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Hydroponics technology is a method for growing plants and vegetables of a commercial value without soil. The plants are either floated or treated with a nutrient water film, to supply the optimum nutritional requirement for specific plants or fruiting vegetables. As a closed system, hydroponics results in very insignificant water loss to the environment. This technology is becoming more popular with communities and governments as the preservation of water becomes more of an issue. This is especially important in regions where water is a scarce and hence an expensive commodity. Hydroponic systems may be located within industrial complexes near to the point of consumption.

Aquaculture is the science of raising aquatic animals such as fish, prawns etc. Aquaponics is technology developed from the aquaculture industry that integrates intensive farming of fish and utilizes plants (integrates hydroponics) in a continuous closed loop to clean the water for the fish. For aquaponics to work there must be a symbiotic, closed loop relationship between both subsystems. There are some natural symbiotic features, for example, fish produce ammonia, which is converted by bacteria into nitrates. Nitrates are toxic to fish above certain levels; however, nitrates represent a nutritional requirement of plants thereby reducing nitrate levels in the shared medium i.e. a symbiotic relationship.

However, aquaponics is a complex system of interacting parameters some of which are mutually incompatible. For example, the pH range best suited to bacteria activity differs significantly from that required by plants such as fruiting vegetables.
In effect whilst there are natural symbiotic relationships in aquaponics, there are also systems that are antibiotic.

The ideal parameters have been identified for each subsystem and the challenge has been to optimally control these parameters and address the problems of antibiotic subsystems. Supplying optimal parameters could increase the number of viable commercial crop varieties including fruiting vegetables in an aquaponics system. In order to achieve these goals process control systems have been investigated. A control solution was developed using standard design methods such as Process Flow Diagrams (PFDs), Failure Mode Analysis and Piping & Instrumentation Diagrams (P&IDs) which resulted in instrumentation tag and alarm lists. Work to date indicates this is the first process control automated approach to aquaponics.

The use of process control and the automation that it incorporates is able to measure and maintain multiple control loops, having multiple control loops that are not dependent on others would remove some of the identified limitations by dividing the process to meet those ranges that have been researched as optimum at particular stages.
CHAPTER 2. MOTIVATION

Research carried out by Dr. James Rakocy (Rakocy, 2013) looks at sizing or controlling the process by the amount of fish feed that is introduced into the system in comparison to the amount of growing area to control the process by limiting the amount of nutrients in the system.

Additional research by Dr. James Rakocy (Rakocy, 2013) has looked at the nutrients required within the aquaponics system that includes additional items that are required and quantities to supplement plant nutrient processes to maintain conditions. These conditions include the addition of essential nutrients for plants that are missing such as (Rakocy, 2013) calcium, iron, and potassium into aquaponics systems.

This research is relevant when sizing components in the process so it can be designed to established and trialled parameters from research Rakocy and Lennard (Wilson Lennard, Aquaponic System Design Parameters) have documented with expected measurable results. However, some of this data does not take into account that automation techniques could also be utilised to keep the process within established parameters, which should provide similar or improved results as with trialled process ranges. The addition of automation and its associated instrumentation could introduce better control over some of the inputs, which can control the ranges of the process, which ultimately controls the outputs of the system. This thesis will look at some of the known data or techniques along with the adaptation of technologies to illustrate some of the ways that automation could benefit the processes by monitoring and controlling the process to assist in optimisation.
It has been suggested by Lennard PhD (Wilson Lennard) “if nitrate concentrations were graphed therefore, they would appear as a “flat line” across the page” as an alternate approach such as if regular testing could take place and actively adjusting the feeding ratio. However there are different forms of testing or measurement and the wastewater industry has developed instrumentation that is able to measure nitrates in parts per million (ppm) in real-time. If nitrate values are measured on a constant basis then controlling the quantity of fish feed inputs to the system is only one way to control nitrate levels.

Along with controlling dissolved nitrates other nutrient levels could also be adjusted, not only by addition of fish feed but also removal of these nutrients to be recycled by supplementing nutrients to other processes. The control and stabilisation of nutrients can also be difficult in an aquaponics system, as fish are grown in batches in separate tanks to stagger production. In certain circumstances, a complete tank can be harvested to meet sales demand or reduce transport overheads. This can shock the system as the nutrient levels also change as the fish feed that supplied the levels of nutrients are not at the same input levels for optimised fish production.

Automation could aid in the control and management of the inputs and outputs, this could provide operators more stability in the system and allow regular fish harvests without interruption to nutrient levels that can effect plant and vegetable production.

This thesis is highlighting some of the systems that could be adapted to be utilised in an aquaponics system as individual components with published ranges and results from existing data. The thesis is aimed at highlighting some of the techniques used in designing a process and how automation could be implemented to aid in
stabilising parameters of the process, by controlling parameters of the process’s with automation techniques. There is a lot of emphasis put on the treatment of water to obtain required water quality, by using established water treatment techniques.

There is a focus on moving nutrients within the system to allow for optimum conditions for the growing of plants such as edible fruiting vegetables. This thesis could also show that automation could aid in obtaining proven hydroponic recipes, along with the addition of recycle nutrients. Being able to recycle these nutrients just doesn’t allow for clean water for fish that can be farmed intensely in an area that requires far less land space, but could also allow for intensive fruiting vegetable food production.

Aquaponics and hydroponic technology is becoming a focus in areas that have shortages in water supply. Farming techniques that are able to (Tess Russo, 2014) deploy low water use with limited or nil wastewater is considered more sustainable than conventional water reticulation systems and in many situations is becoming far more practical. One such project has been referred to as (Sophia Epstein, 2017) Growing Underground, in England old tunnels have been used to grow micro-greens with intensive farming techniques with the benefit of reduced transport costs. Sustainable farming techniques have been recognised not by just individuals but government bodies as well, with an example of this being a rezoning of 28,000 ha of land (Australia) South of Perth Western Australia as an urban farm zone to encourage these types of projects.

Hydroponic system operators have released figures that they are able to save 99 % of water usage (Borras), yet these are under almost laboratory conditions. Aquaponics systems that are in dry conditions with floating raft systems that are
exposed to the environment (wind and associated evaporation) can still use less than half the amount of water (Watch) of traditional techniques, whilst also producing large fish quantities within the same water.

The aquaponics systems have also in some cases been certified as organic (Oi, n.d.), while this can be controversial as supplements are still required to make the solutions viable yet certification has been achieved. Although the use of automation will recycle as many nutrients as possible, during some stages in the process cycle nutrients would also be supplemented, via dosing, for the conditions to remain optimised. Another sustainable feature of aquaponics that should be noted is the technology does not use herbicides in the process, which in areas are becoming a problematic (Sedbrook, 2016) as they can leach into the waterways.

Other techniques such as energy conservation with automation techniques will also be considered by utilising products such as Variable Speed Drive’s (VSD) for motor speed control to control flow rates to desired ranges and to reduce energy consumption wastage. The consumption of energy in the process could also be offset by the production of energy onsite with the use of solar or wind sources, which could also supply batteries to offset power usage and supply a form of redundancy during times of mains electrical supply failure.

While some of these automation techniques could aid in industrial sized commercial systems these would not be practical in smaller systems and is not the focus of this research thesis, as this is targeting large-scale industrial production.
CHAPTER 3. LITERATURE REVIEW

In an aquaponics system the nutrients that accumulate in the system is a result of the accumulation of waste from fish and the feed introduced to grow fish. The fish eat food that they require to remain healthy and grow, yet the food used to feed the fish and the waste it produces does not (James E Rakocy) contain all the needs of various plants. If the technologies are to support the reduction in water and remain competitive in current markets, a greater diversity of products could be required to remain competitive in commercial markets. Existing commercial aquaponics systems are able to grow a range of vegetable greens on a competitive footing yet could come under pressure during seasonal shifts when traditional market growers are able to compete during these seasonal time periods. This could also limit areas in which they are able to compete where established farming techniques could undercut Recirculating Aquaponics System (RAS) operators with the limited varieties that could be competitively grown. The additional range of products that a system is able to produce could also reduce the (Craig W., 2015) financial risk that an investor must carry when entering into a large commercial venture as they would be able to supply a greater number of supply chains limiting market shocks.

Technologies that are able to recover or reduce water use in industry, commercial or farming techniques are becoming practical solutions as water use becomes more of a concern for governments and communities. The development of viable solutions for urban farming techniques (Australia) that are able to produce vegetables and fish products with less water is becoming a favoured approach for both private operators and government departments. This is particularly favourable when established water saving techniques can be realized in environments where water is
becoming a valuable resource and conservation techniques are becoming more of a priority in the community. The use of plants and the process’s to remove waste (Amirkolaie) from fish production reduces environmental impacts that could result from intense fish production.

These existing technologies, although they use water in their systems, do not use large quantities in comparison to current techniques such as irrigated farming, which can be subject to the environment and associated water evaporation. The use of hydroponics and aquaponics techniques are able to reduce their water usage between 99% (in almost laboratory conditions) (Borras) and 50% (quantified against plant usage only) (Watch) while still being outside in similar environments to irrigated farming techniques. As these systems can provide large reductions in water usage, a review from an automation perspective should take place and if automation techniques could aid in large-scale commercial production.

Aquaponics systems can produce crops profitably (T. Vermeulen, n.d.), although the crops in which they are producing successfully can limit the markets in which they are able to supply and compete in. This is due to established limitations either from biological restrictions or from nutrient availability restrictions in the process, which can limit varieties of plants produced.

Most mid to small aquaponics systems will initially begin to operate their systems between pH of 6.8 and 7.2 (Ecolife), although this sets limitations on the amount of fish due to ammonia build up within the system. The higher pH requirements normally above 7 pH to lower ammonia levels, can limit the commercially successful aquaponics crop varieties to green leafy varieties such as lettuce (James E. Rakocry), chard, kales, Chinese green vegetables, Bok and Pak Choi
or watercress or herbs like Basil. Research into RAS aquaponics systems has determined that there are not enough available nutrients in aquaponics (N. Vergotr) systems to commercially grow fruiting plants such as tomatoes. This has been verified by additional research, which noted that the poor quality of fruit produced in aquaponics could be measured by the dry weight of tomatoes in aquaponics versus hydroponics that resulted in “22 grams/kg dry matter versus 40.8 grams/kg,” (Andreas Graber, 2007) which was determined to be from nutrient limitations.

There are differences in the systems as aquaponics recycles waste from fish excrement that is consumed by bacteria, which absorb some of the nutrients in this process, which can bind up some of the nutrients and become part of the Total Dissolved Solids (TDS). Hydroponics solutions on the other hand introduce the nutrients into system in an (Nga T. Nguyen, 2016) ion form, which also allows the nutrients to be measured with simple electrical conductivity metres. The research of Dr Rakocy from the University of Virgin Islands (UVI) recognised that nutrients still needed to be added such as (Rakocy, 2013) potassium, calcium and iron in the aquaponics process. This research also identified that feed rates could be used of (Rakocy, 2013) between 60–100 grams of feed introduced into the system to feed a square metre of plants such as basil. The experiments carried out by Rakocy also used a design referred as the UVI system, which used a solids clarifier to capture and removed solids from the system. Another criteria that was identified by this research was that mineralisation increased the acidity of the effluent and pH buffers are required such as calcium or potassium.

Lennard & Leonard, 2006 researched the amount of dissolved oxygen in different system types that plants require per day and the amount of dissolved oxygen
(Wilson A. Lennard, 2006) that would be required for the bacteria, to change the ammonia to usable nitrates for the plants, which remained equal across different system types. Lennard’s work also includes alkalinity buffering agents to be added to the water to be utilised during the nitrification process and also reduces the feed per square metre to (Wilson Lennard) 16 grams and if the plants are reduced from 30 lettuces to 25 grown in a square metre would reduce feed to 13 grams per square metre. These figures rely on the amount of nutrients being treated and the amount that can be recovered in the process.

The proposed thesis will look at control techniques to make established conditions possible with an engineering approach that treats the system as a process with ranges that need to be met for the system to remain productive. Automation and control can function as both measurement and adjustment to the system on a constant basis, some of the conditions that would normally be difficult to maintain in a system would be contained within the desired range. Process control with automation is able to increase the complexity of the control parameters, which can allow Multiple Inputs and Multiple Outputs (MIMO) to be measured and controlled to achieve desired ranges. The use of ranges that have been established in aquaponics and hydroponics with known viable results can be used to develop a control solution that could overcome some of the limitations that aquaponics operators must tolerate. Currently these parameters can rely on biological process to obtain established system ranges by controlling the system by balancing the nutrients with the amount of fish feed that enters the system in comparison to the amount of plants that are in the system. This approach can restrict other components of the system and compromises are required to keep the system balanced to meet the biological requirements.
Automation techniques could also add alternate methods of controlling these nutrient levels, by adapting current or existing technologies from other industries. These control techniques could aid in controlling both the inputs and the outputs of the system with the use of instrumentation, measurement, and automation control. These control strategies would not just include adding additional nutrients to meet the needs of the plants but recycling those currently present in the system to reduce waste as much as possible, by streaming them into other independent control loops.

As the fish do not need certain nutrients in their diet, they are not added to the fish feed and have to be added to the water to create conditions that can grow crops successfully. Yet as there are dissolved solids in the water from the fish waste, it can be difficult to add large quantities of additional dissolved nutrients as the water quality would be diminished. As part of the process, ammonia from fish waste is also produced and must be removed, as it is toxic to fish even in very small quantities. The ammonia is converted by bacteria into different forms firstly nitrates then nitrites, which is safe to fish at certain levels. This process also produces carbon dioxide, which also introduces chemical processes. The bacteria also has optimum ranges in which it can carry out its biochemical process, which includes temperatures and a range of pH’s (Ecolife). The fish also have some particular water quality requirements that can also include the amount of (Lennard, Aquaponics System Design Parameters: Solids Filtration, Treatment and Re-use, 2012) suspended solids and preferred levels of dissolved solids within the water for them to remain healthy and productive.

Fish can survive in a variety of pH levels depending on their species with most able to survive in ranges of 6.5 to 8.5pH (Nations; FAO, Bacteria in Aquaponics, n.d.), although there are species that can live in ranges below and above this range.
such as tilapia, which can survive in as little as 6.0 pH. Some carp and catfish varieties can survive up to ranges of 9.0 pH. However, the nitrifying bacteria prefer to be above the 7-pH range to work efficiently, (Wilson Lennard) with optimum ranges between 7-pH to 8-pH. This factor can limit the range otherwise the water will become toxic to fish as ammonia levels will rise no matter what species of fish is used within the system. Alternatively, there would have to be a lowered number of fish density in the system, which would not be optimum for system production rates or an extremely large nitrification tank would need to be constructed to maintain the system.

![Bacteria Preferred Ranges](image)

**Figure 1 Productive Nitrification Levels.**

The process ranges of plants however differ from the requirements of certain species of fish and nitrification bacteria (Figure 1) and the requirement can be much
lower than that required in soils for the plants to have full availability to nutrients. Nutrients such as “Mn, Cu, Zn and especially Fe are reduced at higher pH” (Bugbee), although this nutrient availability is only reduced it can be important in more (Larry Cooper, 2015) complex fruiting vegetables to consistently grow fruit that is of uniform size without deformities for the product to remain marketable.

![Plant Preferred Ranges](image)

**Figure 2 Plant Nutrient Availability.**

Although there are differences in the ranges between plants and bacteria, (Figures 1 and 2) these system requirements alone, do not stop commercial aquaponics operators from producing a variety of crops that are normally green leafy varieties. Although operators will look for a compromise between these ranges, even though they recognize (Chito F. Sace) “the pH was disadvantageous to vegetables.” Automation techniques could also be utilized that are able to move nutrients into sub
systems of the process that are not subject to the same limitations, such as pH (Konrad Mengel) which can restrict nutrient uptake by plants.

3.1 Process Ranges

3.1.1 Plants

The plants in an aquaponics system utilise the nutrients that are in the water to take up the nutrients via their roots to feed the plant. The solution is made up of various nutrients and is often referred to as the hydroponic solution. The plants need 16 elements in various levels of concentration to grow at their optimum levels, which include (Latham, n.d.) “nitrogen, phosphorus, potassium, calcium, magnesium, and sulphur”. While there are other nutrients supplied in smaller amounts referred to as micronutrients which include (Latham, n.d.) “iron, manganese, boron, zinc, copper, molybdenum, and chlorine are also needed but in very small amounts” while air and water are able to supply others. The plants are able to absorb these nutrients from the hydroponic solution, yet they are only available to the plant in certain pH ranges. These pH levels are at lower pH levels than vegetables normally grown in soil, which are normally (Bickelhaupt, 2017) around the 6.0 to 7.0 range.
The hydroponic solution (Figure 3) requires the pH to be a lot lower in pH of values around 5.5 and up to 6.2, which are lower than soil (these values can vary with the type of plant to be grown). The types of plants to be grown have different nutrient requirements and different pH levels allow absorption of specific nutrients such as some of the micronutrients at lower pH levels. Access to some of these micronutrients (Larry Cooper, 2015) are important to more complex fruiting vegetables to form fruits that are not deformed and produce uniformed sizes for marketability of the product.

### 3.1.2 Bacteria

The nitrogen cycle within an aquaponics system is what turns the waste from the fish into a form of nitrogen that can be accessed by the plant for it to feed sustain and to grow. The earth’s atmosphere contains (Boundless, 2016) 78% of nitrogen yet it is not accessible to plants in this form and must be altered before it can become
available to the plant. The plants (Sambal's, 2015) utilise this nitrogen (1 of 5 elements) to form a substance called chlorophyll, which gives leaves their green colour. This chlorophyll (Sambal's, 2015) combines water, carbon dioxide, and sunlight to produce sugars in a process called photosynthesis. There are two main types of nitrifying bacteria that transform the alternate forms of nitrogen into a usable plant form, the fish excrete waste in the form of ammonia. As there are alternate forms of bacteria the nitrogen must go through two steps before the plant can take up the nitrogen.

The first type of bacteria in the process is the (Paul C. Burrell, 2001) Nitrosomonas bacteria type, which change the ammonia by oxidizing the ammonia into nitrites. The second type are the nitrite oxidizing bacteria, which change the nitrites into nitrates, which are available to the plants, these bacteria are the (FAO, Bacteria in Aquaponics, n.d.) Nitrobacteria bacteria.

- “AOB bacteria convert ammonia (NH₃) into nitrite (NO₂⁻)” (FAO, Bacteria in Aquaponics, n.d.)

- “NOB bacteria then convert nitrite (NO₂⁻) into nitrate (NO₃⁻)” (FAO, Bacteria in Aquaponics, n.d.)

These bacteria are slow to inhabit a system and take weeks to establish themselves at adequate levels within an aquaponics system. This factor must be considered when starting up any type of aquaculture or aquaponics system, as if these bacteria are not present. As fish are introduced into the system, ammonia can build up to toxic levels very quickly and lead to fish kills and failure of the process, yet can be mitigated by the cycling of water.
The time it takes to introduce these bacteria is referred to as cycling (Figure 4) and can be sped up with the introduction of ammonia and bacteria into the system before any fish are introduced. Once the bacteria establish themselves they can be seen as a brown (Imran Ali, 2014) slime on surface areas and will establish themselves throughout the system, where there are surface areas for them to attach. The nitrifying bacteria also need other environmental elements for them to establish in healthy numbers, the bacteria are sensitive to light whilst establishing and prefer not to be exposed to direct sunlight. The bacteria also prefer temperatures of between (FAO, Bacteria in Aquaponics, n.d.) 17 – 34 Degrees Celsius with pH values of between 7.2 – 7.8pH for Nitrosomanas and 7.2 – 8.2pH for Nitrobacteria.

The other environmental condition these require is a healthy supply of dissolved oxygen, as the bacteria require oxygen as part of the oxidation process, which feeds the bacteria and changes the structure of the nitrogen. Fish and bacteria also require dissolved oxygen for their survival and levels of between (Simon Goddek, 2015) 4 – 8 mg/litre, are considered optimum for the (FAO, Bacteria in Aquaponics, n.d.) bacteria’s survival. If the level of dissolved oxygen falls below
(Alenka Prinčič, 1998) 2 mg/litre the nitrification process stops and the process becomes at risk of toxic levels of ammonia and nitrites.

