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DEVELOPING AN AQUAPONICS SYSTEM TO LEARN SUSTAINABILITY AND SOCIAL COMPROMISE SKILLS

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Abstract

The goal of this project, one of the proposals of the EPS@ISEP Spring 2014, was to develop an Aquaponics System. Over recent years Aquaponics systems have received increased attention since they contribute to reduce the strain on resources within 1st and 3rd world countries. Aquaponics is the combination of Hydroponics and Aquaculture, mimicking a natural environment in order to successfully apply and enhance the understanding of natural cycles within an indoor process. Using this knowledge of natural cycles, it was possible to create a system with capabilities similar to that of a natural environment with the support of electronics, enhancing the overall efficiency of the system. The multinational team involved in the development of this system was composed of five students from five countries and fields of study. This paper describes their solution, including the overall design, the technology involved and the benefits it can bring to the current market. The team was able to design and render the Computer Aided Design (CAD) drawings of the prototype, assemble all components, successfully test the electronics and comply with the budget. Furthermore, the designed solution was supported by a product sustainability study and included a specific marketing plan. Last but not least, the students enrolled in this project obtained new multidisciplinary knowledge and increased their team work and cross-cultural communication skills.

Keywords – Aquaponics, Sustainability, Natural environment, Efficiency.

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1 INTRODUCTION

Engineering, through its role in the creation and implementation of technology, has been a major driver of economy, health and quality of life. Today, in the developed world, we take for granted that transportation is affordable and reliable, good health care is accessible, information and entertainment are provided on call, and safe water and healthy food are readily available. However, there are also negative impacts of technology, e.g., pollution, global warming, depletion of scarce resources, and catastrophic failures of poorly designed engineering systems.

Given these concerns, several studies identify the need to change the way Education is delivered and, in particular, Engineering Education (Committee on the Engineer of 2020, 2005). The world is changing at a fast pace and, in order to prepare students to face these new challenges, new topics must be addressed. Among other aspects, these studies insist that students should attain an understanding of professional and ethical responsibility, as well as the broad education necessary to understand the impact of technical solutions in a global, economic, environmental, and societal context. They also state that students must have knowledge of contemporary issues (Committee on the Engineer of 2020, 2005).

According to the report Engineering for a Changing World (Duderstadt, 2008), among other aspects, 21st-century engineers must:

- be technically competent, globally sophisticated, culturally aware, innovative and entrepreneurial;
- be nimble, flexible and mobile; and
- accommodate a far more holistic approach to addressing social needs and priorities, linking social, economic, environmental, legal, and political considerations with technological design and innovation.

Similar concerns are raised by the American Society for Engineering Education (2010) and the Committee on the Engineer of 2020 (2005).

Therefore, besides scientific and technical subjects, several studies reinforce the need to introduce new topics and concerns in engineering education. Not only aspects such as ethics and deontology should be given more emphasis in engineering (the World Federation of Engineering Organizations model code of ethics is presented in (UNESCO, 2010)) to reduce our vulnerability, by avoiding to repeat the mistakes of the past, and increase our opportunities to emulate “best practice” successes, but also aspects such as sustainability (Committee on the Engineer of 2020, 2005; UNESCO, 2010).

The European Project Semester (EPS) is a one-semester capstone project/internship programme offered to engineering, product design and business undergraduates by 16 European engineering schools which follows these recommendations. EPS aims to prepare future engineers to think and act globally, by adopting project-based learning and teamwork methodologies, fostering the development of complementary skills and addressing sustainability, ethics and multiculturalism. In particular, sustainable development is a pervasive concern within EPS projects (Malheiro, Silva, Ribeiro, Guedes & Ferreira, 2014).

The work described in this paper was developed during the EPS@ISEP 2014 spring edition. Since the broad objective is training engineers to face the challenges of the 21st century, the aquaponics system is aligned with UNESCO Millennium Development Goal 1 (Eradicate extreme poverty and hunger) and Goal 7 (Ensure environmental sustainability) (UNESCO, 2010) as well as with the “Develop carbon sequestration methods”, “Manage the nitrogen cycle” and “Provide access to clean water” Grand Challenges for Engineering (National Academy of Engineering, 2008).

