓	importance
ID	Full Attribute/Goal/Add'l Info	Short Name	100%
1	User friendly to the operator	User Friendly	3%
2		Maintence	3%
3	Ability to run semi-autonomously	Autonomous	20%
4	Effective Life span	Structural Integrity	11%
5	Cost until operation	Capital Cost	20%
6	Cost of operation (chemicals/labor/electricity)	Operational Cost	12%
7	Safety of system (NSF regulatory)	Safety	5%
8	Securing of system (remote access)	Security	5%
9	Size of the system (project surface area)	Effective Area	6%
10	Modulability for various sytem componenet	Upgradability	1%
11	Operator control of the system beyond autonomos	Control	4%
12		Reliability	10%

In our model, we established that the most important criteria was the ability to run autonomously, followed by capital costs, operational costs, and lastly, the reliability of the system. All of the other criterias’ importance didn't place as highly as we believe that our customers don't place as much value on them which can be verified using a customer affinity process.



ID	Direction	Element	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
1	↑	Number of Sensors																										
2	↓	Number of Pumps																										
3	↑	Number of System Processes		1																								
4	↑	Treatment Quality			2																							
5	↓	Residence Time			-1	2																						
6	↓	Sensor Repair Cost	-2																									
7	↓	Sensor Repair Time	-2					-2																				
8	↓	Pump Repair Cost		-2																								
9	↓	Pump Repair Time		-2						-2																		
10	↓	Number of Moving Parts		-2	-2																							
11	↓	Time to coagulant Dosing			2/0																							
12	↓	Time to Operator Dosing			2/0																							
13	↓	Backwash Time			2	2																						
14	↑	Backwash Interval Time			2	2									2													
15	↑	Flow Rate Variability			1	2	1																					
16	↓	Manufacture Time	-2	-2	-2							-2																
17	↓	Assembly Time	-2	-2	-2							-2						2										
18	↓	Regulatory Approval Time	2	1	-2	2	-2								-2	1	1											
19	↓	Total Area			-2													2	2									
20	↑	Maximum Flow Rate				2											2											
21	↑	Maximum Turbidity			2	2									2													
22	↑	Maximum Color			2	2																						
23	↓	Minimum Electrical Energy	-1	-2								-2																
24	↓	Minimumn Headloss			-2		-2								-2	1						-1						
25	↑	Offline Capacity	-2	-1			-2					-2	1	1			2					2	2		-1	-1		
26	↑	Coagulant Response Rate	1				2						2	2														

The next step is to determine what impacts the performance criterias have and the direction of these impacts. Essentially, we are asking "does an increase in element *x* increase *y* or vice versa."

In our system, for example, the number of sensors will negatively increase the sensor repair cost which will carry through into the performance metrics that we discussed earlier, both in terms of capital and operational costs. We can take that same process for many of the other influencing components. As you can see, important key elements are the number of systems processes because the number of systems processes is going to affect things like the number of moving parts, the time the operator has to repair, as well as, manufacturer and assembly time.

		#	#	#	Sigma	min	$	hr	$	hr	#	min	min	min	hr	L/s	Mn	Mn	Mn	m^2	L/s	NTU	UTC	W	m	day	min
5	Measurement Units	#	#	#	Sigma	min	$	hr	$	hr	#	min	min	min	hr	L/s	Mn	Mn	Mn	m^2	L/s	NTU	UTC	W	m	day	min
6	Arcadis	5	2	3	4	40	500	1	2000	2	40	100	100	45	72	1	12	12	6	500	5	100	10	750	2	0	-
7	Tetra Tech	5	10	4	5	60	500	1	####	2	50	100	100	45	72	3	12	12	6	1000	10	150	20	1000	2	0	-
8	(External) Requirement Thresholds	N/A	N/A	N/A	4	N/A	1000	1	5000	2	N/A	100	100	45	72	N/A	N/A	N/A	N/A	N/A	N/A	100	10	N/A	N/A	N/A	N/A
9	**Targets**	**N/A**	**N/A**	**N/A**	**5**	**20**	**200**	**1**	**2000**	**2**	**10**	**20**	**100**	**20**	**96**	**2**	**6**	**6**	**6**	**<100**	**7**	**150**	**20**	**100**	**2**	**7**	**10**
0	Imputed Importance	####	####	82%	18%	36%	14%	20%	14%	20%	85%	46%	46%	15%	25%	49%	41%	41%	41%	47%	51%	51%	51%	37%	69%	####	58%
1	Positive Imputed Importance	65%	74%	15%	6%	24%	11%	4%	11%	4%	8%	46%	26%	0%	10%	49%	0%	0%	0%	11%	51%	51%	51%	37%	69%	####	58%
2	Negative Imputed Importance	38%	58%	67%	12%	12%	3%	16%	3%	16%	77%	0%	20%	15%	15%	0%	41%	41%	41%	36%	0%	0%	0%	0%	0%	0%	0%
3	Technical Difficulty (1 Low, 5 High)	1	1	1	5	5	3	3	3	3	4	5	5	5	5	5	3	3	5	4	5	4	4	3	2	4	5
4	Estimated Cost (1 Low, 5 High)	2	4	5	4	4	2	2	2	2	2	2	2	3	3	3	2	2	1	2	5	4	4	2	2	4	2

The next category allows us to determine and evaluate our solution relative to competitors. We assign the units of measurement and with them, we can determine what value each of our elements has in our ,and our competitors' solutions.

For instance, the treatment quality in terms of Sigma deviation differs depending on our solution versus their's. We also set a target of 5 sigmas so, in other words, our system has to treat a level of 5 sigmas every time and any solution that treats below that is not a valid solution. We then assign the relative computed importance, positive and negative importance, the expected technical difficulty, and estimated costs associated with each of the elements. This allows for further comparison. As you can see certain elements have a much greater importance than others and thus, affect the comparison to a much higher degree.

The last thing we do is assign customer perception and performance scores which are then normalized and weighed. We also establish what would be the high, low, and target values for our system to compare with theirs. This allows us to see how far we are from our target and gives us the impression of what leverage we can use to get to our target. This informs the design engineer of what they could potentially improve on in order to increase our score and make us more competitive in the eyes of our customers. It also shows us where we trail and what niches we might fill.

Customer Perception / Performance Scores									
Normalized & Unweighted					Normalized & Weighted				
A(low)	A(high)	A(target)	B	C	A(low)	A(high)	A(target)	B	C
2	5	4	3	3	0.1	0.2	0.1	0.1	0.1
2	4	3	2	3	0.1	0.1	0.1	0.1	0.1
0	3	3	0	0	0.0	0.6	0.6	0.0	0.0
2	5	4	4	4	0.2	0.6	0.4	0.4	0.4
1	5	5	2	3	0.2	1.0	1.0	0.4	0.6
1	5	5	2	2	0.1	0.6	0.6	0.2	0.2
3	5	5	5	5	0.2	0.3	0.3	0.3	0.3
3	5	5	5	5	0.2	0.3	0.3	0.3	0.3
2	5	4	3	2	0.1	0.3	0.2	0.2	0.1
1	3	3	2	2	0.0	0.0	0.0	0.0	0.0
2	5	4	4	5	0.1	0.2	0.2	0.2	0.2
4	5	5	4	5	0.4	0.5	0.5	0.4	0.5
					157.0	**455.0**	**428.0**	**249.0**	**280.0**

Sub-System Table

Subsystems	Sensor	Data Collection	Data Represenation	User Input	Model/Processing	Online	Pump
	The CFDS shall collect inflow quality data	The CFDS shall be able to differentiate between various sensors data	The CFDS shall present inflow quality data	The CFDS shall collect operator inputs	The CFDS shall calculate a suggested optimal chemical dose	The CFDS shall be able to transmit wirelessly	The CFDS shall be able to receive pump operational input
	The CFDS shall collect process quality data		The CFDS shall present sensors data	The CFDS shall allow for operator to select input data types	The CFDS shall send instructions to chemical pumps	The CFDS shall be able to transmit data	
			The CFDS shall allow for adjustments to data presentation	The CFDS shall be able to accept operator input for historical data	The CFDS shall have an option to be calibrated	The CFDS shall be able to transmit via wifi	
			The CFDS shall be able to alert the operator when chemical tanks are low	The CFDS shall alert the operator the operational status of the pumps	The CFDS shall allow for sensors input data		
			The CFDS shall be able push and pull select data		The CFDS shall be able store data		
			The CFDS shall be able to present selected data		The CFDS shall be able reset current data		
			The CFDS shall be able to present real time performance data		The CFDS shall be able to present differentiated data		
					The CFDS shall be able to scale data according to format		
					The CFDS shall be able to collect real time performance data		
					The CFDS shall be able to collect data while display is off		
					The CFDS shall be able to receive pump operational status		
					The CFDS shall be able to output pump operations		
Concept Fragments							
	Turbidimeter	*Excel*	*LCD screen*	*Arduino*	*PID*	*offsite server*	*Arduino*
	pH meter	*Dataframe*	*LED indicators*	*App*	*evolutionary*	*onsite server*	*Micocontroller*
	Colorimeter	*Sheets*	*SCADA patch in*	*Physical buttons*	*systems dynamics*	*publiclly available*	*PDB board*
	Flowrate sensor	*Labview data*	*Online*	*No control*	*Integral PID*	*private*	*Smartphone*
	Encoder	*ProCoDa Data*	*Graphs*	*Website*	*Feed forward*	*direct connection*	*Computer connected*
	Volume		*Statistical representation*				*Via ethernet port*
			Only suggested numbers				*Signal power actuator*
							Grav power actuator

The subsystem table tool is a way to organize all the various subsystems and tie them into the requirements that we have established. This allows the modeler and the engineer to see how various requirements are satisfied by subsystem categories which is important because (as is frequently the case in engineering design) development will be categorized by the various subsystems. By using this tool we can break down the overall system into bite-sized units which also allows us to specify what kind of solutions become relevant in each subsystem.

In our case the major subsystems are sensor, data collection, data representation, user input, model processing, Online, and pumps. After subdividing our overall system into these categories we assigned specific concepts as potential solutions. In the "Modeling" sub-system some of the concepts that satisfy the requirements are the use of a PID controller, an evolutionary controller, or perhaps a feed forward process. Another example is with the subsystems of "user input" and "pump control" given concept overlap that exists with the use of arduinos. As we can see by subdividing our system into subsystems, we were able to attach ideas to requirements and see which ideas would be the most encompassing and viable.

Interface Matrix

AguaClara CFDS Modeling Interface

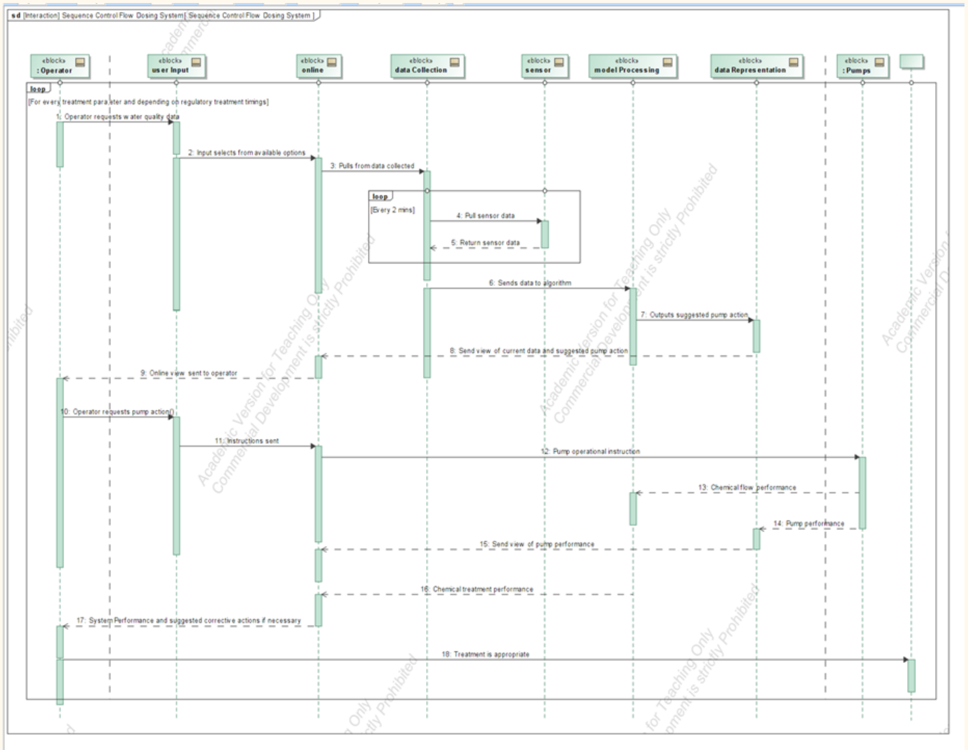
Model Subsystem Sheet

Sensor	Suggestive Model	Power	User Input	Value	Units	E
			Provided to	Design specified range	mg/L	
	Provided to			0-4500	NTU	
	Provided to			0-14	H+	
	Provided to			Transmittence	%	
			Provided to	0-50 (cm to steps of stepper motor)	steps	
	Provided to			Sigmas	%	
	Provided to			Design specified range	L/s	
		Provided to		5 DC	V	
		Provided to		11	mA	
	Provided to			Error Range	=+-(0.5%)	

Sensor	Data Collection	Data Representation	User Input	Model/Processing	Online	Pump	Value	Units
				Provided to	Provided to		Design specified range	mg/L
	Provided to	Provided to		Provided to	Provided to		0-4500	NTU
	Provided to	Provided to		Provided to	Provided to		0-14	H+
	Provided to	Provided to		Provided to	Provided to		Transmittence	%
	Provided to	Provided to		Provided to	Provided to		Sigmas	%
	Provided to	Provided to		Provided to	Provided to		Design specified range	L/s
	Provided to			Provided to	Provided to		Error Range	=+-(0.5%)
			Provided to	Provided to	Provided to		Visual, Calibration, Testing	(0,1)
		Provided to		Provided to	Provided to		Primary Particle Conversation	%
		Provided to		Provided to	Provided to	Provided to	Visual, Calibration, Testing	(0,1)

The interface matrix is a way to see how these subsystems will work with each other and what kind of information needs to flow between them. It enables us to begin to set more thorough and specific parameters that we're going to need in order to achieve the intended outcomes. For instance the sensors are going to be providing various pieces of information like color data via transmittance percentage or turbidity data via nephelometric turbidity units to the model, but at the same time they need to be powered by the power subsystem potentially using a 5 DC volts at 11 milliamps. This kind of detail clearly shows exactly what kind of information is flowing and necessary and is often updated with the value and units. This tool enables us to set up the design constraints accordingly.

Sequence Diagram



The sequence diagram is similar to an activity diagram however it follows one specific set of operations from start to end and it includes elements relevant to transfer of each step like information flow, logic gates, and even equations. It helps us to see how the sequence of operation will go through each of these subsystems and the kinds of usage and flow of information that each element will be providing and when it would be providing it.

In our circumstance we can see that from the operator to pumping the coagulant dose, the sequence brings the operator through six subsystems all of which need to be performing according to correct parameters. This is extremely insightful because the granularity can show exactly what needs to be done in each subsystem to advance steps and when in the process it happens. You can even see what looks like two almost independent sequences although in the end it terminates with just dosing through the pump. Those two flows are through data collection and model processing as it relates to the sensors first and then repeats in model processing as it relates to the pump. This tool enables development to divide work into specific engineering designs for each element of the sequence and then one can test each of those independently.

Operation Description Template

Water Treatment Plant Operator	Sensor	Data Collection	Data Representation	User Input	Model/Processing	Online	Pump	State	Target Timing
Operator turns on the system								System off	
	OR.8 The CFDS shall allow for sensors input data							Data Collection	
		OR.1 The CFDS shall collect inflow quality data							
			OR.2 The CFDS shall present inflow quality data					Sensor View	
					OR.3 The CFDS shall calculate a suggested optimal chemical dose				< 30 secs (minimum movement of dosing arm)
Operator analyzes quality and suggested dose									
Operator inputs dose									
				OR.4 The CFDS shall collect operator					
						OR.5 The CFDS shall send instructions to chemical pumps		Dosing	
							Pump dispenses chemicals at inputted rate		
Operator turns on the system								System off	
		OR.6 The CFDS shall have an option to be calibrated						Calibration	
				OR.7 The CFDS shall allow for operator to select input data types					
Operator selects input data types	OR.8 The CFDS shall allow for sensors input data								
	Sensors sends data to CFDS								<5 min (should be intuitive and not bothersome to operators so it can encourage continual calibration)
			OR.9 The CFDS shall present sensors data						
Operator cross references data with knowns									
			OR.10 The CFDS shall allow for adjustments to data presentation						
				OR.4 The CFDS shall collect operator					
Operator adjusts CFDA data									
Operator turns on the system								System off	
	OR.8 The CFDS shall allow for sensors							Data Collection	

The operation description template or the ODT is similar to an activity diagram however what you'll notice is that it includes the states of the system. When the sequence of information flow happens those flows can correspond to specific states that the system exists in and you can set up those states as kind of checkpoints. You can also supplement it with information on how long you want the system to take to complete a set of actions.

In our model you'll see that the data collection state begins as soon as the system is turned on by the operator. The state changes from collection to view once the operator enters view mode. The originating requirements as they correspond to those states and state changes are as related to the collection of data, the input of data and the presentation of data. The entire operation should take less than 30 seconds to dose.

State Matrix

States	System Off	Data Collection	Calibration	Sensor View	Monitoring	Alert
System Off		Power sensor and collection system				
Data Collection	Power Off		Operator enters calibration mode	Operator selects view and sensor	Operator selects monitor view	System sensor triggers alert
Calibration	Power Off	Idle, Operator finishes				System sensor triggers alert
Sensor View	Power Off	Idle, Operator exits view	Operator enters calibration mode		Operator selects monitor view	System sensor triggers alert
Monitoring	Power Off	Idle, Operator exits view	Operator enters calibration mode	Operator selects view and sensor		System sensor triggers alert
Alert	Power Off	Manual override, Sensor error clears	Manual override, Sensor error clears	Manual override, Sensor error clears	Manual override, Sensor error clears	

The State Matrix is a table that helps us understand how various states of our system will transition into each other. It can help serve as a way to see which states are default states and which states are only used at certain times. It is also useful as a way for seeing the sequential nature of the states interface as was complimented in the ODT.

You can notice this nature by seeing how various states trigger transitions, for instance, an alert state would only by exited if the error is cleared and the only way that it can clear and return into previous default states is through a manual override. Similarly the way that an alert state becomes active is through a system sensor trigger.

You can also see how the operator can play a crucial role in determining the states and switching between them. This can show what kind of influence the user has in state transitions, which can be helpful for determining the various users and the types of interaction those users have control over.

Behavioral Test Plans

Test #	Test Method	Test Facilities	Entry Condition	Exit Condition
TP.1	Adjusts chemical dose reomtley	User interface, wireless transmitter, wireless reciever, pumps, dosing calibrated, chemcial feed	Wireless transmission is set up. Wireless reciver is set up to receive, user interface is set up to view data, Operator input section is coded and connected.	Operators input changes the dose according to specified range within 3 sigmas of deviation
TP.2	Read performance data	User interface, sensor calibrated and working, wireless tranmitter, wireless reciever, water sample	Wireless transmission is set up. Wireless reciver is set up to receive, user interface is set up to view data, water sample is availbe with known quality, sensors are calibrated and performing	Data is visuallized and
TP.3	Change presentation of performance data	User interface, sensor calibrated and working, wireless tranmitter, wireless reciever, water sample	Wireless transmission is set up. Wireless reciver is set up to receive, user interface is set up to view data, water sample is availbe with known quality, sensors are calibrated and performing, data view is coded and displaying at standard	Data visualization changes to selected ranges and conditions
TP.4	Send sensor inputs for optimal dosing	User interface, sensor calibrated and working, wireless tranmitter, water sample	Wireless transmission is set up. Wireless reciver is set up to receive, user interface is set up to view data, water sample is availalbe with known quality, sensors are calibrated and performing, data view is coded and displaying at standard, Model is functional and connected to interface via remote server	Optimal dosing is automatically suggested in the operators dosing input section

Now that we've set up ways to compare our system and the metrics we'll use to gauge its success, we need a way to test our system. The behavioral test plan speaks to the motto of this tools analysis "test early, test often". It's important to set up those test criterias in a way that is documented, objective, and clear. Clarity being the key word here, where if the criteria for the entry condition and the exit condition are met, as well as, the methodologies and the facilities needed are clear then the test can truly be an indicator for the measured objective. With the test results, conclusions and whatever design changes need to be made can then be done accordingly.

In our model you can see that for test plan 1, the test method "is to adjust the chemical does remotely" which requires the various test facilities to be ready and in place such as the user interface, wireless transmitter and pumps. The entry condition for this case is similar to the various other test cases however it's in the difference that there are some key insights. We learn that in order for this test plan the operators input section has to be coded and operational which itself requires testing. The exit condition is that the operators dose changes within a certain deviation. The clarity here is in the documented, objective, and numeric exit condition.

Non-Behavioral Test Plans

Req #	Requirement	Abstract	#	Test Method	Verification	Test Facilities	Entry Condition	Exit Condition
OR.5	The CFDS shall send instructions to chemical pumps	Pump Commands	**TP.5**	Test the measured dosing flow rate given an operational instructions. This should be repeated weekly during normal operations and analyzed monthly for expected decalibration error.	D	Pump, calibrated flow rate sensor or volumetric flask and timer, control flow dosing system.	Pump speed and associated flow rate are calibrated, operational instructions are electronically recievable.	Dosing error is within 3 standard deviations from expectd dosing flow rates and expected adjustment due to calibration errors are one week from 3 standard deviations from
OR.17	able to receive pump operational input	Receive Pump Operation Input	**TP.6**	Test time delay of operational instructions sent from user interface	I	control flow dosing system, operator user interface	user interface is set up, control flow dosing system is built	timing delay is within 1 minute with respect to pump rpm (i.e. dose
OR.20	The CFDS shall alert the operator the operational status of the pumps	Pump Operation Alert	**TP.7**	Test alert system by putting the pump through all of its state cases and its regular function and see if it reports the right time	D	User interface, wireless transmitter, wireless reciever, pumps	Wireless reciver is set up to receive, user interface is set up to view data, Pump operational data is transmitting and being received	Pump operational infromation is being transmitted correctly within the trasmission time rate
OR.3	The CFDS shall calculate a suggested optimal chemical dose	Chemical Dose Calculation	**TP.8**	Test PID control system where quality data (turbidity) dowstream of the doser sends data to control flow dosing system that than ajusts dose accordingly	A	control flow dosing system, pumps, chemical stock, turbidity sensors	turbidty data is being received form sensors, PID controller is built and can send oprational controls, dosing model is programmed.	PID changes a dose according to the model as a result of a turbidity downstream and not that of user input

The non-behavioral test plan is similar to the behavioral test in that it focuses on a way to verify that the system is developing as intended however it differs in that it doesn't test users interaction. This is important for testing aspects of a project that don't have any user experience as a dependency. For instance, to be able to test that the CFDS shows alerts to the operator of the operational status of the pumps is not dependent on what the operator (i.e. the user) is doing and so this kind of test has nothing to do with the behavior of the operator. However, it needs to be conducted because requirements depend on it and make of those requirements are operator dependent.

As is similar with behavioral types of plans, you need to have the appropriate test methodologies, verification type, the test facilities and the entry and exit conditions. In our example the test methodology for the requirement of the CFDS shall calculate a suggested optimal chemical dose, we need to have the sensors, the pumps, and the control flow dosing system already built. It’s entry conditions need to be met where all the sensors are working by transmitting data appropriately and the exit condition is that the model changes accordingly. This can happen with or without pumping set up or even the actual mechanism for changing the dose created. As long as the model works according to the exit condition then our test is considered a success and that requirement is considered met.

Verification Cross Reference Matrix

Test / Originating Requirement	OR.1	OR.2	OR.3	OR.4	OR.5	OR.6	OR.7	OR.8	OR.9	OR.10	OR.11	OR.12	OR.13	OR.14	OR.15	OR.16	OR.17	OR.18	OR.19	OR.20	OR.21	OR.22	OR.23	OR.24	OR.25	OR.26	OR.27	OR.28	OR.29	OR.30
TP.1				X	X	X	X				X			X			X	X												
TP.2	X	X					X	X	X		X					X											X	X		
TP.3							X	X	X		X					X					X	X	X			X	X	X		
TP.4			X	X			X	X	X		X			X		X					X		X							
TP.5				X	X						X					X	X	X												
TP.6				X	X						X					X	X	X	X											
TP.7											X					X			X	X										
TP.8				X	X	X	X				X			X			X	X			X		X							

With test early tests often as our motto it's important to be able to track how everything is being tested and that all of the requirements are being tested. The verification cross reference matrix is a table that keeps track of all of the requirements and subsequent tests as they relate to those requirements. This method of keeping track of all of the tests becomes more important as the project develops and its scope includes various kinds of requirements such as functional requirements as well as various models of increasing degrees of detail.