The nitrification bacteria attach themselves to surface areas, which provide a home for the bacteria, the bacteria require (Burke, 2014) high specific surface areas to establish large colonies. One way to increase the surface area size is to utilise items within a specific tank that have large (James M. Ebeling P., 2006) surface areas such as volcanic rocks, clay, bio filter balls which can be made into variable sized plastic balls.

3.1.3 Dissolved Oxygen

The aquaponics process relies on dissolved oxygen being present throughout the process. The fish in the aquaponics system require minimum values to be present not just to survive but also to remain (Hijran Yavuzcan Yildiz, 2017) healthy from disease in a low stress environment. The nitrification process also consumes dissolved oxygen to change the ammonia into nitrites and nitrates. Plants also compete for dissolved oxygen in the effluent. Aerated (Hendrik Monsees, 2017) aerobic mineralisation also takes oxygen for the bacteria to digest the solids, these solids can take several steps to break down, and even after they become soluble, they may not necessarily be plant available. If media beds or mineralisation (further explanation of this process component in additional sections) is utilised in the system and have oxygen demand, attention must be payed to oxygen levels to prevent any anaerobic conditions (FAO, Bacteria in Aquaponics, n.d.) in the tank, as larger organic molecules can be present using oxygen as they travel around the system.

As different components of the process use oxygen, there are also different methods of adding dissolved oxygen (Wilson Lennard, Solids Filtration, Treatment
and re-use, n.d.) which should be considered that could benefit that overall part of the plant. The addition of pure dissolved oxygen to the water before it goes via the fish tanks to increase the density in the fish tanks. This thesis however is more focused on automation methods and how the process could utilise nutrients with the use of automation, however process expansion will be considered when making design choices to limit capital impacts if the process requires increases in fish production to respond to market demands. Mixing in the process by agitation was considered initially yet can be expensive as the electricity costs can be high, which has led to the development of various types of bubble diffusers (Mooers, 2013) which are able to supply a greater exchange of gases due to the larger surface area of the numerous bubbles. Blowers that are able to supply air on a constant basis once they are operating can supply these diffusers. Compressors on the other hand are able to supply air via pressure control valves and can (Kaeser, 2007) supply multiple items that may need pressurised air at various pressures. The other advantage of using compressors is that they are able to store compressed air, which has the advantage of being able to supply the system during a power outage even if only for a small period, yet potentially could prevent a fish loss during this time. A fish loss could be a (Hambrey, 2013) large financial loss on a process which could cause 10’s of thousands of dollars of financial losses in a single incident which could financially ruin an operator.

Diffusers that release bubbles come in different bubble sizes such as fine or coarse and can be designed to operate under harsh conditions such as the wastewater industry. The fine (Narapong Hongprasith, 2016) bubbles allow greater gas exchange due to the greater increase in the surface area. The course bubbles are used where there is a requirement to agitate the solution as well as supply gas exchange. Another
consideration should be where they are going to be placed, as diffusers need space from the bottom of the tank, which could allow solids to settle and create an anaerobic zone. This could be designed out of the process by using technology such as diffuser mats that line the bottom of the tank to prevent oxygen deficient or dead spots being created underneath diffusers, including those areas that use finer bubbles where less agitation would be present.

3.1.4 pH

The pH in the system is a measure of the hydroponic fluids (water) acidic or alkalinity with 1 on the range being the most acidic and 14 being the most alkaline, while 7 is considered neutral. The pH of the system is monitored with the use of pH probes and meters, local meters or transmitters that can interface to such items as Distributed Control Systems (DCS) or Supervisory Control and Data Acquisition (SCADA) system, which can display and alarm desired ranges.

The fish, plants, and bacteria all have preferred ranges for them to survive in, they can also have preferred ranges in which they are most productive. Plants can have different pH requirements so they are able to take up different nutrients at different pH’s to grow either their leaves steams or fruits. This is similar to bacteria which will grow and survive at different pH’s yet have known values which they will perform at the most productive to oxidise ammonia or change nitrites into nitrates. As the performance of the system can rely on the levels that are present, the levels at which they are controlled is very important.

There are a number of processes in the system that influence changes to the pH levels with the following being addressed as part of the process control solution;
• The amount of alkaline nutrients (Simon Goddek, 2015) that are added to the system have a natural alkaline effect.

• Another is the bacteria that break down solid waste (James E Rakocy) and ammonia that is supplied from the fish feed and its associated waste products produce Carbon Dioxide.

Carbon Dioxide dissolves in water has an acidic effect in the water and results in changes to the pH of the water, which can reduce the effectiveness of the bacteria that are aiding in the process of transforming ammonia to plant available forms. Carbon dioxide is also toxic to fish with most species not being able to go above 20 ppm (Swann, n.d.) (tilapia can survive in up to 60 ppm).

3.1.5 Control pH

The pH can be monitored and be controlled through a number of strategies that could include both chemical and by carbon dioxide stripping with the use of (L Dediu, 2012)degassing tank or column/towers.

The monitoring of both carbon dioxide and alkalinity content within the water allows the operator to determine treatment of the water. If the alkalinity nutrients (Simon Goddek, 2015) (“based on Potassium, Calcium and Magnesium Compounds”) are at certain levels, there can be a predicted pH level, additionally if the (Bjorgvin Vilbergsson, 2016) carbon dioxide levels rise the pH will fall.

The other is that carbon dioxide is removed from the system if it is aerated as it naturally equalises with the air that is passed through the water. As the air passes through the water oxygen is dissolved in the water as carbon dioxide and Nitrogen are passed into the atmosphere. Carbon Dioxide can also be stripped from water by
mechanical processes or with the use of carbon dioxide stripping towers, which can be calculated to size through a set of known data that is based on the number of fish and the amount of feed that is introduced into the system. Carbon Dioxide can also be stripped out of the water by increasing the aeration at various stages of the process until it is brought within optimum ranges.

If alkalinity levels fall, it could be appropriate to increase the dosing rate to bring into the desired range (BAQUE), or leave it at current levels if it is within the desired alkalinity levels.

3.1.6 Sodium Control

The addition of salt into a system will eventually add up to levels that will not fall into ranges that are optimum for plant production. The levels of salt could also build-up if nutrients are being captured into a concentrate, which could also unintentionally concentrate the salt from the aquaponics effluent. Salt in the aquaponics water in (Louis A. Helfrich, 2013) small quantities is acceptable and in certain circumstances used to treat fish if diseases have entered the system. To control the salt levels in both the aquaponics and hydroponics systems, sources that introduce it should be managed. Traditional aquaponics systems use a fishmeal product or fishmeal based product to feed the fish in the system.

Fishmeal comes from waste from the fishing industry, which is cooked dried and made into a powered or pelleted product (the oils can also be separated during this process). Fishmeal has been referred to as a sustainable fishery as it is produced from waste yet this is controversial (Newman, 2014) and is contested in many forums. The fishmeal has high levels of protein that is useful in an aquaponics system as it allows for optimum growth of the fish. The fishmeal however can also contain salt as
it normally comes from salt-water waste products such as unintentional fish bycatch. The salt and sand levels in poor quality fishmeal can approach 1 to 4% (Station) of the total meal within the feed supply. High quality fishmeal can contain less than 1% salt, although this can be lowered if the fishmeal is mixed with other products.

Fish feeds (Cant, 2007) can be based on lupins or soybean mix that has proven palatability for different fish species. These products have high protein availability and percentages, which can exceed the requirements for optimum fish growth. To obtain palatability of the feed product for different fish species, a small percentage of fishmeal is added to the feed, yet at much lower levels to traditional fishmeal based feedstock. There are some additional benefits to the feedstock being based on lupins or soybeans besides their high protein content. Lupins also contain very low salt levels in comparison to fishmeal with (Coorowseeds) mean weights of 0.4 grams per kilo. In addition, the cost to produce lupins is approximately 45 percent (Coorowseeds), while soybean is approximately 60 percent in comparison to fishmeal, although this can fluctuate with spot prices of products.

The other benefit to using plant based fed products is that the lupins or soybeans also naturally contain a range of micronutrients including non-essential micronutrients that might normally need to be supplemented in an aquaponics/hydroponics systems.

3.2 Design Components

To gain a better understanding of equipment that have been successfully incorporated and designed for use in an aquaponics system including their current design parameters. An investigation was carried out to find some of the components that are already used successfully in aquaponics design solutions.
3.2.1 Baffles - Solids Separation

The solids within the aquaponics solution must be removed from the main stream as these can foul pipes and fittings and build up in areas and create anaerobic conditions, which can harm the system.

Clarifiers have been utilised in the successful treatment of the wastewater industry to capture and treat solid wastes. In wastewater treatment, flocculants (protein chains) are used before the wastewater enters the clarifier in the process to remove solids that are suspended in the water by the solids attaching themselves to the protein chain and falling the bottom of the clarifier (Maine, 2009) with the aid of gravity. Flocculants and belt filters have been tested in aquaculture waste management with them being able to (James M.Ebeling, 2006) remove 82% solids and “sequestering reactive phosphorus (92%)”. This amount of removal of solids from the process is not practical in the main aquaponics system as solids contain the minerals/nutrients that are required to feed plants.

There has been the use of baffles installed in clarifiers to separate the solid wastes from the aquaponics solution, which is referred to as the UVI clarifier (University of Virgin Islands who developed the clarifier).
Figure 5 UVI Filter (State, 2017).

The UVI clarifier uses water that is pumped at a 45-degree angle towards a baffle, (James E Rakocy) approximately 50% of the solids then settle on the bottom cone section for collection at the bottom of the tank. This type of filter is designed to capture the larger solid particles that are able to settle on the bottom of the tank, although further treatment is required to remove smaller solids that are suspended in the aquaponics solution.

3.2.2 **Swirl – Solids Separation**

Solids in an aquaponics system will build up if left unchecked and will form layers of sludge in the system, which will become anoxic, which could poison or kill the fish in the system. The solids come from left over fish feed, organic matter from plants or even algae within the system, which consume dissolved oxygen and release the system of valuable nitrogen while producing other forms of toxins. In a commercial process where decreasing fish numbers to combat this issue is not realistic, the implementation of water quality techniques must be designed as part of the process to balance the system and allow for commercial scale fish stocks.
As solids are considered a resource in the aquaponics process there must be an allowance in the process to remove these for further treatment. The removal of solids allows them to be separated for mineralisation by bacteria, into a form that can be taken up by plants. The removal and treatment of these solids also allow for greater levels of water quality for the fish to survive and grow in. There are two main types of settling filters used to remove suspended solids in aquaculture systems the swirl filter or the radial flow filter.

Swirl filters are commonly used by operators with small to medium aquaponics systems and have used these with success in these systems, the influent is pumped in parallel with the tank to begin a slow swirling motion in the tank. The solids are allowed time to gently swirl in a spiral action, which assists with the solids settling at the bottom of the tank for removal. The design of the swirl filter often has a cone shape at the bottom of the filter to collect and funnel the solids down to a single point for collection. A radial flow filter as shown in Figure 6 allows flow of the effluent into baffles located in the centre of the tank and the solids settle at the bottom of the tank for removal.
Figure 6 Radial Flow Settling Filter (Technologies, n.d.).

Experiments with the use of both swirl and radial filters show that the radial settling design removes a greater amount of total suspended solids, than the swirl filters. The results from this study showed that the radial filter removed (John Davidson, 2005) 77.9 % of the total suspended solids, while the swirl separator removed 37.1 % of the total suspended solids.

3.2.3 Mineralisation

A mineralisation tank is utilised to treat the solids in the aquaponics solution. Mineralisation can be done by either of two methods the aerobic or anaerobic process.

The anaerobic mineralisation or digestion of solids by bacteria is done without the presence of oxygen. The bacteria in the (Conrado Moreno-Vivián, 1999) anaerobic process can use nitrogen instead of oxygen to carry out digestion, which is
counter intuitive to aquaponics as nitrogen is a resource. The anaerobic process also releases toxins and bacterial strains that are deadly to fish, for this reason it has been discounted as part of a possible design solution.

The bacteria in the aerobic process use oxygen to grow, reproduce, and feed on the organic solids that are present in the aquaponics solution. The aerobic process uses oxygen, which would already be present in the aquaponics solution, as it is required to be maintained for fish and plants. The oxygen levels are maintained by introducing air into the system, by either agitating the liquid or injecting bubbles of air into the fluid with either an air blower or compressed air.

In wastewater treatment, an extended aeration aerobic process normally takes 24 hours (Michigan, n.d.) to establish good quantities of bacteria that digest or breakdown the solids within the fluid. This however would be impractical, as holding the fluid could either restrict the treatment of water or make the tank extremely large. Wilson Lennard PhD (Wilson Lennard, Solids Filtration, Treatment and re-use, n.d.) has taken the process offline to treat solids over a longer period. If the solids are withheld in the process stream for treatment, the fish are not being supplied with a constant supply of clean water that could possibly lead to fish deaths due to the build-up of ammonia in the water.

3.2.4 Nitrification

Aquaponics nitrification tanks (James M. Ebeling P., 2006) are designed specifically to provide an increase in the surface area of the process for the nitrifying bacteria to oxidise the ammonia into a usable form for the plants. The bio filter design relies on there being adequate dissolved oxygen supplied to the nitrifying bacteria to
optimise the nitrifying process, this design must also not allow deoxygenated spots to build up in the tank.

There are many types of nitrification tank designs available and tested, including works by James Ebeling Ph.D. (James M. Ebeling P., 2006). The designs are to treat nitrates from water supplies as well as being incorporated into aquaponics systems. These methods can include trickling bio filters, which rely on the aquaponics solution being trickled over media within a tank. This media can be made up of crushed rocks, plastic packing materials or specialised bio balls shown in Figure 7, beads, or even sand to increase the surface area within the tank.

![Figure 7 Increased Surface Area with Plastic Bio-filtering (Watertech, n.d.).]

There are also mechanical operated designs (Figure 8) that used a rotating biological discs that rotate at 1 to 3 RPM’s in the solution with half of these in the solution and half out of the solution. The discs are exposed to air, which provides oxygen to the biofilm that is present on the surfaces of the disc as it rotates both in and out of the solution.
The rotating bio discs are constructed with discs, which supply an increase in the surface area. This type of nitrification tank design has the advantage that it allows for gas exchange as it rotates through the air, this includes the exchange of oxygen into the solution but also carbon dioxide to be removed into the atmosphere.

Up flow fluidised sand bio-filters are similar to a pool sand filter although are built on a larger scale can also be used as a nitrification tank within an aquaponics system. These tanks pump water up through sand or small plastic beads that have a large surface area of over 4000 m2/m3.

This type of filter uses large pumps to pump the solution through the sand and can be subject to fouling from solids within the solution, besides taking additional power to operate the pumps this system can also be susceptible to mechanical failures. The Upflow Sand bio filters however have the advantage of being able to be scaled to suit large commercial aquaponics systems to treat ammonia that are produced within these systems.
A technique used by the water treatment industry to nitrification solutions is a technique known as Moving Bed Biofilm Reactors (MBBR), which utilise similar plastic packing as a trickle bio-filtering tank, which are suspended inside a tank. The nitrifying bacteria establish themselves within the bio-filtering media and attach themselves to the inside of the media, which can allow for populations of the bacteria to establish themselves without any settling or holding time within the tank.

![Moving Bed Bioreactors (MBBR)](image)

**Figure 9 Simplified Moving Bed Bioreactors (Palayesh, 2015).**

The bio-filtering material is suspended in the tank and aerated to supply an available source of oxygen to the nitrifying bacteria that grows on the bio-filtering media. The media is contained within the tank by sleeves on the outlet of the tank, yet allows the solution to flow to next part of the process with little or no maintenance. This type of nitrification has some benefits as the media can be (Palayesh, 2015) packed from 30 % to 60-70% density within the tank, which allows for easy growth of the reactor by adding more media into the tank, which increases the surface area of the bio-filter. The other advantage of an MBBR is that as the media is agitated it allows the outside of the media to be scrubbed and excess biomass comes loose and
prevents the media from clogging with biomass. This process is able to self-maintain the biomass, which is captured with a downstream clarifier for further removal and treatment in the mineralisation tank. The media that is used for this type of process has an internal surface area normally referred to as the protected area, which can exceed the 400 m2/m3 (Watertech, n.d.).

### 3.3 Nutrient Removal

Controlling the amount of nutrients in comparison to the amount of fish food entering the system versus the amount of plant growth area to control the nutrient levels within the aquaponics system has been used to size aquaponics systems. This data is relevant in the sizing of the process and the components that can feature in water treatment, however this thesis is focused on automation and control. Automation functions that can be utilised to control the parameters such as nutrient levels within the aquaponics system will be researched to find alternate control solutions than just the amount of fish feed entering the system to control the nutrient content in the system.

There are established data on solutions (Rakocy, 2013) that are contained within successful commercial aquaponics systems (which mostly grow green vegetables, as the nutrient mix is suitable for this purpose). There are also established hydroponic mixes that are used commercially to grow fruiting vegetables, although some of these mixes can be proprietary especially if the resulting fruit is consistent in size and shape as these are much more easily marketed, making the process solution competitive. As the author is approaching the aquaponics system as a process with established ranges that need to be met, this will involve the use of effective yet efficient mechanical or electrical processes. This is not just to keep the nutrient levels
constant within the system but also to move nutrients to a separate hydroponic system, which can control the nutrients at established solution levels.

The removal of nutrients from the aquaponics system has some obvious benefits besides keeping the aquaponics system at safe and consistent nutrient levels for fish production. They can also be used to supplement the hydroponics system that operates at different nutrient levels or at a solution that requires different pH levels, which can make use of established nutrient recipes to grow different types of fruiting vegetables on commercial scales.

Nutrients can be stored, for use when required such as between a plant or crop cycle then re-introduced into the system as a batch with the required nutrient mix, thus supplying an additional resource from fish production and reducing additional nutrient inputs into the hydroponic system.

When comparing the nutrient solutions used in an aquaponics and hydroponics one of the most obvious differences between them is that the hydroponic solution has a larger quantity of nutrients, in comparison to available nutrients in aquaponics systems (this is required to grow complex fruiting vegetables instead of green leafy vegetables). Nitrate levels are much higher in hydroponics solution in comparison to the aquaponics nutrient recipe, as the aquaponics system also must take into account that the fish are part of the process. As the process control in this part of the process relies on nutrient removal, the recipes are considered when selecting a means to move the nutrients within the process. To remove the nutrients from the aquaponics solution research of existing technologies was done to find an existing technology that could be adapted to remove the nutrients safely in a sustainable manner. To keep within the principles of sustainable technology the use of chemicals was considered when
researching different types of technologies, as such chemicals and the way the technologies use them was closely scrutinised. The technologies used mainly for desalination purposes were initially researched, as the technology is mature and details are readily available from various case studies.

3.3.1 Reverse Osmosis

Reverse Osmosis systems were considered by the author as the technology is readily available along with various studies including those carried out by Xie (Xie, 2015) to clean wastewater, this technology is commercially available and a mature product (cost competitive). Most reverse osmosis systems use (Bhausaheb L. Pangarkar, 2011) high pressures to pump influent through a membrane to produce a clean solution and a concentrate solution. This technology does require reasonable high pressures to pump the solutions through the system, which requires a lot of energy and is not ideal in a sustainable engineering solution. Reverse Osmosis systems require (José Miguel Arnal, 2011) chemicals to clean the system (which can include chlorine), which could contaminate the water and kill the bacteria that prevent ammonia and nitrites building up to toxic levels. This could lead to a fish kill if this type of contamination event was to take place in the aquaponics system.