In 2014, during the first week of the EPS@ISEP, the students were presented with several project proposals, including the development of an aquaponics system, incorporating eco-friendly sustainable techniques (Malheiro et al., 2014). Aquaponics is based on a productive system that can be found in nature. It can be described as the combination of aquaculture and hydroponics and this is where the name comes from: aqua-ponics. The team composed by Anna – a Spanish Mechanical Engineer student, Arlene – a Scottish student of Electrical, Electronic and Energy Engineering, Gwénaël – a French student of Environmental Sciences, Natalia – a Polish student of Logistics and Sean – a student of Product Design from the UK, accepted this challenge. The team stated that "*As a group we came to an early decision that we would like to choose a proposal that incorporated sustainable techniques and be eco-friendly, as this is the future of all design/engineering. As a group we were all interested in creating our own aquaponics system as this is a system/technique that is becoming ever more popular throughout the world, more so in poorer regions and where water is a limited resource*.” (Mesas Llauradó, Docherty, Méry, Sokolowska & Keane, 2014).

The goal was to design and build an aquaponics system, as sustainable as possible, to support both fish and plant culture (without the use of soil), based on water recirculation. The system should be able to monitor and control the most important system parameters, to ensure optimum conditions for both fish and plants. This means using sensors to measure several parameters like temperature. The overall budget for the prototype was 250 € (EPS@ISEP Team, 2014) and there were a number of mandatory requirements namely: to use open source and freeware software, reuse any provided components and adopt low cost hardware solutions. Additionally, all EPS teams are instructed to adopt the International System of Units (NIST International Guide for the use of the International System of Units) and to be compliant with the Machines Directive (MD), Low Voltage Directive (LVD) and Restriction of the use of certain Hazardous Substances (RoHS) Directive (EPS@ISEP Team, 2014).

Intensive agriculture and aquaculture present high economic and environmental impacts. This type of agriculture requires large amounts of fertilizers and water, but a large part of these contributions gets lost in the ground and does not benefit the plants, causing waste and pollution. On the other hand, the intensive breeding of fish generates a large amount of organic waste which threatens the environment when released. The combination of both cultures cancels their individual drawbacks (Rakocy, Masser & Losordo, 2006).

In EPS, the first task of a team is to define the set of team governing rules – Team Work Agreement – using the mechanism proposed by Hansen (Malheiro et al., 2014). This set of conflict resolution rules is determined and signed by all team members and is archived in the team folder. The next high priority task is the creation of the project work plan and corresponding Gantt chart. It involves the identification of the project tasks, the definition of their time span and allocation to the team members according to their skills and knowledge. Natalia was responsible for the marketing plan, Sean for the product design, Arlene and Sean for the communication (since they are native English speakers), Gwen and Sean for the ecological footprint and sustainability issues, while Anna was in charge of the ethical and deontological concerns. All other tasks, such as collecting background information for the project, searching for components and materials, designing of the aquaponics system and the project development, besides producing all deliverables needed for evaluation purposes, were responsibilities of all team members.

Although this article is more focused on the technical aspects of this work, according to the EPS rules (Malheiro et al., 2014), the students also had to address other aspects concerning their project, namely the detailed project planning and scheduling for the entire duration of the work, the marketing plan for this product, the ethical and deontological concerns related to the product development and lifecycle, and their project management. These aspects, presented in Section 3, are detailed in the team final report (Mesas Llauradó et al., 2014).

Bearing these ideas in mind, this article is structured into four more sections, namely: Aquaponics, covering related work and methods/technologies within the product; Project Development including overall architecture and components; Experimental Tests and Results presenting the results of tests performed on the prototype; Conclusions, discussing the final thoughts and achievements and some ideas for future developments.

2 AQUAPONICS

The team started by making a study of the state of the art in Aquaculture and Hydroponics, and their integration, i.e., Aquaponics. Hydroponic systems rely on the use of nutrients made by humans to optimise plant growth. Nutrients are manufactured from a blend of chemicals, mineral salts and trace elements to form the “perfect” balance. Water in hydroponic systems must be discharged periodically, so that the salts and chemicals do not accumulate in the water, which could become very toxic to plants. Aquaponics combines the two systems in a symbiotic environment, cancelling their individual weaknesses. Instead of adding toxic chemical solutions to cultivate plants, Aquaponics uses highly nutrient effluent from fish, containing virtually all the nutrients needed for optimum growth of plants. Instead of discharging water, Aquaponics circulates the water between the fish tank and the plant grow bed, allowing the plants to feed from the water and returning clean and purified water back into the aquarium. The water must be topped up at certain stages due to losses from evaporation and plant usage. A simple flood and drain system is recommended so the plants are able to receive oxygen and small breaks from the water to reduce the chance of root-rot (Backyard Aquaponics, 2012; Green Society Association, 2013; Rakocy et al., 2006; Love et al., 2015).