As you can see, part of the insight that you can gain from this, is an understanding of what kinds of requirements are necessary to conduct what kinds of tests. For instance, originating requirement number 11 which has to do with the ability to collect data is important for conducting every single one of the test cases that we have specified. Therefore we can conclude that this originated requirement is extremely influential and essential and helps us prioritize and allocate the appropriate resources for its development. We can also see that there are a few originating requirements that aren’t being met by tests and so we have to continue the development of the test plans to include them.

Failure Mode and Effect Analysis

Failure Mode #	Subsystem	Failure Mode	Failure Effects	Possible Cause	Severity	Occurrence Likelihood	Risk Priority Number	Risk Criticality	Corrective Action
F.1	Pump	Failure for checmical dosing to exit tubing accurately	The treatment of the the plant is no longer controllable. Water is not treated as operator intends.	Tubing is clogged	4	2	8	Medium-Low	Periodically inspect and flush tubing
				Tubing rigidity deteriorates	4	5	20	High	Periodically replace tubing or use corrosion resistent tubing
				Peristaltic speed is not accurate	3	2	6	Medium-Low	Recalibrate speed sensor as often as necessary
F.2		Failure to communicate with wireless controll	The treatment of the the plant is no longer controllable wirelessly. Operator must be phyiscally present at plant. Water is not treated as operator intends.	Power is lost to transmission system	5	3	15	High-Medium	Institute multiple power back ups. Set up system to alert when back up power is being used. Develop system to draw as little power as possible when not in use
				Interface is disconected with pump operational data	3	3	9	Medium-Low	Set up alterior interface view systems such as visual perfermance through video cameras.
F.3	Data Processing	Failure to diferentiate sensor and pump data	Model will not be able to suggest the correct dose. Operator will not be able to control the plant. Pumps will be offline. Operator will have to manually dose.	Diferentiation code does not include comprehensive test cases	4	2	8	Medium-Low	Review code periodically. Code test cases based on expected failures. Incorporate failures into updates
				Data exceeds designed range	2	1	2	Low	Expand range to include fringe cases. Revaluate the designed thresholds
				Wireless transmission systems are shorted	4	4	16	High-Medium	Set up back up systems. Waterproof transmission enclosures.
F.4	Sensor	Failure to transmit data	Model will not be able to suggest the correct dose. Operator will have to manually dose. Data collect history will be lost. Operator wil have to physiacally be at the plant	Wireless transmission systems are shorted	4	4	16	High-Medium	Set up back up systems. Waterproof transmission enclosures.
				Power is lost to transmission system	5	3	15	Medium-Low	Institute multiple power back ups. Set up system to alert when back up power is being used. Develop system to draw as little power as possible when not in use
				Servers cannot receive data	5	3	15	High-Medium	Have back up server at various locations. Send to cloud and not on local servers.
F.5		Failure to collect accurate data	Model will not be able to suggest the correct dose. Operator will have to manually dose. Operators dose may not be based on good enough information. Plant may not operate as intended.	Sensors lose callibration	1	2	2	Low	Recalibrate sensors as often as necessary. Inspect via quality expectations often.
				Sensors degrade over time	5	2	10	Medium	Replace sensors or conduct relevant maintence often.
F.6	Modeling	Failure to dose optimally	The Plant will not be able to runn autonomously. The operator will have to be in control of the system for the majority of the time.	The model did not incorporate penalty functions	2	3	6	Medium-Low	Reprogram the model to continually improve via machine learning. Incorpate penalty functions in updates
				Extreme cases were not planned for and occured	2	3	6	Medium-Low	Incoproate extrema into updates. Use uncertaintly analysis in design process
				The model restarted while in operation	1	5	5	Low	Desing system to run using historical data if within relevant time range and incorporate goal seeking behavior

Failure mode and effect analysis is an analysis done to design around expected failure points. It would be foolish to assume that everything works all the time and designers understandably design around their system working properly. This analysis forces engineers and designers to design around what happens not if but when things fail. It does so objectively by assigning a severity and likelihood score to develop a risk priority number. This number is associated with how critical of risk this failure point is.

For our system this is particularly important because as a water treatment system, failures are intolerable as they affect public health. It is often the case that a large portion of associated costs are built around the resiliency and redundancy that is incorporated as a result of these analyses.

In our model when analyzing the pumps a failure mode could be inaccurately dosing due to the exit tubing. This can affect the treatment of the plant drastically and drastic consequences where the worst case scenario is having unsafe drinking water. This failure happens all the time as a result of the tubing rigidity deteriorating and is reflected with having the highest associated risk priority number associated. You can now design around it and put in place management systems to replace and maintain tubing is necessary.

Risk Priority Number System and Stoplight Graph

Risk Priority Number Definition Table

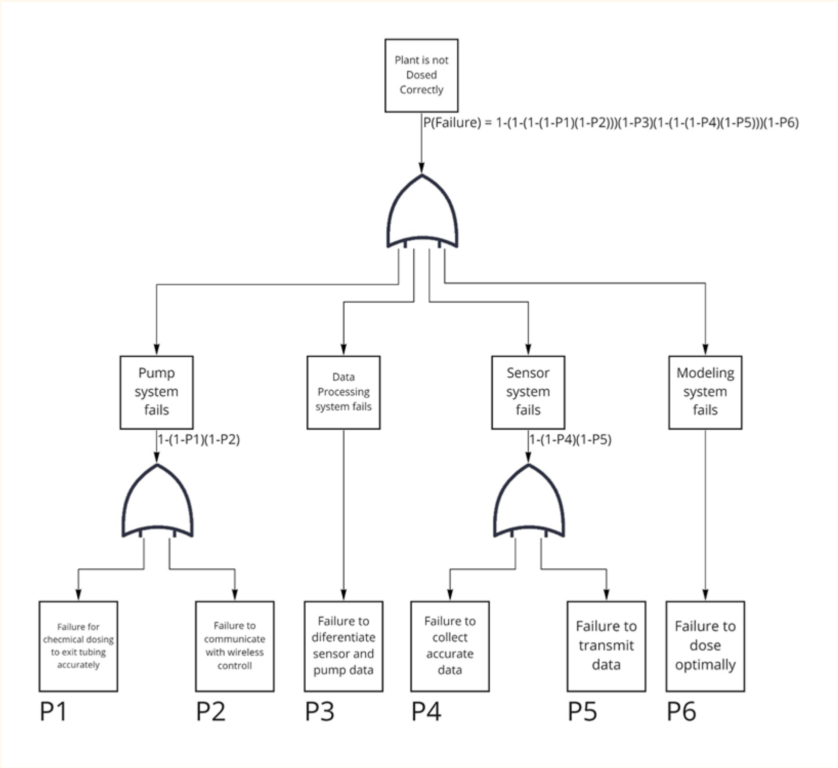
Likelihood	**5**	5	10	15	20	25		20-25	High Risk
	4	4	8	12	16	20		15-19	Medium-High Risk
	3	3	6	9	12	15		10-14	Medium Risk
	2	2	4	6	8	10		5-9	Medium-Low Risk
	1	1	2	3	4	5		1-4	Low Risk
		1	**2**	**3**	**4**	**5**	*Severity*		

Likelihood	**5**	1	0	0	1	0	
	4	0	0	0	1	0	
	3	0	2	1	0	2	
	2	1	0	1	2	1	
	1	0	1	0	0	0	
		1	**2**	**3**	**4**	**5**	*Severity*

The risk priority number system and stoplight graph is a visual way to see where along the likelihood and severity graph our system failure operates. In other words, it shows how resilient or at risk our system is. In the stoplight table graph, we can see how many times various risks are developed. In our model you can see that we have few medium to high risk instances and some low-risk ones as well. This kind of graph can help the design engineer focus on reducing those risks by increasing the corrective actions associated with them thus bringing the overall risk of the system down and making it more robust and resilient.

For instance, there's a high risk associated with power outage and through increasing redundancy we can essentially remove or reduce those risks and put them into a medium low risk to low-risk category. This is exactly what has happened in our development. We now have two sources of backup power as well as alert systems in place all with enough time for corrective action to take place and ensuring our system continues intended operation without total system failure.

Fault Tree Diagram



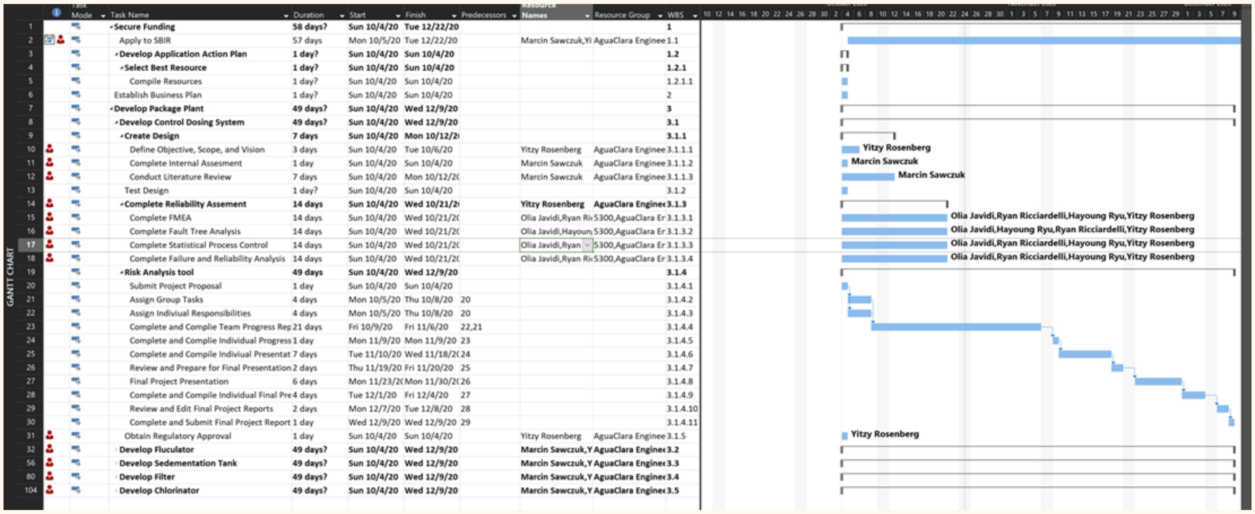
Failure	Probability of Failure
P1	0.1
P2	0.3
P3	0.2
P4	0.1
P5	0.2
P6	0.1

System	Total Probability
Overall	0.673408
Pump	0.37
Data	0.2
Sensor	0.28
Modeling	0.1

The fault tree diagram is an analysis of the steps that have to fail in order for our system as a whole to fail. This is done using logic gates of "and" and "or" where "or'' corresponds to if either point a or point B fail then the system failures and "and" corresponds both point a and point B have to fail in order for the system to fail. This kind of diagram can show the robustness of the system by showing how many subsystems or gates have to be operating in order for the total system to be operating and how much redundancy needs to be built. It can be helpful especially when it's used to determine *where* redundancy should be applied.

In our system you can see that if any one of the subsystems fails the entire system will follow suit. You can also assign various probabilities for these failures to occur and then mathematically determine the overall reliability of the system. This is important for water treatment as you often need to numerically demonstrate how reliable the system is in order for it to be adopted by the client.

Timeline

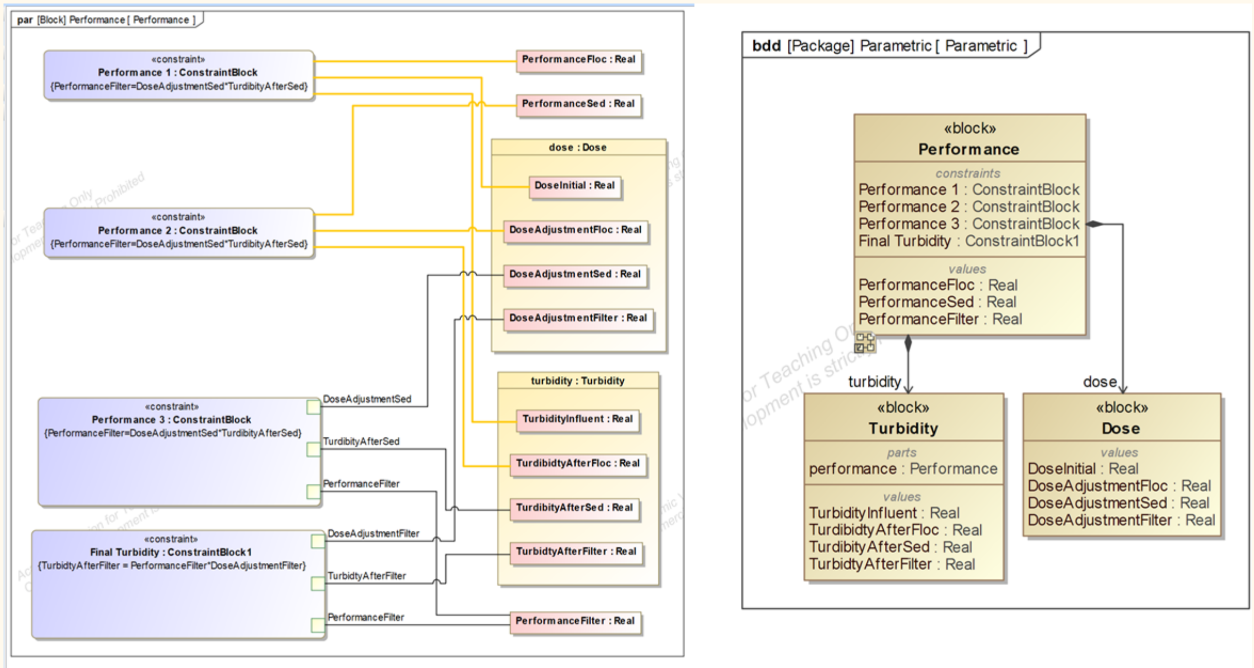


	Task Name	Duration	Start	Finish	Predecessors	Resource Names	Resource Group	WBS
1	**Secure Funding**	**58 days?**	**Sun 10/4/20**	**Tue 12/22/20**				**1**
2	Apply to SBIR	57 days	Mon 10/5/20	Tue 12/22/20		Marcin Sawczuk,Yi	AguaClara Enginee	1.1
3	**Develop Application Action Plan**	**1 day?**	**Sun 10/4/20**	**Sun 10/4/20**				**1.2**
4	**Select Best Resource**	**1 day?**	**Sun 10/4/20**	**Sun 10/4/20**				**1.2.1**
5	Compile Resources	1 day?	Sun 10/4/20	Sun 10/4/20				1.2.1.1
6	Establish Business Plan	1 day?	Sun 10/4/20	Sun 10/4/20				2
7	**Develop Package Plant**	**49 days?**	**Sun 10/4/20**	**Wed 12/9/20**				**3**
8	**Develop Control Dosing System**	**49 days?**	**Sun 10/4/20**	**Wed 12/9/20**				**3.1**
9	**Create Design**	**7 days**	**Sun 10/4/20**	**Mon 10/12/2**				**3.1.1**
10	Define Objective, Scope, and Vision	3 days	Sun 10/4/20	Tue 10/6/20		Yitzy Rosenberg	AguaClara Enginee	3.1.1.1
11	Complete Internal Assesment	1 day	Sun 10/4/20	Sun 10/4/20		Marcin Sawczuk	AguaClara Enginee	3.1.1.2
12	Conduct Literature Review	7 days	Sun 10/4/20	Mon 10/12/2(		Marcin Sawczuk	AguaClara Enginee	3.1.1.3
13	Test Design	1 day?	Sun 10/4/20	Sun 10/4/20				3.1.2
14	**Complete Reliability Assement**	**14 days**	**Sun 10/4/20**	**Wed 10/21/2**		**Yitzy Rosenberg**	**AguaClara Engine**	**3.1.3**
15	Complete FMEA	14 days	Sun 10/4/20	Wed 10/21/2(		Olia Javidi,Ryan Ri	5300,AguaClara Er	3.1.3.1
16	Complete Fault Tree Analysis	14 days	Sun 10/4/20	Wed 10/21/2(		Olia Javidi,Hayoun	5300,AguaClara Er	3.1.3.2
17	Complete Statistical Process Control	14 days	Sun 10/4/20	Wed 10/21/2(		Olia Javidi,Ryan	5300,AguaClara Er	3.1.3.3
18	Complete Failure and Reliability Analysis	14 days	Sun 10/4/20	Wed 10/21/2(		Olia Javidi,Ryan Ri	5300,AguaClara Er	3.1.3.4
19	**Risk Analysis tool**	**49 days**	**Sun 10/4/20**	**Wed 12/9/20**				**3.1.4**
20	Submit Project Proposal	1 day	Sun 10/4/20	Sun 10/4/20				3.1.4.1
21	Assign Group Tasks	4 days	Mon 10/5/20	Thu 10/8/20	20			3.1.4.2
22	Assign Indiviual Responsibilities	4 days	Mon 10/5/20	Thu 10/8/20	20			3.1.4.3
23	Complete and Complie Team Progress Rep	21 days	Fri 10/9/20	Fri 11/6/20	22,21			3.1.4.4
24	Complete and Complie Individual Progress	1 day	Mon 11/9/20	Mon 11/9/20	23			3.1.4.5
25	Complete and Compile Indiviual Presentat	7 days	Tue 11/10/20	Wed 11/18/2(	24			3.1.4.6
26	Review and Prepare for Final Presentation	2 days	Thu 11/19/20	Fri 11/20/20	25			3.1.4.7
27	Final Project Presentation	6 days	Mon 11/23/2(	Mon 11/30/2(	26			3.1.4.8
28	Complete and Compile Individual Final Pre	4 days	Tue 12/1/20	Fri 12/4/20	27			3.1.4.9
29	Review and Edit Final Project Reports	2 days	Mon 12/7/20	Tue 12/8/20	28			3.1.4.10
30	Complete and Submit Final Project Report	1 day	Wed 12/9/20	Wed 12/9/20	29			3.1.4.11
31	Obtain Regulatory Approval	1 day	Sun 10/4/20	Sun 10/4/20		Yitzy Rosenberg	AguaClara Enginee	3.1.5
32	**Develop Fluculator**	**49 days?**	**Sun 10/4/20**	**Wed 12/9/20**		**Marcin Sawczuk,Y**	**AguaClara Engine**	**3.2**
56	**Develop Sedementation Tank**	**49 days?**	**Sun 10/4/20**	**Wed 12/9/20**		**Marcin Sawczuk,Y**	**AguaClara Engine**	**3.3**
80	**Develop Filter**	**49 days?**	**Sun 10/4/20**	**Wed 12/9/20**		**Marcin Sawczuk,Y**	**AguaClara Engine**	**3.4**
104	**Develop Chlorinator**	**49 days?**	**Sun 10/4/20**	**Wed 12/9/20**		**Marcin Sawczuk,Y**	**AguaClara Engine**	**3.5**

The timeline or Gantt chart is a way to plan the development of the system and to identify what are the limiting factors in its overall development. It's crucial here to place various milestones that correspond to testing early and testing often and by incorporating various development methodologies like agile and scrum approaches. This can help prevent any unexpected delays as a by product of necessary elements not working and helps to solve problems before they arise. It can also help to see what developments are dependent on aspects having been created. Based on this a project manager can then assign the resources to either speed up that process or to address that process as they deem necessary.

With our system, you can see that there are many dependencies. The testing of each of those processes is required throughout the stages of their development. For instance in order to develop the package plant we need to develop all of the subcomponents. In order to develop all the subcomponents we need to develop the power supply, the wireless transmitter, and build the components themselves all the while having scheduled testing. This gives an overall understanding of how long it will take to build the CFDS and when each step can be expected to be accomplished.

Parametric Diagram



The parametric diagram is a way to demonstrate equations in a visual system. These can then be used to set constraints on the actual blocks in the system which can then be incorporated into various design elements.

For instance, you can see in our parametric diagram how various blocks and values correspond to the equations. “Performance” can be shown as it relates to the performance of the flocculator which is dependent on the initial dose as well as the initial turbidity. This equation has an effect on the turbidity after the flocculator. Subsequently, the performance of the sedimentation tank is now dependent on the dose adjustment after the flocculator, which affects the turbidity after the sedimentation tank which affects the performance of the filter excetera. This diagram demonstrates the interrelatedness of the equations that would go into the dosing model.

For further details I created a model using venison that clearly shows all of the interrelated patterns in a similar way to a parametric diagram, see attached index.

Section 3: A Systems Dynamics Approach

An Attempt at a Dosing Model

Introduction and Justification

Fifteen years ago, the founder of AguaClara Dr. Monroe Weber-Shirk was doing humanitarian refugee work in Honduras when he noticed that the communities that he was working with didn't have access to safe drinking water. That need that he recognized created the AguaClara program whose mission it is to study the physics behind how water is treated and turn those physics equations into designs for communities in need of safe water. These designs are founded on a few guiding principles that make them suitable for rural communities who often lack access to expertise, equipment, and electricity. The designs must be operable by staff with a maximum of fourth grade education. They must be entirely built and managed by local resources found within the community. They must be powered entirely by gravity and not dependent on electricity or other exterior energy resources.

Through these design foundations and the equations that have come out of the lab AguaClara has created over 20 water treatment plants across Central America and India with the majority having been constructed and maintained by Agua Para El Pueblo, a non-governmental organization in Honduras. These plants collectively service over 80,000 people and consistently treat water to below the local standards over 99.99% of the time.

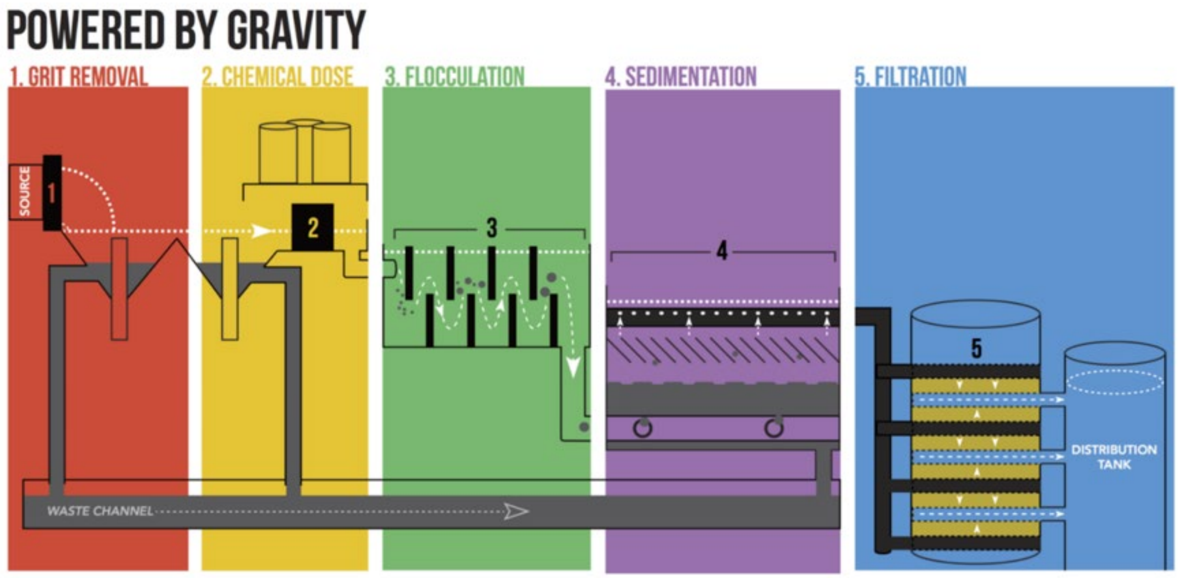
This summer the AguaClara team participated in the National Science Foundation Innovation Core program where team interviewed over 100 relevant water stakeholders in the United States with the intention of seeing if there is a market for AguaClara technologies in North America. The perspective of the stakeholders spanned across a variety of water treatment professions from the director of water enforcement for the Environmental Protection Agency to operators of small rural water systems across the country. In addition to the problems addressed above regarding access, the interviews demonstrated that there is indeed a problem to be solved for rural communities in North America namely the lack of operational staff.

The water treatment industry is very complex because it requires an understanding of chemistry, fluid mechanics, mechanical engineering to solve mechanical problems related to moving parts such as pumps, and electrical engineering to solve management problems such as the work behind the SCADA systems. Additionally, operational staff with the above-mentioned resources and skills often work for similar professions that pay better such as oil and gas and chemical plant management. Furthermore, the water treatment sector is not as sexy a sector when compared to other public services such as firefighters or the police force.