3.3.2 Electro dialysis

Another technology the author considered is the use of electro dialysis, which can operate at low pressures and has quite a low energy consumption when in operation. The system is used in water treatment where the total suspended solids (Amit Sonune, 2004) can be quite high without negative effects on the system. Electro dialysis is cleaned simply by reversing the polarity to clean the system without the use of any chemicals known as Electro Dialysis Reversal (EDR). This system would be
able to reduce the nitrates in the aquaponics solution from anywhere between 50% to over 90% (Elyanow, 2005). This process produces two different streams a dilute stream and the other containing a concentrate stream that normally contains less than 5% of the original solution, yet can contain over 90% of the original nutrients. This concentrate is indiscriminate in the other types of dissolved solids that it removes from wastewaters. This would mean that the concentrate solution would have similar ratios of nitrates to minerals, as the dissolved solids ratios would be similar to the influent of the process.

3.3.3 Selective Electro Dialysis

As a more novel approach may be required to obtain the level of control required to move nutrients within the system, further research was required to find an electro dialysis system that could be adapted to the process. The membranes used in the electro dialysis (M. Pirsaheb, 2015) process has been the focus of research in recent years to reduce nitrates from well water to aid in reducing nitrates to safe drinking levels. The nitrates that contaminated the well water entered the environment from fertilisers used in farming techniques and practices, which can led to (Alyce M. Richard, 2014) medical issues from drinking the water with these high nitrate levels.

The process that was developed to overcome this nitrate issue in the water is referred to as Selective Electro Dialysis (SED), this technology could be adapted for use in other systems such as aquaponics. The selective membranes only remove around 30% of the total dissolved solids (minerals in the aquaponics solution) and 59% (Vivian B. Jensen J. L.) of the nitrates into an almost 5.7% concentrate solution. This is not as efficient in the overall removal of nitrates in comparison to an EDR system, it should be highlighted that to control the nutrient limits within the system is
to lower the nitrates, not eliminating them altogether. It should be also noted that with having control over the solids within a mineralisation tank allows for control over most of the nutrients entering the system from waste products.

The nitrates however enter the system mostly in an initial ammonia dissolved form, which would only allow control to take place by controlling what enters the system (fish feed). Having an alternate method of controlling the dissolved or liquid nutrient allows for greater control of the system and allows recycling and distribution of these nutrients in a plant available form.

A case study of an operational process in Israel (Vivian B. Jensen J. L.) which has similar effluent inputs, it was noted that it took only 0.6 kW/h of energy to treat a cubic metre of solution to recover 94.3% of nitrate-reduced solution and approximately 57 litres of concentrated solution. Although this system would only be required to treat part of the aquaponics solution, as it approached the 45 ppm to lower it towards 35 ppm to keep it within desired ranges of established aquaponics recipes.

The pH of the concentrate would also be much lower, because the process uses an acidic base on the concentrate side of the membrane to prevent calcium build up, and keep it operating at optimum levels.

3.4 Systems Selection Discussion

3.4.1 Recycling Nutrients

Traditionally aquaponics nutrients that are contained in solid waste are removed from the system through a series of settling tanks that can be of a baffle design or clarifier design such as swirl or radial clarifiers. These designs have been trialled in many environments (Jason J. Danahe, 2013) including aquaponics and has
proven to successfully remove solids to preferred levels. There are other techniques such as mechanical separators that can remove solids from the aquaponics cycle very efficiently with up to 75 - 90% (James M. Ebeling) of the solids being removed with these designs. As the process would be constantly altering, with fish harvests or crop rotations and natural seasonal changes that could affect growth rates and requirements of both fish and plants, the requirement for solids recycling in the system would be constantly changing. This would change the amount of solids that would be required to be removed from the process or the amount that could be treated and incorporated back into the system. A combination of these techniques are used to remove the solids into an offline process for treatment. If the process did not require the addition of solids, mechanical means could then be used to remove these totally from the system.

In conjunction with mechanical removal, there are also existing techniques from the wastewater industry that are able to decant water from the solids nutrient stream. When additional dissolved nutrients can be utilized, the decanting process could be put in line with the process making the process able to be both online and offline for effective removal, treatment or reintroduction of nutrient solids. The solids that are totally removed from the process as waste should be treated as a value-adding product, not just as waste and could be on sold as organic fertilizer or to compost manufacturers to enrich their products with nutrients.

Normally a Recirculating Aquaponics System (RAS) would be treated as a single closed loop, which must allow for all environmental conditions for biological processes to take place. As process control and automation can add additional functionality to the process, it could be broken up into more than one closed loop, with nutrient exchange taking place between the loops to supply cleaning of the fish
water but also provide conditions that allow a variety of plants to grow including fruiting vegetables to their full potential.

Recycling of the solids waste from fish that contain nutrients could be in the form of treating waste as a resource in an offline / online process then reintroducing as much as possible back into the process, as the system uses it (mineralization).

Control over the main system nutrients either by removal to the sub system or removal to recycling have some advantages to the main system.

1. The aquaponics system can be regulated with addition of nutrients from more than one source (increase-recycled nutrients reintroduced after a fish harvest to prevent any losses in leafy green plant production).

2. The aquaponics system could also have a much greater survival rate of fish (excess nutrients could be removed when larger quantities of fish/feed are present in the system).

Having control over the nutrients in a sub system that is not reliant on requirements of the main system also has some advantages.

1. The nutrients are being supplemented from the main system (maximise recycled nutrients from excess fish waste)

2. The restrictions of pH levels that can reduce the efficiency of nitrification bacteria are no longer a restriction in the sub system.

3. Plant nutrient uptake can be optimised by allowing for pH levels that are specific to the plants requirements (increase in successful crop varieties)
4. The Total Dissolved Solids (TDS) limitations for fish are not a requirement for the sub system and established nutrient levels for plant varieties can be introduced into the sub system (increase in plant production).

Measured nutrient values that are present in aquaponics systems and some of the nutrients that are deficient can be controlled by the addition of the missing nutrients. The same process of calculation and addition can be replicated on a much more regulated scale by measurement with instruments and control of nutrient dosing systems from control systems such as a Distributed Control Systems (DCS) or Supervisory Control and Data Acquisition (SCADA). These control systems and the technology they are constructed from is considered a mature technology (Stephen J. Sosik) and are produced by many manufacturers, which compete for market share making these systems relatively cost effective. Even minimalistic versions of SCADA have built in Proportional (P), Proportional-Integral (PI), and Proportional Integral Derivative (PID) controller algorithms (Stephen J. Sosik) that can control and maintain ranges such as flow, levels and even control the speed of pumps to keep flow rates at measured limits. This could also include other control techniques such as the monitoring of levels, which could control automatic starting or stopping of pumps, or the measurement of nutrient ranges, which could be increased or decreased by adjusting the speed of dosing pumps.

3.4.2 Nutrient Redistribution

Technology from the wastewater industry (Carlos Felipe Hurtado, 2016) has been utilised in applications for the aquaponics and aquaculture industry in the past, mainly to clean water of excess nutrients or remove salt from water. The technology has included the use of reverse osmosis units and low operating cost equipment such
as electro dialysis or reverse electro dialysis, which is able to automatically clean its membrane by reversing the process. This has predominantly been used to clean water so it can be used in a process or recycled back into the process to lower water usage rates.

However, the automation solution proposed in further sections of this thesis is focusing on controlling nutrient levels by lowering them to established ranges by removal of dissolved nutrients from the aquaponics solution to be reused in the hydroponic sub system. These would be at pre-determined nutrient levels required for the aquaponics system to remain successful, not to remove nutrients totally from the process. One such technology that could be adapted to this purpose is Selective Electro Dialysis (SED). SED has been developed for many industries, which includes membranes (Vivian B. Jensen J. L.) designed specifically to remove nitrates from contaminated water. These membranes transport ions and anions through membranes with the aid of a DC current, which attract or repel these nutrients. Along with the membrane design, the DC current allows certain percentages of different nutrients to pass through the membrane such as nitrates in slightly higher densities than the rest of the dissolved solids.

The SED moves nutrients that are dissolved in their ionic form and not those that are bound up in larger forms such as those contained in larger solids that have not been broken down. The dissolved solids continue in the non-concentrate stream, as the SED is designed to operate at specific pressures to prevent build-up on the non-concentrate side of the membranes. It also makes use of a pre-filter to remove suspended solids before entering the membrane. This allows further opportunity to control the level of suspended solids by sending any that are filtered to the
online/offline mineralisation tank for further treatment. The concentrate side of the membrane also needs to be kept clean which case studies show is normally from calcium carbonate, which would be present in the aquaponics system. A different process that uses acid dosing to prevent build-up of deposits or any scale that would form on the membrane achieves the cleaning of this side of the membrane. This however has the result of keeping the pH level the same or nearly the same on the non-concentrate side and lowering it on the concentrate side to values similar to plants requirements.

![Table]

Figure 10 Estimated Additional Nutrients (George J. Hochmuth) (Vivian B. Jensen J. L.) (James E. Rakocy).

Although this selective electro dialysis membrane does advertise that it removes 59% of nitrates and 30% Total Dissolved Solids (Vivian B. Jensen J. L.) the results of its percentage of removal rates are taken from an existing water treatment plant and represented in Figure 10. This is due to the system has more data on the actual percentages on a greater number of specific nutrient types, although it should be noted that the ones identified were all within a few percentage points. The original aquaponics recipe used as an example contains Total Ammonia Nitrogen/Nitrates (TAN) that would be transported to the hydroponics solution, which would breakdown and create additional nitrogen in the hydroponic mixture. TAN is
encouraged in some hydroponic mixtures and is not toxic to plants in small amounts as it can be to fish.

3.5 Typical Process Ranges

To design a process control solution known optimized values must be recognized to determine instrumentation that could be implemented into the systems. As there are also requirements for particular fish species one will be chosen as a base point to be used to design parameters to, as the author lives in Australia a non-evasive species such as Silver Perch is selected as a basepoint to determine levels which are illustrated in Figure 11.

Figure 11 Requirements Overview (Ecolife) (George J. Hochmuth) (Zealand, 2000) (Fisheries, 2012).
The total nitrogen that is present or measured in an aquaponics system (Wilson Lennard) does not represent the total nitrogen that is available to plants as bacteria absorb it. There is also no data on bacterial exchange through the Selective Electro Dialysis (SED) process, and these bacteria can absorb or contain nutrients, including nitrates. The hydroponics solution which is expected to be ion based (additions to make up complete solution would be in ion form) and measurement may need to be treated similar to aquaponics solutions, with lower hydroponic solution recipes initially being applied until true nutrient availability can be determined. The hydroponic solution used as an example starts at (George J. Hochmuth) 70 ppm and eventually increases its nitrogen levels up to 150 ppm as the plant reaches different clusters.

A similar approach could be used until any of the Total Ammonia Nitrogen/Nitrates (TAN) that has entered the system is biochemically changed into nitrates (nitrification bacteria will survive in lower pH levels although are not as efficient), or taken up by plants. Although the hydroponic solutions have predicted levels of nutrients or hydroponic recipe, the nutrients could be in biological forms yet there are methods available to calibrate hydroponic recipes. The variances in nutrient forms would be mitigated and the recipe adjusted to suit the particular plant variety with a process referred to as (Self, 2013) plant tissue testing.

3.6 Additional Component Research

The recycling of nutrients would be beneficial and a method to control these could be to isolate the solids by a number of passive process’s (settling) then remove them to a single mineralization tank where solids could be removed as required by mechanical means. This however presents a challenge, as the tank would need to be
decantered of excess water while the dissolved solids are at lower levels in the system. Technology to allow this to take place has been developed by the wastewater industry which uses a floating decanter within the tank, which would allow removal of product to take place without the tank having to be full (gravity fed). Allowing the tank not to be full would allow for a greater amount of control over the amount of solids and how they are removed, treated or recycled back into the system.

This however also presents another challenge as the solids could be in greater concentrations than are normally present in aquaponics waste streams and typical methods of mechanical removal such as drum filters (micro-screen) might not be suitable, as this type could clog with excessive concentrations of solids. The micro-screen typically has a cloth filter that is sized between 40-100 microns (Bregnballe, 2015), which removes waste from the process by mechanical means. In this process design, the aim is to remove the waste by passive means (settlers and baffles) and only use mechanical means when total removal based on measured values is required. As the mineralization tank can be online or offline with the process a different type of filter would be required to contain levels within the mineralization tank if dissolved solids are at measured saturation point within the system. A filter that was developed for the pulp and paper/food and beverage/textile/agricultural industries to treat wastewater could be adapted for this purpose. The filter is able to cycle the solids concentrate from and back to the mineralization tank, remove solids to a single stream, and remove filtered water to another stream (Figure 10), which could be returned back to the process. This filter is also chemical free and is self-cleaning as part of its normal operation, it is also able to remove solids down to the 10-15 micron size.
The filter also advertises a high water recovery with up to “99% able to be returned back into the process, while also being energy efficient with a 0.25 to 2 PSI pressure drop across the filter” (DOW, n.d.).

This filter has been developed on a skid (Figure 13) with its own Human Machine Interface and associated programmable PLC, yet can also be integrated into a SCADA system with signals such as start and stop already incorporated into the
design. Other programmable features such as timers or tank levels and self-cleaning functions are already available and could be utilized to adapt this alternate equipment into the design.

### 3.7 Discussion

Conducting a study on the individual requirements and designing an alternate control solution that meets the identified ranges could highlight that some of the compromises that are currently required to operate a Recirculating Aquaponics System (RAS) could be overcome and make it possible to grow vegetables with established hydroponics recipes. The systems may not necessarily be restricted to compromising between the different biological requirements of fish, plants, or bacteria but could be separated into alternate control loops. This could allow control loop requirements for segregation such as pH levels, which could be achieved by only transferring nutrients between control loops instead of allowing flow from one control loop to another. This segregation between loops also allows for temperatures of one system not relying on another system, which could allow for fish production or plant production to be independently supplied with optimum ranges.
CHAPTER 4. PROPOSED CONTROL SOLUTIONS USING STANDARD DESIGN METHODS

The second part of the thesis is to identify a control solution to some of the current limitations that are present in current systems. This will be achieved by using established design techniques such as an initial Process Flow Diagram (PFD), which will be followed up by a Piping & Instrumentation Diagram (P&ID) with an associated instrumentation/tag and alarm list, which will represent a design solution. The design solution will have an automation solution not represented by hardware, but by Human Machine Interface screenshots that represent levels, or nutrients levels. The field instruments that would be present in a practical process will be software driven to act as a simulation of the process. The automation control functions will be represented by IEC 61131-3 to operate a simulation of some of the processes required for control and monitoring.

The aquaponics processes are often perceived as relatively simple, yet if an unexpected event occurs can often have drastic financial consequences on new operators, which could be initially operating within tight margins. Standard techniques Hazard and Operability studies (HAZOP) are conducted by process and chemical industries to do systematic analysis on a process and its sub-systems. Many aquaponics operators are not familiar with these design processes (Nelson, 2013) and find design inadequacies after an event, which normally has financial consequences. This design process is able to identify disturbances that could lead to product deviation and identify hazards that could affect the environment. Identifying process issues and designing engineering controls to prevent or mitigate issues is carried out in multiple forms or design tools. Failure Mode Effect Analysis (FMEA) is one such
tool in a designer’s toolbox and is recognized as an international standard (IEC 60812), which describes techniques to analyse processes that can effect the reliability of a process or determine what possible hazards could be present.

The use of FMEA has been utilized by industries to aid in carrying out HAZOP design processes, the use of these design processes can lead to inherently reliable processes. Piping and Instrumentation Diagrams also referred to as Process and Instrumentation Diagram (P&ID) are used in the process industry to show an overview of the process. The P&ID also identifies instruments that could be required for measurement and any associated alarms that are present to warn operators and mitigate failures in the process.

4.1 Component Selection

![Diagram](image)

**Figure 14 System Selection.**

The integration of automation into systems that typically do not have high levels of automation can be challenging. A number of techniques could be utilized to determine design items that could identify control to be incorporated into the process.
Aquaponics is such an industry where Programmable Logic Controller’s (PLC’s) and monitoring have been incorporated although higher levels of automation such as SCADA or DCS control are not standardized. To design a functioning process and the associative automation a Process Flow Diagram was used to identify major components that are to be incorporated into the process. The Process Flow Diagram also aided in developing the Piping and Instrumentation Diagram that contains the instrumentation and alarms that the process needs to function.

As the different components must interact to complete an operating process, the components chosen must be able to function with the other design choices. In unison with the design choices, a Failure Mode Effect Analysis (FMEA) was done at this stage and at the implementation stage of the design, to assist in making design choices.

As air/oxygen is supplied to the process to account for the biological oxygen demand for the plants, mineralization bacteria, nitrification bacteria and fish that all require oxygen it will weigh heavily on the design choices made.

The Failure Mode Effect Analysis (results shown in further section as ongoing process to select instrumentation) has highlighted that a fish kill caused by power failure is a large risk to the process. One way to assist in preventing this is to select power sources that could provide some additional redundancy. One is the power source itself could be selected to have a hybrid system such as storage batteries to provide a source during a mains power failure (also stored renewables to reduce energy costs). The other is to use compressors in the process and use it to fill air storage bottles to supply air to the fish during a power failure event.
As power would also be a large operating cost, where possible the tanks and process will be gravity fed from one tank to another and must be considered when making design choices to reduce ongoing power usage. Doing an energy budget is currently outside the scope of this thesis but further detailed design to this concept would make further consideration to offset power and equipment selections.

4.2 Design

4.2.1 Process Flow Diagram

The author created a Process Flow Diagram (PFD) of the design with the systems selected as part of the initial investigation into main components. The Failure Mode Effect Analysis results, which are discussed in further sections, are already incorporated into the Process Flow Diagram. The final design of the Process Flow Diagram is represented in Figure 15.

Having an overall view of the process aided in the selection and design of instrumentation and alarms that need to be generated at certain points to allow control to be optimized.
4.2.2 Failure Mode Effect Analysis (FMEA)

Aquaponics operators that have transitioned from hobby to commercial operators (Lennard, Commercial Aquaponics) have commonly failed to meet commercial expectations. One of the reasons for failures is the occurrence of severe technical errors. Unexpected events can often have drastic financial consequences on new operators, which could be initially operating within tight margins. Standard techniques like Hazard and Operability studies (HAZOP) are conducted by process and chemical industries to do systematic analysis on a process and its sub-systems. Design processes are able to identify disturbances that could lead to product deviation and identify hazards that could affect the environment. Identifying process issues and designing engineering controls to prevent or mitigate issues can be carried out in
multiple forms or design tools. Failure Mode Effect Analysis (FMEA) is one such tool and is recognized as an international standard (IEC 60812), which describes techniques to analyze processes that can effect the reliability of a process or determine what possible hazards could be present.

The use of FMEA has been utilized by industries to aid in carrying out HAZOP design processes, the use of these design processes can lead to inherently reliable processes. Piping and Instrumentation Diagrams also referred to as Process and Instrumentation Diagram (P&ID) are used in the process industry to show an overview of the process. The P&ID also identifies instruments that could be required for measurement and any associated alarms that are present to warn operators and mitigate failures in the process. The use of these design tools have identified and mitigated the risks within the initial design concept to prevent these technical errors with engineering controls designed into the process.

4.2.3 Failure Mode and Effect Analysis in Aquaponics

Aquaponics operators that have taken on commercial operations have often suffered large financial losses (Kanae, 2013) during initial operation either from (Hambrey, 2013) technical or financial errors.

Financial errors such as not planning to obtain market share (product selection and analysis) (Donald) and turnover would be part of a well-planned business venture.

Engineering issues that can cause financial losses from technical issues are engineering problems, which could be designed out of the process with careful planning and design. Utilizing established procedures and tools such as techniques developed by engineers from the chemical/process industry could assist in designing
reliable systems. The application of a number of tools that include Process Flow Diagrams (PFD) (Nihal, 2015) to show the major components of the process is a step in developing process automation and control. A PFD depicts an overview of the process, to show the directions of flows and to aid in further development of the design that is put into Piping and Instrumentation Diagram, also recognized as a Process and Instrumentation Diagram (P&ID).