While those systemic problems are certainly issues to be addressed the purpose of this model is to recreate the AguaClara treatment system and design it run without any operational staff aside from routine maintenance. Currently the operator’s primary job is to control the dosing of chemicals by manually adjusting the lever on the dosing system (see below). If we were able to create a way with which the AguaClara system can dose itself, we would remove the need for an operator and increase accessibility to safe drinking water across the country.

This report and model aims to create a digital twin and semi-accurate representation of the AguaClara treatment processes and through understanding the process from a systems perspective create a software that controls chemical feed pumps thus eliminating the need for a full time operational water treatment staff. With an understanding of how water is treated by adjusting performance coefficients to match empirical plant data, we will be able to demonstrate the guiding principle and understand key variables that actually guide the treatment of water through an AguaClara plant.

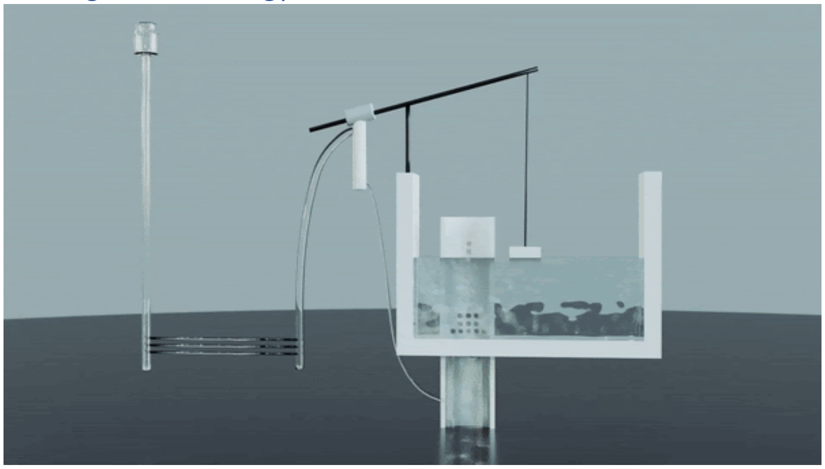
The AguaClara Treatment Train



Grit Removal

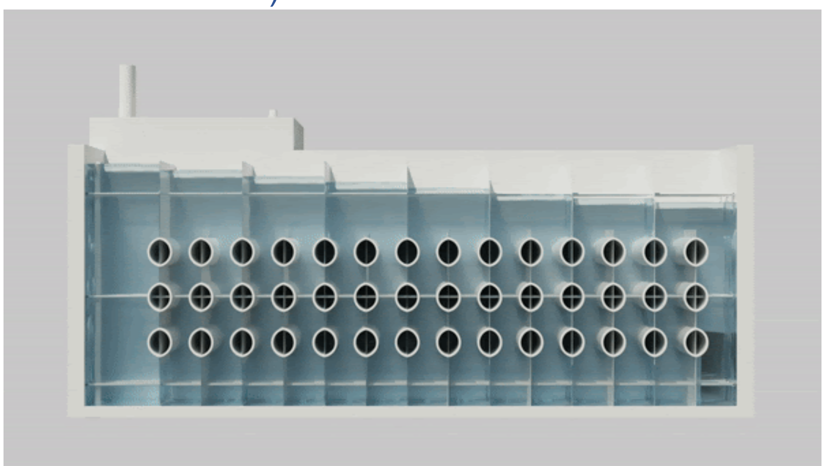
We begin with the grit removal process. During this stage the raw water is cleared of any surface debris and contaminants. Water passes through a grit filter (a large mesh metal screen) at the water inlet and any large surface debris such as sticks, dead animals, trash, or leaves are removed from the water. This stage is often not considered a part of the treatment process because it usually takes place at the water source and not in the treatment plant itself.

Coagulation (Dosing and Mixing)



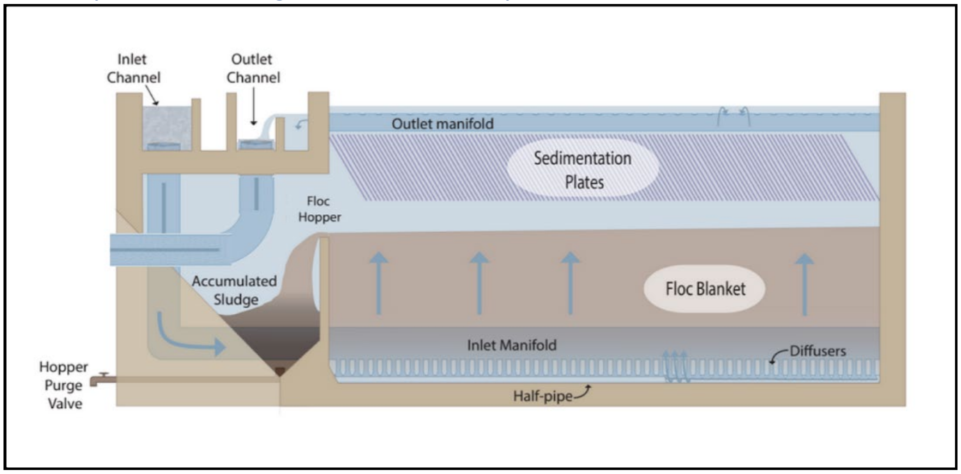
The next stage is coagulation or the chemical dosing stage. This is the stage that our model is focusing on. During this stage the water is injected with a chemical called coagulant which in the case of AguaClara is Poly Aluminum Chloride (PACl). This coagulant causes primary particles in the water to become sticky and eventually stick to each together. As more and more primary particles stick together, they form flocs and these flocs eventually settle out and are removed from the plant in later processes. It is important during this stage that the correct amount of coagulant is added and that the chemistry of the water flowing through the plant is understood because coagulant will only work if it's within a certain pH range. The amount of coagulant is also a function of the incoming water quality measured in Nephelometric Turbidity Units (NTU) which is referred to as turbidity and is a measure of the amount of light that can pass through the water, essentially how dirty the water is. During this stage that the operator conducts a “jar test” where the operator place a range of coagulant doses into three to five jars with raw water. After mixing the jars and letting the formed flocs settle the jar with the least turbidity is selected and its corresponding coagulant doses is used to set the dose for the plant and is pumped or fed into the doser.

Flocculation (Particle Collisions)



The now dosed water flows into the flocculator were primary particle are forced to collide with each other. The flocculator is a series of baffles and obstacles that constrict the water as it flows around the corners of the baffles and across the obstacles. This constriction forces particles to touch each other and now that the particles are sticky due to the coagulant, when they touch each other they will stay stuck together this is called floc formation of flocculation. As the primary particles flocculate, they form larger and larger flocs that will eventually become heavy enough to settle out of the plant. At the end of this stage the majority of primary particles have now flocculated together however there are still many primary particles that have not come into contact with each other and these will be removed in subsequent processes.

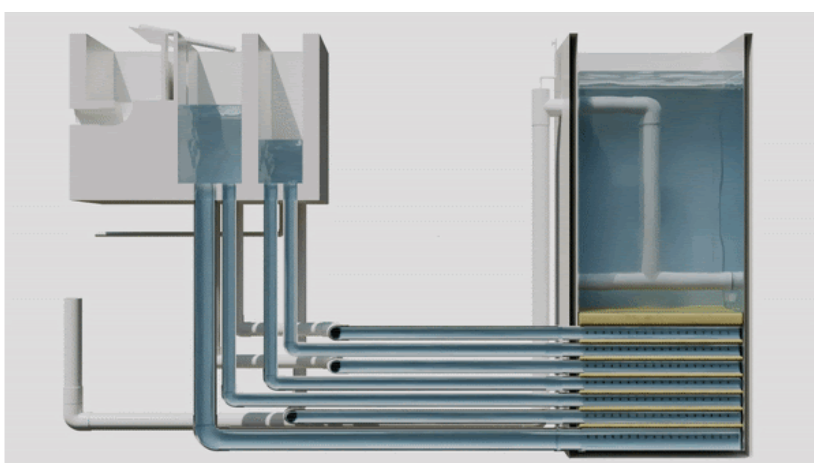
Sedimentation (Floc Settling and Removal)



It is during this stage that over 90% of the turbidity is removed. The flocculated water then flow into the sedimentation tank through a manifold on the bottom. The direction of flow water is reversed by a half pipe and the particles now flow upwards through the sedimentation tank. As the heavier now flocculated particles are denser than water they begin to settle down against the flow and form a thick layer of flocs called a floc blanket. Raw water flows up through that layer many of the remaining non-flocculated primary particles come into contact with the heavier flocs in suspension. As these flocs continue to grow they add more density until finally the floc blanket is high enough that the dense flocs pour over weir called a floc hopper and through an outlet waste channel.

Primary particles that escaped the floc blanket then go through a series of angled baffles called sedimentation plates. The baffles are designed so that a primary particle will have to travel long distance at an angle that encourages it to settle out onto one of the sedimentation plates. Once the primary particle touches the sedimentation plates begins to roll down as it does, so it creates a snowball effect where it collected other primary particles and eventually falls off the sedimentation plates and into the floc blanket where it is removed through the floc hopper with the rest of the floc blanket waste.

Filtration



Any primary particle that escapes floc blanket and the sedimentation plates then gets filtered through the Stacked Rapid Sand (STaRS) filter. The STaRS filter is a six-layer multi directional filter where water flows both up and down through layers of sand. The space between the sand particles causes a constriction that eventually catches the remaining primary dirt particles. As those constrictions begin to fill with dirty the water the pressure builds up forces acting through the sand particles increases to the point where no more primary particles will be filtered. At this point the filter is no longer removing dirt and needs to be cleaned by a back wash. A back wash fluidizes all of the sand in the filter and removes the trapped by going flowing from the bottom up and in the opposite direction with which they were initially attached to the sand particles. This backwash water then has all of the primary particle that the filter caught the water is then removed with waste.

Water that has gone through the filter is now at a very low turbidity. Often less than one percent of the turbidity of the initial raw water. It is only after this stage that chlorine is added to kill and neutralize any pathogens or really stubborn particles. Following chlorination, the water is sent to the storage tank and eventually through the distribution system to people's homes.

The Model Formulation

In the approach to creating a digital twin of the AguaClara treatment process system it is important to keep in mind the scope of work and the limitations of our model's design. Each of the treatment processes have entire textbooks written about them and the parameters, variables, and physics models that go into these process number in the hundreds if not thousands. To create a comprehensive model of each subsystem would be foolish and full of hubris. The approach taken here is to create a simplified approach that incorporates many of the effects of these processes and simplifies them into overarching guiding equations.

There are two overarching coefficient equations that will model the water treatment process. The performance equation will determine how much of the turbidity is removed during each water treatment process while the coagulant dose equation will determine how much coagulant is needed and the effects that that coagulant dose has during each process. These coefficients will be set by empirically matching up the data of the water turbidity at after each water treatment process to what the model generates. Once the turbidity in our model matches the turbidity in the empirical data, we will have a simplified but accurate representation of the effects of the water treatment process and the performance of each stage as well as the effects of the coagulant dose.

With these coefficients documented and the model created we can then optimize the performance by setting the dose of coagulant based on the incoming raw water, the exit turbidity goal, and the measured turbidity at the end of each treatment process. This adjustment to the coagulant dose will then be sent to the dosing system and will represent the operator by adjusting the dose accordingly to optimal performance.

Key Variables

The important key variables are the turbidity at each of the processes (raw water, after flocculator, after flock blanket, after filter, and waste), the actions that affect the flow of turbidity between each process, the residence times and performance associated with each action. Additionally, the turbidity relevance factor, the aluminum performance factor, the aluminum dose rate as well as the initial conditions and the turbidity goal.

Time Horizon

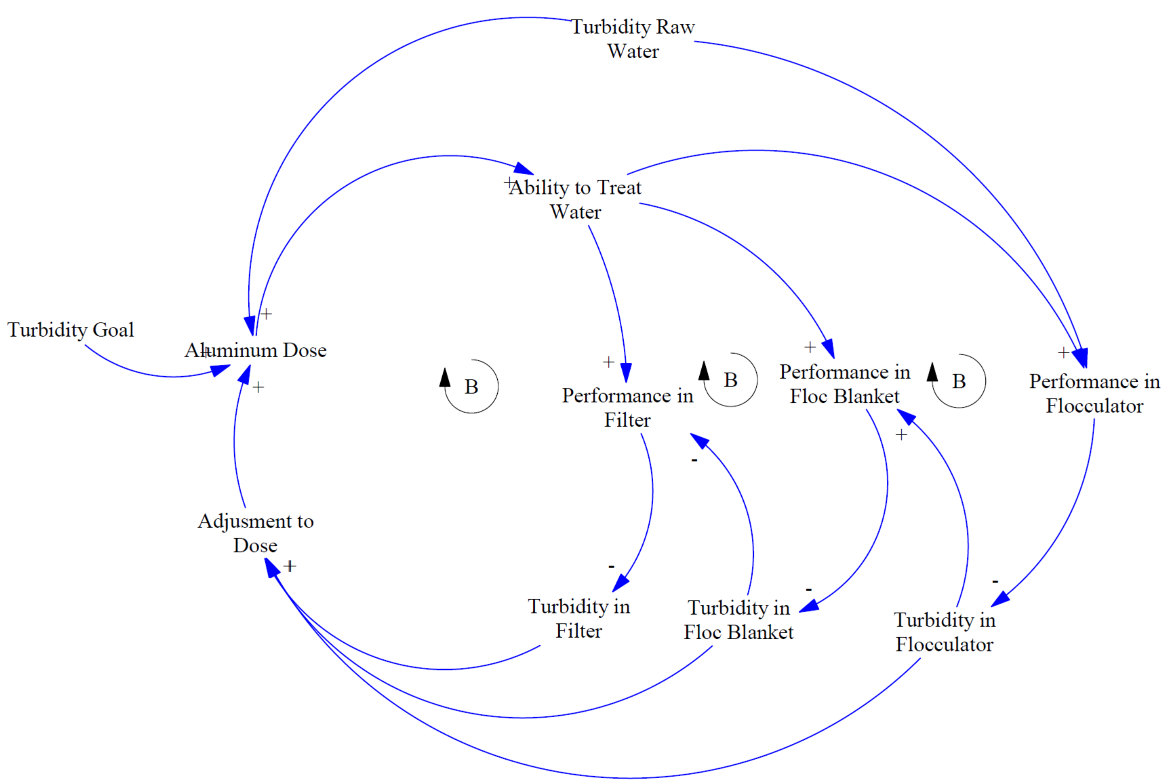
The time horizon is at a minimum, the total length each residence time through the plant and at a maximum of 72 hours which corresponds to the expected treated water storage capacity for any given community. The time step will be in 1/60th of an hour corresponding to minutes as the residence times units are in minutes. Additionally, delays are included in the dose response rates.

Dynamic Problem Definition

When assessing how water is treated it can be analogous to system dynamic goal seeking behavior where the responses to the initial condition affect the way that the water is treated throughout each process all towards an end turbidity goal. This turbidity goal and subsequent goal seeking behavior is often set by local and international regulatory standards such as the Environmental Protection Agency (EPA) or the World Health Organization (WHO). Furthermore there are many balancing loops and response delays that take place within each process and in how each process interacts with one another. For instance, the turbidity exiting the flocculator affects the performance of the floc blanket, however the turbidity exiting the flocculator sets the aluminum dose rate which then affects the performance of the flocculator affecting the turbidity exiting the flocculator and so on as it converges to its optimal goal.

Mapping the Problem

The causal loop diagram shown below demonstrates the three important feedback loops that affect the water treatment process. The first loop corresponds to the aluminum adjustment after the performance of each process affecting the turbidity exiting each process. The second and third loop correspond to how the performance of each process effect the performance in the subsequent processes that follow.



Structure and Decision Rule

Below are some of the guiding equations that demonstrate the decision rules followed by each of the treatment processes. Illustrated are the equations for the flocculator however these equations propagate throughout each process save for the floc blanket and filter which both have outflows for waste associated with them.

$$Q_{process}\left(\frac{NTU}{Time}\right) = Q_{in} - Q_{out}$$

$$Q_{Flocculator} = Q_{raw\ water} - Q_{Flocculator\ Action} - Q_{Primary\ Particles}$$

$$Q_{Flocculator\ action} = Turbidity_{Raw\ water}(NTU) * Performance_{Flocculator}\ (1/Minute)$$

$$Q_{Primary\ Particles} = Turbidity_{Raw\ water}(NTU) * (1 - Performance_{Flocculator}\ (1/Minute))$$

$$Performance_{Flocculator}\left(\frac{1}{Minute}\right) = \frac{Aluminum\ Dose_{Flocculator}(Dimensionless) + Turbidity\ relevence\ factor_{Raw\ water}(Dimensionless)}{Residence\ Time\ Floculator(Minute)}$$

$$Aluminum\ Dose_{Flocculator}(Dimensionless) = DELAY\ FIXED(Turbidity\ Aluminum\ Ratio_{Flocculator}(Dimensionless), Residence\ Time\ Floculator(Minute), 0)$$

$$Turbidity\ Aluminum\ Ratio_{Flocculator}(Dimensionless) = Ratio\ Performance\ Factor_{Flocculator}(Dimensionless) * \frac{Aluminum\ Dose\ Rate(NTU)}{Turbidity_{Raw\ water}(NTU)}$$

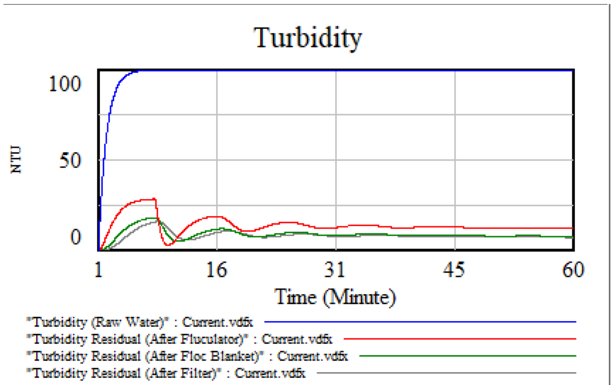
$$Aluminum\ Dose\ Rate(NTU) = Aluminum\ Dose\ Rate_{Initial}(NTU)$$

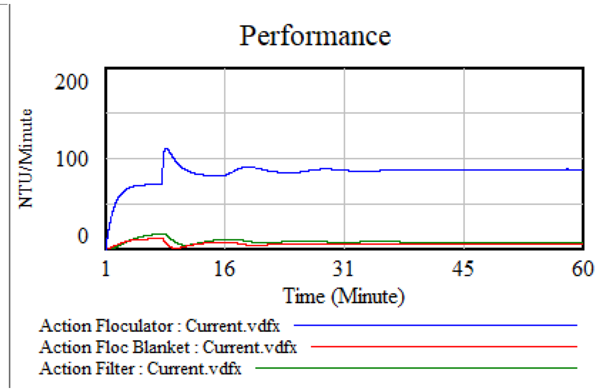
$$Aluminum\ Dose\ Rate_{Initial}(NTU) = Turbidity_{Goal}(NTU) + 5 * \frac{Turbidity_{Raw\ water}(NTU) - Turbidity_{Goal}(NTU)}{100}$$

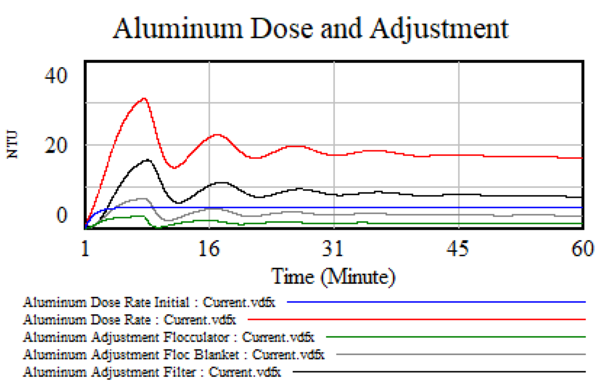
$$Aluminum\ Adjustment_{Flocculator} = Turbidity\ Residual_{Flocculator}(NTU) * Adjustment\ Coefficient_{Flocculator}(Dimensionless)$$

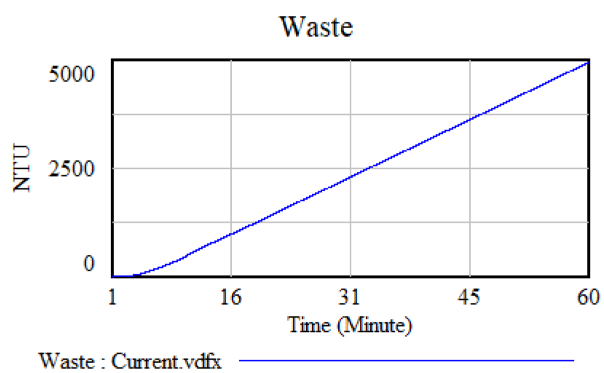
Results Conclusion

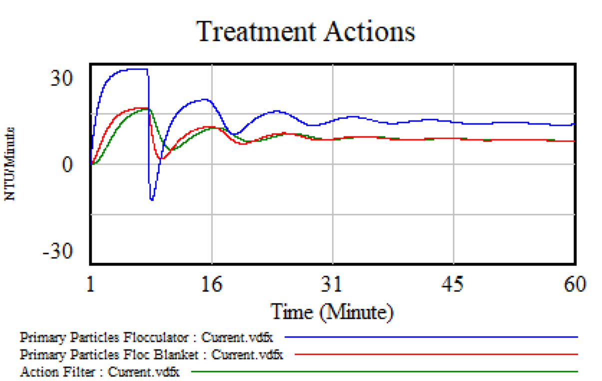
The result from this model are inconclusive. While we were able to successfully create a digital twin that accurately represents the AguaClara water treatment process and exhibits the systems dynamics goal seeking behavior as well as the correct response delay response behavior, it is impossible to draw meaningful conclusions without having appropriate data to compare it to. However there is what to be learned from adjusting and playing with various coefficients. For instance it may come as a surprise to learn that the effect of turbidity on the flocculated performance is more important then the coagulant dose in terms of responses. Additionally it is important that future analysis place conditionals on the ratios of coagulant dose concentration to exiting turbidity. Furthermore, this analysis serves more than just as a way to model the AguaClara system but can serve as a re-framing of water treatment processes as a whole. It is evident by analyzing any graph seen below that water treatment processes behave within the systems dynamics framework and approaches to developing the water treatment processes approaches to further developing and researching physics behind water treatment should take into account a systems dynamics perspective especially when focusing on water treatment as a holistic process as opposed to a collection of isolated processes

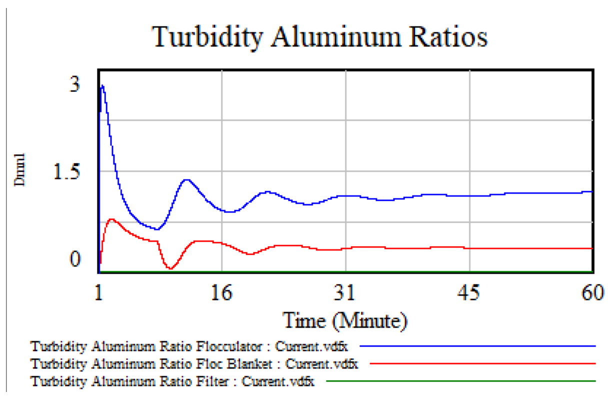












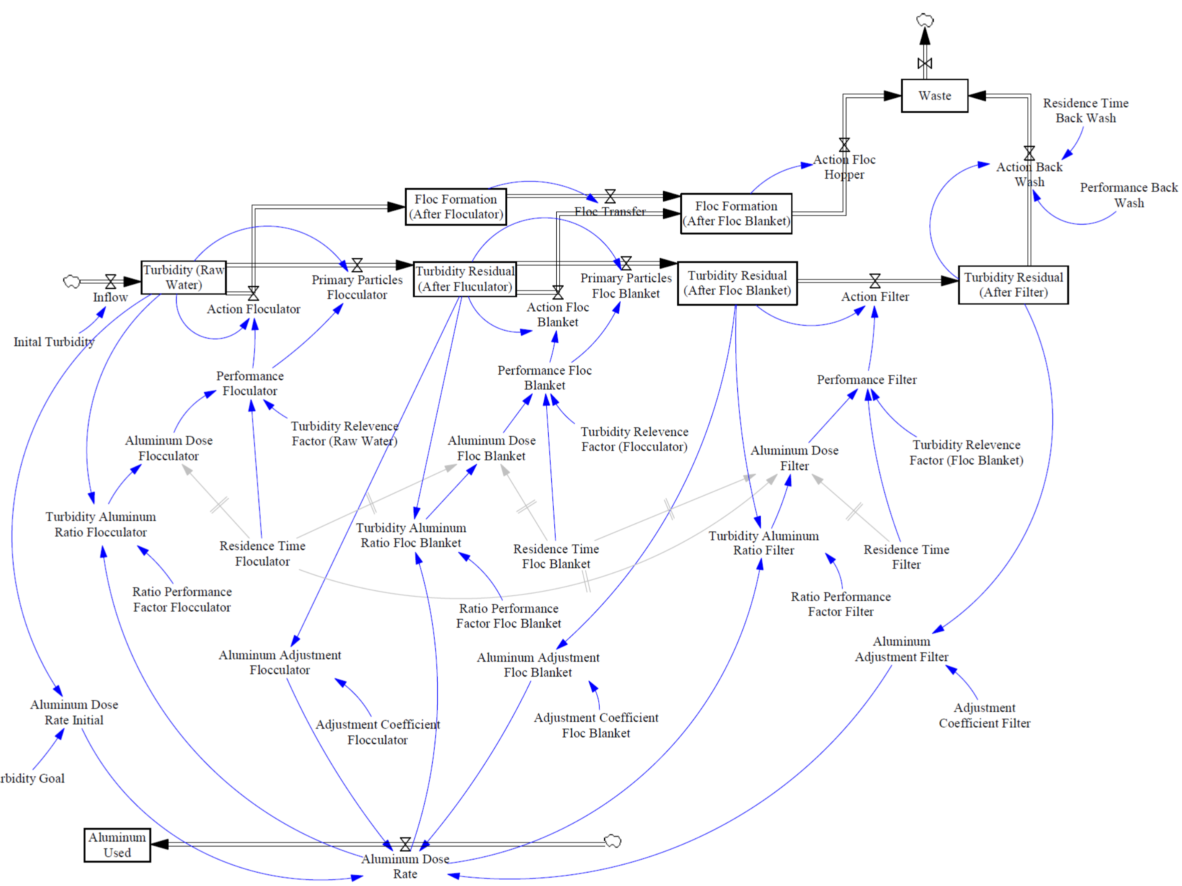
Next Steps

The next steps for this systems dynamics perspective on water treatment process is to collect data from our pilot plants that are currently running and match that data with the representation of turbidity at the end of each process created by this model. With the coefficients that we get from this model we will then program software to run chemical feed pumps that set the dose as a function of the sensor turbidity data they receive. After experimentally testing and verifying the importance of those coefficients with the use of the actual pumps and troubleshoot problems with the management dosing system we will then begin to provide our treatment process to communities through development grants by the United States Department of Agriculture and the National Science Foundation.

This process will depend on obtaining funding from the National Science Foundation SBIR grant which will enable us to dedicate the time to code, build, and deploy the automatic dosing system. Additionally, the insights gained from this systems dynamics model can help guide treatment plants across the country and even globe by providing an objective formula to categorically dose a treatment plant based on the turbidity exiting each process.

There is much work to be done regarding the coding, the data analysis, and the incorporation of additional important variables into the model before we can consider it complete. This will come through continued work on our pilot and through continued research and development at the AguaClara Cornell program.

Stock and Flow Diagram



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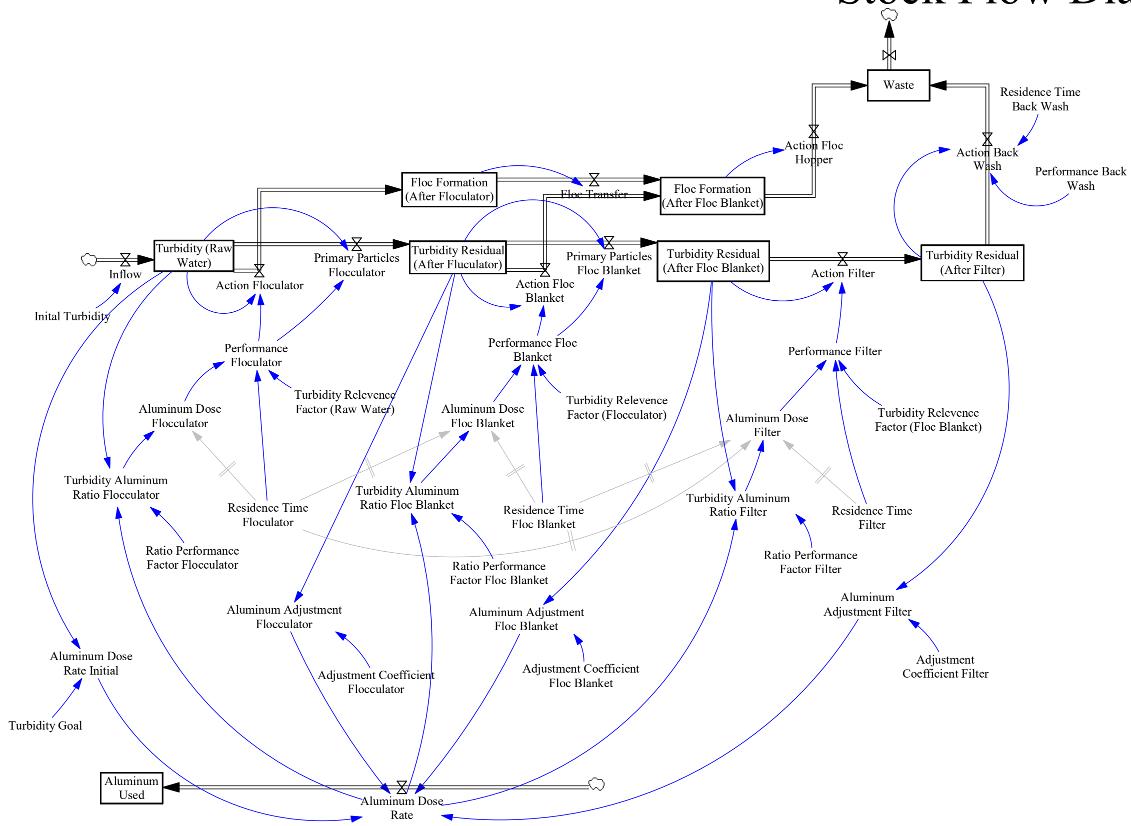
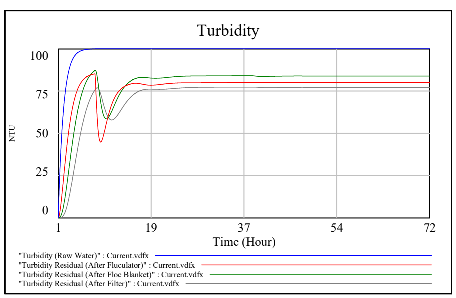
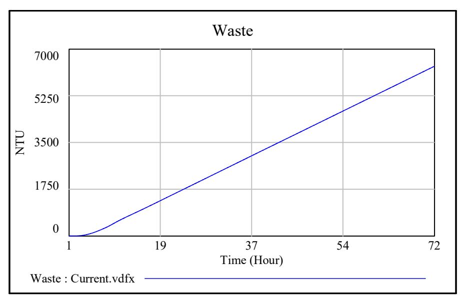
EPA Treatment Guidelines

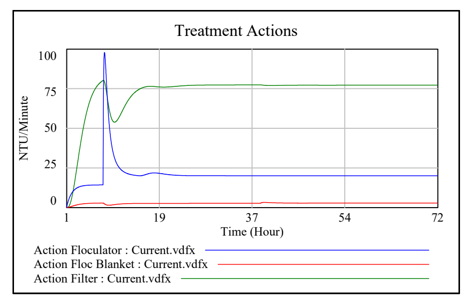
https://www.epa.ie/pubs/advice/drinkingwater/EPA_water_treatment_mgt_coag_flocc_clar2.pdf

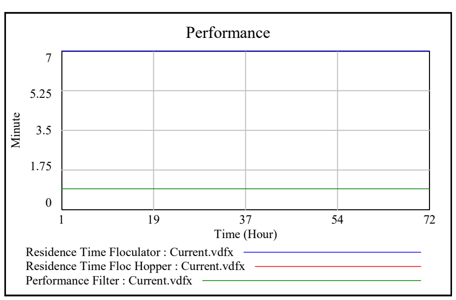
Stock Flow Diagram

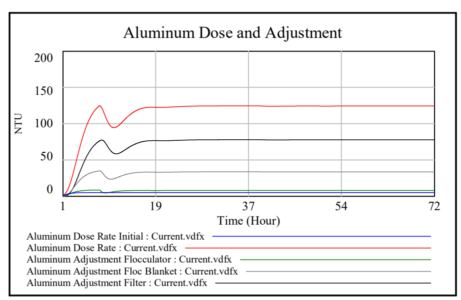


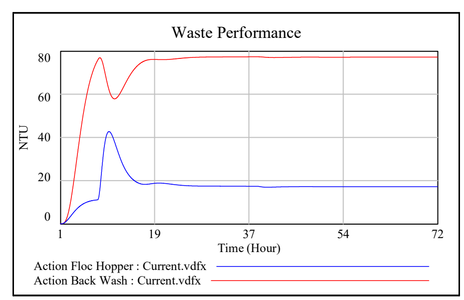












Section 4: An FMEA

A failure mode and effect analysis of a pump-based solution

Abstract

Clean water is a commodity that one out of every three people around the world do not have access to. Even in America, many rural areas struggle to bring safe drinking water to their communities. AguaClara is a gravity-powered water treatment system that purifies raw, unsanitary water into safe drinking water. Abroad, the subsystems used in the AguaClara system function without electricity but require human operators to continue the flow of water through the system. As AguaClara looks to be expanded into rural American communities that have access to electricity, the limiting factor will be the lack of trained, operational staff. AguaClara hopes to address this need by supplementing its gravity-powered treatment system with remote-access control, which requires the need for new electrical components and pumps to operate the system autonomously. In our project, we analyze the risks and potential failures of this new automated AguaClara system. We conducted cause and effect analysis, FMEA, and fault tree analysis and we created digital twins and a failure simulation on our most vulnerable subsystem to understand how the AguaClara system must improve to be successful and reliable in America. Through our analysis, we found that the automated chemical dosing system is the most vulnerable to failure and should be the primary focus of improvements going forward with AguaClara design.

Contents

I. Project Overview

i. Introduction

The project being proposed is a reliability analysis of AguaClara, a resilient, gravity-powered water treatment system specifically the flow-control dosing system, for use in North America. In the 1980s, Dr. Monroe Weber-Shirk, the founder of AguaClara was in Honduras volunteering at refugee camps when he observed that there was no safe drinking water nor any system to provide safe drinking water. Inspired to address this issue and meet the community's needs, Weber-Shirk went back to research the fundamentals of drinking water. After realizing that there were no fundamental physics that truly explained how drinking water works, he made it his mission to understand the physics to come up with an optimal solution. He was joined by a group of students and researchers, and for the past 15 years have worked to create a set of criteria and alternative types of solutions to address the challenge of making safe drinking water accessible. The group has kept the following characteristics in mind:

1. Must be gravity powered so that communities without electricity can use the technology
2. Must be locally sourced, so that the materials are readily available and can be readily replaced
3. Must have as few moving parts as possible to increase the lifespan

If the device breaks, the communities are often unable to afford any specialized equipment necessary to make repairs, thus it is crucial for members of the community to be able maintain and repair without additional capital or specialized expertise. Therefore, the key design criteria have always been user-friendliness where the operators are able to intuitively interact with the system to perform proper maintenance and fault diagnosis encountered. Over the years the AguaClara group with their Honduran partner Agua Para El Pueblo, have researched, published, and implemented a new municipal water treatment train design, based on the fundamental physics that has come out of the AguaClara lab. AguaClara designs now service over 85,000 people in more than 20 plants across India, Honduras, and Nicaragua.

By the summer of 2019, members of the AguaClara team participated in the National Science Foundation Innovation Corps program with the intention of understanding whether AguaClara technologies have a potential market in the United States. Through conducting over 100 interviews in 8 weeks the team was able to determine who would be the first customers, what were their specific pain points, what solutions might they purchase, and what regulatory and financial challenges need to be overcome to build a business.

The team concluded that rural water systems in North America are not robust and provide ease-of-use to operators to maintain, diagnose and resolve system failures. Thus, AguaClara intends to plan out the automatic dosing control system in a pre-packaged plant that will be distributed to rural areas in the United States. This removes the requirement for an operator to not be present while the plant is in operation. Unlike previous designs conducted for Honduras and other locales, this system plans on incorporating the use of electricity. This will introduce the use of pumps and other components not previously considered in failure mode and reliability analyses. This introduces the need for a reliability assessment to obtain verification, so that the system can be marketed and sold for use within the United States. A system view of the AguaClara North America Flow-Control Dosing System can be seen in Figure 1-1.

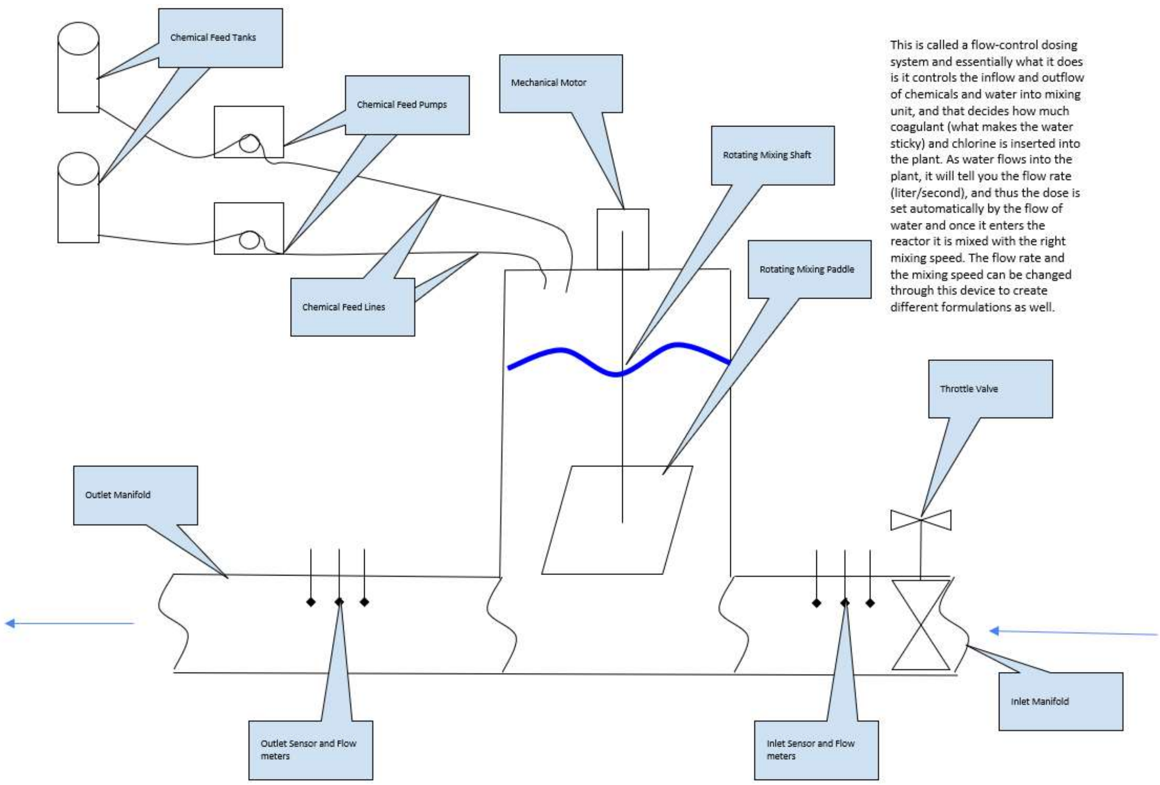


Figure 1-1 AguaClara North America Flow-Control Dosing System Diagram

Given that the primary, driving components in this new design are the electrical pumps and the chemical feed subsystems, the plan is to build a prototype of these two main subsystems and analyze its failure modes, in addition to redoing the analysis on the mixing tank and water flow manifold subsystems. Inclusive of these components planned to be built throughout the semester, an overall system that is the size of an average human adult which can fit on a pallet and serve nearly 500 people, which is equivalent to a flow rate of about one liter per second, will be enabled to be delivered. The timeline and deliverable schedule for this component of project can be seen in Figure 2.

In order to implement the AguaClara systems in the U.S., AguaClara must first receive NSF 61 Approval. NSF 61 outlines a series of system component requirements which are specific to drinking water systems, which Agua Clara creates. According to the NSF 61 website, there are specific requirements for subsystems and components which include, “Protective barrier materials (cements, paints, coatings), Joining and sealing materials (gaskets, adhesives, lubricants), Mechanical devices (water meters, valves, filters), Pipes and related products (pipe, hose, fittings), Plumbing devices (faucets, drinking fountains), Process media (filter media, ion exchange resins), Non-metallic potable water materials.” As part of our Systems reliability analysis, all subsystems and components must be validated to ensure that they meet the NSF 61 requirements for drinkable water safety.

ii. Project Goal

The primary goal for this project will be to understand the reliability of the AguaClara North American system and suggest improvements that will increase its reliability. Given that the U.S. design implementation of the AguaClara system is different from the systems which have been implemented globally previously, several types of Systems reliability testing must be conducted. First, to get an overall understanding of systems and subsystems, fishbone diagrams and FMEA analyses are to be conducted to understand the potential weak points of our overall system. The five subsystems identified are as follows:

1. Grit Removal Subsystem
2. Chemical Dose Subsystem
3. Flocculation Subsystem

4. Sedimentation Subsystem
5. Filtration Subsystem

The team will determine the existing system's process capability and casual relations and identify any variability within the system. Then an evaluation will be done to ascertain the new AguaClara North American design process's capability and identify areas to eliminate and/or reduce failure cases. The Six Sigma approach will be utilized throughout this project to identify, rank, and analyze all potential risks and hazards of the system to improve the design and thus increase the system's reliability. Additionally, all components of each of the five primary subsystems will be assessed to quantify the reliability of the components and ultimately determine the aggregate reliability of the system in its entirety.

iii. Project Schedule

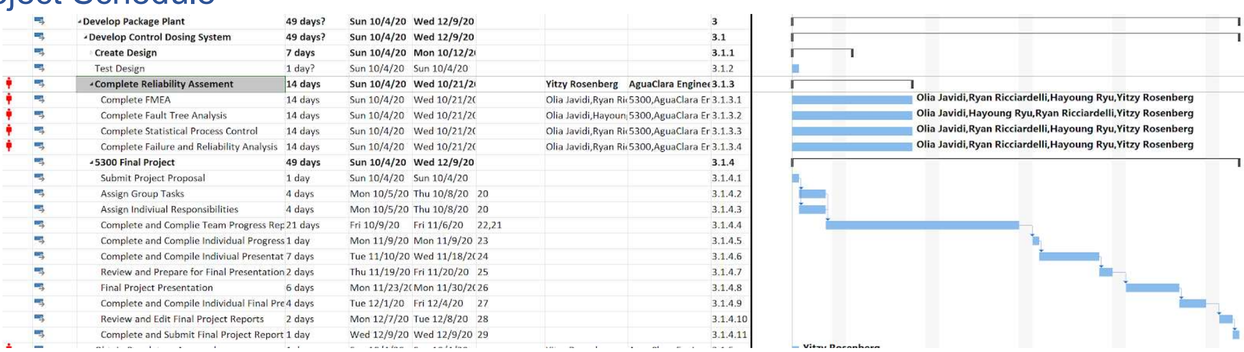


Figure 1-2 AguaClara North America Flow-Control Dosing System Reliability Assessment Timeline

iv. Approach Methodology

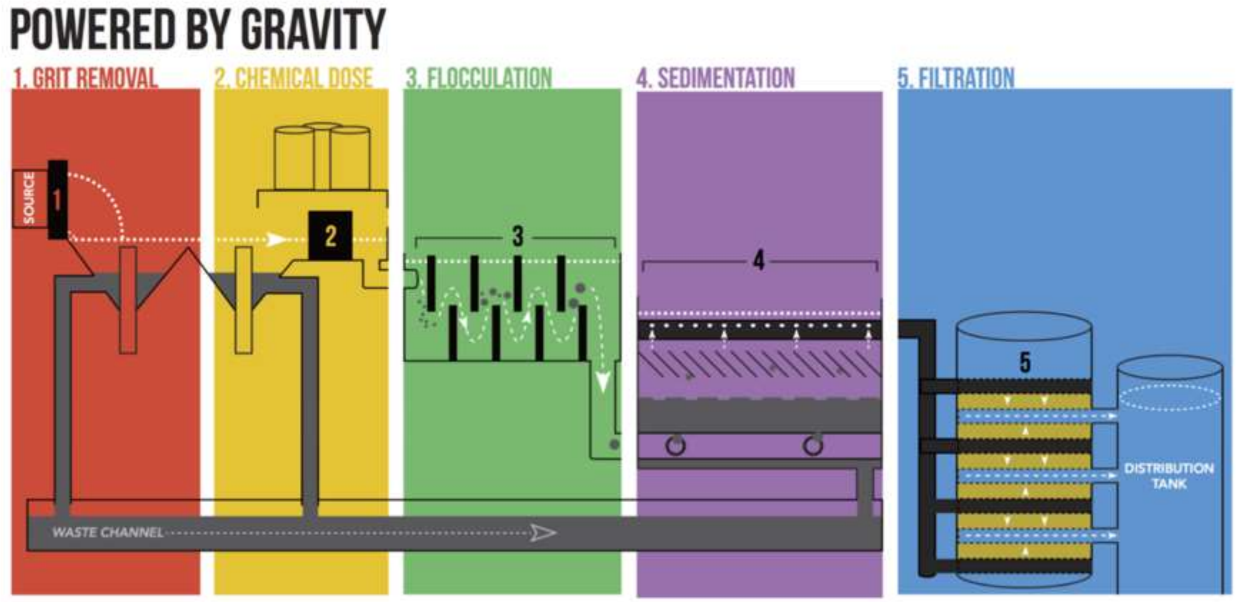


Figure 1-3 AguaClara Process Chart

The approach for this project began with performing a literature review on the conventional water treatment processes and existing AguaClara designs. Following review, the team decided to analyze each primary process of the water treatment system at a macro-level. As discussed previously, these five primary processes are what have been identified subsystems of the AguaClara system. The analysis started with developing detailed network diagrams illustrating the system's overall flow path and total reliability. The purpose of these diagrams was to support the identification of the least reliable components. Additionally, these diagrams are to be leveraged to develop the fault tree diagrams and respective analysis.

To support the development of the Failure Mode and Effects Analysis, the team developed cause-and-effect "fishbone" diagrams for each of the five subsystems.

Calculating Mean-time-to-repair (MTTR) is perhaps the most important analysis for this project. Given that the majority of the components are non-moving constructed out of material such as PVC, rebar, concrete, and corrugated PVC sheets, these components are readily available and simple to repair. However, the pumps, electrical and computational components require specialized maintenance and there should be considered the primary source for extending MTTR.

The following assumptions and simplifications have been made for the analysis of this project:

- The plant is running at the designed flow rate.
- The plant is operated according to standard operations and procedures and therefore we are not analyzing operator induced failures.
- Only structural, mechanical, and electrical failures are considered.
- Failure rates for the implementation procedures like glue/welding pvc fittings will have to be assumed.
- Failure rates for computational components

II. Detailed System Design and Operation

i. Introduction

To analyze where the most vulnerable and influential reliability factors are present in the overall system, we have begun the process of creating two network diagrams. One describes the flow of water through the plant and the other is the critical path that must work in order for the water to be treated. This is represented as nodes in series where if any of the nodes fails then the system fails. There are a few exceptions that must be taken into consideration such as where partial failure occurs the systems performance decreases however the system itself can still function. This is the case with a failed obstacle or baffle in the flocculator. For instance, one design calls for 3 obstacles per baffle spacing and has 19 baffles spacing which means there are 57 obstacles in the flocculator and if one or two were to fail the flocculation subsystem would still work. We therefore have to make an assumption as to how many obstacles have to fail for the flocculator itself to fail. Same goes for how many baffles in the flocculator or how many settling plates in the sedimentation tank. Additionally, this will inform how many extra we should therefore place in each system to improve reliability. See Appendix A for diagrams.

ii. Grit Removal Subsystem

Grit removal is the first stage in the conventional water treatment system. In this stage large debris and surficial organic contaminants are physically separated from the water through a grate or screen at the either the entrance of the plant or the intake of water influent pipe by the water source which is typically a short dam.