Aquaponics is an industry where Programmable Logic Controllers (PLC’s) and monitoring (Johanson) have begun to be incorporated, although higher levels of automation such as SCADA or DCS control are not standard. A literature search of industry journals has shown numerous PLC articles or microcontroller systems yet does not mention higher-level control and supervisory systems. A number of techniques could be utilized to determine design items that could identify control that could be incorporated into the process. To design a functioning process and the associative automation a Process Flow Diagram (Seborg) was used to identify major components that are to be incorporated into the process. This Process Flow Diagram was used as an overview of the process to develop a Piping and Instrumentation Diagram that contains the instrumentation and alarms that the process requires to function in an optimized process. The development of these diagrams is achieved with design processes that can aid in developing these drawings one such process is a failure mode and effect analysis.

A Failure Mode and Effect Analysis (FMEA) can be used at various steps in a design process (NPDsolutions, 2016) to identify issues that can affect the reliability of the process. Ideally a group of multifunctional engineers or designers that have skill sets in various disciplines could carry out the FMEA. Identifying weaknesses in a
process design early in the concept and design phase of the project can allow engineering controls to be implemented long before the process is operational. The use of a FMEA can be quite standard and uses a scorecard to identify a Risk Reduction Number (RPN) (Swapnil, 2013). The score identifies areas that can be of concern and where engineering controls could be implemented to prevent or mitigate the identified systems or subsystems of the process. The engineering controls do not necessarily need to be automation controls but could be in various other forms such as additional engineering reviews or mitigating hazards by alternate design.

O – probability of Occurrence 1 very rare – 10 very frequent (Swapnil, 2013)

S – Severity of occurrence 1 No effect – 10 Most severe (Swapnil, 2013)

D – Probability of Detection 1 certain to detect - 10 cannot detect (Swapnil, 2013)

Although the combination of these factors gives an overall score or RPN, the number could still have more weight if there was a stand-alone high number such as the severity of occurrence to operations. A fish kill has been graded at a severity of at least 7 as this could have a significant financial set back to a large commercial aquaponics operation, as the fish could have tens of thousands of dollars in feed invested in them to reach various stages of maturity. It could also take the operator some months to recover if the operator is staggering (Nick, 2005) the fish batches to keep a constant turnover over the whole year.

The FMEA review results are documented into a table to record any responses and to determine the RPN score. Design notes were also taken at this stage as the analysis also identified possible design solutions. Recording the outcomes of the analysis will aid in the design process as it allows validation data to be collected that can be referred to for verification as the design develops.
A Failure Mode Effect Analysis (FMEA) in a design phase is normally carried out by multidiscipline team members, yet as this design is being carried by the author, an alternate approach is required. Sources from existing operators that have experienced failures or reported issues with their aquaponics systems (past history approach (NPDsolutions, Failure Modes and Effects Analysis (FMEA), 2016)); will be incorporated into the analysis to obtain a better understanding of failures. The FMEA could design controls that would aid in the prevention of these incidents, or finalizing selection of the major components could benefit the reliability of the project and reduce risk (Adrienne, 2012) for the long-term goals of a project. The results have been reviewed with a current version of the Process Flow Diagram that is being used to develop an initial design concept.

**Table 1 Failure Mode Effect Analysis Responses.**

| FUNCTION                  | FAILURE                           | EFFECTS          | S | CAUSES                              | O | CURREN METHO | D | RPN | DESIGN NOTES                                                                 |
|---------------------------|-----------------------------------|------------------|---|-------------------------------------|---|---------------|---|-----|-----------------------------------------------------------------------------|
| Maintain Dissolved Oxygen | Aeration System                   | Kill Fish/Plants | 7 | Mechanical Failure or maintenanc e downtime | 4 | None          | 2 |  56 | Using Compressed air as it can be stored allowing for failure to be repaired without loosing fish eg. 2 Compressors for redundancy |
|                           |                                    |                   |   |                                     |   |               |   |     |                                                                             |
| Anearobic Conditions      | Kill Fish                          |                   | 7 | System dead spots / anearobic zones | 4 | None          | 8 | 224 | Select air driven processes / additional DO instruments / Investigate         |
| Scenario                          | Cause          | Effect                  | Frequency | Probability | Severity | Technology Description |
|----------------------------------|----------------|-------------------------|-----------|-------------|----------|------------------------|
| Power Outage                     | Kill Fish      | Mains Outage / total loss | 7         | None        | 1        | Install Fail to open/close valves to divert oxygen/compressed air to fish tanks during power loss |
| Store Fish Feed                  | Oils Catch Fire | Injury                  | 10        | None        | 8        | Design System to automatically start fire drench - Storage Area (SIS) / to have Hazardous Area assessment as part of design |
| Feed Fish                        | Gas buildup    | Injury                  | 10        | None        | 3        | CO2 Air monitoring to alarm |
| Ammonia / Nitrite build-up       | Kill Fish      | pH or temperature shocks to system | 7         | None        | 2        | Allow additional sizing in nitrification to handle system shocks |
| Fill/Clean Tanks                 | Effluent Spill | Kill wildlife           | 6         | None        | 3        | Add Bunding Drainage storage to be sized to contain largest tank volume |
| Empty Tanks                      | Kill fish      | Process Failure         | 7         | None        | 2        | Add low level monitoring and alarms to DCS also add audible alarms |
| Solids build-up                  | Kill fish      | Pump failure            | 7         | None        | 4        | Flow switch from solids removal to provide alarm |
The results of the FMEA (Table 1) highlighted some safety issues that also need to be addressed in further analysis such as a hazardous area review for the safe storage of fish feeds that contain oils. It also identified some changes that could be implemented to increase reliability of the process, either by redesigning subsystem components or by adding additional instrumentation to monitor identified process limits, yet also design techniques to control the limitations.

4.2.5 **Failure Mode and Effect Analysis Automation and Aeration Control Strategies**

The Failure Mode Effect Analysis (FMEA) (Table 1) has highlighted that there is instrumentation and controls that could mitigate or prevent some of the technical failures that have occurred in aquaponics processes in the past. One of these
highlighted was the use of aeration within the process as it can be stored as a reserve for a mains power failure. The other is that the stored air could be utilized to operate multiple parts of the process to prevent anaerobic conditions. This could allow some innovation to take place and adapt technologies mainly used in processes or those that could be adapted from the wastewater industry to carry out similar functions.

The process control industry has used Fail Open (FO) and Fail Close (FC) valves (Marlin, 2005) to return a process to a safe state during a disturbance or failure to the process. A simple relay or contactor that is energized by the mains supply could control an extra low voltage supply that feeds a solenoid, when power is lost to the process the contactor de-energizes returning the Fail Open valve (Figure 16) to a position where air could flow from the stored air in the compressed air bottles. This could supply additional dissolved oxygen to the fish tanks for short periods, until the power is restored or an emergency source could be provided.

![Figure 16 Fail Safe Design.](image)

Aeration techniques have been developed in the wastewater industry and in many circumstances would be required to operate in harsher conditions than what would be expected in an Aquaponics environment.
The uses of diffusers have had large amounts of research and development applied to them to supply the wastewater industry. They are able to supply a range of bubbles with varying sizes, which alternately can reduce power usage as the bubble size optimizes gas exchange. The aquaponics process relies on Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) (Endut, 2012) throughout the process for materials be converted or broken down into usable forms for plants. Diffusers suitable for this application could be utilized to supply this gas exchange. Automation can be configured to supply dissolved oxygen as required (bubbles) with the use of control from a SCADA/DCS system. The system could control an output from the measurement of dissolved oxygen levels from instruments placed in areas with known BOD and COD.

In plant beds, disease such as Pythium can be caused by anaerobic conditions, which are present when (Sutton, 2006) less dissolved oxygen is available. This can also be caused by higher temperatures in the aquaponics/hydroponic solution that lead to lower levels of oxygen being present. Traditionally aquaponics growers will install air stones, which will dissolve oxygen into the aquaponics solution, although there are diffusers that are able to supply ultra-fine or fine bubbles (Kossay, 2006) that have an overall greater surface area that maximize gas exchange. The use of evenly spread diffusers within the floating beds would be able to supply an evenly spread amount of gas exchange, lowering the risk of anaerobic conditions developing in isolated positions of the beds.

4.2.6 Failure Mode and Effect Analysis Instrumentation Adaptation

The Failure Mode Effect Analysis (FMEA) (Table 1) also identified that there could be a requirement to monitor some of the parameters that are in the aquaponics
process, which could include adapting instrumentation technologies that were
developed for the wastewater treatment process.

The FMEA (Table 1) identified features that could be incorporated onto the
P&ID such as instrumentation used to measure solids for the measurement of Total
Dissolved Solids (TDS) and Total Suspended Solids (TSS). The TSS in an aquaponics
system is required to be monitored but also kept in control as the solids “cause sub-
optimal water quality characteristics” (Danaher, 2009). Having monitoring within the
process allows processes not only to be monitored but also adjusted to known
researched ranges that are optimal for production. This could be by streaming parts of
the process that contain solids to a sub-system that is designed to remove excess
solids from the process. As the PFD for this proposed design currently has an inline
filter for the process, an additional flow path was added to make use of this filter by
bypassing the process flow if suspended solids exceeded recommended values.

Instruments that monitor solids are commercially available and development
has been mostly refined to meet stringent regulations, required by the wastewater
industries, which can be (Tom Davies, 2017) “accountable to a range of state
authorized bodies such as Department of Environment Regulations (DER) and
Department of Health (DoH)”. These regulations include the accurate measurement of
contaminants to meet drinking water standards. The instruments that are available are
capable of monitoring TSS down to or lower than the 1 mg/L range. Various makes
and models that are able to supply (Teltherm Instruments, 2017) (BTG Australia Pty,
2004) complex models with local displays with built in relays that are able to trigger
local alarms. The measurement of TDS has also been developed mainly for use in the
wastewater industry and can be in various ranges with resolution of 1 ppm or lower
not uncommon. Monitoring the TDS and TSS in the system would be related to the amount of solids that are re-introduced into the system. As the current process design has a mineralization tank that contains the solids, an additional sludge level-monitoring instrument will be added to the design. The sludge level monitor has a controller with programmable outputs, which could be utilized to operate a filter to remove excess solids and prevent the dissolved solids from exceeding optimum levels.

4.2.7 Failure Mode and Effect Analysis Discussion

The discussion points from the Failure Mode Effect Analysis (FMEA) are listed below -

- The FMEA identified risks to the process and impacts to the surrounding environment. It was documented in the FMEA that aquaponics systems could result in spills.
- Where possible gravity feed will be used to supply the system and pumps would only be used to supply flow if there was a requirement to boost pressure or pump back uphill in the process.
- The use of bunding, which could be a simple curb structure surrounding the process area was also documented to contain liquid in the greenhouse or water treatment areas (EPA, 2017) to prevent nutrient rich water from entering the environment. With the addition of a sump drain and pump installed in the floor area, the liquid could be easily removed after a spill event.
- The FMEA also identified that if there are shocks to the system such as changes of temperature or pH imbalances, there would be reduced optimization in the nitrification process, which could lead to ammonia and
nitrites reaching excessive levels. The calculations to size nitrification tanks and the relationship with protein (FAO, Calculating the amount of ammonia and biofilter media for an aquaponic unit) entering the system are well documented, however allowing this component of the system to be oversized could prevent toxic build-up of ammonia or nitrates if the system was exposed to unexpected or uncontrollable system shock events.

- The FMEA also documented that there are hazards in the process such as Carbon Dioxide that is heavier than air. The accumulation of gases could potentially accumulate and injure workers in the process and could go unnoticed until an incident took place.

- Other hazards to the process that required monitoring also bought about some additional instrumentation to control the parameters before they re-entered the process, allowing the ranges downstream to have an additional layer of control upstream in the process.

- The FMEA also documented results for further consideration as the design begins to develop such as handrails around floating beds, which would be further considered if the tanks were recessed into the floor.

4.2.8 Piping and Instrumentation Diagrams

The Instrumentation and alarm list is attached as an Appendix 1 to this thesis, to support the items within the design that are drawn further on the Piping and Instrumentation Diagrams in Figures 17 and 18 as part of the design completed by the author of this thesis. The instrument and alarm list also contains alarms and their priorities, this list and its results are discussed in more detail in further sections of this thesis.
Figure 17 P&ID Sheet 1.

Figure 18 P&ID Sheet 2.
4.3 HMI Screenshots

An aquaponics automation design was undertaken to interpret the system requirements to integrate automation to operate the system. The system was designed to increase the layers of control over the inputs and outputs to operate the system with a process control approach. The viability of these levels of control over the process was investigated by doing a design of the process to assess types of instrumentation required and control functions that could be incorporated into the design to optimize the process.

The design process incorporated sub-systems that did not rely on a main system, to increase ranges of commercial viable crops. The subsystems do not have the same environmental requirements of the main system and the subsystems environment could be calibrated to meet specific requirements of a selected crop including fruiting vegetable types. The results of the automation design have been tabulated into this thesis to assess the viability of increased levels of process control to obtain subsystem designs with maximized optimization.

4.3.1 Tank Area

![Tank HMI Layout](image)

Figure 19 Tank HMI Layout.
A Main Tank Alarm (featured as tag FA199 on the instrumentation list Appendix 1) has been depicted as a large red light on the screenshot to replicate a software version for the hardware. The output for this hardware would be a relay that operated a flashing beacon and audible alarm, although as this is a software version a large red light has been used to represent this operation. Once the pump is started, there must be flow from both the flow switches, if not after 10 seconds the Main Tank Alarm will be triggered, as there could be a blocked pipe or water levels are becoming inadequate. Either of these circumstances could flood or drain a tank. This was identified in the FMEA design process as having a significant financial risk to the operator of the process factory. Failure of both of these flow switches to activate in 10 seconds will also trigger an additional small light next to the tank to identify which tank has triggered the alarm for fast recognition by the operator to take action. There would also be an alarm banner displaying the monitored issue to the operator.

**Figure 20 Typical Ladder Diagram for Tank.**
This ladder diagram (Figure 20) controls the operation of a single tank and its associated pump, this ladder includes monitoring of level of the tank to initiate the Main Tank Alarm (FA199) and the monitoring of pipe blockage functions.

The pump has a standard start/stop ladder diagram, with an emergency stop feature that enables an additional alarm function. The stop button itself would be fitted with 2 normally closed contacts (latching) one which signaled the SCADA software to alarm and stop the start signal and another which would be hardwired in series to the pump starter to stop the pump immediately.

The Main Tank Alarm could be triggered from either of the level switches that monitored each of the specific tanks. This however would only trigger the main flashing beacon and audible alarm (large red light (Figure 21)) and an alarm banner message.

**Figure 21 Main Alarm Indication.**
The alarm banner would resemble (Figure 21) Tank 1 suffered a pipe blockage and the tank blockage alarms are triggered. This could cause the level to be out of range that has also initiated an additional warning on the alarm banner. The emergency stop alarm has also been initiated indicating that an operator (which could be expected if the Main Warning beacon had been activated in the process area) has depressed the local emergency button stopping the tank 1 pump.

4.3.2 Mineralization

![Figure 22 Mineralisation Functioning Screenshot.](image)
The mineralization page has both monitoring and control components that enable the inputs into the mineralization process tank to be controlled. The flow from clarifiers is controlled by adjusting the speed to pumps with the use of variable speed drives that could have the speed controlled from a 4-20mA output. Other functions such as flow control of the baffle separator are controlled from this page with the use of a slider (Figure 22), this flow allows the solids transfer to the mineralization tank for further treatment. The flow of air also controls the amount of available dissolved oxygen required by bacteria to process the captured solids and can be adjusted by moving a slider to increase or decrease the flow as required.
4.3.3 Nitrification

Figure 24 Nitrification Monitoring.

Figure 25 Nitrification Ladder.

The Nitrification page (Figure 24) contains both monitoring and control of equipment in this process area. There are touchscreen start/stop functions (Figure 25) to operate pumps and additional speed control to control the flow from the pump. There is also a slider to operate a valve that controls the flow re-entering the process...
from mineralization process, note this is currently exceeding the limits for the fish species and an alarm has been triggered which should result in the operator using the slider to decrease the flow from mineralization to reduce the total dissolved solids within the process.

4.3.4 Degassing

The Degassing Human Machine Interface screen page (Figure 26) has control of the compressors and the measurement of the compressors. It also monitors CO2 in the environment and allows ventilation to be controlled along with the control of exhaust louvres to allow ventilation to be circulated through the process. Other devices that could be situated in this area of the process also have their start/stop functions available on the screen to allow for control.

Figure 26 Degassing Monitoring.
4.3.5 *Aquaponics*

The Aquaponics Human Machine Interface (Figures 27 & 28) rely more on monitoring and alarming to warn of unfavorable conditions for the fish. There is some limited control (Figure 28) with the control of dosing pump speed for addition of nutrients, which are required to grow green leafy varieties of vegetables.

**Figure 27 Aquaponics Monitoring.**
4.3.6 Hydroponic

Figure 28 Aquaponics Nutrient Monitoring and Control.

Figure 29 Hydroponics Nutrient Monitoring and Control.
The hydroponics pump was required to cycle on and off for a period of 30 minutes on then 45 minutes off (Figure 30). This function coats the nutrient rich water onto the plants roots, while also flushing away-unused nutrients back to storage tank for measurement and adjustment. To achieve this pump cycling a start/stop ladder diagram was developed to start a software sequencer that carries out the constant rotation of flood and filming of the nutrient rich water to the plant crop roots.

Figure 30 Hydroponics Pump Sequencer Control.

Figure 31 Hydroponics Nutrient Measurement & Control.
The hydroponic Human Machine Interface (Figure 31) has a lot more control features if comparing with the aquaponics page. The sliders that control analogue outputs are able to control the dosing rates of certain nutrients to make the desired nutrient levels required by the crop that is being grown.
CHAPTER 5. RESULTS AND DISCUSSIONS

5.1 Discussions of Design

5.1.1 Aquaponics Automation by Decoupling Requirements

The aquaponics cycle is a biological process between plants, fish and bacteria, yet these all have unique optimum ranges for survival. The introduction of automation to the aquaponics cycle introduces additional forms of control by manipulating the inputs of the system to aid in controlling the process outputs. To understand the level of equipment that must be introduced into the process and the level of software development that would be required, a comprehensive design was undertaken to define the requirements of an aquaponics system that had full automation similar to a process controlled operation.

Process control is able to reduce inefficiencies with constant monitoring and reduce (Evans, 2016) process variability. Process Control automation is able to apply repeatable results as ranges or parameters of the process can be programmed or measured, which can be controlled for (Bozich, 2010) predictable results. Aquaponics have existing known parameters that optimize (Richard V. Tyson, 2011) results for fish and bacteria, yet plants that produce fruiting vegetables also have known optimum conditions that include lower pH for nutrient uptake and nutrient levels.

According to Scattini (Scattini, 2017) “The use of process control and the automation that it incorporates is able to measure and maintain multiple control loops, having multiple control loops that are not dependent on others would remove some of the identified limitations by dividing the process to meet those ranges that have been researched as optimum at particular stages of the process.”
5.1.2 Aquaponics Subsystems

The wastewater treatment component of the process allows biological bacterium and there relevant processes to take place, which change waste ammonia to nitrites and nitrates. The fish effluent requires pH’s of 7.2 to 7.8 (FAO, n.d.) for the bacteria to transform the ammonia nitrates. Once changed to nitrates the nitrogen is in a form (Sawyer, 2013), which can be taken up by plants as a food source in turn cleaning the water for re-use by the fish.

The wastewater treatment also allows solids to be removed or reintroduced back into the system as dissolved solids (Hijran Yavuzcan Yildiz, 2017) that supply plants additional nutrients. The fish species to be grown have limitations on the amount of (Zealand, 2000) Total Dissolved Solids and other water quality requirements that must be met if the produce is to be resold. The dissolved solids are able to be removed to a storage tank in a concentrated form, which allows for decoupling of the pH’s between the fish effluent and the effluent concentrate to optimize both the main systems and the subsystems requirements. The nutrient concentrate is to be reintroduced into a hydroponic sub-system to reduce fertilizer requirements that would be required to produce the chosen crop. The hydroponic system ranges are controlled by instrumentation measurement and the delta in nutrients are met by adjustment to meet desired nutrient ranges depending on the crop of vegetables to be grown.

Supplying the optimum requirements into multiple subsystems and separating control loops between fish, bacteria, and plants is achieved with increased levels of process control automation. To determine the amount of effort to implement this level of control on an aquaponics process a preliminary design was required. This design
determined the complexity of measurement and types of automation control that would be required to keep parameters ranges under control. Achieving these levels of control could assist commercial aquaponics operators to benefit by being able to produce an increased range of produce that does not rely on a single control loop or a single control loop that needs to compromise to sustain all requirements. Process control that increases the level of control over secondary loops could maximize the recycling of nutrients from waste, lower fertilizer costs and increase the viability of a technology that reduces water usage within its system.

5.1.3 Viability of Process Control Automation in Aquaponics

To gain an understanding of what is required to automate components of the process, the author has created an initial design (Noel Scattini, Aquaponics Automation – Design Techniques, 2017) to identify equipment required to add control functions to the process with additional levels of control with automation.

Automation to operate a process has many types of equipment from hardware that could include flow switches, instrumentation, various types of control valves, analysers and Variable Speed Drives. To operate the process within desired ranges software functions are provided from a distributed control system or SCADA to control the system within desired parameters.

The instrumentation hardware and SCADA software can be broken down into further sections either passive devices or active devices. Passive devices are those that provide a readout or indication (ANSI, 2009) which is represented as a local gauge or a software representation on the Human Machine Interface. Other passive devices could include monitoring functions that can be used to determine ranges that are outside of the optimized range.
Active devices are those that operate a function or an auxiliary device (ANSI, 2009); these auxiliary functions could be from hardware such as control valves, relays and solenoids. The output normally initiates a variable that modulates the device or process to a predetermined set point, which in this design would be a range that has been documented as optimum for the particular control loop.

5.1.4 Process Control Equipment used for Optimization

Flow switches are commonly used in process control to identify that flow is taking place within piping which in an aquaponics system would identify if there were pipe blockages in the system. Flow switches are used to monitor flow detection in tank drains and can be a reliable method (Craig, n.d.) of protecting equipment. In the design being assessed in this thesis, the flow switches are used to identify multiple flows from a tank that could have failures from pumps or from a blocked pipe. The identification of such a failure could prevent a tank from draining or overflowing or the tank not receiving enough cycled water that could cause a fish kill in the system.

Flow control valves are used to control the flow by restriction yet can often be interpreted as wasteful (Tahara, 2016) as they oppose the flow by restricting it. The flow valves in the design of the process have been utilized in circumstances where head pressure from a tank can supply energy required for flow. Additionally flow restrictive valves have been selected where flow restriction could aid the process by circulating more of the opposing flow to prevent anaerobic pockets building up when upstream flow is not required in the process.

Variable Speed Drives are used in conjunction with pumps by adjusting the speed to control flow (Muhammad H Al-Khalifah, 2012), to aid in the control process streams. Variable speed drives not only supply a greater level of control to flow but
also minimizes the energy costs as pumping systems can account for 20% energy usage (Technologies, n.d.) in process facilities (depending on final configuration or if the process has heating, pumping costs could be a considerable higher percentage). In an aquaponics wastewater system, clarifiers are used to settle out the solids produced by fish waste. The clarifiers allow solids to be removed for either total removal or in this design to a mineralization tank (Lennard, 2012) for further biological treatment. Having flow control over the solids from the clarifiers has the benefit of limiting the total amount of effluent being removed from the main process stream for further treatment as additional energy would be required to treat or pump the additional effluent.

Instrumentation is introduced as passive devices to measure the process constantly. The instrumentation used to aid in process control includes pH and nitrate analyzers to relay measurements, which are displayed on the Human Machine Interface. The monitoring also includes more complex analyzers that are able to carry out multiple measurements to monitor the minerals or nutrients that are available in the process.

5.2 Results for Process Control

A design has taken place using established design tools such as (ISA, 2014) a Process Flow Diagram (PFD) to develop a more detailed Piping and Instrumentation Diagram (P&ID) to document the design as it was developed. Existing research was used to determine the ranges required for the system to remain optimized in different control loops and existing methods to maintain these ranges. The control loops for the subsystems and its associated requirements for optimization are met by adapting existing technologies to provide conditions, which have the ability to provide known
documented outcomes. The use of established design techniques such as Failure Mode and Effect Analysis (Noel Scattini, Aquaponics Automation – Design Techniques, 2017) “has highlighted that there are many instrumentation and controls that could mitigate or prevent some of the technical failures that have occurred in aquaponics processes in the past.” The combination of existing research and results from design tools and procedures were used to determine the number and type of instruments, which could be used to automate features of the process.

The number of instruments and types of alarms and alarm tags were listed onto an instrumentation and alarm list to identify the level of automation that would be required to control the process.

5.2.1 Process Configuration

To compare the design and number of devices that can be put into perspective with similar designs such as those that contain batch processing a design configuration was selected that contained multiple tanks. The aquaponics process consists of eight fish rearing tanks and a wastewater treatment processes that treats the effluent from the fish tanks. The design of the project would have to be scaled to suit a large commercial operation, yet this design has incorporated numbers of devices to operate it as a process with automation. The biological wastewater treatment component of the processes also included a degassing tower that can accommodate an additional fan to force air through the degassing tower. The fan however is not expected to be required in the processes day to day operations (designed with but not fitted), this type of fan is required in processes that have high stock densities. The fan however could be fitted in process operations that risk high density farming practices
or processes that require additional cooling during summer as it has a (James M. Ebeling P., 2006) cooling effect on the water.

The instrumentation list does not include the stand-alone instruments on the skid-mounted equipment for the adapted filters. The filters do however allow for start stop functions, along with fault functions to interface with the SCADA/DCS system.

The design was established with known existing ranges that have been documented from past research as being optimized for different components of the process, this includes ideal bacterial pH ranges, also ranges of nutrients that are required for the plants to produce fruiting vegetables. These are separated into subsystem control loops to reach optimized production rates to the established known ranges. To separate these alternate control loops, technologies from alternate industries have been adapted to obtain these established ranges.

5.2.2 Results of Integrating Process Control Functions

The data (Tables 2 and 3 below) represents an overview of different components of the process and what is required to automate sections of the process. This data represents items that would be required to establish cost data, to do cost analysis of integrating the equipment into the process. The data could be used to establish data for integrating equipment into an existing process and a comparison of cost savings could be analysed against additional viable commercial crops or the risk mitigations that benefit the process operator. This data could also be used to establish design data for a new process, which would be expected to be easier to integrate as the system could be designed with the process features initially in the design.
The results are divided into two sections one that has an overview of the hardware components and two a section that has an overview of software components. The two sections list the relevant results, which elaborate on some of the uses of hardware and software, additionally the level of complexity required to automate the processes with process control functions is explained in detail.

5.2.3 Software Data Analysis

The results are tabulated from the instrumentation and alarm list that was incorporated onto a piping and instrumentation diagram that represents the process. The results of software requirements equipment selection to be incorporated into the design was selected and the quantities quantified in Table 2 to represent the overall requirements of this process layout. The alarms and associated levels of priority are also listed in Table 2. The alarms also have event alarms which may note when a pump is started or stopped for later reference which could be used to determine operating or failure times of pumps to introduce maintenance measures in the future operations to increase the reliability of the process.

Table 2 Software Functions.

| Software Alarms/Tags | Number |
|----------------------|--------|
| Tags / Human Machine Interface | 241    |
| Alarms / Event Only  | 61     |
Table 2 shows the number of Human Machine Interface Software tags required for functionality of the Human Machine Interface. These include tags from instrument measurements or from digitised push buttons that can function from a mouse or touchscreen from the Human Machine Interface, some of which include start or stop functions for process equipment.

Other software components of the design included tags from analogue signals that operate displays on the Human Machine Interface to display ranges of measured devices. The alarms could be driven from analogue or digital devices from measurement being out of range from an analogue signal. Digital signals to operate alarms could be from an initiation of an emergency stop in the field or from a relatively basic instrument such as a float level switch.

The software besides including analogue and digital interfaces to operate displays can also include more complex software features. The hydroponics pump has requirements to operate for a period on then another period off, to flush unused nutrients from the root zone, and rehydrate the zone for a set period. This operation required a start tag on the Human Machine Interface that initiated timers to carry out this function; this is also commonly referred to as a software sequencer or PLC sequencer. Additional functions using inputs from flow switches and the start functions of pumps have been utilised to initiate flow alarms to individual tanks and
alarm a main audible and visual alarm, these individual tank alarms are able to identify and localise the fault.

5.2.4 Hardware Data Analysis

The process also requires hardware devices either to control measured values for them to remain in optimum known ranges or to obtain those measured values. The results of the design have been accumulated into Table 3 for discussion.

Table 3 Hardware Devices.

| Devices                              | Number |
|--------------------------------------|--------|
| Compressors                          | 2      |
| Variable Speed Drives                | 5      |
| Fans                                 | 3      |
| Adapted Filter Units                 | 2      |
| Valves                               | 32     |
| Instruments (includes multiple output Analysers) | 73     |
| Pumps                                | 15     |
The devices in Table 3 represent totals of hardware devices to operate the process with a DCS/SCADA system. The devices included instruments that incorporate basic operations that communicate with digital signals and measurement analyser to supply values such as pH ranges. Complex instrumentation such as nutrient analysers could be described as small field laboratories that contain multiple outputs to send analogue outputs to the SCADA/DCS system to represent ranges of measured nutrient values.

The variable speed drives are utilised in the process to carry out speed control with indication displayed on the SCADA/DCS Human Machine Interface with speed control also displayed. The variable speed drives are able to control the motor speed that in turn controls the flow, in areas of the process to optimise the process or alternately only use energy required to carry out function to save on energy costs.

5.3 Discussion and Future Work

The completion of an automation design allows the requirements of a process to be understood before implementing a project. To gain a better understanding of the fertiliser’s savings that would be made to an operator a test process that incorporates the Selective Electro Dialysis filter would be required to obtain quantifiable test results that could be scaled, of the nutrients that can be distributed to the plants in the hydroponics tanks before implementing a major project.

The results of further work would allow for cost savings in fertilisers in comparison to size of known processes to be calculated and the value of return understood on capital investments required to implement this technology. Although process systems could vary in size with items such as the number of fish rearing tanks, a complete instrumentation list has been developed and the list could be
adjusted to meet the requirements of individual process systems. This type of overall installation of this industrial automation equipment is aimed at supplying large commercial operations that have large overheads such as high fertilizer or pumping costs, or alternately need to compete with diverse crop ranges.

An additional function that the instrumentation and control provides, besides the measurement of ranges required for optimum production rates, is the additional control allows for subsystem separation and optimization. The additional functions also allow for implementation of risk mitigations to prevent failures in the process and increase reliability.
CHAPTER 6.  CONCLUSION

Conducting a study on the individual requirements and designing an alternate control solution that meets the identified ranges could highlight that some of the compromises that are currently required to operate a Recirculating Aquaponics Systems could be overcome and make it possible to grow fruiting vegetables with established hydroponics recipes. The systems may not necessarily be restricted to compromising between the different biological requirements of fish, plants, or bacteria but could be separated into alternate control loops.

Further work studied a control solution that utilised an alternate design, which would allow the nutrients to be distributed to an alternate control loop that is independent to the main aquaponics system.

This research included newer methods to balance the Total Dissolved Solids entering the aquaponics system to balance those being removed. The thesis also investigated methods to collect concentrated nutrients to control the water quality in the main system, with a focus on dissolved nutrients. Automation techniques included the investigation of automation and the addition of nutrients and nutrient concentrate to the hydroponic solution, to provide consistent nutrient ranges.

The results from using established design process’s such as Failure Mode Effect Analysis identified that there can be forms of risk mitigation to the process and processes that could be incorporated into the design. These include active devices, which could be in the form of measurement and control with the use of instrumentation, or active control devices to maintain the process within required
ranges. The Failure Mode Effect Analysis also identified passive devices in the process such as handrails in areas where they would be appropriate.

This Failure Mode Effect Analysis also identified that barriers such as bunding in the form of curbing could contain spills and prevent nutrient rich water entering water supplies. After further investigation from the identification of the possibility of nutrient rich water damaging the environment it was determined, that it is a regulatory operational requirement in some areas.

The Failure Mode Effect Analysis results have shown that there could be some additional analysis done on the process to determine if an appropriate hazardous area or regulations for correct storage should be included in the design of the system (there are storage distance requirements from main buildings in some locations).

This design process however is only one design tool that could be used to identify hazards to the process and is only identifying process inadequacies that are in the current concept stages of the design. This design process should be repeated at the detailed design stage using the current documented results to validate if the identified responses have been incorporated into the design or if the design has deviated and alternate solutions could be required. Additionally as the process design develops, there could be unforeseen risks to the process that were not present during the concept stages of the design.

This design process could also be carried out before the commissioning stages of the process. The commissioning process can have a very different set of risks to the process that must be considered before introducing fluids or forms of energy to the process, which have their own set of associated risks.
The results from the automation design showed that there was a large number of software tags required to automate the process, with built in process control functions. The instruments selected to integrate process control functions into the process included relatively cheap instruments such as flow switches that can be purchased for small costs. There was also more complex instrumentation required to measure minerals or nutrients to monitor the ranges for correct dosing. These are more expensive yet some of these can monitor multiple nutrient levels and can carry out functions that are similar to a small laboratory, and display results in real time. Although expensive, the constant monitoring of these nutrients supplies constant nutrient ranges that could be calibrated to specific plants requirements.

Benefits besides cost savings of fertilizers should also be considered as the Distributed Control Systems or Supervisory Control and Data Acquisition system combined with the constant monitoring would mitigate the risk of fish kills or other unexpected events. Fish kills potentially cost operators in lost fish stock and the amount of fish feed they had invested in them and risk loosing established trade with established customers.

The development of this technology would allow operators to take full advantage of sustainable technologies such as aquaponics. The reduction in fertilizers for fruiting crops, taking advantage of water savings, reduced chemical use and eliminated herbicides for growing a greater range of fruiting produce is not only commercially beneficial to operators but communities in areas where water is becoming a valuable resource.
CHAPTER 7. REFERENCES

[1] Adrienne, W. (2012). Project Management – Chapter 16 Risk Management Planning. Retrieved from https://opentextbc.ca/projectmanagement/front-matter/introduction-2

[2] Alenka Prinčič, I. M. (1998). Effects of pH and Oxygen and Ammonium Concentrations on the Community Structure of Nitrifying Bacteria from Wastewater. Retrieved from Applied and Environmental Microbiology: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC106468

[3] Alyce M. Richard, J. H. (2014). Reexamining the Risks of Drinking-Water Nitrates on Public Health. Retrieved from The Oschsner Journal: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4171798

[4] Amirkolaie, A. K. (n.d.). Reduction in the environmental impact of waste discharged by fish farms through feed and feeding. Retrieved from http://onlinelibrary.wiley.com/doi/10.1111/j.1753-5131.2010.01040.x/full

[5] Amit Sonune, R. G. (2004). Developments in wastewater treatment methods. Retrieved from https://doi.org/10.1016/j.desal.2004.06.113

[6] Andreas Graber, R. J. (2007). Aquaponic Systems: Nutrients recycling from fish wastewater by vegetable production. Retrieved from www.researchgate.net/publication/222537337_Aquaponic_Systems_Nutrient_recycling_from_fish_wastewater_by_vegetable_production
[7] ANSI. (2009, September). *ANSI/ISA-5.1-2009 Instrumentation Symbols and Identification*. Retrieved from https://edisciplinas.usp.br/pluginfile.php/1881581/mod_resource/content/0/ISA%205-1-2009.pdf

[8] Australia, G. o. (n.d.). *Peel Regional Investment Blueprint*. Retrieved 2015, from www.peel.wa.gov.au/wp-content/uploads/2015/12/Peel-Blueprint-15_LR.pdf

[9] BAQUE. (n.d.). *The Importance of Aquaponic Buffer*. Retrieved from PH AND AQUAPONIC BUFFER: http://www.baqua.org.uk/ph-and-the-importance-of-aquaponic-buffer/

[10] Bhausaheb L. Pangarkar, M. G. (2011). *Reverse Osmosis and Membrane Distillation for Desalination of Groundwater: A Review*. Retrieved from International Scholarly Research Notices: http://dx.doi.org/10.5402/2011/523124

[11] Bickelhaupt, D. (2017). *Soil pH: What it Means*. Retrieved from ESF: http://www.esf.edu/pubprog/brochure/soilph/soilph.htm

[12] Bjorgvin Vilbergsson, G. V. (2016). *Taxonomy of Means and Ends in Aquaculture Production—Part 2: The Technical Solutions of Controlling Solids, Dissolved Gasses and pH*. Retrieved from MDPI: doi:10.3390/w8090387

[13] Borras, J. (n.d.). *In Japan, They’re Farming With 99% Less Water*. Retrieved from http://bluelivingideas.com/2014/11/07/japan-farming-99-percent-less-water
[14] Boundless, B. M. (2016, May). *The Nitrogen Cycle*. Retrieved from Boundless: https://www.boundless.com/microbiology/textbooks/boundless-microbiology-textbook/microbial-ecology-16/nutrient-cycles-195/the-nitrogen-cyc

[15] Bozich, D. (2010). *The Process Control Imperative*. Retrieved from http://www.productionmachining.com/articles/the-process-control-imperative(2)

[16] Bregnballe, J. (2015). *A Guide to Recirculation Aquaculture*. Retrieved from http://www.fao.org/3/a-i4626e.pdf

[17] BTG Australia Pty, L. (2004). Suspended solids measurement. Retrieved from http://www.processonline.com.au/content/unknown/article/suspended-solids-measurement-1315401208

[18] Bugbee, B. (n.d.). *Nutrient Management in Recirculating Hydroponic Culture*. Retrieved from http://cpl.usu.edu/files/publications/publication/pub__9984184.pdf

[19] Burke, H. L. (2014). *The Nitrogen Cycle*. Retrieved from Michigan State: https://www.michigan.gov/documents/dnr/SIC_Nitrogen_Cycle_Guide_468249_7.pdf

[20] Cant, B. (2007). *Feed grains - Grain alternatives sought for fish*. Retrieved from GroundCover: https://grdc.com.au/resources-and-publications/groundcover/ground-cover-issue-70-september-october-2007/feed-grains-grain-alternatives-sought-for-fish
[21] Carlos Felipe Hurtado, B. C.-M. (2016). Separation of nitrite and nitrate from water in aquaculture by nanofiltration membrane. Retrieved from http://dx.doi.org/10.1080/19443994.2016.1160440

[22] Chito F. Sace, K. M. (n.d.). Vegetable production in a recirculating aquaponic system using Nile tilapia (Oreochromis niloticus) with and without freshwater prawn (Macrobrachium rosenbergii). Retrieved from https://academia-publishing.org/journals/ajar/pdf/2013/Dec/Sace%20and%20Fitzsimmons.pdf

[23] Conrado Moreno-Vivián, P. C.-L. (1999). Prokaryotic Nitrate Reduction: Molecular Properties and Functional Distinction among Bacterial Nitrate Reductases. Retrieved from Journal of Bacteriology: http://jb.asm.org/content/181/21/6573

[24] Coorowseeds. (n.d.). LUPIN KERNEL MEAL FOR FISH DIETS. Retrieved from Coorowseeds: http://www.coorowseeds.com.au/uploaded/files/client_added/Lupin%20meal%20for%20fish%20diets.pdf

[25] Craig, S. (n.d.). Flow Switches For Refinery Water/Wastewater Control. Retrieved from http://www.fluidcomponents.com/assets/media/Articles/Refinery-Water-WWT-0513.pdf

[26] Craig, W. (2015). Business Diversification: The Risk And The Reward. Retrieved from forbes: https://www.forbes.com/sites/williamcraig/2015/04/24/business-diversification-the-risk-and-the-reward/#7b09c8e67d09

[27] Danaher, J. J. (2009). Alternate Water Treatment Technologies for An aquaponics System. Retrieved from https://water.usgs.gov/wrri/AnnualReports/2009/FY2009_VI_Annual_Report.pdf
[28] Donald, S. B. (n.d.). Economic Analysis Of A Commercial-Scale Aquaponics System For The Production Of Tilapia And Lettuce. Retrieved from https://images.indiegogo.com/.../20120818104616-Economic_Analysis_of_

[29] DOW. (n.d.). TEQUATICTM PLUS F-150 Filter, B-Series Skid. Retrieved from http://msdssearch.dow.com/PublishedLiteratureDOWCOM/dh_0967/0901b80380967c6b.pdf?filepath=liquidseps/pdfs/noreg/795-50208.pdf&fromPage=GetDoc

[30] Ecolife. (n.d.). Water Quality in Aquaponic Systems. Retrieved from www.ecolifeconservation.org/water-quality-in-aquaponic-systems-part-2-ph

[31] Elyanow, D. (2005). Advances in Nitrate Removal. Retrieved from https://www.gewater.com/kcpguest/documents/Technical%20Papers.../TP1033EN.pdf

[32] Endut, A. N. (2012). Effect of flow rate on water quality parameters and plant growth of water spinach (Ipomoea aquatica) in an aquaponic recirculating system. Retrieved from www.tandfonline.com/doi/abs/10.5004

[33] EPA. (2017). Bunding and Spill Management. Retrieved from http://www.epa.nsw.gov.au/mao/bundingspill.htm

[34] Evans, K. (2016, Oct 7). Advantages of Process Control. Retrieved from http://www.engineeringresourcecenter.com/blog/advantages-of-process-control

[35] FAO. (n.d.). Bacteria in Aquaponics. Retrieved from http://www.fao.org/3/a-i4021e/i4021e05.pdf
[36] FAO. (n.d.). Calculating the amount of ammonia and biofilter media for an aquaponic unit. Retrieved from www.fao.org/3/a-i4021e/i4021e15.pdf

[37] FAO. (n.d.). *Wastewater treatment in the fishery industry.* Retrieved from FAO Corporate Document Repository: http://www.fao.org/docrep/003/V9922E/V9922E05.htm

[38] Fisheries, D. o. (2012). *Water quality and disease.* Retrieved from http://www.fish.wa.gov.au/Documents/aquatic_animal_health/water_quality_and_disease.pdf

[39] George J. Hochmuth, R. C. (n.d.). *Nutrient Solution Formulation for Hydroponic (Perlite, Rockwool, NFT) Tomatoes in Florida.* Retrieved from https://edis.ifas.ufl.edu/pdffiles/CV/CV21600.pdf

[40] Hambrey, C. (2013). *The relevance of aquaponics to the New Zealand aid programme, particularly in the Pacific.* Retrieved from www.spc.int/aquaculture/index.php?option=com_docman&task=doc...gid...