The main source of failure is poor operational maintenance. These grates or screens need to be periodically cleaned of debris especially after large rainfall events. If they are not cleaned, they can clog which can create additional pressure on the screen and subsequent pressure on the supporting components.

iii. Chemical Dose (Rapid Mix) Subsystem

Rapid mix is the second stage of the water purification process. In this stage raw water is mixed with various chemicals to achieve the intended quality of treated water. The most important chemical is Poly-Aluminum Chloride (PACl) which acts as a coagulant that coats primary particles allowing them to stick together to each other and eventually settle out and get removed as waste during stages four and five.

This is where the majority of day-to-day operations of plants take place. The operator must set the dosage of the chemicals given the quality of the raw water measured in turbidity (NTU). Currently operators set the dosage using a jar test. For the jar test the operator sets up 5 jars with the raw water and into the first one adds a guesstimate of the optimal dose and plus and minus one and two deviations of the guesstimated dose into the other four jars. The jars are then mixed for 20 minutes and whichever jar has the most settled particles water the operator selects the corresponding dose for the plant.

The current system has an automatic adjuster for the flow rate which reduces the workload on the operator. The system that is currently in development is one that eliminates the need for an operator altogether by setting the dose with a pump and programmed automations that change dosage automatically given raw water quality and treatment performance through the subsequent stages. We expect that this integration of moving parts and electrical components will significantly reduce the mean time to failure and have given a fishbone diagram of this system failure in Figure 2-1. A closer look at potential failure modes gives us 3 additional fishbone diagrams below. We anticipate this reliability assessment will then give us an expected lifespan of the system as a result of this process alone.

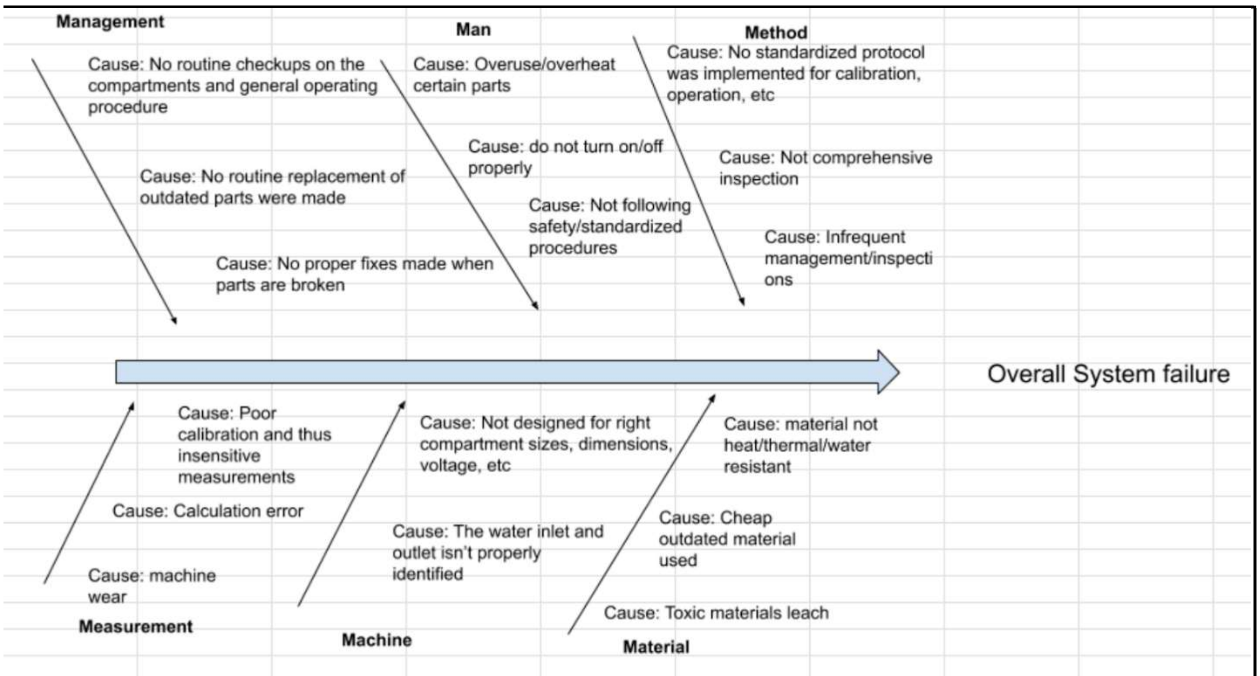


Figure 2-1 Rapid Mix Fishbone Diagram

iv. Flocculation Subsystem

Flocculation is the 3rd stage of the water purification process. In this stage, the inorganic and organic particles in the water aggregate together. Although none of the particles are removed in flocculation, the aggregation of particles–or sticking-together of particles–in the flocculation stage allow for easier purification in later stages. Particle aggregates, or flocs, are formed as the particles collide. Because the particles are suspended in water, the flocs are created as the water collides.

In order to simply and efficiently create collisions, the water flow path goes through a series of baffles, which create sharp corners and turns in the water flow path. In this cross-section view, these turns can be seen clearly and look like switchbacks on a hiking trail. To further maximize collision throughout the water flow path, obstacles are attached to each baffle. These obstacles, shown in Figure 2-6, are half cylinders that are highlighted red. These turns and obstacles force constrictions on the flow of the water inducing a shear that makes the particles collide encouraging floc formation.

In the Flocculation subsystem, the only moving part is the water itself. The baffles and obstacles are made of PVC and themselves are stationary, and thus have low failure rates. However, with many baffles and obstacles positioned in series, it only takes one failure for a baffle or obstacle to shut down the subsystem for maintenance. We still must do research on what the failure rate of each baffle and obstacle are, but once we have that information, we will be able to find the Mean Time to Failure (MMTF) of the Flocculation System by calculating the series failure rate. We have also created a fishbone diagram of potential failures in the Flocculation system, shown in Figure 2-7.

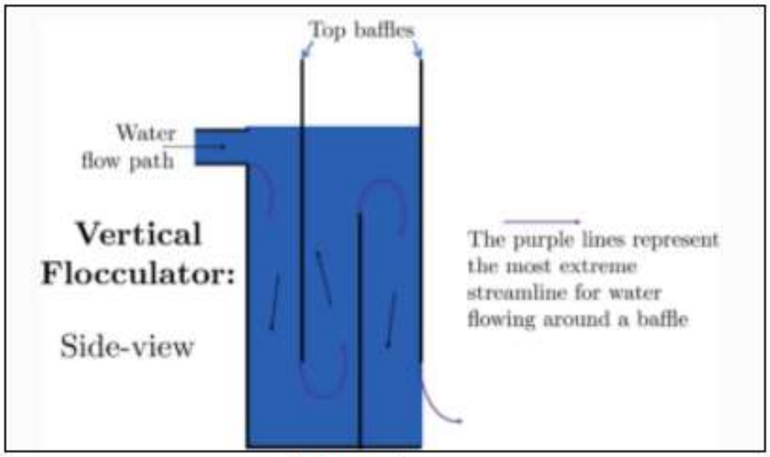


Figure 5

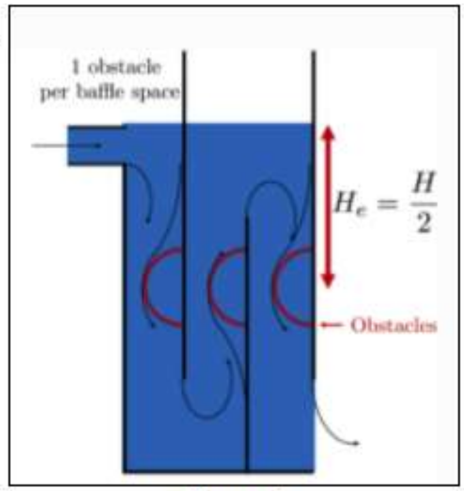


Figure 6

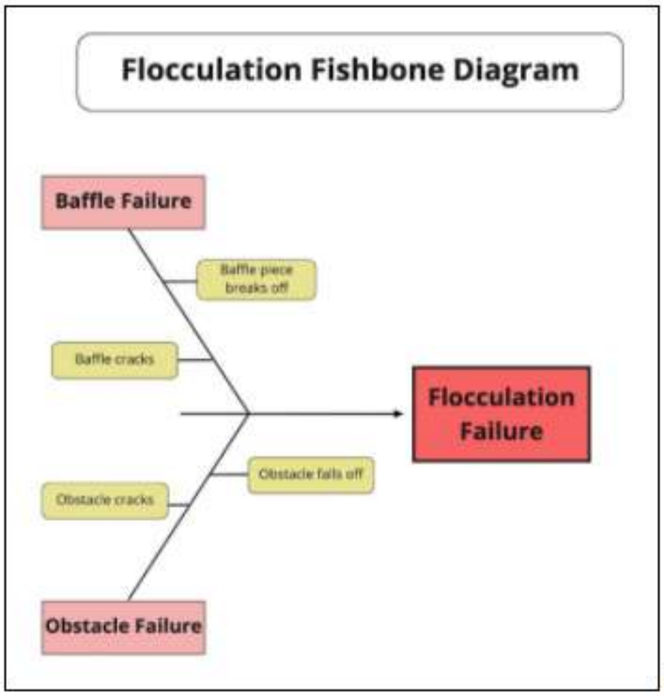


Figure 7

Figure 2-5-7 Flocculation Fishbone Diagram

v. Sedimentation Subsystem

Once the water has moved through the Flocculation system, the particles have now aggregated to large flocs. In the Sedimentation system, those flocs are removed from the water through the sedimentation process. In this process, which is shown in Figure 2-8, water is released downwards at the bottom of a tank from the inlet manifold and diffusers (which release the water downwards). Below the diffusers is a stream of water which creates enough pressure to push clarified water upwards to the top of the tank while keeping a Floc Blanket, or water with a high concentration of flocs, on the bottom of the tank. The Floc Blanket is then accumulated into the Floc Hopper, which further separates the Floc Blanket into Sludge and Water. The ‘sludge’ is emptied from the Floc Hopper through the Hopper Purge Valve. The clarified water is moved through Sedimentation plates which are a series of angled, PVC plates pushed close together which prevent small flocs from re-entering the clarified water. After the clarified water passes through the Sedimentation Plates, it is sent to the Filtration System through the outlet manifold and channel. Below, we show a fishbone diagram of potential failure modes of the sedimentation system.

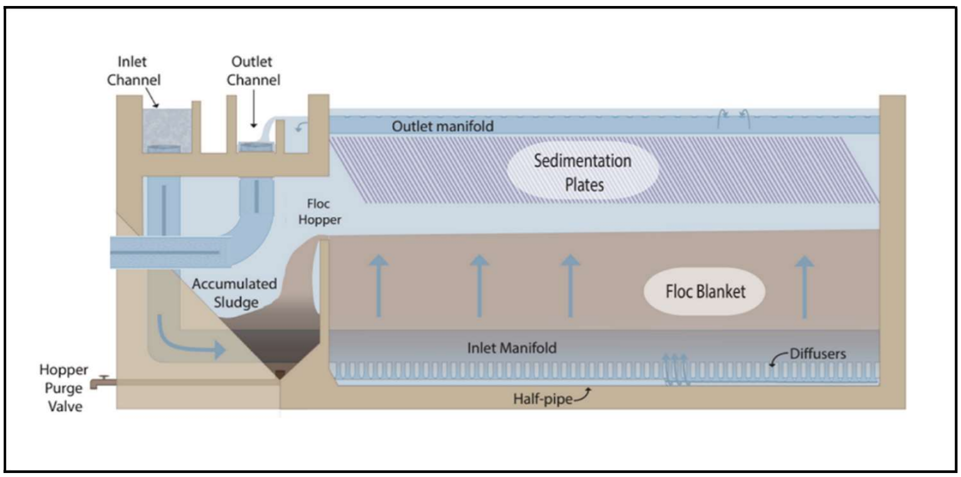


Figure 2-8 Sedimentation Diagram

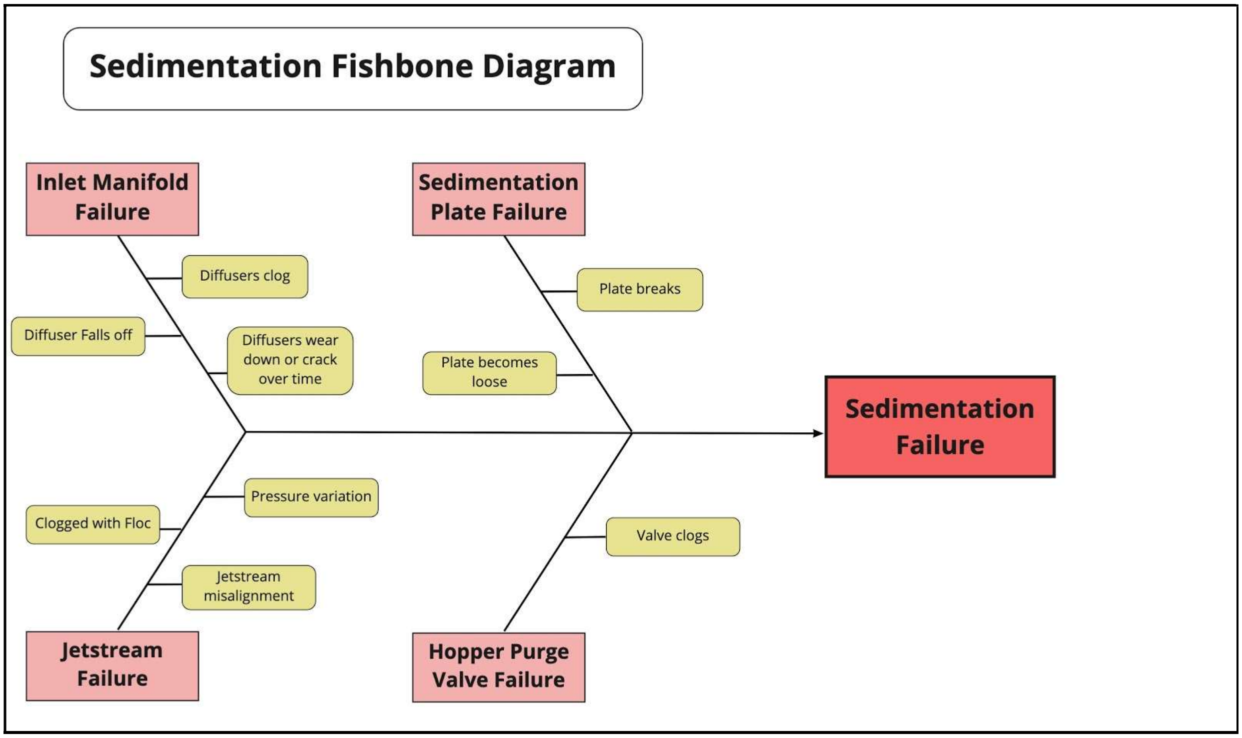


Figure 2-9 Sedimentation Fishbone Diagram

vi. Filtration Subsystem

By the time the water has gone through the sedimentation tank the majority of the primary particles have been converted to flocs large enough to settle out in the floc hopper the remaining primary particle comprise of about .01-10% of the initial NTU. The filtrations stage is the final removal before chlorination, storage, and distribution. The AguaClara Stacked Rapid Sand (StaRS) Filter is entirely gravity powered and requires much less sand surface area and therefore has shorter run times. It works by sandwiching sand in between the 4 influent and 3 effluent pipes creating layers of sand to filter through rather than one large sand filter with one influent and one effluent.

After the sand has been fully saturated with particles (as indicated by an increase in head loss and subsequent rise in water level), a backwash cycle is commenced to wash away all of the particles and clean the sand beds. To accomplish this hydraulically without pumps a siphon, activated by opening an airlock, sucks the water from the lowermost influent pipe effectively fluidizing the sand bed and pulling water and the less dense dirty particles with it while allowing the clean sand to resettle for further filtering. The backwash water is combined with the sedimentation and grit removal waste streams.

The primary sources of failure are all of the PVC connectors and connections such as caps and elbows, the structure itself which is dependent on the materials, and the siphon and its valve. During backwash there are tremendous forces pulling up on the influent and effluent pipes and they have been the source of failure in the past but have since been reinforced with welded steel rods.

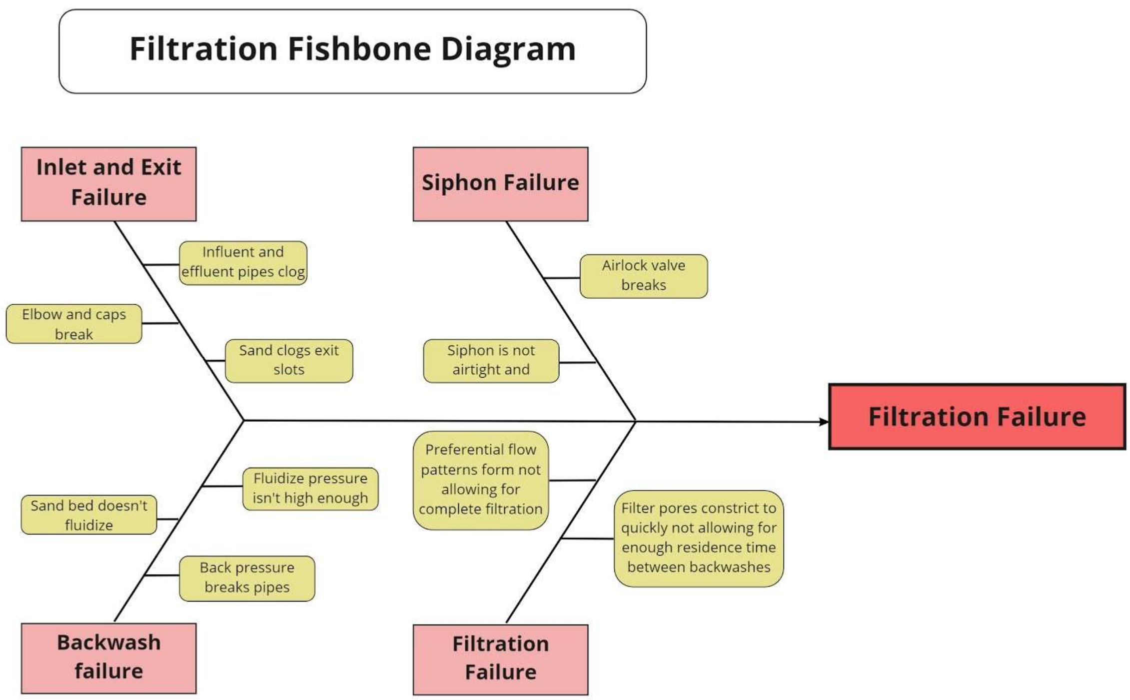


Figure 2-10 Filtration Fishbone Diagram

III. Failure Mode and Effects Analysis [FMEA]

v. Introduction

One of the first steps our team took was to analyze the different failure modes of each subsystem and perform an effects analysis. A failure mode and effects analysis (FMEA) is one of most common system reliability analysis tools. Every system has means by which it can fail, and before one can improve a system's reliability one must understand how it can fail. As will be shown in the subsequent sections, our team analyzed each of the subsystem failures mentioned in Section II and calculated a Risk Priority Number (RPN) based on different criteria ranking values assigned to each failure mode. There were three categories with values rated on a 1-5 scale that each subsystem failure mode was assigned with 1 being least at risk and 5 being most at risk. The three categories are as follows: Severity, Occurrence and Detection.

The RPN is calculated by calculating the product of each category's ranking. The failure mode with the highest RPN value poses the greatest risk to the system and overall mission success. Following calculation of all the subsystems' failure modes RPN values, our team further examined failure modes with the highest risk to identify mitigations and actions to reduce its RPN.

vi. Failure Modes

Table 3-1 details all the subsystem failure modes identified for the AguaClara system.

Subsystem	Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Potential Cause(s) / Mechanism(s) of Failure	Current Design Controls
Doser	SCADA/ Electronic auto-response system	Auto-responses not working appropriately	Chemicals mixed with incorrect proportions, or potentially not mixed at all	The automation set up improperly, software bug	No current design control in place to detect without component shutdown or failure
Doser	Chemical Feedline	Chemical Feed line stopped	Spilling chemicals (Chlorine)	Feed line is clogged	Clear tubing for easier visual inspections, alerts in SCADA reporting system
Doser	Outlet Sensor/s	Outlet sensors broken	Unable to sense pH, color, etc of the resultant water supply	Sensors wear due to aging	Alerts in SCADA system. Emergency shutoff
Doser	Inlet Sensor/s	Inlet sensors broken	Unable to sense pH, color, etc of the incoming water supply	Sensors wear due to aging (sensitivity goes down)	Alerts in SCADA system.

					Emergency shutoff
Doser	Chemical Pump/s	Chemical Pump not calibrated	Incorrect measurements of chemical dosage	Calibration Error	Legally mandated inspections and calibration on daily, monthly, and annual timescales.
Doser	Flow meter/s	Flow meter not calibrated	Unit mixing improperly and water being treated incorrectly	Calibration error	Alerts in SCADA system. Emergency shutoff
Doser	Mechanical Mixer	Mechanical Mixer broken	The chemical substances do not mix homogenously with water	Motor dysfunction, battery drainage	Alerts in SCADA system. Emergency shutoff
Doser	Throttle Valve/s	Throttle valve jammed	Mix unit is not working at capacity	Debris, rust, wear and tear, aging, deteriorating gaskets	No current design control in place to detect without component shutdown or failure
Doser	Inlet / outlet piping	Clogged inlet or outlet	Outlet: Mix unit to fill up all the way and overflow & Inlet; no flow into the system	Throttle valve jammed; Blockage due to debris	Alerts in SCADA system cross reference flow metering
Doser	Mix Tank/s	Overflow mix tanks	The mix unit would fill and potentially spill over	more water enters the tank than can exit. Blockage, or constricted outflow	Overflow auto-shutoff
Doser	Chemical Tank/s	Overflow chemical tanks	The chemical tanks would fill up and potentially spill over	Pumps weren't allowing for enough outflow. Clogged chemical feed lines	No current design control in place to detect without component shutdown or failure

Flocculation	Baffle	Crack in baffle	The water would spill over or out, and not go through all the necessary channels to create the necessary level of flocs	Wear and tear, or debris gets into Flocculator and causes cracks	Alerts in SCADA system cross reference flow metering
Flocculation	Baffle	Baffle component breaks off	The water would spill over or out, and not go through all the necessary channels to create the necessary level of flocs	Wear and tear, or debris gets into Flocculator and causes cracks	Alerts in SCADA system cross reference flow metering
Flocculation	Obstacle	Crack in Obstacle	The water would spill over or out, and not go through all the necessary channels to create the necessary level of flocs	Wear and tear, or debris gets into Flocculator and causes cracks	Alerts in SCADA system cross reference flow metering
Flocculation	Obstacle	Obstacle component breaks off	The water would spill over or out, and not go through all the necessary channels to create the necessary level of flocs	Wear and tear, or debris gets into Flocculator and causes cracks	Alerts in SCADA system cross reference flow metering
Sedimentation	Inlet Manifold	Diffusers clog	Water will not be released properly and more pressure e on remaining diffusers to release water	Debris, rust, wear and tear, aging, deteriorating gaskets	Alerts in SCADA system cross reference flow metering
Sedimentation	Inlet Manifold	Diffuser breaks off	Water will not be released properly and more pressure on remaining diffusers to release water	Debris, rust, wear and tear, aging, deteriorating gaskets	Alerts in SCADA system cross reference flow metering
Sedimentation	Inlet Manifold	Diffuser cracks	Water will not be released properly and more pressure on remaining	Debris, rust, wear and tear, aging, deteriorating gaskets	Alerts in SCADA system cross reference flow metering

			diffusers to release water		
Sedimentation	Jetstream	Pressure Variation	Clarified water does not reach top of tank to pass through sedimentation plates	Calibration Error	Alerts in SCADA system cross reference flow metering
Sedimentation	Jetstream	Clogged with Floc	Clarified water does not reach top of tank to pass through sedimentation plates	Calibration Error or Hopper Purge Valve malfunction	Alerts in SCADA system cross reference flow metering
Sedimentation	Jetstream	Jetstream Misalignment	Clarified water does not reach top of tank to pass through sedimentation plates	Calibration Error	Alerts in SCADA system cross reference flow metering
Sedimentation	Sedimentation Plate	Plate breaks	Allows increased rate of small flocs enter into outlet manifold	Debris, wear and tear, aging	Alerts in SCADA system cross reference flow metering
Sedimentation	Sedimentation Plate	plate becomes loose	Allows increased rate of small flocs enter into outlet manifold	Fastenings wear and tear, aging	Alerts in SCADA system cross reference flow metering
Sedimentation	Hopper Purge Valve	Valve clog	Sludge fills up jetsteam and sedimentation container	Debris, rust, wear and tear, aging, deteriorating gaskets	Alerts in SCADA system cross reference flow metering Manual inspection
Filtration	Inlet and Exit Pipe	Elbow or End Cap breaks	Water spill and Filtration process is halted or reduced	Above specification pressure in pipes	Alerts in SCADA system cross reference flow metering Manual inspection
Filtration	Inlet and Exit Pipe	Influent or effluent pipe clog	Filtration process is halted or reduced	Debris and excess floc in water	Alerts in SCADA system cross reference flow metering Manual inspection

Filtration	Inlet and Exit Pipe	Sand fills exit slots and clogs them	Filtration process is halted or reduced	Excess floc in water	Alerts in SCADA system cross reference flow metering Manual inspection
Filtration	Backwash Prevention	Sand bed does not fluidize	Dirty particles will not be removed, and filtration process will be degraded	Preferential flow occurs	Alerts in SCADA system cross reference flow metering Manual inspection
Filtration	Backwash Prevention	Backwash pressure bursts pipes	Water spill and Filtration process is halted or reduced	Blockages in pipes or poor joint fittings	Alerts in SCADA system cross reference flow metering Manual inspection
Filtration	Backwash Prevention	Fluidize pressure is not high enough	Dirty particles will not be removed, and filtration process will be degraded	Not enough water height differential to drive water through the sand fast enough (e.g. not enough water in plant due to water source dried up)	Alerts in SCADA system cross reference flow metering Manual inspection
Filtration	Siphon	Airlock valve breaks	Pressure is released and water cannot travel through the pipes	Fastenings wear and tear, aging	Alerts in SCADA system cross reference flow metering Manual inspection
Filtration	Siphon	Siphon not sealed properly	Pressure is released and water cannot travel through the pipes	Manual error, Siphon seal wear and tear, aging	Alerts in SCADA system cross reference flow metering Manual inspection
Filtration	Filter	Preferential flow patterns form do not allow for complete filtration	Improper filtration	Not enough pressure, non-uniform sand particle sizes, blockage in the sand bed	Alerts in SCADA system cross reference flow metering Manual inspection

Filtration	Filter	Filter pores constrict quickly not allowing for enough residence time between backwashes	Improper filtration	Sediment build-up or blockage. Non-uniform sand particle sizes	Alerts in SCADA system cross reference flow metering Manual inspection

Table 3-1 - Subsystem Failure Modes

vii. Risk Priority Number (RPN) of Failure Modes

This section will attempt to prioritize the failure modes identified based on their effects and likelihood of occurrence. The method that will be utilized is one of the most commonly used, and that is the Risk Priority Number (RPN). As stated previously, the RPN is calculated as the product of the ranking assign to each of the following factors:

- Severity Ranking
- Occurrence Ranking
- Detection Ranking

The subsequent subsections present the ranking guidelines for each of the RPN factors mentioned.

a. Severity of Failure Modes

Before the effect(s) of each failure mode can be given a severity score, guidelines for how said ranking must be established. Table 3-2 describes the criteria for each given severity ranking.

Rank	Criteria
1	Machine breakdown or degraded performance
2	Complete or partial system failure, or breakdown leading to major nuisance e.g. extreme noise, but no injury, fire, or leakage
3	Mild injuries, small fires, minor leakages of gas, hydrogen, etc.
4	Severe injury, major component damage due to fire, rupture, etc.
5	Loss of human life, or total or near-total loss of the facility

Table 3-2 Severity Ranking Guidelines

Utilizing the severity ranking table, severity rankings were given to the identified failure modes, seen in Table 3-3. The severity ranking was applied using prior knowledge and experience working with existing AguaClara systems.

Subsystem	Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity

Doser	SCADA/ Electronic auto-response system	Auto-responses not working appropriately	Chemicals mixed with incorrect proportions, or potentially not mixed at all	2
Doser	Chemical Feedline	Chemical Feed line stopped	Spilling chemicals (Chlorine)	3
Doser	Outlet Sensor/s	Outlet sensors broken	Unable to sense pH, color, etc of the resultant water supply	3
Doser	Inlet Sensor/s	Inlet sensors broken	Unable to sense pH, color, etc of the incoming water supply	2
Doser	Chemical Pump/s	Chemical Pump not calibrated	Incorrect measurements of chemical dosage	2
Doser	Flow meter/s	Flow meter not calibrated	Unit mixing improperly and water being treated incorrectly	2
Doser	Mechanical Mixer	Mechanical Mixer broken	The chemical substances do not mix homogenously with water	2
Doser	Throttle Valve/s	Throttle valve jammed	Mix unit is not working at capacity	2
Doser	Inlet / outlet piping	Clogged inlet or outlet	Outlet: Mix unit to fill up all the way and overflow & Inlet; no flow into the system	2

Doser	Mix Tank/s	Overflow mix tanks	The mix unit would fill and potentially spill over	2
Doser	Chemical Tank/s	Overflow chemical tanks	The chemical tanks would fill up and potentially spill over	3
Flocculation	Baffle	Crack in baffle	The water would spill over or out, and not go through all the necessary channels to create the necessary level of flocs	2
Flocculation	Baffle	Baffle component breaks off	The water would spill over or out, and not go through all the necessary channels to create the necessary level of flocs	1
Flocculation	Obstacle	Crack in Obstacle	The water would spill over or out, and not go through all the necessary channels to create the necessary level of flocs	2
Flocculation	Obstacle	Obstacle component breaks off	The water would spill over or out, and not go through all the necessary channels to create the necessary level of flocs	1
Sedimentation	Inlet Manifold	Diffusers clog	Water will not be released properly and more pressure e on remaining diffusers to release water	2

Sedimentation	Inlet Manifold	Diffuser breaks off	Water will not be released properly and more pressure on remaining diffusers to release water	1
Sedimentation	Inlet Manifold	Diffuser cracks	Water will not be released properly and more pressure on remaining diffusers to release water	1
Sedimentation	Jetstream	Pressure Variation	Clarified water does not reach top of tank to pass through sedimentation plates	2
Sedimentation	Jetstream	Clogged with Floc	Clarified water does not reach top of tank to pass through sedimentation plates	2
Sedimentation	Jetstream	Jetstream Misalignment	Clarified water does not reach top of tank to pass through sedimentation plates	2
Sedimentation	Sedimentation Plate	Plate breaks	Allows increased rate of small flocs enter into outlet manifold	1
Sedimentation	Sedimentation Plate	plate becomes loose	Allows increased rate of small flocs enter into outlet manifold	1
Sedimentation	Hopper Purge Valve	Valve clog	Sludge fills up jetsteam and sedimentation container	2
Filtration	Inlet and Exit Pipe	Elbow or End Cap breaks	Water spill and Filtration process is halted or reduced	2

Filtration	Inlet and Exit Pipe	Influent or effluent pipe clog	Filtration process is halted or reduced	2
Filtration	Inlet and Exit Pipe	Sand fills exit slots and clogs them	Filtration process is halted or reduced	2
Filtration	Backwash Prevention	Sand bed does not fluidize	Dirty particles will not be removed, and filtration process will be degraded	2
Filtration	Backwash Prevention	Backwash pressure bursts pipes	Water spill and Filtration process is halted or reduced	2
Filtration	Backwash Prevention	Fluidize pressure is not high enough	Dirty particles will not be removed, and filtration process will be degraded	2
Filtration	Siphon	Airlock valve breaks	Pressure is released and water cannot travel through the pipes	2
Filtration	Siphon	Siphon not sealed properly	Pressure is released and water cannot travel through the pipes	2

Filtration	Filter	Preferential flow patterns form do not allow for complete filtration	Improper filtration	1
Filtration	Filter	Filter pores constrict quickly not allowing for enough residence time between backwashes	Improper filtration	1

Table 3-3 AguaClara Failure Mode Severity Rankings

b. Occurrence of Failure Modes

Next, the potential root causes of each failure mode are to be given an occurrence score, which is a scale of the frequency with which each cause of failure occurs. Table 3-4 provides the scale used for the occurrence rankings.

Rank	Criteria
1	Once in 50 years
2	Once in 10 years
3	Once in 5 years
4	Once per year
5	Once per month

Table 3-4 Occurrence Ranking Guidelines

Utilizing the occurrence ranking table, occurrence rankings were given to the identified failure modes, seen in Table 3-5. The occurrence ranking was applied using prior knowledge and experience working with existing AguaClara systems.

Subsystem	Item / Function	Potential Failure Mode	Potential Cause(s) / Mechanism(s) of Failure	Occurrence
Doser	SCADA/ Electronic auto-response system	Auto-responses not working appropriately	The automation set up improperly, software bug	4

Doser	Chemical Feedline	Chemical Feed line stopped	Feed line is clogged	4
Doser	Outlet Sensor/s	Outlet sensors broken	Sensors wear due to aging	3
Doser	Inlet Sensor/s	Inlet sensors broken	Sensors wear due to aging (sensitivity goes down)	3
Doser	Chemical Pump/s	Chemical Pump not calibrated	Calibration Error	5
Doser	Flow meter/s	Flow meter not calibrated	Calibration error	5
Doser	Mechanical Mixer	Mechanical Mixer broken	Motor dysfunction, battery drainage	4
Doser	Throttle Valve/s	Throttle valve jammed	Debris, rust, wear and tear, aging, deteriorating gaskets	2
Doser	Inlet / outlet piping	Clogged inlet or outlet	Throttle valve jammed; Blockage due to debris	4
Doser	Mix Tank/s	Overflow mix tanks	more water enters the tank than can exit. Blockage, or constricted outflow	3
Doser	Chemical Tank/s	Overflow chemical tanks	Pumps were not allowing for enough outflow. Clogged chemical feed lines	1
Flocculation	Baffle	Crack in baffle	Wear and tear, or debris gets into Flocculator and causes cracks	2

Flocculation	Baffle	Baffle component breaks off	Wear and tear, or debris gets into Flocculator and causes cracks	2
Flocculation	Obstacle	Crack in Obstacle	Wear and tear, or debris gets into Flocculator and causes cracks	2
Flocculation	Obstacle	Obstacle component breaks off	Wear and tear, or debris gets into Flocculator and causes cracks	2
Sedimentation	Inlet Manifold	Diffusers clog	Debris, rust, wear and tear, aging, deteriorating gaskets	2
Sedimentation	Inlet Manifold	Diffuser breaks off	Debris, rust, wear and tear, aging, deteriorating gaskets	2
Sedimentation	Inlet Manifold	Diffuser cracks	Debris, rust, wear and tear, aging, deteriorating gaskets	2
Sedimentation	Jetstream	Pressure Variation	Calibration Error	4
Sedimentation	Jetstream	Clogged with Floc	Calibration Error or Hopper Purge Valve malfunction	3
Sedimentation	Jetstream	Jetstream Misalignment	Calibration Error	4
Sedimentation	Sedimentation Plate	Plate breaks	Debris, wear and tear, aging	2

Sedimentation	Sedimentation Plate	plate becomes loose	Fastenings wear and tear, aging	3
Sedimentation	Hopper Purge Valve	Valve clog	Debris, rust, wear and tear, aging, deteriorating gaskets	2
Filtration	Inlet and Exit Pipe	Elbow or End Cap breaks	Above specification pressure in pipes	4
Filtration	Inlet and Exit Pipe	Influent or effluent pipe clog	Debris and excess floc in water	4
Filtration	Inlet and Exit Pipe	Sand fills exit slots and clogs them	Excess floc in water	4
Filtration	Backwash Prevention	Sand bed does not fluidize	Preferential flow occurs	3
Filtration	Backwash Prevention	Backwash pressure bursts pipes	Blockages in pipes or poor joint fittings	2
Filtration	Backwash Prevention	Fluidize pressure is not high enough	Not enough water height differential to drive water through the sand fast enough (e.g. not enough water in plant due to water	1

			source dried up)	
Filtration	Siphon	Airlock valve breaks	Fastenings wear and tear, aging	3
Filtration	Siphon	Siphon not sealed properly	Manual error, Siphon seal wear and tear, aging	4
Filtration	Filter	Preferential flow patterns form do not allow for complete filtration	Not enough pressure, non-uniform sand particle sizes, blockage in the sand bed	4
Filtration	Filter	Filter pores constrict quickly not allowing for enough residence time between backwashes	Sediment build-up or blockage. Non-uniform sand particle sizes	4

Table 3-5 AguaClara Failure Mode Occurrence Rankings

c. Detection of Failure Modes

The last RPN factor to be ranked is the Detection measure, which is the chance that the failure will be detected before It affects the customer. Table 3.6 describes the scoring criteria for the detection measure ranking.

Rank	Criteria
1	Easily detected in middle of normal activities, e.g. operator hears an unusual noise coming from failed component and detects failure
2	Detected with regular inspections that are easy to carry out by ordinary on-site staff
3	Visit by manufacturer's representative with specialized technical expertise required to detect, but major shutdown of component not required

4	Extensive shutdown of component required to detect failure
5	No detection possible since failure is triggered instantaneously

Table 3. 6 Detection Ranking Guidelines

Utilizing the detection ranking table, detection measure rankings were given to the identified failure modes, seen in Table 3.7. The detection ranking was applied using prior knowledge and experience working with existing AguaClara systems.

Subsystem	Item / Function	Potential Failure Mode	Current Design Controls	Detection
Doser	SCADA/ Electronic auto-response system	Auto-responses not working appropriately	No current design control in place to detect without component shutdown or failure	4
Doser	Chemical Feedline	Chemical Feed line stopped	Clear tubing for easier visual inspections, alerts in SCADA reporting system	2
Doser	Outlet Sensor/s	Outlet sensors broken	Alerts in SCADA system. Emergency shutoff	2
Doser	Inlet Sensor/s	Inlet sensors broken	Alerts in SCADA system. Emergency shutoff	2
Doser	Chemical Pump/s	Chemical Pump not calibrated	Legally mandated inspections and calibration on daily, monthly, and annual timescales.	1

Doser	Flow meter/s	Flow meter not calibrated	Alerts in SCADA system. Emergency shutoff	1
Doser	Mechanical Mixer	Mechanical Mixer broken	Alerts in SCADA system. Emergency shutoff	1
Doser	Throttle Valve/s	Throttle valve jammed	No current design control in place to detect without component shutdown or failure	2
Doser	Inlet / outlet piping	Clogged inlet or outlet	Alerts in SCADA system cross reference flow metering	1
Doser	Mix Tank/s	Overflow mix tanks	Overflow auto-shutoff	1
Doser	Chemical Tank/s	Overflow chemical tanks	No current design control in place to detect without component shutdown or failure	1
Flocculation	Baffle	Crack in baffle	Alerts in SCADA system cross reference flow metering	1
Flocculation	Baffle	Baffle component breaks off	Alerts in SCADA system cross reference flow metering	1

Flocculation	Obstacle	Crack in Obstacle	Alerts in SCADA system cross reference flow metering	1
Flocculation	Obstacle	Obstacle component breaks off	Alerts in SCADA system cross reference flow metering	1
Sedimentation	Inlet Manifold	Diffusers clog	Alerts in SCADA system cross reference flow metering	1
Sedimentation	Inlet Manifold	Diffuser breaks off	Alerts in SCADA system cross reference flow metering	1
Sedimentation	Inlet Manifold	Diffuser cracks	Alerts in SCADA system cross reference flow metering	1
Sedimentation	Jetstream	Pressure Variation	Alerts in SCADA system cross reference flow metering	1
Sedimentation	Jetstream	Clogged with Floc	Alerts in SCADA system cross reference flow metering	1
Sedimentation	Jetstream	Jetstream Misalignment	Alerts in SCADA system cross reference flow metering	1
Sedimentation	Sedimentation Plate	Plate breaks	Alerts in SCADA system cross reference flow metering	1
Sedimentation	Sedimentation Plate	plate becomes loose	Alerts in SCADA system cross reference flow metering	1

Sedimentation	Hopper Purge Valve	Valve clog	Alerts in SCADA system cross reference flow metering Manual inspection	1
Filtration	Inlet and Exit Pipe	Elbow or End Cap breaks	Alerts in SCADA system cross reference flow metering Manual inspection	1
Filtration	Inlet and Exit Pipe	Influent or effluent pipe clog	Alerts in SCADA system cross reference flow metering Manual inspection	1
Filtration	Inlet and Exit Pipe	Sand fills exit slots and clogs them	Alerts in SCADA system cross reference flow metering Manual inspection	1
Filtration	Backwash Prevention	Sand bed does not fluidize	Alerts in SCADA system cross reference flow metering Manual inspection	1
Filtration	Backwash Prevention	Backwash pressure bursts pipes	Alerts in SCADA system cross reference flow metering Manual inspection	1
Filtration	Backwash Prevention	Fluidize pressure is not high enough	Alerts in SCADA system cross reference flow metering Manual inspection	1

Filtration	Siphon	Airlock valve breaks	Alerts in SCADA system cross reference flow metering Manual inspection	1
Filtration	Siphon	Siphon not sealed properly	Alerts in SCADA system cross reference flow metering Manual inspection	1
Filtration	Filter	Preferential flow patterns form do not allow for complete filtration	Alerts in SCADA system cross reference flow metering Manual inspection	1
Filtration	Filter	Filter pores constrict quickly not allowing for enough residence time between backwashes	Alerts in SCADA system cross reference flow metering Manual inspection	1

Table 3-7 AguaClara Failure Mode Detection Rankings

d. RPN Calculations

Now that all factors for each failure mode have been ranked, the RPN value can be calculated.

The resulting RPN value for each failure mode is given in Table 3.8.

Subsystem	Item / Function	Potential Failure Mode	Severity	Occurrence	Detection	RPN
Doser	SCADA/ Electronic auto-response system	Auto-responses not working appropriately	2	4	4	32

Doser	Chemical Feedline	Chemical Feed line stopped	3	4	2	24
Doser	Outlet Sensor/s	Outlet sensors broken	3	3	2	18
Doser	Inlet Sensor/s	Inlet sensors broken	2	3	2	12
Doser	Chemical Pump/s	Chemical Pump not calibrated	2	5	1	10
Doser	Flow meter/s	Flow meter not calibrated	2	5	1	10
Doser	Mechanical Mixer	Mechanical Mixer broken	2	4	1	8
Doser	Throttle Valve/s	Throttle valve jammed	2	2	2	8
Doser	Inlet / outlet piping	Clogged inlet or outlet	2	4	1	8
Doser	Mix Tank/s	Overflow mix tanks	2	3	1	6
Doser	Chemical Tank/s	Overflow chemical tanks	3	1	1	3

Flocculation	Baffle	Crack in baffle	2	2	1	4
Flocculation	Baffle	Baffle component breaks off	1	2	1	2
Flocculation	Obstacle	Crack in Obstacle	2	2	1	4
Flocculation	Obstacle	Obstacle component breaks off	1	2	1	2
Sedimentation	Inlet Manifold	Diffusers clog	2	2	1	4
Sedimentation	Inlet Manifold	Diffuser breaks off	1	2	1	2
Sedimentation	Inlet Manifold	Diffuser cracks	1	2	1	2
Sedimentation	Jetstream	Pressure Variation	2	4	1	8
Sedimentation	Jetstream	Clogged with Floc	2	3	1	6

Sedimentation	Jetstream	Jetstream Misalignment	2	4	1	8
Sedimentation	Sedimentation Plate	Plate breaks	1	2	1	4
Sedimentation	Sedimentation Plate	plate becomes loose	1	3	1	3
Sedimentation	Hopper Purge Valve	Valve clog	2	2	1	4
Filtration	Inlet and Exit Pipe	Elbow or End Cap breaks	2	4	1	8
Filtration	Inlet and Exit Pipe	Influent or effluent pipe clog	2	4	1	8
Filtration	Inlet and Exit Pipe	Sand fills exit slots and clogs them	2	4	1	8
Filtration	Backwash Prevention	Sand bed does not fluidize	2	3	1	6
Filtration	Backwash Prevention	Backwash pressure bursts pipes	2	2	1	4

Filtration	Backwash Prevention	Fluidize pressure is not high enough	2	1	1	2
Filtration	Siphon	Airlock valve breaks	2	3	1	6
Filtration	Siphon	Siphon not sealed properly	2	4	1	8
Filtration	Filter	Preferential flow patterns form do not allow for complete filtration	1	4	1	4
Filtration	Filter	Filter pores constrict quickly not allowing for enough residence time between backwashes	1	4	1	4

Table 3-8 AguaClara Failure Mode RPN Calculations

Upon further evaluation of the failure modes and their respective RPN values, it is believed the maximum acceptable value for RPN is 12. The reason is we want 90% coverage for failure modes, so maximum acceptable RPN value is (125) - (125) (.9) = 12 (rounded down). Given that reasoning, the following failure modes in the Chemical Doser subsystem exceed the acceptable value and likely need to be remedied:

- SCADA/Electronic auto-response system
- Chemical Feedline

- Outlet Sensor(s)

Note: The full Failure Modes and Effect Analysis (FMEA) worksheet can be found in the Appendix B.

viii. Action Results

For each of the top 3 failure mode, corrective actions were recommended and examined, resulting in updated Severity-Occurrence-Detection rankings. Thereafter, new RPN values were recalculated for the top three failure modes analyzed in this section.

System - Failure Mode	Severity	Occurrence	Detection	New RPN Value
SCADA auto-responses not working appropriately	**Current: 2** **New: 2** **Corrective Action(s):** • Insert mechanical interlock to stop chemical mixing and dosing process if software communications are lost	**Current: 4** **New: 2** **Corrective Action(s):** • Monthly training for operators • Operator oversight • Manufacturing quality assurance	**Current: 4** **New: 2** **Corrective Action(s):** •Standardized inspection operations • Upfront investment for detection • Instrumentation: gauges, alert system, multimeter etc. • Team dedicated to performing routine maintenance and calibration	Current RPN: 32 New RPN: 6
Chemical Feed line stopped	**Current: 3** **New: 2** **Corrective Action(s):** • Insert sensor to detect clogged chemical feed line • Insert mechanical interlock to stop chemical mixing and dosing process if critical fault detected in chemical feed line	**Current: 4** **New: 2** **Corrective Action(s):** • Monthly training for operators • Operator oversight • Manufacturing quality assurance • Standardized clog inspection	**Current: 2** **New: 1** **Corrective Action(s):** • Insert sensor to detect clogged chemical feed line • Daily gauge inspection • Alert system for significant pressure/flow changes • Large user-friendly display of pressure/flow • Routinely unclog/renew chemical feed lines	Current RPN: 24 New RPN: 4
Outlet sensors broken	**Current: 3** **New: 2** **Corrective Action(s):** • Insert mechanical interlock to stop chemical mixing and dosing process if critical fault detected beyond range of acceptable sensor values of incoming water supply	**Current: 3** **New: 2** **Corrective Action(s):** • Monthly training for operators • Operator oversight • Manufacturing quality assurance	**Current: 2** **New: 2** **Corrective Action(s):** • Routine sensory sensitivity check using supplemental instrumentation equipment component check • Team dedicated to performing routine maintenance and calibration	Current RPN: 18 New RPN: 6

Table 3-9 Top Failure Modes Corrective Actions and Updated RPN Values

As seen in the table, the RPN values for the top three failure modes were all able to be significantly reduced using the corrective actions listed.

IV. Fault Tree Analysis

i. Fault Tree and Digital Twin Analysis

We created a fault tree that represents the current flow through the plant. This fault tree represents all the components the water will encounter as it travels through each subsystem. We factored them on an essential use basis, where the overall diagram represents what must be working. If any one of these components fails, the system itself will fail. The exception is with subcomponents that while not redundant if one fails the efficiency of the system is reduced through operational. An example would be an obstacle in the flocculator, where if one obstacle fails the system will not fail but the flocculation performance would be reduced. Our redundancy factors were then calculated as in parallel failure rates rather than in series failure rates. This means that components whose quantity is considered to be in parallel have a much greater overall mean time to failure.

This is an incomplete and imperfect digital twin of an AguaClara treatment system. It helps determine what components are most failure-prone and what that can do to an overall system. As the research and the final product develops categories and failure times will be added to this digital twin. In the future, this will be a living document that will be updated with failure times of all our plants across the country, and with it, will come the ability to fine-tune, troubleshoot, and solve persistent failure modes.

ii. Design of Digital Twin

For drinking water treatment, the most important factor is to have safe drinking water consistently. Often drinking water storage tanks have enough safe drinking water for 72 hours and therefore important factors to consider are a mean time to repair as well as a mean time to failure. Those can then be interpreted as how long a system will stay in operation and what its lifecycle looks like. Additionally, through it, we were able to calculate the availability of components. Lastly, we summed all the collected values and adjusted for how much component costs as a function of the other relative cost to assign it a cost multiplier in its overall reliability. This cost multiplier is an important consideration given that often why plants fail is because the necessary components are not replaced or repaired adjusting for cost as the reason, they do not get replaced is an additional multiplying factor.