[41] Hendrik Monsees, J. K. (2017). *Potential of aquacultural sludge treatment for aquaponics: Evaluation of nutrient mobilization under aerobic and anaerobic conditions.* Retrieved from AQUACULTURE ENVIRONMENT INTERACTIONS: doi: 10.3354/aei00205

[42] Hijran Yavuzcan Yildiz, L. R. (2017). *Fish Welfare in Aquaponic Systems: Its Relation to Water Quality with an Emphasis on Feed and Faeces—A Review.* Retrieved from DOI: 10.3390/w9010013
[43] Hydro, B. G. (n.d.). *No Stress Guide to pH and TDS*. Retrieved from http://www.bghydro.com/kbase-no-stress-guide-to-ph-tds

[44] Imran Ali, M. K. (2014). *Effect of Season and Organic Loading Variation on the Operation of an Indigenously Developed Maize Cobs Trickling Filter (MCTF)*. Retrieved from International Journal of Engineering Works: https://www.researchgate.net/publication/303632035_Effect_of_Season_and_Organic_Loading_Variation_on_the_Operation_of_an_Indigenously_Developed_Maize_Cobs_Trickling_Filter_MCTF

[45] ISA. (2014). *Control and Field Instrumentation Documentation*. Retrieved from https://www.isa.org/pdfs/news/chapter7-control-loop

[46] James E Rakocy, M. P. (n.d.). *Recirculating Aquaculture Tank Production Systems: Integrating Fish and Plant Culture - Page 2*. Retrieved from http://sustainable-aquaponics.com/wp-content/uploads/2016/02/SRAC-454-revised-2006.pdf

[47] James E. Rakocry, M. P. (n.d.). *Integrating Fish and Plant Culture*. Retrieved from http://darc.cms.udel.edu/AquaPrimer/fishplants454fs.pdf Pg. 6.

[48] James E. Rakocy, R. C. (n.d.). *Aquaponic Production of Tilapia and Basil: Comparing a Batch and Staggered Cropping System*. Retrieved from http://uvi.edu/files/documents/Research_and_Public_Service/AES/Aquaculture/Tilapia_and_Basil.pdf

[49] James M. Ebeling, P. (2006). *Biofiltration-Nitrification Design Overview*. Retrieved from https://cals.arizona.edu/azaqua/ista/ISTA7/RecircWorkshop/Workshop%20PP%20%20%20%20Misc%20Papers%20Adobe%202
[50] James M. Ebeling, P. M. (n.d.). An Engineers View of Recirculating Aquaculture Systems. Retrieved from http://slideplayer.com/slide/4651634

[51] James M. Ebeling, C. F. (2006). Performance evaluation of an inclined belt filter using coagulation/flocculation aids for the removal of suspended solids and phosphorus from microscreen backwash effluent. Retrieved from https://doi.org/10.1016/j.aquaeng.2005.08.006

[52] Jason J. Danaher, R. C. (2013). Alternative Solids Removal for Warm Water Recirculating Raft Aquaponic Systems. Retrieved from Wiley Online Library: DOI: 10.1111/jwas.12040

[53] Johanna Suhl, D. D. (2016). Advanced aquaponics; Evaluation of intensive tomato production in aquaponics vs. conventional. Agricultural Water Management, 335–344.

[54] Johanson, E. K. (n.d.). Aquaponics and Hydroponics on a Budget. Retrieved from www.scribd.com/document/149323663/Aquaponics2-pdf

[55] John Davidson, S. T. (2005). Solids removal from a coldwater recirculating system - comparison of a swirl separator and a radial-flow settler. Retrieved from http://integrated-aqua.com/wordpress/wp-content/uploads/2012/09/Radial_Flow_Settler_Whitepaper.pdf
[56] José Miguel Arnal, B. G.-F. (2011). *Membrane Cleaning*. Retrieved from ResearchGate: https://www.researchgate.net/file.PostFileLoader.html?id...assetKey

[57] Kaeser. (2007). *Designing Your Compressed Air System*. Retrieved from Kaeser Compressors: http://www.kaeser.ca/Images/USGUIDE3_DesigningYourCompAirSys-tcm67-12601.pdf

[58] Kanae, T. C. (2013). Economics of Commercial Aquaponics in Hawaii. 22. Retrieved from www.ctsa.org/files/publications/HawaiiAquaponicsEconomics_Nov2013.pdf

[59] Konrad Mengel, E. A. (n.d.). *Principles of Plant Nutrition – 5th Edition*. Retrieved from https://books.google.com.au/books?hl=en&lr=&id=WhNDJdbLgEC&oi=fnd&pg=PA2&dq=as+pH+restrict+nutrient+hydroponic+uptake+by+plants&ots=z2LY190rcI&sig=wbusDk-i1AtXbfRtkUYbZbK94T

[60] Kossay, K. A.-A. (2006). Analysis of Oxygen Transfer Performance on Sub-surface Aeration Systems. Retrieved from www.mdpi.com/1660-4601/3/3/301/pdf

[61] L Dediu, V. C. (2012). *Waste production and valorization in an integrated aquaponic system with baster and lettuce*. Retrieved from African Journal of Biotechnology: https://www.ajol.info/index.php/ajb/article/view/100608

[62] Larry Cooper, D. R.-G. (2015). *Micronutrients Are The Key To Better Yields*. Retrieved from http://www.croplife.com/crop-inputs/micronutrients/micronutrients-are-the-key-to-better-yields
[63] Latham. (n.d.). *16 ESSENTIAL NUTRIENTS*. Retrieved from http://www.lathamseeds.com/made-for-you/pathway-to-production/16-essential-nutrients

[64] Lennard, P. W. (2012). *Aquaponics System Design Parameters: Solids Filtration, Treatment and Re-use*. Retrieved from https://www.aquaponic.com.au/Solids%20filtration.pdf

[65] Lennard, P. W. (n.d.). *Commercial Aquaponics*. Retrieved from Aquaponic Solutions: httpwww.aquaponic.com.au/Commercial%20Aquaponic%20Systems%20-%20TOC%20&%20Intro.pdf

[66] Louis A. Helfrich, G. L. (2013). *Fish Farming in Recirculating Aquaculture Systems RAS*. Retrieved from Virginia Tech: http://fisheries.tamu.edu/files/2013/09/Fish-Farming-in-Recirculating-Aquaculture-Systems-RAS.pdf

[67] M. Pirsaheb, T. K. (2015). *Comparing operational cost and performance evaluation of electrodialysis and reverse osmosis systems in nitrate removal from drinking water in Golshahr, Mashhad*. Retrieved from Journal of Desalination and Water treatment: http://dx.doi.org/10.1080/19443994.2015.1004592

[68] Maine, S. o. (2009). *NOTES ON ACTIVATED SLUDGE PROCESS CONTROL*. Retrieved from http://www.maine.gov/dep/water/wwtreatment/activated_sludge_process_control.pdf

[69] Marlin, T. (2005). Operability in Process Design: Achieving Safe, Profitable, and Robust Process Operations. Retrieved from www.pc-education.
[70] Michigan, S. o. (n.d.). *ACTIVATED SLUDGE PROCESS CONTROL*. Retrieved from Department of Environmental Quality: https://www.michigan.gov/documents/deq/wrd-ot-activated-sludge-manual_460007_7.pdf

[71] Mooers. (2013). *Bubble Diffuser Differences*. Retrieved from Mooers Products: http://www.mooersproductsinc.com/bubble-diffuser-aeration-differences

[72] Muhammad H Al-Khalifah, G. K. (2012). *Control valve versus variable speed drive for flow control*. Retrieved from http://automation.isa.org/wp-content/uploads/2012/06/Control-Valve-vs-Variable-Speed-Drive1.pdf

[73] N. Vergotr, J. V. (n.d.). *Recirculation aquaculture system (RAS) with tilapia in a hydroponic system with tomatoes*. Retrieved from www.actahort.org/members/showpdf?booknrarnr=927_6

[74] Narapong Hongprasith, N. D. (2016). *Study of different flexible aeration tube diffusers: Characterization and oxygen transfer performance*. Retrieved from Science Central: https://doi.org/10.4491/eer.2015.082

[75] Nations, F. a. (n.d.). *Aquaponic Systems: Nutrients recycling from fish wastewater by vegetable production*. Retrieved from www.researchgate.net/publication/222537337_Aquaponic_Systems_Nutrient_recycling_from_fish_wastewater_by_vegetable_production
[76] Nelson, R. (2013). *Failures in Aquaponics*. Retrieved from Nelson Pade: https://aquaponics.com/failures-in-aquaponics

[77] Newman, S. (2014). *Fishmeal: The good, the bad and the ugly*. Retrieved from SeafoodSource: https://www.seafoodsource.com/blogs/archive/fishmeal-the-good-the-bad-and-the-ugly

[78] Nga T. Nguyen, S. A.-C. (2016). *Hydroponics: A Versatile System to Study Nutrient Allocation and Plant Responses to Nutrient Availability and Exposure to Toxic Elements*. Retrieved from Journal of Visualized Experiments: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5091364

[79] Nick, S. P. (2005). Evaluation and Development of Aquaponic Production and Product Market Capabilities in Alberta. 11. Retrieved from www.ecogrow.ca/pdf/CDC_Report_Phase_II.pdf

[80] Nihal, A. S. (2015). Study of P&ID, Safeguarding Philosophy, Design Basis and Its Features. Retrieved from ohsfejournal.com/wp.../Article-01-Vol-3-Issue-1-Jan-1-to-March-31-2015_Final.pdf

[81] Noel Scattini, S. P. (2017). Aquaponics - A Process Control Approach. *Modern Applied Science*, 43 - 48. Retrieved from doi.org/10.5539/mas.v11n11p43

[82] Noel Scattini, S. P. (2017). Aquaponic Integration and Automation – A Critical Evaluation. *Modern Applied Science*, 165-171. Retrieved from https://doi.org/10.5539/mas.v11n9p165
[83] Noel Scattini, S. P. (2017). Aquaponics Automation – Design Techniques. *Modern Applied Science*, 28 - 33. Retrieved from doi.org/10.5539/mas.v11n11p28

[84] NPDsolutions. (2016). *Failure Modes and Effects Anlysis (FMEA)*. Retrieved from www.npd-solutions.com/fmea.html

[85] Oi, A. N. (n.d.). *The freshest certified organic lettuce in Maui*. Retrieved from https://apnko.com/en

[86] Palayesh, A. (2015). *Moving Bed Bioreactors (MBBR)*. Retrieved from http://absunpalayesh.com/en/2015/12/30/moving-bed-bioreactors-mbbr

[87] Paul C. Burrell, C. M. (2001). *Identification of Bacteria Responsible for Ammonia Oxidation in Freshwater Aquaria*. Retrieved from *Applied and Environmental Microbiology*: doi: 10.1128/AEM.67.12.5791-5800.2001

[88] Rakocy, J. (2013, June). *Ten Guidelines for Aquaponic Systems*. Retrieved from http://santarosa.ifas.ufl.edu/wp-content/uploads/2013/06/Aquaponics-Journal-10-Guidelines.pdf

[89] Richard V. Tyson, D. D. (2011, February). *Opportunities and Challenges to Sustainability in Aquaponic Systems*. Retrieved from http://horttech.ashspublications.org/content/21/1/6.full

[90] Sam.W. (n.d.). *Ammonia Nitrate and Nitrite*. Retrieved from http://www.geocities.ws/mmst2_sam_w/ANN.htm

[91] Sambal's. (2015). *Photosynthesis*. Retrieved from KS3 Science: http://sambal.co.uk/?page_id=218
[92] Seborg, E. M. (n.d.). Process Dynamics and Control. In E. M. Seborg, *Process Dynamics and Control*. WILEY.

[93] Sedbrook, D. (2016). *2,4-D: The Most Dangerous Pesticide You've Never Heard Of*. Retrieved from NRDC: https://www.nrdc.org/stories/24-d-most-dangerous-pesticide-youve-never-heard

[94] Self, J. (2013). *Plant Analysis*. Retrieved from Colorado State University: http://extension.colostate.edu/docs/pubs/crops/00116.pdf

[95] Simon Goddek, B. D. (2015). *Challenges of Sustainable and Commercial Aquaponics*. Retrieved from MDPI: doi:10.3390/su7044199

[96] Sophia Epstein. (2017). *Growing underground: the hydroponic farm hidden 33 metres below London*. Retrieved from Wired: http://www.wired.co.uk/article/underground-hydroponic-farm

[97] State, O. (2017). *Recirculating Aquaculture Tank Production Systems: Aquaponics—Integrating Fish and Plant Culture*. Retrieved from http://factsheets.okstate.edu/documents/srac-454-recirculating-aquaculture-tank-production-systems-aquaponics-integrating-fish-and-plant-culture

[98] Station, T. R. (n.d.). *FAO - Fish meal*. Retrieved from FAO Corporate Document Repository: http://www.fao.org/wairdocs/tan/x5926e/x5926e01.htm

[99] Stephen J. Sosik, C. P. (n.d.). *SCADA Systems in Waste Water Treatment*. Retrieved from http://www.process-logic.com/content/images/SCADA.pdf
[100] Steven T. Summerfelt, A. Z. (2015). Effects of alkalinity on ammonia removal, carbon dioxide stripping, and system pH in semi-commercial scale water recirculating aquaculture systems operated with moving bed bioreactors. Retrieved from www.elsevier.com/locate/aqua-online

[101] Sutton, J. C. (2006). Etiology and epidemiology of Pythium root rot in hydroponic crops: current knowledge and perspectives. www.scielo.br/scielo.php?script=sci_arttext&pid=S0100-54052006000400001

[102] Swann, L. (n.d.). A Fish Farmer's Guide to Understanding Water Quality. Retrieved from Department of Animal Sciences: https://www.extension.purdue.edu/extmedia/as/as-503.html

[103] Swapnil, B. A. (2013). A Review: Implementation of Failure Mode and Effect Analysis. Retrieved from www.ijeit.com/vol%202/Issue%208/IJEIT1412201302_07.pdf

[104] T. Vermeulen, A. K. (n.d.). The need for systems design for robust aquaponics systems in the urban environment. Retrieved from http://www.actahort.org/books/1004/1004_6.htm

[105] Tahara, C. (2016, June). VFDS: AN ALTERNATIVE TO VALVES FOR MECHANICAL THROTTLING. Retrieved from https://www.flowcontrolnetwork.com/vfds-an-alternative-to-valves-for-mechanical-throttling

[106] Technologies, U. D. (n.d.). Variable Speed Pumping — A Guide to Successful Applications. Retrieved from https://www1.eere.energy.gov/manufacturing/tech_assistance/pdfs/variable_speed_pumping.pdf
[107] Technologies, W. M. (n.d.). *WMT RADIAL FLOW SETTLER*. Retrieved from http://www.w-m-t.com/wmt-radial-flow-settler

[108] Teltherm Instruments, L. (2017). Cerlic Total Suspended Solids Sensor. Retrieved from Teltherm Instruments LTD—Cerlic Total Suspended Solids Sensorl – Article - http://www.teltherm.co.nz/shop/Specialty+Products/Cerlic+Total+Suspended+Solids+Sensor.html

[109] Tess Russo, K. A. (2014). *Sustainable Water Management in Urban, Agricultural, and Natural Systems*. Retrieved from MDPI Journals: doi:10.3390/w6123934

[110] Tom Davies, S. P. (2017). *Wastewater Automation – The Development of a Low Cost, Distributed Automation System*. Retrieved from Modern Applied Science: https://doi.org/10.5539/mas.v11n6p41

[111] Vivian B. Jensen, J. L. (n.d.). *Drinking Water Treatment for Nitrate*. Retrieved from http://groundwaternitrate.ucdavis.edu/files/139107.pdf

[112] Vivian B. Jensen, J. L. (n.d.). *Nitrate in Potable Water Supplies: Alternative Management Strategies*. Retrieved from www.tandfonline.com/doi/abs/10.1080/10643389.2013.828272?src=recsys&journalCode=best20

[113] Watch, F. a. (n.d.). *Water Usage in Recirculating Aquaculture/Aquaponic Systems*. Retrieved from http://fisheries.tamu.edu/files/2013/10/Water-Usage-in-Recirculating-AquacultureAquaponic-Systems.pdf
[114] Watertech, W. n. (n.d.). *Wastewater Treatment - Biological Treatment.* Retrieved from http://www.watertech.ca/solutions/wastewater-treatment/biological-treatment.html

[115] Wilson A. Lennard, B. V. (2006). *A comparison of three different hydroponic sub-systems (gravel bed, floating and nutrient film technique) in an Aquaponic test system.* Retrieved from academia.edu: DOI 10.1007/s10499-006-9053-2

[116] Wilson Lennard, P. (n.d.). *Aquaponic System Design Parameters.* Retrieved from www.aquaponic.com.au/Fish%20to%20plant%20ratios.pdf

[117] Wilson Lennard, P. (n.d.). *Solids Filtration, Treatment and re-use.* Retrieved from https://www.aquaponic.com.au/Solids%20filtration.pdf

[118] Xie, M. (2015). *Membrane-based Processes for Wastewater Nutrient Recovery: Technology, Challenges, and Future Direction.* Retrieved from ResearchGate: DOI: 10.1016/j.watres.2015.11.045