Note: The Digital Twin can be found in Appendix C.

iii. Fault Tree and Digital Twin Conclusions

As expected, the doser with its dependency on pumps, electrical systems and an autonomous SCADA system makes it the least reliable sub-system. With a quantity of 21 components, an overall cost multiplier of 80% the reliability contribution was 5.85E-4 and an adjusted MTBF of 71.25 days. The least reliable component was surprisingly the SCADA system that alone accounted for 40% of the cost multiplier and had the highest reliability contribution by an order of magnitude at 4.99E-4.

This analysis points to the tradeoff between an autonomous system that comes at the expense of reduced reliability vs a robust system that requires continual operator control. A SCADA system is an additional tool used to manage the water treatment process. Part of that added control comes to the requirement for pumps and an electrical system however that trade-off is mitigated by the fact there aren’t enough operators and any way to reduce that even at the expense of reliability is the problem to be solved.

V. Chemical Doser Failure Simulation: Weibull Distribution

To further understand the failure of subsystem 2, the chemical doser, we conducted a failure simulation. In this simulation, we wanted to see how the 3 main components of the chemical doser, the pumps, the SCADA, and the electrical system, can fail individually but also lead to total failure of the chemical doser. We used a 2-parameter Weibull distribution for each of the components. We did research online to find the characteristic life in hours for each of the components, and then chose our shape parameters depending on the types of failures we expected to see from each of the components. For the electrical and SCADA components, we expected to see useful life or random failures, so we chose a shape parameter of 1. For the pumps, we expected to see wear out failure from the normal wear and tear of tubing and seals over time, so we chose a shape parameter of 2. Since there are 4 pumps in the chemical doser, we had to adjust our characteristic life value for the pumps. The 4-pump characteristic life ended up being ½ of the 1-pump characteristic life. The values for our characteristic life and shape parameters for each component are shown in Table 5-1.

	Characteristic Life (hours)	**Shape Parameter**
Pumps	10950	2
SCADA	7884	1
Electrical	8153	1

Table 5-1 Chemical Doser Life and Shape Parameters

We ran the simulation 1000 times. In the simulation, we assumed that if one component failed, then the whole chemical doser failed. For each simulation, we collected the failure times of the pumps, SCADA, and electrical systems. We took the minimum of the component failures to be the total system failure, and then we indicated which component caused the system failure. After 1000 simulations we find that our Mean Time to Failure (MTTF) for the chemical doser is 3388 hours, with SCADA and Electrical components our most common sources of failure. Table 5-2 shows the MTTFs for each component as well as the total system and Figure 5-1 shows the breakdown of cause of failure from each component.

	Pumps	**SCADA**	**Electrical**	**Total System**
MTTF (hours)	9824	7986	8042	**3388**

Table 5-2 Chemical Doser Subsystem and Component MTTF

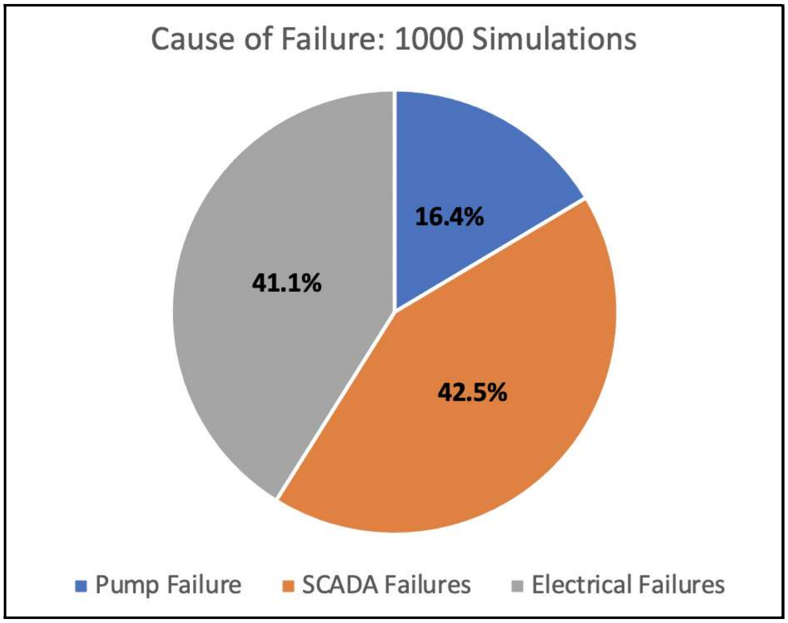


Figure 5-1 Chemical Doser Simulated Component Failure %

VI. House of Quality

iv. Criteria

To analyze and compare the true value of our system against its competitors a house of quality was created. We began by analyzing the most important performance criteria based on the interviews conducted during the NSF I-Corps Program. Our criteria in order of relative importance were as follows.

Autonomous (20%): the number one issue that rural communities are facing is the lack of operations staff. This is a problem because of the high barrier to entry given that operations require specialized training because water treatment is complex because it requires an understanding of chemistry, fluid mechanics, mechanical engineering (i.e. maintenance of pumps and other moving parts), and electrical engineering (i.e. SCADA and sensor control and management). Coupled with the relatively low return such as low salary and other high-paying jobs that require the same skill set such as oil and gas or chemical plant management. Additionally, it's not as sexy as other public service professions such as firefighting and or police officers. We, therefore, placed the relative importance of the system running autonomously as high as capital costs.

Capital costs (20%): When decision-makers analyze what system to purchase they base their decision-making processes on two primary factors: capital cost and operational costs. Furthermore, we've incorporated the reduction in operational cost within the other performance criteria and have scaled their relative importance accordingly. This essentially equates to higher importance in operational costs due to additive relative importance of the other related performance criteria like effective life span and maintenance.

Operational Costs: This is one of our primary value adds to the customer because of three major factors. First, our system is majority gravity powered and therefore requires much less electricity to run. Second, we use a dosing system the is much less wasteful than current operational procedures. Third, our system will be essentially autonomous, and given the lack of moving parts will be quite easy to repair and maintain so the resulting labor costs are greatly reduced.

Structural Integrity: Civil infrastructure is measured in effective lifespan. Comparing the effective lifespan of our system vs other systems is an integral aspect that future clients will be evaluating. What makes our system unique is that the effective lifespan is based on the structural integrity of the concrete and PVC components and so its lifespan is much longer than the competition systems.

Reliability: This category is defined by the types of water quality conditions that it can treat and the expected percentage of time that the water is treated to below those standards. This is not the reliability of the components themselves but that of the treatment capabilities. Our system performs just as well in key treatment characteristics such as turbidity and color however we lack the prominence to treat newer more advanced contaminants like PFAS.

Effective Area: This criterion is especially important when available land is scarce. This is more of a problem in urban areas and not so much of a problem in rural communities however this often lends to greater construction costs as material and personnel costs are often proportional to the surface area.

Safety and security: These criteria are more thresholds than worthy comparing factors. The regulations require certain aspects to be met and though some may be more susceptible to safety and security risks this factor is often not considered as heavily.

User Friendly, Maintenance, and Upgradability: These criteria are encompassed in some of the other criteria and often not as much of a concern from a decisions maker standpoint and therefore have lower relative importance.

v. Characteristics

An essential component of our House of Quality analysis is the appropriate selection of comparative characteristics. The following were selected based on their propensity to add factors to the performance criteria, their ability to be objectively measured with specific values, and their overall importance to the function of our system. They are as follows; Number of Sensors (Dimensionless), Number of Pumps (Dimensionless), Number of System Processes (Dimensionless), Treatment Quality (sigmas in percent of time below standards), Residence Time (Minute), Sensor Repair Cost ($), Sensor Repair Time (Hour), Pump Repair Cost ($), Pump Repair Time (Hour), Number of Moving Parts (Dimensionless), Time to coagulant Dosing (Minute), Time to Operator Dosing (Minute), Backwash Time (Minute), Backwash Interval Time (Hour), Flow Rate Variability (Liter/Second), Manufacture Time (Month), Assembly Time (Month), Regulatory Approval Time (Month), Total Area (Meter^2), Maximum Flow Rate (Liter/Second), Maximum Turbidity (NTU), Maximum Color (UTC), Minimum Electrical Energy (Watt), Minimum Head Loss (Meter), Offline Capacity (Day), Coagulant Response Rate (Minute).

We compared our system with that of a similar system created by tetra tech and one by Arcadis. We concluded from the imputed importance that the most important factors were Number of Pumps, Number of Sensors, Number of System Processes, Minimum Head Loss, Number of Moving Parts, and Offline Capacity. After normalization and weighting the criteria our target for the development of our system sums 428 and 249 for the tetra tech system and 280 for the

Arcadis system. However, we must also be cautious to maintain systems within our target. Lastly, it is within our current insights to include factors like moving parts and number of pumps, etc. This approach is not uniform across the industry and different decision-makers may undervalue those aspects and overvalue aspects like backwash interval time.

Note: House of Quality can be found in Appendix D.

VII. Conclusion & Next Steps

The future of water treatment is in autonomy, and this autonomy comes with additional challenges that increase failure rates and the specialized training needed to address said failures. Those failures include pumps, electrical systems and SCADA-control faults. However, the tradeoff in reliability comes at the benefit of accessibility. AguaClara's North America's clients have stated the number one issue is lack of on-site operational staff and solving that problem is the primary job to be done. In conclusion, we aimed to solve this problem in identifying failure modes and rates in the new AguaClara design to ensure on-site staff will not be required at all times by understanding which components need to be improved.

Now that we have completed a thorough analysis of the system and pinpointed the vulnerabilities in the Agua Clara system, our next steps are to reduce the frequency and scale of the failures. Rural communities in America and abroad will rely on this system as a source of clean water, and in many circumstances, their only source of clean, potable water. In our next steps, we believe that we must investigate alternatives to the components we currently have. For example, for the SCADA system in the chemical doser, we might find several options of SCADA systems and compare their performance regarding both accuracy and reliability. The SCADA system must be accurate because it signals the amount of chemical to add to the water. It must be reliable because it is an autonomous process, and no operators will be present. In the next phases of our analysis, we would collect data on the long-term reliability of the system. In the simulation, we assumed that the SCADA operated under a useful life. However, physical analysis and accelerated life tests of potential SCADA systems could indicate different usage, such as early life or wear out life.

This document will be used as part of the National Science Foundation's SBIR grant to fund the pilot project of AguaClara in North America. In addition, it demonstrates while autonomous plant operations reduced reliability, the AguaClara's robust water treatment process aides in making up that lost. This document will also be used to demonstrate to local and state regulators, future clients, and water treatment stakeholders the overall life span and reliability of the overll AguaClara treatment process. It will be expanded to include maintenance, operational and process recommendations to improve the overall reliability.

In addition, future AguaClara research will be performed using the tools developed in the creation of this document and emphasis will be places on solutions that not only increase performance but take reliability into account, most notably the Chemical Doser subsystem. Finally, the Digital Twin will serve as a living document to continually be updated with Build of Material (BOM) to fully understand the system's failure modes.

Project Team Members Bio

Olia Javidi
OJ33

Olia Javidi is a senior at Cornell University College of Engineering studying Operations Research and minoring in Engineering Entrepreneurship. Her professional experience is primarily in data science and she has experience working in satellite communications and CPG industries. She is passionate about food sustainability and accessibility and wants to use her data science skills to create data-driven solutions for the food industry. Currently, Olia works part-time in marketing and sales analytics for a food technology company called Antithesis Foods, which makes crunchy snacks out of chickpeas; their first brand is Grabanzos, a nutrient-dense crunchy, chocolate snack. After graduating in May, Olia will work full time for PepsiCo as a Global Procurement Analyst. Olia was born and raised in San Diego, CA and is a first-generation American.

Ryan Ricciardelli
RR742

Ryan Ricciardelli is a graduate student pursuing his M.E. Systems Engineering. Professionally, Ryan is a Senior Systems Engineer for Lockheed Martin working in its Laser & Sensor Systems business unit focused on building Directed Energy Laser Weapon Systems. He graduated from Lehigh University in 2015 with a B.S. Computer Science. Ryan worked as a software engineer and software lead for multiple radar-based programs before moving over to lasers. He is a subject matter expert in Model-Based Systems Engineering practices driving end-to-end model automation. Currently, Ryan is a lead systems integration and test engineer for a first of a kind ground vehicle laser weapon system for an Army's Program of Record. Originally born and raised in New Jersey, Ryan now lives in Seattle, WA with his fiancé Annalynn and puppy Maverick.

Yitzy Rosenberg
YYR2

Yitzy Rosenberg, is a senior at Cornell University College of Engineering studying Environmental Engineering and Business as well as a first semester Systems Master of Engineering Candidate. He managed the business and public relations for AguaClara for two years. He has worked for Broward County Water Resources Department and helped create the future condition modeling and worked for Tetra Tech in water resources and engineering. His work has brought him from the beaches in Miami, to jungles of Borneo, to rural communities in Israel and coffee plantations in Honduras. He is passionate about entrepreneurship and has spent multiple years working with startups and is currently working as a venture analyst for Chloe Capital, a venture capital firm that invests exclusively in women led businesses. On campus he is very involved as the President of the INCOSE student chapter, the vice president of Rotaract, a Hillel intern and the House manager for the Triphammer Cooperative. He loves music, the outdoors, and laughing till he cries.

Appendix A – Network Diagrams

Fig. 11
Critical Path

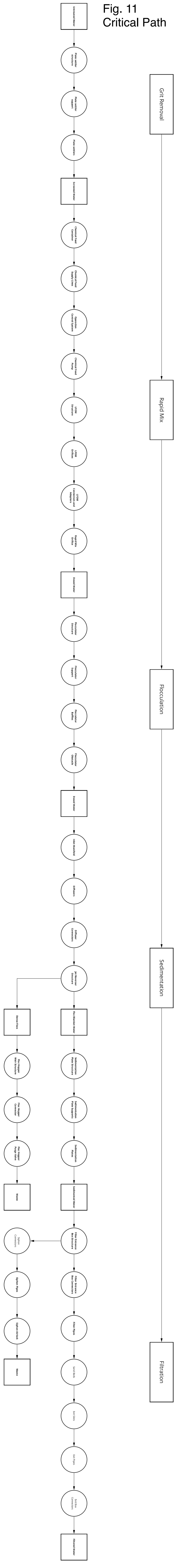
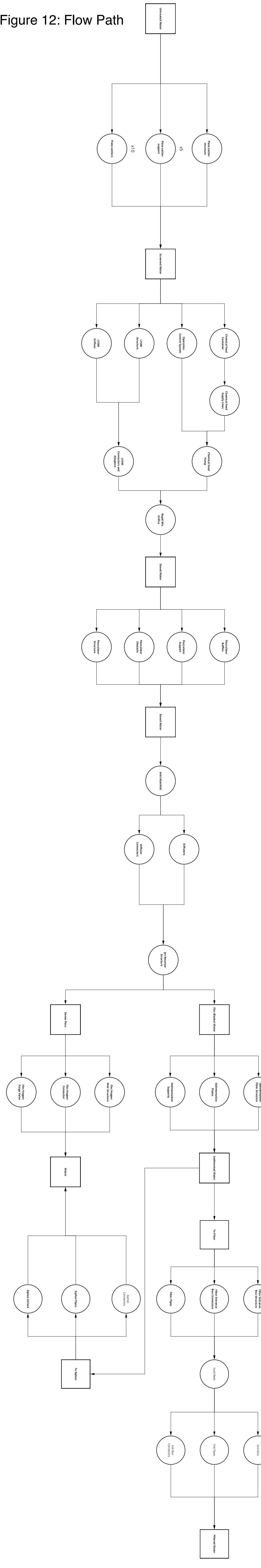


Figure 12: Flow Path



Appendix B – FMEA Table

Subsystem	Item / Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Current Design Controls	Detect	RPN
Doser	SCADA/ Electronic auto-response system	Auto-responses not working appropriately	Chemicals mixed with incorrect proportions, or potentially not mixed at all	2	The automation set up improperly, software bug	4	No current design control in place to detect without component shutdown or failure	4	32
Doser	Chemical Feedline	Chemical Feed line stopped	Spilling chemicals (Chlorine)	3	Feed line is clogged	4	Clear tubing for easier visual inspections, alerts in SCADA reporting system	2	24
Doser	Outlet Sensor/s	Outlet sensors broken	Unable to sense pH, color, etc of the resultant water supply	3	Sensor wear due to aging	3	Alerts in SCADA system. Emergency shutoff	2	18
Doser	Inlet Sensor/s	Inlet sensors broken	Unable to sense pH, color, etc of the incoming water supply	2	Sensor wear due to aging (sensitivity goes down)	3	Alerts in SCADA system. Emergency shutoff	2	12
Doser	Chemical Pump/s	Chemical Pump not calibrated	Incorrect measurements of chemical dosage	2	Calibration Error	5	Legally mandated inspections and calibration on daily, monthly, and annual timescales.	1	10

Doser	Flow meter/s	Flow meter not calibrated	Unit mixing improperly and water being treated incorrectly	2	Calibration error	5	Alerts in SCADA system. Emergency shutoff	1	10
Doser	Mechanical Mixer	Mechanical Mixer broken	The chemical substances do not mix homogenously with water	2	Motor dysfunction, battery drainage	4	Alerts in SCADA system. Emergency shutoff	1	8
Doser	Throttle Valve/s	Throttle valve jammed	Mix unit is not working at capacity	2	Debris, rust, wear and tear, aging, deteriorating gaskets	2	No current design control in place to detect without component shutdown or failure	2	8
Doser	Inlet / outlet piping	Clogged inlet or outlet	Outlet; Mix unit to fill up all the way and overflow & Inlet; no flow into the system	2	Throttle valve jammed, Blockage due to debris	4	Alerts in SCADA system cross reference flow metering	1	8
Doser	Mix Tank/s	Over flow mix tanks	The mix unit would fill and potentially spill over	2	more water enters the tank than can exit. Blockage, or constricted outflow	3	Overflow auto-shutoff	1	6
Doser	Chemical Tank/s	Over flow chemical tanks	The chemical tanks would fill up and potentially spill over	3	Pumps weren't allowing for enough outflow. Clogged chemical feed lines	1	No current design control in place to detect without component shutdown or failure	1	3
Flocculation	Baffle	Crack in baffle	The water would spill over or out, and not go through all the necessary channels to create the necessary level of flocs	2	Wear and tear, or debris gets into Flocculator and causes cracks	2	Alerts in SCADA system cross reference flow metering	1	4

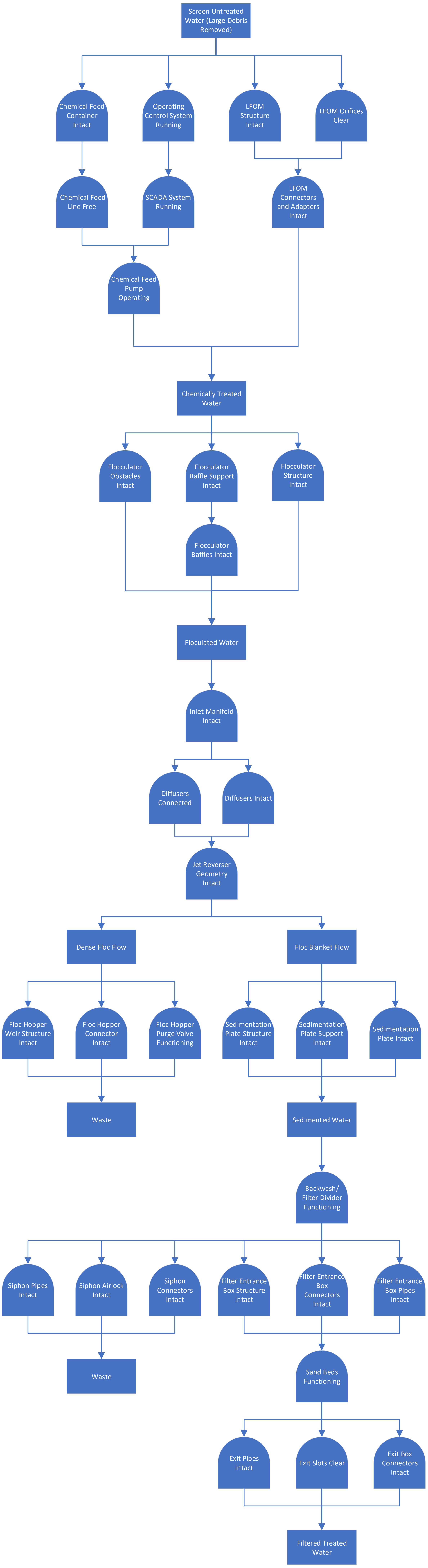
Flocculation	Baffle	Baffle component breaks off	The water would spill over or out, and not go through all the necessary channels to create the necessary level of flocs	1	Wear and tear, or debris gets into Flocculator and causes cracks	2	Alerts in SCADA system cross reference flow metering	1	2
Flocculation	Obstacle	Crack in Obstacle	The water would spill over or out, and not go through all the necessary channels to create the necessary level of flocs	2	Wear and tear, or debris gets into Flocculator and causes cracks	2	Alerts in SCADA system cross reference flow metering	1	4
Flocculation	Obstacle	Obstacle component breaks off	The water would spill over or out, and not go through all the necessary channels to create the necessary level of flocs	1	Wear and tear, or debris gets into Flocculator and causes cracks	2	Alerts in SCADA system cross reference flow metering	1	2
Sedimentation	Inlet Manifold	Diffusers clog	Water will not be released properly and more pressure on remaining diffusers to release water	2	Debris, rust, wear and tear, aging, deteriorating gaskets	2	Alerts in SCADA system cross reference flow metering	1	4
Sedimentation	Inlet Manifold	Diffuser breaks off	Water will not be released properly and more pressure on remaining diffusers to release water	1	Debris, rust, wear and tear, aging, deteriorating gaskets	2	Alerts in SCADA system cross reference flow metering	1	2
Sedimentation	Inlet Manifold	Diffuser cracks	Water will not be released properly and more pressure on remaining diffusers to release water	1	Debris, rust, wear and tear, aging, deteriorating gaskets	2	Alerts in SCADA system cross reference flow metering	1	2