[119] Zealand, A. a. (2000). *Australian and New Zealand Guidelines for Fresh and Marine Water Quality.* Retrieved from https://www.environment.gov.au/system/files/resources/e080174c-b267-455e-a8db-d3f79e3b2142/files/nwqms-guidelines-4-vol3.pdf
### 8.1 Instrumentation and Alarm List

| Tag Number | Instrumentation / Equipment Type | I/O Type | Service Description | Location | High Priority | Low Priority | Event Only |
|------------|-----------------------------------|----------|---------------------|----------|---------------|--------------|------------|
| LI100      | Fish Tanks                        |          |                     |          |               |              |            |
| LI101      | Level Indication                  | DI       | Tank 1 Level High   | Field    |               |              |            |
| LAH100     | Level Alarm                       | N/A      | Tank 1 Level High   | HMI      | X             |              |            |
| LAL101     | Level Alarm                       | N/A      | Tank 1 Level Low    | HMI      | X             |              |            |
| Sensor | Action | Method | Alarm | Field |
|--------|--------|--------|-------|-------|
| G121   | Pump   | N/A    | Tank 1 Pump | Field |
| HY130  | Start Switch | DO | Tank 1 Start Solids Pump | HMI   | X     |
| HY131  | Stop Switch | N/A | Tank 1 Stop Solids Pump | HMI   | X     |
| UHS150 | Emergency Stop Switch | DI | Tank 1 Emergency Stop Solids Pump | Field |
| UHA150 | Emergency Stop | N/A | Tank 1 Emergency Stop Solids Pump | HMI   | X     |
| FS170  | Flow Indications | DI | Tank 1 Flow Solids | Field |
| FS171  | Flow   | DI | Tank 1 | Field |
|       | Indications          | Flow | Suspected |
|-------|----------------------|------|-----------|
| LI102 | Level Indication DI  | Tank | Field     |
|       |                      | 2    | Level High|
|       |                      |      | Alarm     |
| LI103 | Level Indication DI  | Tank | Field     |
|       |                      | 2    | Level Low |
|       |                      |      | Alarm     |
| G122  | Pump N/A             | Tank | Field     |
|       |                      | 2    | Pump      |
| HY132 | Start Switch DO      | Tank | HMI       |
|       |                      | 2    | Start Solids|
|       |                      |      | Pump      |
|       |                      |      | X         |
|   |   |   |   |   |   |
|---|---|---|---|---|---|
| HY13 3 | Stop Switch | N/A | Tank 2 Stop Solids Pump | HMI | X |
| UHS1 51 | Emergency Stop Switch | DI | Tank 2 Emergency Stop Solids Pump | Field |   |
| UHA1 51 | Emergency Stop | N/A | Tank 2 Emergency Stop Solids Pump | HMI | X |
| FS172 | Flow Indications | DI | Tank 2 Flow Solids | Field |   |
| FS173 | Flow Indications | DI | Tank 2 Flow Suspended | Field |   |
| LI104 | Level Indication | DI | Tank 3 Level High Alarm | Field |   |
| LI105 | Level Indication | DI | Tank 3 | Field |   |
|   |   |   |   |   |   |
|---|---|---|---|---|---|
| LAH1 04 | Level Alarm High | N/A | Tank 3 Level High Alarm | HMI | X |
| LAL1 05 | Level Alarm Low | N/A | Tank 3 Level Low Alarm | HMI | X |
| G123 | Pump | N/A | Tank 3 Pump | Field |   |
| HY13 4 | Start Switch | DO | Tank 3 Start Solids Pump | HMI | X |
| HY13 5 | Stop Switch | N/A | Tank 3 Stop Solids Pump | HMI | X |
| UHS1 52 | Emergency Stop Switch | DI | Tank 3 Emergency Stop Solids Pump | Field |   |
|    |       |     |     |         |    |     |
|----|-------|-----|-----|---------|----|-----|
| UHA1 | Emergency Stop | N/A | Tank 3 Emergency Stop Solids Pump | HMI | X   |
|     | Flow Indications | DI  | Tank 3 Flow Solids | Field |     |
|     | Flow Indications | DI  | Tank 3 Flow Suspended | Field |     |
| LI106 | Level Indication | DI  | Tank 4 Level High Alarm | Field |     |
| LI107 | Level Indication | DI  | Tank 4 Level Low Alarm | Field |     |
| LAH1 | Level Alarm High | N/A | Tank 4 Level High Alarm | HMI  | X   |
| LAL1 | Level Alarm | N/A | Tank 4 | HMI  | X   |
|   | Low | Level Low Alarm | N/A | Tank 4 Pump | Field |
|---|-----|-----------------|-----|-------------|-------|
| G124 | Pump | Tank 4 Pump | Field |
| HY136 | Start Switch | Tank 4 Start Solids Pump | HMI | X |
| HY137 | Stop Switch | Tank 4 Stop Solids Pump | HMI | X |
| UHS153 | Emergency Stop Switch | Tank 4 Emergency Stop Solids Pump | Field |
| UHA153 | Emergency Stop | Tank 4 Emergency Stop Solids Pump | HMI | X |
| FS176 | Flow Indications | Tank 4 Flow Solids | Field |
| Ref  | System       | Type   | Sensor | Location         | Method |
|------|--------------|--------|--------|------------------|--------|
| FS177| Flow Indications | DI     |        | Tank 4 Flow Suspended | Field |
| LI108| Level Indication | DI     |        | Tank 5 Level High Alarm | Field |
| LI109| Level Indication | DI     |        | Tank 5 Level Low Alarm | Field |
| LAH1| Level Alarm High | N/A    |        | Tank 5 Level High Alarm | HMI X |
| LAL1| Level Alarm Low | N/A    |        | Tank 5 Level Low Alarm | HMI X |
| G125| Pump          | N/A    |        | Tank 5 Pump       | Field |
| HY13| Start Switch  | DO     |        | Tank 5 Start Solids | HMI X |
| ID   | Description           | Type  | Related Component          | Location   | Status |
|------|-----------------------|-------|----------------------------|------------|--------|
| HY139| Stop Switch           | N/A   | Tank 5 Stop Solids Pump    | HMI        | X      |
| UHS154| Emergency Stop Switch| DI    | Tank 5 Emergency Stop Solids Pump | Field      |        |
| UHA154| Emergency Stop        | N/A   | Tank 5 Emergency Stop Solids Pump | HMI        | X      |
| FS178| Flow Indications      | DI    | Tank 5 Flow Solids         | Field      |        |
| FS179| Flow Indications      | DI    | Tank 5 Flow Suspended      | Field      |        |
| LI110| Level Indication      | DI    | Tank 6 Level High Alarm    | Field      |        |
| LI111 | Level Indication | DI | Tank 6 | Level Low | Field |
|-------|------------------|----|--------|-----------|-------|
| LAH1  | Level Alarm      | N/A| Tank 6 | Level High| HMI X |
|       | High             |    |        | Alarm     |       |
| LAL1  | Level Alarm      | N/A| Tank 6 | Level Low | HMI X |
|       | Low              |    |        | Alarm     |       |
| G126  | Pump             | N/A| Tank 6 | Pump      | Field |
| HY14  | Start Switch     | DO | Tank 6 | Start Solids Pump | HMI X |
|       |                  |    |        |           |       |
| HY14  | Stop Switch      | DO | Tank 6 | Stop Solids Pump | HMI X |
|       |                  |    |        |           |       |
| UHS1  | Emergency Stop Switch | DI | Tank 6 | Emergency Stop Solids | Field |
|       |                   |    |        |           |       |
|                  | Pump                  | Tank 6                | Tank 7                |
|------------------|-----------------------|-----------------------|-----------------------|
| UHA1 55          | Emergency Stop        | N/A                   | N/A                   |
|                  | Emergency Stop Solids |                      |                       |
|                  | Pump                  | HMI                   | X                     |
| FS180            | Flow Indications      | Di                    | Field                 |
|                  |                       |                       |                       |
| FS181            | Flow Indications      | Di                    | Field                 |
|                  |                       |                       |                       |
| LI112            | Level Indication      | Di                    | Field                 |
|                  |                       |                       |                       |
| LI113            | Level Indication      | Di                    | Field                 |
|                  |                       |                       |                       |
| Tank 7           | Level High Alarm      | HMI                   | X                     |
| Tank 7 Level Low Alarm | HMI | N/A | X |
|------------------------|-----|-----|---|
| G127 Pump N/A           | Tank 7 Pump Field |
| HY14 2 Start Switch DO  | Tank 7 Start Solids Pump HMI |
| HY14 3 Stop Switch N/A  | Tank 7 Stop Solids Pump HMI |
| UHS1 56 Emergency Stop Switch DI | Tank 7 Emergency Stop Solids Pump Field |
| UHA1 56 Emergency Stop N/A | Tank 7 Emergency Stop Solids Pump HMI X |
|     | Description          | Type | Sensor | Location   | Field   |
|-----|----------------------|------|--------|------------|---------|
| FS182 | Flow Indications     | DI   | Tank 7 Flow Solids | Field |
|     |                      |      |        |             |         |
| FS183 | Flow Indications     | DI   | Tank 7 Flow Suspended | Field |
|     |                      |      |        |             |         |
| LI114 | Level Indication    | DI   | Tank 8 Level High Alarm | Field |
|     |                      |      |        |             |         |
| LI115 | Level Indication    | DI   | Tank 8 Level Low Alarm  | Field |
|     |                      |      |        |             |         |
| LAH1 14 | Level Alarm High | N/A  | Tank 8 Level High Alarm | HMI X   |
|     |                      |      |        |             |         |
| LAL1 15 | Level Alarm Low | N/A  | Tank 8 Level Low Alarm  | HMI X   |
|     |                      |      |        |             |         |
| G128  | Pump                 | N/A  | Tank 8 Pump              | Field   |
|     |                      |      |        |             |         |
|   |   |   |   |   |   |
|---|---|---|---|---|---|
| HY14 4 | Start Switch | DO | Tank 8 Start Solids Pump | HMI | X |
| UHS1 57 | Emergency Stop Switch | DI | Tank 8 Emergency Stop Solids Pump | Field |   |
| UHA1 57 | Emergency Stop | N/A | Tank 8 Emergency Stop Solids Pump | HMI | X |
| FS184 | Flow Indications | DI | Tank 8 Flow Solids | Field |   |
| FS185 | Flow Indications | DI | Tank 8 Flow Suspended | Field |   |
| FA199 | Audible/Visual | DO | Main Alarm | HMI | X |
| Product Code | Beacon | Alarm | Field |
|--------------|--------|-------|-------|
| SY191        | VSD    | N/A   | Field |
|              |        |       | Sump Return Pump 1 VSD |
| SY191        | VSD SPEED | AO | HMI |
|              |        |       | Sump Return Pump 1 speed control |
| HY192        | Start  | DO    | HMI |
|              |        |       | Start Sump Return Pump 1 |
| HY193        | Stop   | N/A   | X |
|              |        |       | Stop Sump Return Pump 1 |
| UHS194       | Emergency Stop Switch | DI | Field |
|              |        |       | Emergency Stop Sump Return Pump 1 |
| UHA1 94 | Emergency Stop Indication | N/A | Emergency Stop Sump Return Pump 1 | HMI | X |
|---------|--------------------------|-----|----------------------------------|-----|---|
| G189    | Sump Pump                | N/A | Sump Return Pump 1               | Field |   |
| SY195   | VSD                      | N/A | Sump Return Pump 2 VSD           | Field |   |
| SY119 5 | VSD SPEED                | AO  | Sump Return Pump 2 speed control | HMI |   |
| HY19 6  | Start                    | DO  | Start Sump Return Pump 2         | HMI | X |
| HY19    | Stop                     | N/A | Stop Sump                        | HMI | X |
|    |          |                |         |         |
|----|----------|----------------|---------|---------|
| 7  |          | Return Pump 2  |         |         |
| UHS1 98 | Emergency Stop Switch | DI | Emergency Stop Sump Return Pump 2 | Field |
| UHA1 98 | Emergency Stop Indication | N/A | Emergency Stop Sump Return Pump 2 | HMI   | X |
| G190 | Sump Pump | N/A | Sump Return Pump 2 | Field |
| Baffle Separator | | | | |
| FCV2 00 | Baffle Flow control Valve | AO | Flow Valve | Field |
| FC200 | Baffle Flow | N/A | Flow Valve | HMI   |
|                | Control                  | Controller               |    |    |
|----------------|--------------------------|--------------------------|----|----|
| FCI200         | Baffle Flow Indication   | N/A                      | Flow Control Indication | HMI |
|                |                          |                          |    |    |
|                |                          |                          |    |    |
|                |                          |                          |    |    |
|                |                          | Radial Clarifier         |    |    |
|                |                          |                          |    |    |
| SY210          | VSD                      | N/A                      | Solids Return Pump 1 VSD | Field |
|                |                          |                          |    |    |
| SY1210         | VSD SPEED                | AO                       | Solids Return Pump 1 speed control | HMI |
|                |                          |                          |    |    |
| HY211          | Start                    | DO                       | Start Solids Return Pump 1 | HMI |
|                |                          |                          |    |    |
|                |                          |                          |    | X  |
| HY21 2 | Stop | DO | Stop Solids Return Pump 1 | HMI | X |
|--------|------|----|--------------------------|-----|---|
| UHS2 13 | Emergency Stop Switch | DI | Emergency Stop Solids Return Pump 1 | Field |   |
| UHA2 13 | Emergency Stop Indication | N/A | Emergency Stop Solids Return Pump 1 | HMI | X |
| G215 | Pump | N/A | Radial Clarifier Pump | Field |   |

**Mineralisation**

| HY22 0 | Start | DO | Start Aquatic Filter | HMI | X |
| Location | Function          | Signal | Source | Target | Status |
|----------|-------------------|--------|--------|--------|--------|
| HY22 1   | Stop DO           | DO     | HMI    | X      |
| UHS2 23  | Emergency Stop Switch | DI     | Field  |        |
| UHA2 23  | Emergency Stop Indication | N/A    | HMI    | X      |
| G225     | Filter Pump       | N/A    | Field  |        |
| HY23 0   | Start DO          | DO     | HMI    | X      |
| HY23 1   | Stop DO           | DO     | HMI    | X      |
| Code   | Equipment                  | Location | Function              | Location |
|--------|----------------------------|----------|-----------------------|----------|
| UHS2   | Emergency Stop Switch      | DI       | Emergency Decanting Pump | Field    |
| 32     |                            |          |                       |          |
| UHA2   | Emergency Stop             | N/A      |                       | HMI      | X       |
| 32     | Decanting Pump             |          |                       | Field    |
| G235   | Filter Pump                | N/A      | Decanting Pump        | Field    |
| AT240  | Oxygen Analyser            | N/A      | Mineralisation Oxygen Analyser | Field |
| AI240  | Oxygen Indication          | N/A      | Mineralisation Oxygen Indication | HMI |
| AAH2   | Analyser                   | N/A      | Mineralisation Oxygen High Alarm | HMI |
| 40     |                            |          |                       |          |
| AAL2   | Analyser                   | N/A      | Mineralisation        | HMI      | X       |
|   |   | on Oxygen Low Alarm |   |   |
|---|---|---------------------|---|---|
| AT245 | Sludge Analyser | N/A | Mineralisation Sludge Level Analyser | Field |
| AI245 | Analyser Indication | N/A | Mineralisation Sludge Level Indication | HMI |
| AAH2 45 | Analyser | N/A | Mineralisation Sludge Level High Alarm | HMI |
| FCV2 50 | Flow Control Valve | AO | Mineralisation Air Flow Valve | Field |
| FC250 | Flow Controller | N/A | Air Flow Valve Controller | Field |
| Code  | Description                      | Function       | Location | Remarks |
|-------|----------------------------------|----------------|----------|---------|
| FCI25 | Flow Control Indication         | N/A            | HMI      |         |
| PCV251| Pressure Control Valve           | N/A            | Field    |         |
| SY270 | VSD                             | N/A            | Field    |         |
| SYI270| VSD SPEED                       | AO             | HMI      |         |
| HY271 | Start DO                        |                | HMI      | X       |
| HY272 | Stop DO                         |                | HMI      | X       |
|          |               |               |               |               |               |
|----------|---------------|---------------|---------------|---------------|---------------|
| UHS2 73 | Emergency Stop Switch | DI | Emergency Stop Solids Return Pump 1 | Field |
| UHA2 73 | Emergency Stop Indication | N/A | Emergency Stop Solids Return Pump 1 | HMI | X |
| G275    | Solids Pump | N/A | Solids Return Pump | Field |
| HY28 0  | Start | N/A | Start UV Bank 1 | Field |
| HY28 1  | Stop | N/A | Stop UV Bank 1 | Field |
|          | **Nitrification** |               |               |               |               |
|    | Flow Control Valve | Decanting Flow Valve | Field |
|----|-------------------|----------------------|-------|
| FCV300 | Flow Controller | Decanting Flow Controller | HMI |
| FCI300 | Flow Control Indication | Decanting Flow Indication | HMI |
| AT305 | Oxygen Analyser | Nitrification Oxygen Analyser | Field |
| AI305 | Oxygen Indication | Nitrification Oxygen Indication | HMI |
| AAH305 | Analyser | Nitrification Oxygen High Alarm | HMI |
| AAL305 | Analyser | Nitrification Oxygen | HMI | X |