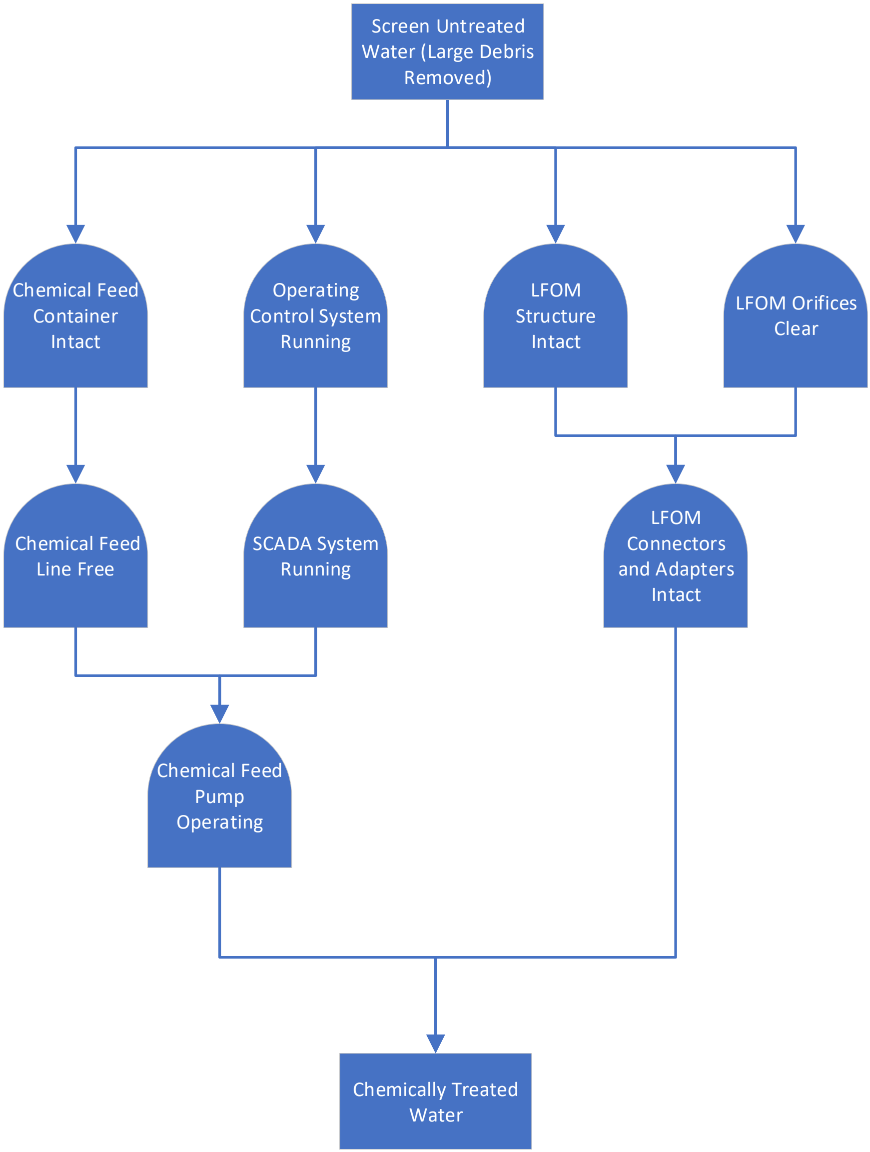
Sedimentation	Jetstream	Pressure Variation	Clarified water does not reach top of tank to pass through sedimentation plates	2	Calibration Error	4	Alerts in SCADA system cross reference flow metering	1	8
Sedimentation	Jetstream	Clogged with Floc	Clarified water does not reach top of tank to pass through sedimentation plates	2	Calibration Error or Hopper Purge Valve malfunction	3	Alerts in SCADA system cross reference flow metering	1	6
Sedimentation	Jetstream	Jetstream Misalignment	Clarified water does not reach top of tank to pass through sedimentation plates	2	Calibration Error	4	Alerts in SCADA system cross reference flow metering	1	8
Sedimentation	Sedimentation Plate	Plate breaks	Allows increased rate of small flocs enter into outlet manifold	1	Debris, wear and tear, aging	2	Alerts in SCADA system cross reference flow metering	1	4
Sedimentation	Sedimentation Plate	plate becomes loose	Allows increased rate of small flocs enter into outlet manifold	1	Fastenings wear and tear, aging	3	Alerts in SCADA system cross reference flow metering	1	3
Sedimentation	Hopper Purge Valve	Valve clog	Sludge fills up jetsteam and sedimentation container	2	Debris, rust, wear and tear, aging, deteriorating gaskets	2	Alerts in SCADA system cross reference flow metering Manual inspection	1	4
Filtration	Inlet and Exit Pipe	Elbow or End Cap breaks	Water spill and Filtration process is halted or reduced	2	Above specification pressure in pipes	4	Alerts in SCADA system cross reference flow metering Manual inspection	1	8

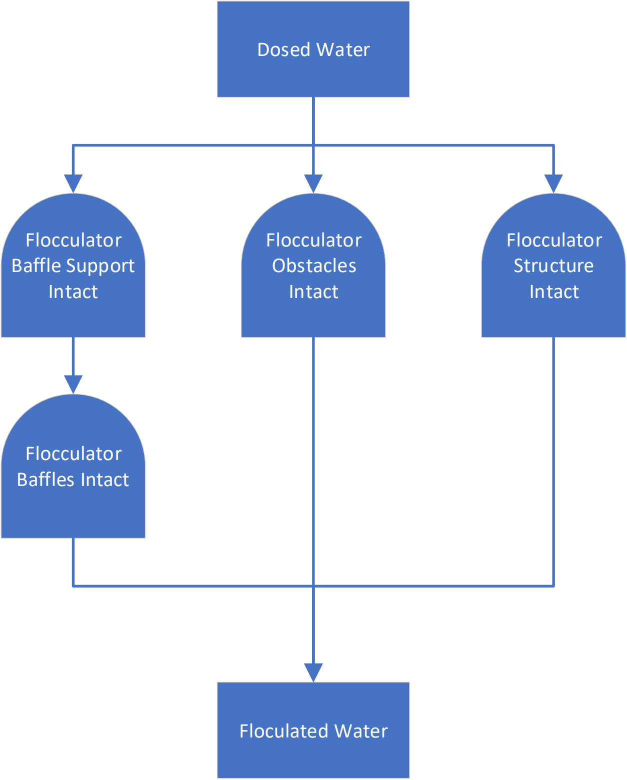
Filtration	Inlet and Exit Pipe	Influent or effluent pipe clog	Filtration process is halted or reduced	2	Debris and excess floc in water	4	Alerts in SCADA system cross reference flow metering Manual inspection	1	8
Filtration	Inlet and Exit Pipe	Sand fills exit slots and clogs them	Filtration process is halted or reduced	2	Excess floc in water	4	Alerts in SCADA system cross reference flow metering Manual inspection	1	8
Filtration	Backwash Prevention	Sand bed does not fluidize	Dirty particles will not be removed and filtration process will be degraded	2	Preferential flow occurs	3	Alerts in SCADA system cross reference flow metering Manual inspection	1	6
Filtration	Backwash Prevention	Backwash pressure bursts pipes	Water spill and Filtration process is halted or reduced	2	Blockages in pipes or poor joint fittings	2	Alerts in SCADA system cross reference flow metering Manual inspection	1	4
Filtration	Backwash Prevention	Fluidize pressure is not high enough	Dirty particles will not be removed and filtration process will be degraded	2	Not enough water height differential to drive water through the sand fast enough (e.g. not enough water in plant due to water source dried up)	1	Alerts in SCADA system cross reference flow metering Manual inspection	1	2

Filtration	Siphon	Airlock valve breaks	Pressure is released and water cannot travel through the pipes	2	Fastenings wear and tear, aging	3	Alerts in SCADA system cross reference flow metering Manual inspection	1	6
Filtration	Siphon	Siphon not sealed properly	Pressure is released and water cannot travel through the pipes	2	Manual error, Siphon seal wear and tear, aging	4	Alerts in SCADA system cross reference flow metering Manual inspection	1	8
Filtration	Filter	Preferential flow patterns form does not allow for complete filtration	Improper filtration	1	Not enough pressure, non-uniform sand particle sizes, blockage in the sand bed	4	Alerts in SCADA system cross reference flow metering Manual inspection	1	4
Filtration	Filter	Filter pores constrict quickly not allowing for enough residence time between backwashes	Improper filtration	1	Sediment build-up or blockage. Non-uniform sand particle sizes	4	Alerts in SCADA system cross reference flow metering Manual inspection	1	4

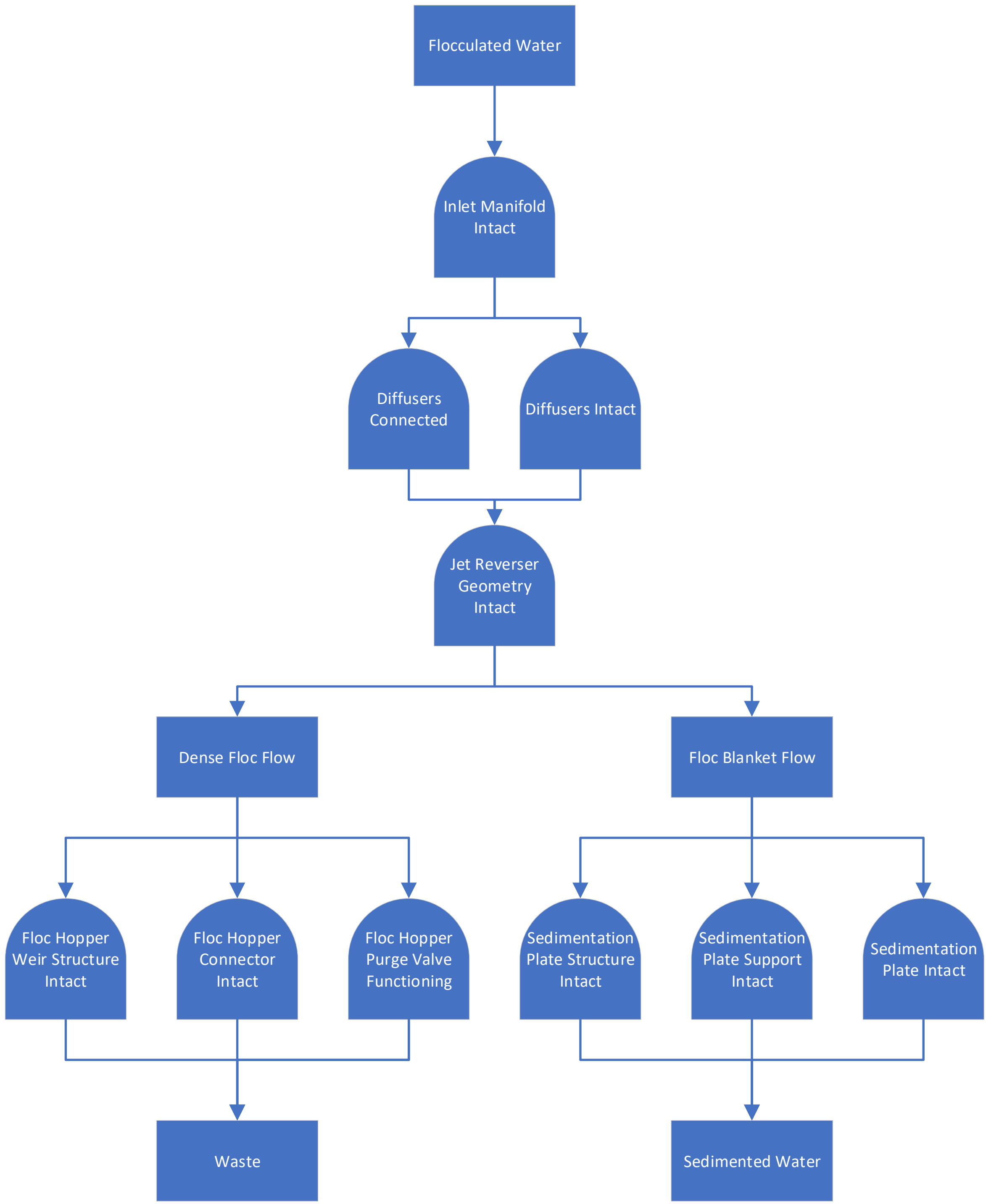
Appendix C – Fault Tree Diagrams

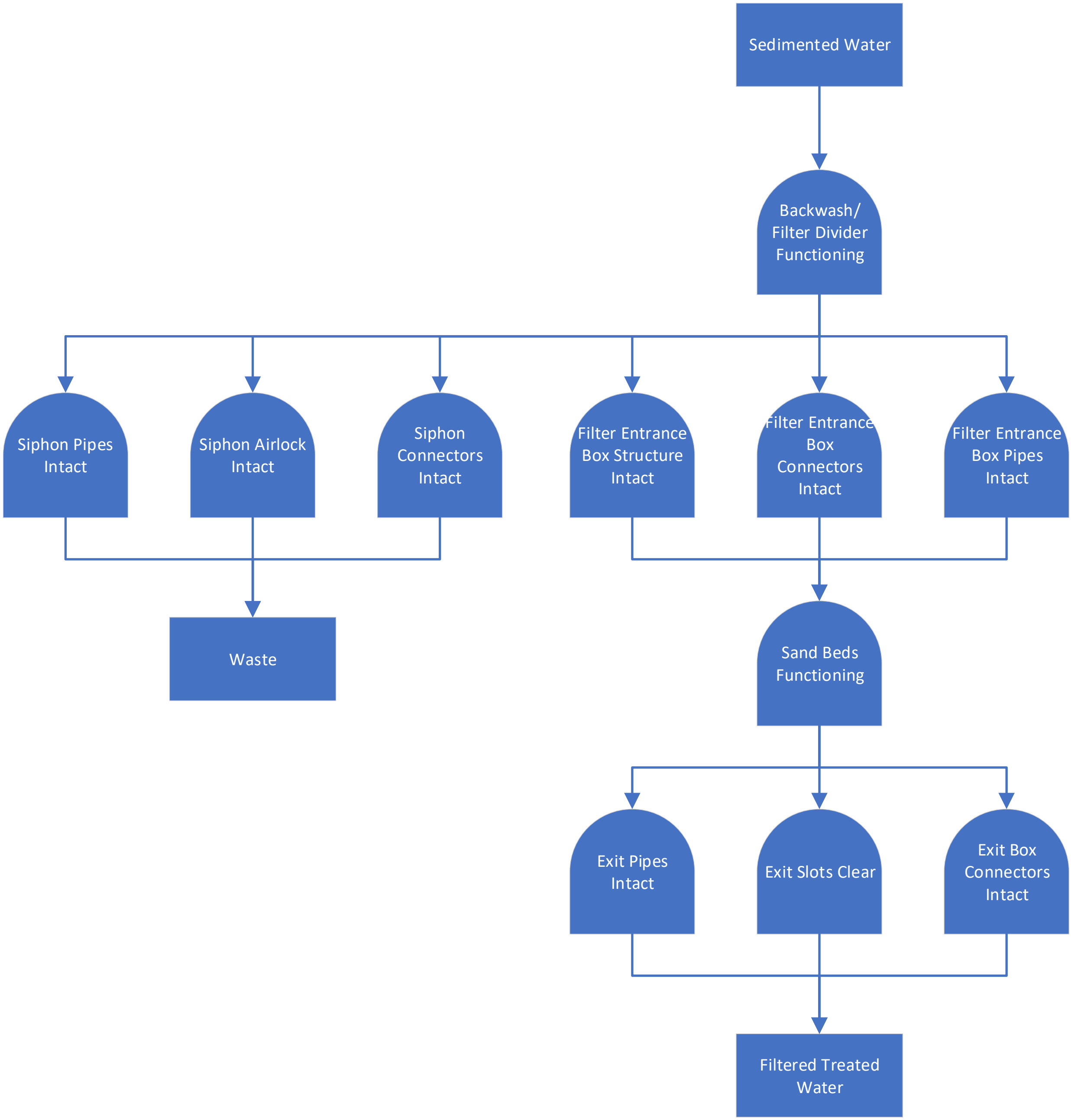

Screen Untreated Water (Large Debris Removed)
Chemical Feed Container Intact
Operating Control System Running
LFOM Structure Intact
LFOM Orifices Clear
Chemical Feed Line Free
SCADA System Running
LFOM Connectors and Adapters Intact
Chemical Feed Pump Operating
Chemically Treated Water
Flocculator Obstacles Intact
Flocculator Baffle Support Intact
Flocculator Structure Intact
Flocculator Baffles Intact
Floculated Water
Inlet Manifold Intact
Diffusers Connected
Diffusers Intact
Jet Reverser Geometry Intact
Dense Floc Flow
Floc Blanket Flow
Floc Hopper Weir Structure Intact
Floc Hopper Connector Intact
Floc Hopper Purge Valve Functioning
Sedimentation Plate Structure Intact
Sedimentation Plate Support Intact
Sedimentation Plate Intact
Waste
Sedimented Water
Backwash/ Filter Divider Functioning
Siphon Pipes Intact
Siphon Airlock Intact
Siphon Connectors Intact
Filter Entrance Box Structure Intact
Filter Entrance Box Connectors Intact
Filter Entrance Box Pipes Intact
Waste
Sand Beds Functioning
Exit Pipes Intact
Exit Slots Clear
Exit Box Connectors Intact
Filtered Treated Water


Screen Untreated Water (Large Debris Removed)
Chemical Feed Container Intact
Operating Control System Running
LFOM Structure Intact
LFOM Orifices Clear
Chemical Feed Line Free
SCADA System Running
LFOM Connectors and Adapters Intact
Chemical Feed Pump Operating
Chemically Treated Water



Dosed Water
Flocculator Baffle Support Intact
Flocculator Obstacles Intact
Flocculator Structure Intact
Flocculator Baffles Intact
Floculated Water


Flocculated Water
Inlet Manifold Intact
Diffusers Connected
Diffusers Intact
Jet Reverser Geometry Intact
Dense Floc Flow
Floc Blanket Flow
Floc Hopper Weir Structure Intact
Floc Hopper Connector Intact
Floc Hopper Purge Valve Functioning
Sedimentation Plate Structure Intact
Sedimentation Plate Support Intact
Sedimentation Plate Intact
Waste
Sedimented Water


Sedimented Water
Backwash/ Filter Divider Functioning
Siphon Pipes Intact
Siphon Airlock Intact
Siphon Connectors Intact
Filter Entrance Box Structure Intact
Filter Entrance Box Connectors Intact
Filter Entrance Box Pipes Intact
Waste
Sand Beds Functioning
Exit Pipes Intact
Exit Slots Clear
Exit Box Connectors Intact
Filtered Treated Water

Appendix D – Digital Twin

Screenshot below, however, please reference supplemental file "Failure_Tracker.xlsx" on Google Drive.

Link: https://docs.google.com/spreadsheets/d/169W__0wuQ0KDGdGc1PUeqWRVG8lUJrBhPHzWUYl6gaA/edit?usp=sharing
i

Component	PUMP	ELECTRICAL	SCADA	STORAGE_TANK	PVC_PIPES	PVC_JOINTS	PVC_WELDS	CORROGATED_SHEETS	FASTNERS	CONCREATE
Failure Type	Seal and tubing wear	Shorts and component Lifetime	Short and system failure	Puncture	Wear	Leaks	Pressure	Wear	Pressure	Wear
MTBF (hrs)	21900	8153	788.4	389	876000	43800	876000	87600	876000	438000
Failure Rate	0.00004566210046	0.0001226542377	0.001268391679	0.002570694087	0.000001141552511	0.00002283105023	0.000001141552511	0.00001141552511	0.000001141552511	0.000002283105023
MTTR (hrs)	64	4.1	9.5	1	2	1	24	12		
Availability	0.002913859042	0.000502629611	0.01190625392	0.002564102564	0.00000228309981	0.00002283052898	0.00002739650968	0.0001369675387	0	0
Average Cost	5000	10000	10000	100	100	20	20	50	10	100
Cost Multiplier	0.1968503937	0.3937007874	0.3937007874	0.003937007874	0.003937007874	0.0007874015748	0.0007874015748	0.001968503937	0.0003937007874	0.003937007874
Source	http://vuir.vu.edu.au/32259/1/Resilienc	https://www.bsee.gov/sites/bsee.gov/fi	https://www.bsee.gov/sites/bse	http://vuir.vu.edu.au/32259/1/Resilienc	http://www.thinkpipesthinkpvc.com.au/a					
Distribution	Weibull	Weibull	Weibull	Exponential	Exponential	Exponential	Exponential	Exponential	Weibull	Exponential

Failure	Chemical Feed Container Intact	Operating Control System Running	Chemical Feed Line Free	SCADA System Running	Chemical Feed Pump Operating	LFOM Structure Intact	LFOM Orifices Clear	LFOM Connectors and Adapters Intact	Flocculator Obstacles Intact	Flocculator Baffle Support Intact	Flocculator Structure Intact	Flocculator Baffles Intact
Process	Doser	Doser	Doser	Doser	Doser	Doser	Doser	Doser	Flocculator	Flocculator	Flocculator	Flocculator
Variable Name	D_CF_C	D_CS_R	D_CF_L	D_SC_R	D_CF_P	D_LF_I	D_LF_C	D_LF_A	F_O_I	F_B_S	F_B_S	F_B_S
Component	STORAGE_TANK	ELECTRICAL	PVC_PIPES	SCADA	PUMP	CONCREATE	PVC_PIPES	PVC_JOINTS	PVC_PIPES	CONCREATE	PVC_PIPES	CORROGATED_SHEETS
Failure Type	Puncture	Seal and tubing wear	Wear	Short and system failure	Seal and tubing wear	Wear	Wear	Leaks	Wear	Wear	Wear	Wear
MTBF (hrs)	389	21900	876000	788.4	21900	438000	876000	43800	876000	438000	876000	87600
Failure Rate	0.002570694087	0.00004566210046	0.000001141552	0.001268391679	0.00004566210046	0.00000228310502	$0.00	0.00002283105023	0.000001141552511	0.000002283105023	0.00000114155	0.00001141552
MTTR (hrs)	1	64	2	9.5	64		$2.00	1	2		2	12
Availability	0.002564102564	0.002913859042	0.00000228309	0.01190625392	0.002913859042	0	$0.00	0.00002283052898	0.00000228309981	0	0.00000228301	0.00013696753
Average Cost	100	5000	100	10000	5000	100	$100.00	20	100	100	100	50
Cost Multiplier	0.003937007874	0.1968503937	0.003937007874	0.3937007874	0.1968503937	0.003937007874	$0.00	0.0007874015748	0.003937007874	0.003937007874	0.00393700787	0.00196850393
Quantity	4	1	4	1	4	1	1	5	108	1	108	12
Redundancy?	N	Y	N	N	N	N	N	N	Y	Y	Y	Y
Reliability Contribution	4.06E-05	8.99E-06	1.80E-08	4.99E-04	3.60E-05	8.99E-09	4.49E-09	8.99E-08	0.00E+00	8.99E-09	0.00E+00	1.66E-82

Failure	Inlet Manifold Intact	Diffusers Connected	Diffusers Intact	Jet Reverser Geometry Intact	Jet Reverser Geometry Intact	Floc Hopper Weir Structure Intact	Floc Hopper Connector Intact	Floc Hopper Purge Valve Functioning	Sedimentation Plate Structure Intact	Sedimentation Plate Support Intact	Sedimentation Plate Intact	Backwash/Filter Divider Functioning
Process	Sedimentation Tank	Sedimentation Tank	Sedimentation Tank	Sedimentation Tank	Sedimentation Tank	Sedimentation Tank	Sedimentation Tank	Sedimentation Tank	Sedimentation Tank	Sedimentation Tank	Sedimentation Tank	Filter
Variable Name	S_IM_I	S_IM_I	S_IM_I	S_IM_I	S_IM_I	S_IM_I	S_IM_I	S_IM_I	S_IM_I	S_IM_I	S_IM_I	F_
Component	PVCPIPES	PVC_WELDS	PVC_PIPES	CONCREATE	CONCREATE	CORROGATED_SHEETS	PVC_JOINTS	PVC_PIPES	CORROGATED_SHEETS	PVC_WELDS	CORROGATED_SHEETS	PVC_JOINTS
Failure Type	#REF!	Pressure	Wear	Wear	Wear	Wear	Leaks	Wear	Wear	Pressure	Wear	Leaks
MTBF (hrs)		876000	876000	438000	438000	87600	43800	876000	87600	876000	87600	43800
Failure Rate		0.00000114155	0.000001141552511	0.000002283105023	0.0000022831	0.0000114155	0.0000228310	0.0000011415	0.0000114155	0.00000114155	0.0000114155	0.0000228310
MTTR (hrs)		24	2			12	1	2	12	24	12	1
Availability		0.0000273965	0.00000228309981	0	0	0.0001369675	0.0000228305	0.0000022830	0.0001369675	0.0000273965	0.0001369675	0.0000228305
Average Cost		20	100	100	100	50	20	100	50	20	50	20
Cost Multiplier		0.00078740157	0.003937007874	0.003937007874	0.0039370078	0.0019685039	0.0007874015	0.0039370078	0.0019685039	0.00078740157	0.0019685039	0.0007874015
Quantity	1	30	30	4	4	3	1	1	5	15	120	5
Redundancy?	Y	Y	y	y	y	Y	Y	Y	N	N	N	N
Reliability Contribution	0.00E+00	4.08E-272	3.80E-251	6.63E-33	6.63E-33	1.13E-23	1.80E-08	4.49E-09	1.12E-07	1.36E-08	2.70E-06	8.99E-08

Totals	Doser	Flocculator	Sedimentation Tank	Filter
MTBF (hrs)	2278777.4	2321400	4686600	5431200
Failure Rate	0.003957807228	0.00003881278539	0.00006621004	0.0001015981735
MTTR (hrs)	143.5	17	89	14
Availability	0.02032547129	0.0001543642673	0.00049309236	0.000102737615
Average Cost	20420	370	610	780
Cost Multiplier	0.8039370079	0.01456692913	0.02401574803	0.03070866142
Quantity	21	234	214	239
Reliability Contribution	5.85E-04	9.89E-08	2.84E-06	1.68E-06
Relative MTBF (hrs)	1,710	10,113,818	351,507	596,525

References

Agua Clara Website
https://www.aguaclarareach.org/

Agua Clara Textbook
https://aguaclara.github.io/Textbook/index.html

Failure Rates References

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https://www.weibull.com/hotwire/issue14/relbasics14.htm

https://reliabilityanalyticstoolkit.appspot.com/weibull_analysis_details

Acronyms

FMEA	Failure Mode and Effects Analysis
MTTF	Mean Time to Failure
MTBF	Mean Time Between Failure
SCADA	Supervisory Control and Data Acquisition
RPN	Risk Property Number