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|        |                | Low Alarm                  |          |          |          |
|--------|----------------|----------------------------|----------|----------|----------|
| AT310  | Solids Analyser | N/A                        | Field    |          |          |
|        |                | Nitrification Dissolved Solids Analyser |          |          |          |
| AI310  | Solids Indication | N/A                        | HMI      |          |          |
|        |                | Nitrification Dissolved Solids Indication |          |          |          |
| AAH310 | Analyser       | N/A                        | HMI      | X        |          |
|        |                | Nitrification Dissolved Solids High Alarm |          |          |          |
| CV315  | Flow Control Valve | DO                        | Field    |          |          |
|        |                | Air Control Valve          |          |          |          |
| CVI315 | Flow Controller | N/A                        | HMI      |          |          |
|        |                | Air Flow Indication        |          |          |          |
| HY350  | Start          | N/A                        | HMI      | X        |          |
|        |                | Air Flow Controller        |          |          |          |
|   |   |   |   |   |   |
|---|---|---|---|---|---|
| HY35 | Stop | N/A | Air Flow Controller | HMI | X |
| PCV3 | Pressure Control Valve | N/A | Pressure Control | Field |   |
| SY320 | VSD | N/A | Solids Return Pump 1 VSD | Field |   |
| SYI32 | VSD SPEED | AO | Solids Return Pump 1 speed control | HMI |   |
| HY32 | Start | DO | Start Solids Return Pump 1 | HMI | X |
| HY32 | Stop | N/A | Stop Solids Return Pump 1 | HMI | X |
|   |   |   |   |   |   |
|---|---|---|---|---|---|
| G325 | Pump | N/A | Solids Pump | Field |   |
| UHS3 23 | Emergency Stop Switch | DI | Emergency Stop Solids Return Pump 1 | Field |   |
| UHA3 23 | Emergency Stop Indication | N/A | Emergency Stop Solids Return Pump 1 | HMI | X |
| TT340 | Temperature Transmitter | AI | Water Temperature Transmitter | Field |   |
| TI340 | Temperature Indication | N/A | Water Temperature Indication | HMI |   |
| TT341 | Temperature Transmitter | AI | Air Temperature Transmitter | Field |   |
| Device | Function                      | Control | Location       |
|--------|-------------------------------|---------|----------------|
| TI341  | Temperature Indication        | N/A     | HMI            |
| CV375  | Flow Control Valve            | AO      | Field          |
| CVI37  | Flow Controller               | N/A     | HMI            |
|        | Degassing and Nutrient Removal Air Services |         |                |
| AT400  | Carbon Dioxide Analyser       | N/A     | Field          |
| AI400  | Carbon Dioxide Indication     | N/A     | HMI            |
|        |          |            | Carbon Dioxide | HMI     |     |     |
|--------|----------|------------|----------------|---------|-----|-----|
| AHA4 00 | Analyser Alarm | N/A       | High Alarm     | HMI     |     | X   |
| HY40 1  | Start    | DO         | Start          | Scrubbing Fan | HMI |     | X   |
| HY40 2  | Stop     | DO         | Stop           | Scrubbing Fan | HMI |     | X   |
| UHS4 03 | Emergency Stop Switch | DI | Emergency       | Stop       | Scrubbing Fan | Field |     |
| UHA4 03 | Emergency Stop | N/A       | Emergency       | Start      | Scrubbing Fan | HMI |     | X   |
| G450   | FAN      | N/A        | FAN            | Field     |     |     |
| AT404  | Suspended | AO         | Suspended      | Field     |     |     |
|   | Solids Analyser | Solids Analyser |   |   |
|---|----------------|----------------|---|---|
| AI404 | Analyser Indication | N/A | Suspended Solids Indication | HMI |   |
| AHA4 04 | Analyser Alarm | N/A | Suspended Solids High Alarm | HMI | X |
| HY40 5 | Start | DO | Start Booster Pump | HMI | X |
| HY40 6 | Stop | DO | Stop Booster Pump | HMI | X |
| UHS4 07 | Emergency Stop Switch | DI | Emergency Stop Booster Pump | Field |   |
| UHA4 07 | Emergency Stop | N/A | Emergency Stop | HMI | X |
|   |   | Booster Pump |   |   |   |
|---|---|---------------|---|---|---|
| G455 | Pump | N/A | Booster Pump | Field |   |
| CV410 | Flow Control Valve | DO | Control Valve | Field |   |
| CVI410 | Flow Controller | N/A | Flow Controller | HMI |   |
| CV415 | Flow Control Valve | DO | Control Valve | Field |   |
| CVI415 | Flow Controller | N/A | Flow Controller | HMI |   |
| HY420 | Start | DO | Start SED Unit | HMI |   |
| HY421 | Stop | DO | Stop SED Unit | HMI |   |
| XA42 | SED Fault | N/A | SED Fault | HMI |   |
|   | Indication          |   |   |   |   |
|---|---------------------|---|---|---|---|
| 2 | G460                | SED| N/A| SED Unit Field |
|   | LT425              | Level Transmitter| AI| Nutrient Tank Level Transmitter Field |
|   | LI425              | Level Indication| N/A| Nutrient Level Indication HMI |
|   | LAH4 25           | Level Alarm| N/A| Level High Alarm > 90 % HMI X |
|   | LAL4 25           | Level Alarm| N/A| Level Low Alarm < 20 % HMI X |
|   | HY43 0            | Start| DO| Start Air Flow Fan 1 HMI X |
|   | HY43 1            | Stop| DO| Stop Air Flow Fan 1 HMI X |
| UHS4 | Emergency Stop Switch | DI | Emergency Stop Air Flow Fan 1 | Field |
|------|------------------------|----|-------------------------------|-------|
| UHA4 | Emergency Stop N/A     | N/A| Emergency Stop Air Flow Fan 1 Alarm | HMI   | X |
| G440 | Fan N/A                | Fan 1 | Field         |       |
| HY43 | Start DO              | Start Air Flow Fan 2 | HMI   | X |
| HY43 | Stop DO              | Stop Air Flow Fan 2 | HMI   | X |
| UHS4 | Emergency Stop Switch DI | Emergency Stop Air Flow Fan 2 | Field |
| UHA4 | Emergency Stop N/A     | N/A| Emergency Stop Air Flow Fan 2 Alarm | HMI   | X |
|   | Fan | N/A | Fan 2 | Field |   |
|---|-----|-----|-------|-------|---|
| HY43 | Start | DO | Start Compressor 1 | HMI | X |
| HY43 | Stop | DO | Stop Compressor 1 | HMI | X |
| CV438 | Positioner | AO | Exhaust Positioner | Field |   |
| CVI43 | Position Indication | AI | Exhaust Position Indication | HMI |   |
| G443 | Exhaust Louvers | N/A | Exhaust Louvers | Field |   |
| HY47 | Start | DO | Start Compressor 1 | HMI | X |
| HY47 | Stop | DO | Stop Compressor | HMI | X |
| 1 | 1 |
|---|---|
| **UHS4 72** | **Emergency Stop Switch** | **DI** | **Emergency Stop Compressor 1** | **Field** |
| **UHA4 72** | **Emergency Stop** | **N/A** | **Emergency Stop Compressor 1 Alarm** | **HMI** | **X** |
| **C498** | **Compressor** | **N/A** | **Compressor 1** | **Field** |
| **HY47 5** | **Start** | **DO** | **Start Compressor 2** | **HMI** | **X** |
| **HY47 6** | **Stop** | **DO** | **Stop Compressor 2** | **HMI** | **X** |
| **UHS4 77** | **Emergency Stop Switch** | **DI** | **Emergency Stop Compressor** | **Field** |
| Equipment  | Type               | Location | Status | Location | Alarm Type               |
|------------|--------------------|----------|--------|----------|--------------------------|
| UHA477     | Emergency Stop     | N/A      | HMI    | X        |                          |
| C499       | Compressor         | N/A      | Field  |          |                          |
| PT480      | Pressure Transmitter | AI     | Field  |          |                          |
| PI480      | Pressure Transmitter | N/A  | HMI    |          |                          |
| PAL480     | Pressure Transmitter | N/A  | HMI    | X        |                          |
| PAH480     | Pressure Transmitter | N/A  | HMI    | X        |                          |
| PRV4       | Pressure Relief    | N/A      | Field  |          |                          |
|     | Valve                  | Pressure |                |              |              |              |
|-----|------------------------|----------|----------------|--------------|--------------|--------------|
| AT488| Analyser Transmitter  | AO       | CO2 Air        | Field        |              |              |
|     |                        |          | Monitoring     |              |              |              |
| AI488| Analyser Transmitter  | N/A      | CO2            | HMI          |              |              |
|     |                        |          | Indication     |              |              |              |
| AAH488| Analyser Transmitter | N/A      | CO2            | HMI          | X            |              |
|      |                        |          | Alarm          |              |              |              |
|      |                        |          | High > 3000 ppm|              |              |              |
| AHH488| Analyser Transmitter  | N/A      | CO2            | HMI          | X            |              |
|      |                        |          | Alarm          |              |              |              |
|      |                        |          | High High >   |              |              |              |
|      |                        |          | 4000 ppm       |              |              |              |
|     | Aquaponics - Nutrient |          |                |              |              |              |
|     | Monitoring             |          |                |              |              |              |
| AT500| Analyser Transmitter  | AI       | Oxygen         | Field        |              |              |
|     |                        |          | Transmitter    |              |              |              |
| Code     | Description          | Type  | Value  | Unit | Location |
|----------|----------------------|-------|--------|------|----------|
| AI500    | Analyser Alarm       |       | N/A    |      | HMI      |
| ALA500   | Oxygen Low Alarm     |       | N/A    |      | HMI      |
| AHA500   | Oxygen High Alarm    |       | N/A    |      | HMI      |
| AT501    | pH Low Alarm         | Al    | AI     |      | Field    |
| AI501    | pH High Alarm        |       | N/A    |      | HMI      |
| ALA501   | pH Low Alarm         |       | N/A    |      | HMI      |
| AHA501   | pH High Alarm        |       | N/A    |      | HMI      |
| AT502    | Nitrates Low Alarm   |       | AI     |      | Field    |
| Model  | Description               | Indication | Nitrates Indication | HMI | Field |
|--------|---------------------------|------------|---------------------|-----|-------|
| AI502  | Analyser Indication      | N/A        | N/A                 | HMI |       |
| AT503  | Analyser Transmitter     | AI         | Ammonia Analyser    | Field |       |
| AI503  | Analyser Indication      | N/A        | Ammonia Indication  | HMI |       |
| AHA503 | Analyser Alarm           | N/A        | Ammonia High Alarm  | HMI | X     |
|        |                           |            | > 0.5 ppm           |     |       |
| AHH503 | Analyser Alarm           | N/A        | Ammonia High High   | HMI | X     |
|        |                           |            | Alarm > 1 ppm       |     |       |
| LT504  | Level Transmitter        | AI         | Tank Level Transmitter | Field |       |
| LI504  | Level Indication         | N/A        | Level Indication    | HMI |       |
| LAH5   | Level Alarm              | N/A        | Level High Alarm    | HMI | X     |
|        |                           |            | > 90                |     |       |
|   |   | % |   |   |
|---|---|---|---|---|
| LAL5 04 | Level Alarm | N/A | Level Low Alarm < 70% | HMI | X |
| LI505 | Level Indication | DI | Sump Level Indication | Field |   |
| LAHH 505 | Level Alarm | N/A | Level Alarm High High Alarm > 95% | HMI | X |
| AT506 | Analyser Transmitter | AI | Analyser Nutrient Alkalinity | Field |   |
| AI506 | Analyser Indication | N/A | Alkalinity Level Indication | HMI |   |
| LAL5 06 | Level Alarm | N/A | Level Low Alarm < 70 ppm | HMI | X |
|       | Analyser Transmitter | AI  | Nutrient | Iron   | Field |
|-------|----------------------|-----|----------|--------|-------|
| AT510 |                      |     |          |        |       |
| AI510 | Analyser Indication | N/A | Iron Level Indication | HMI |
| FC510 | Flow Control         | AO  | Iron Dosing Meter | Field |
| FCI51 | Dosing System Indication | N/A | Iron Control Dosing Meter | HMI |
| AT511 |                      |     |          |        |       |
| AI511 |                      |     | Nutrient  | Calcium|       |
| FC511 |                      |     | Calcium Level Indication | HMI |
|       |                      |     |          |        |       |
|   |   |   |   |   |
|---|---|---|---|---|
| FCI51 | Dosing System Indication | N/A | Calcium Control Dosing Meter | HMI |
| AT512 | Analyser Transmitter | AI | Analyser Nutrient Calcium | Field |
| AI512 | Analyser Indication | N/A | Potassium Level Indication | HMI |
| FC512 | Flow Control | AO | Potassium Dosing Meter | Field |
| FCI51 | Dosing System Indication | N/A | Potassium Control Dosing Meter | HMI |
| AT513 | Analyser Transmitter | AI | Analyser Nutrient Mg | Field |
|    | Analyser Indicator |    | Mg Level Indicator |    | HMI |
|----|--------------------|----|--------------------|----|-----|
| **AI513** | Analyser Transmitter | AI | Analyser Nutrient Mn | Field |
| **AT514** | Analyser Transmitter | AI | Analyser Nutrient Mn | Field |
| **AI514** | Analyser Transmitter | AI | Analyser Nutrient Mn | Field |
| **AT515** | Analyser Transmitter | AI | Analyser Nutrient Mn | Field |
| **AI515** | Analyser Transmitter | AI | Analyser Nutrient Mn | Field |
| **AT516** | Analyser Transmitter | AI | Analyser Nutrient Mn | Field |
| **AI516** | Analyser Transmitter | AI | Analyser Nutrient Mn | Field |
| **AT517** | Analyser Transmitter | AI | Analyser Nutrient Mn | Field |
| AI517 | Analyser Transmitter | AI | Analyser Nutrient Mo | Field |
|------|----------------------|----|---------------------|-------|
| AI518 | Analyser Indication | N/A | Mo Level Indication | HMI   |
| AT518 | Analyser Transmitter | AI | Analyser Nutrient Phos | Field |
| AT519 | Analyser Indication | N/A | Phos Level Indication | HMI   |
| AT520 | Analyser Transmitter | AI | Analyser Nutrient S | Field |
| AI520 | Analyser Indication | N/A | S Level Indication | HMI   |
| HY55 0 | Start | DO | Start Fill Water | HMI   | X |

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|   |   |   |   |   |   |
|---|---|---|---|---|---|
| HY55 | Stop | N/A | Stop Fill Water | HMI | X |
| 1 |   |   |   |   |   |
| CV550 | Control Valve | N/A | Solenoid | Field |   |
|   |   |   |   |   |   |
| HY55 | Start | DO | Start Air Flow | HMI | X |
| 5 |   |   |   |   |   |
| HY55 | Stop | N/A | Stop Air Flow | HMI | X |
| 6 |   |   |   |   |   |
| CV555 | Control Valve | N/A | Solenoid | Field |   |
|   |   |   |   |   |   |
| PCV5 | Pressure Control Valve | N/A | Pressure Control | Field |   |
| 60 |   |   |   |   |   |
|   | Hydroponic Nutrients |   |   |   |   |
|   | AT600 | Analyser Transmitter | AI | Oxygen Transmitter | Field |   |
|   |   |   |   |   |   |
| AI600 | Analyser Indication | N/A | Oxygen Indication | HMI |   |
| Code   | Device Type      | Function          | Condition         | Location  | Status |
|--------|------------------|-------------------|-------------------|-----------|--------|
| AAL600 | Analyser Alarm   | Oxygen            | Low Alarm < 7     | HMI       | X      |
| AAH600 | Analyser Alarm   | Oxygen            | High Alarm > 10   | HMI       | X      |
| AT601  | Analyser Transmitter | pH Transmitter | Field            |           |        |
| AI601  | Analyser Indication | pH Indication | HMI              |           |        |
| ALA601 | Analyser Alarm   | pH                | Low Alarm < 6.2   | HMI       | X      |
| AHA601 | Analyser Alarm   | pH                | High Alarm > 5.5  | HMI       | X      |
| AT602  | Analyser Transmitter | Nitrates Analyser | Field           |           |        |
| AI602  | Analyser Indication | Nitrates Indication | HMI           |           |        |
|    |     |     |     |     |
|----|-----|-----|-----|-----|
| FC602 | Flow Control | AO | N Dosing Meter | Field |
| LT604 | Level Transmitter | AI | Sump Tank Level Transmitter | Field |
| LI604 | Level Indication | N/A | Sump Level Indication | HMI |
| LAH6 04 | Level Alarm | N/A | Sump Level High Alarm > 90 % | HMI | X |
| LAL6 04 | Level Alarm | N/A | Sump Level Low Alarm < 70 % | HMI | X |
| LI605 | Level Indication | DI | Sump Level Indication | Field |
| LAHH 605 | Level Alarm | N/A | Sump Level Alarm High High > 95 % | HMI | X |
| HY65 0   | Start  | DO    | Start Fill Water | HMI  |   | X   |
|---------|--------|-------|------------------|------|---|-----|
| HY65 1  | Stop   | N/A   | Stop Fill Water  | HMI  |   | X   |
| CV650   | Control Valve | N/A   | Solenoid Field |      |   |     |
| HY65 5  | Start  | DO    | Start Air Flow   | HMI  |   | X   |
| HY65 6  | Stop   | N/A   | Stop Air Flow    | HMI  |   | X   |
| CV655   | Control Valve | N/A   | Solenoid Field |      |   |     |
| PCV660  | Pressure Control Valve | N/A   | Pressure Control | Field | | |
| HY68 0  | Start  | DO    | Start Hydroponic Nutrient Pump | HMI  | | |
| HY68    | Stop   | N/A   | Stop Hydroponic  | HMI  | | |

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|   |           |            |                                |            |            |
|---|-----------|------------|--------------------------------|------------|------------|
| 1 | G685      | Pump   N/A | Hydroponic Nutrient Pump      | Field      |            |
|   | FC609     | Flow Control AO | Recycled Nutrient Flow           | Field      |            |
|   | FCI609    | Flow Indication N/A | Recycled Nutrient Flow Indication | HMI        |            |
|   | FCV609    | Flow Control Valve N/A | Recycled Nutrient Flow Valve | Field      |            |
|   | AT610     | Analyser Transmitter AI | Analyser Nutrient Iron | Field      |            |
|   | AI610     | Analyser Indication N/A | Iron Level Indication       | HMI        |            |
|       | Description               | Location | Measurement | Display |
|-------|---------------------------|----------|-------------|---------|
| FC610 | Flow Control AO           | Field    | Iron Dosing Meter | Field   |
| FCI610| Dosing System Indication  | N/A      | Iron Control Dosing Meter | HMI     |
| AT611 | Analyser Transmitter      | AI       | Analyser Nutrient Calcium | Field   |
| AI611 | Analyser Indication       | N/A      | Calcium     | HMI     |
|       |                           |          | Level       |         |
|       |                           |          | Indication  |         |
| FC611 | Flow Control AO           | Field    | Calcium Dosing Meter | Field   |
| FCI611| Dosing System Indication  | N/A      | Calcium Control Dosing Meter | HMI     |
| AT612 | Analyser                 | AI       | Analyser    | Field   |
|       | Transmitter                  | Nutrient |                  |            |            |
|-------|------------------------------|----------|------------------|------------|------------|
| AI612 | Analysers                   | Nutrient | Potassium        | Indication | HMI        |
|       | Indication                  |          | Level            |            |            |
|       |                              |          |     Indication   |            |            |
|       |                              |          |                  |            |            |
|       | FC612 Flow Control          | Field    | Potassium        | Dosing     | Field      |
|       |                              |          | Dosing           |  Meter     | Field      |
|       |                              |          |                  |            |            |
|       | FCI61 Dosing System         | HMI      | Potassium        | Control    | HMI        |
|       | Indication                  |          | Dosing           |  Meter     | HMI        |
|       |                              |          |                  |            |            |
|       | AT613 Analysers             | Field    | Analyser         | Nutrient   | Field      |
|       | Transmitter                 |          | Nutrient         | Mg         | Field      |
|       |                              |          |                  | Mg         | Field      |
|       |                              |          |                  | Mg         | Field      |
|       | AI613 Analysers             | HMI      | Mg Level         | Indication | HMI        |
|       | Indication                  |          | Level            |            |            |
|       |                              |          |                  |            |            |
|       | FC613 Flow Control          | Field    | Mg Dosing        | Meter      | Field      |
|       |                              |          |                  |            |            |
|       | FCI61 Dosing System         | HMI      | Mg Control       |            | HMI        |
|       |                              |          |                  |            |            |
|   | Indication       | Dosing Meter |            |            |            |
|---|------------------|--------------|------------|------------|------------|
| 3 | AT614 Analyser   | AI           | Nutrient Mn| Field      |            |
|   | Transmitter      |              |            |            |            |
|   | AI614 Analyser   | N/A          | Mn Level   | HMI        |            |
|   | Indication       |              | Indication |            |            |
|   | FC614 Flow Control| AO          | Mn Dosing Meter | Field      |            |
|   | FCI614 Dosing System Indication | N/A | Mn Control Dosing Meter | HMI |            |
|   |                  |              |            |            |            |
|   | AT615 Analyser   | AI           | Nutrient Cu| Field      |            |
|   | Transmitter      |              |            |            |            |
|   | AI615 Analyser   | N/A          | Cu Level   | HMI        |            |
|   | Indication       |              | Indication |            |            |
|   | FC615 Flow Control| AO          | Cu Dosing Meter | Field      |            |
|   | FCI61 Dosing System | N/A | Cu Control | HMI |            |
|   | Indication | Dosing Meter |   |   |
|---|------------|--------------|---|---|
| 5 | AT616      | Analyser Transmitter | AI | Analyser Nutrient Zn | HMI |
|   | AI616      | Analyser Indication | N/A | Zn Level Indication | HMI |
|   | FC616      | Flow Control | AO | Zn Dosing Meter | Field |
|   | FCI616     | Dosing System Indication | N/A | Zn Control Dosing Meter | HMI |
|   | AT617      | Analyser Transmitter | AI | Analyser Nutrient Boron | HMI |
|   | AI617      | Analyser Indication | N/A | Boron Level Indication | HMI |
|   | FC617      | Flow Control | AO | Boron Dosing | Field |
| Device | Type / Description | Meter | Indication | Location |
|--------|--------------------|-------|------------|----------|
| FCI61 7 | Dosing System Indication | N/A   | Boron Control Dosing Meter | HMI |
| AT618  | Analyser Transmitter | AI    | Analyser Nutrient Mo | Field |
| AI618  | Analyser Indication | N/A   | Mo Level Indication | HMI |
| FC618  | Flow Control       | AO    | Mo Dosing Meter | Field |
| FCI618 | Dosing System Indication | N/A   | Mo Control Dosing Meter | HMI |
| AT619  | Analyser Transmitter | AI    | Analyser Nutrient S | Field |
| AI619  | Analyser Indication | N/A   | S Level Indication | HMI |
| FC619 | Flow Control | AO | S Dosing Meter | Field |
|-------|--------------|----|----------------|-------|
| FCI619 | Dosing System Indication | N/A | S Control Dosing Meter | HMI |