The next subsections introduce theoretical aspects related to aquaponics and outline currently available producers/suppliers of such systems, mentioning also its main components.

2.1 Methods and technologies

In order to build a prototype with a high quality standard an in depth research into Aquaponics was performed, covering the existing methods and technologies.

2.1.1 Nitrogen cycle

The nitrogen cycle is the process by which microorganisms convert the nitrogen in the air and organic compounds (such as within soil) into a usable form (see Figure 1). This is an invisible process that is essential for aquaponics systems to work. It is responsible for the conversion of fish waste into nutrients for the plants. Without this process, the water quality would deteriorate rapidly and become toxic to both the fish and plants in the system. The water in Aquaponics does not need to be treated chemically to make it ‘safe’, nor does it have to be replaced. In aquaponics, a system is said to have ‘cycled’ when there are sufficient quantities of bacteria to convert all the ammonia into an accessible form of nitrogen for the plants. The bacteria colonize naturally the system, i.e., the water column and biofilter (clay pebbles in our case) (Gregory, Dyson, Fletcher, Gatland & Shields, 2012; van Kessel et al., 2010).

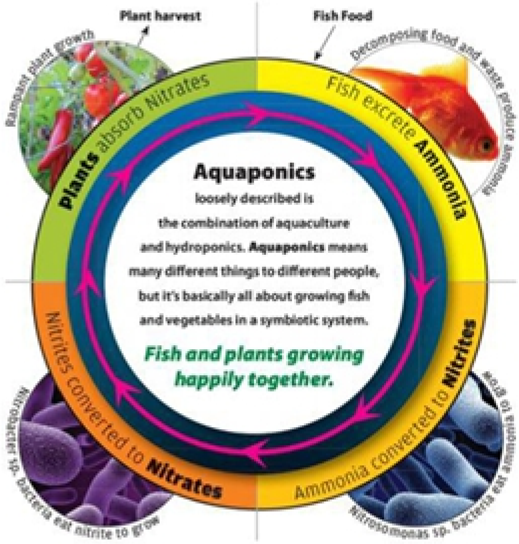

Figure 1. The nitrogen cycle in an aquaponics system (Aquaponics Plans, 2009)

In this case, while some bacteria convert the ammonia into nitrite, other bacteria converts the nitrite into nitrate (NO_3). Nitrate is a very accessible nutrient source for plants. Fish will also tolerate a much higher level of nitrate than they will ammonia or nitrite. When all these bacteria are found in sufficient numbers to convert all of the ammonia and nitrite produced in a system, it is said to have 'cycled' (Greenfish Aquaponics, 2011).

In short, aquaponics is an intensive aquaculture system (Gjedrem, Robinson & Rye, 2012) with a "debugging" system constituted by microorganisms to decompose the organic materials present in the fish's dejects into salts (nitrates, phosphates, etc.) and, finally, a hydroponics system to perform the biofiltering of these salts originated by the microorganisms, ensuring that no accumulation of decomposition products occurs.

2.1.2 Illustrative example

Aquaponics is in fact a near self-sustaining ecosystem, which requires minimal input and includes living systems within an ecological cycle (Figure 2):

- Fish are fed and produce excrement rich in nitrogen (ammonia (NH_3) and urea), phosphor and potassium. This excrement is the source of nutrients for the plants. The fish food returns to the water in the form of fertilizer (excrement). Since ammonia is toxic for fish, the water has to be filtered to reduce the level of the ammonia so the fish will survive (Buzby & Lin, 2014).
- The water of the tank is pumped and sent to the grow bed where plants/vegetables are grown in a neutral substratum of expanded clay balls. Complex natural reactions are set up where bacteria transform ammonia into nitrites then nitrates.
- Plants can use and absorb the nitrates through their roots.
- This natural filter clears the water of its toxic components, reducing the concentration of toxic levels.
- The clean water is sent back to the tank.
- The water on return generates a water fall for oxygenation (this oxygen will be useful for the fish, plants and bacteria).

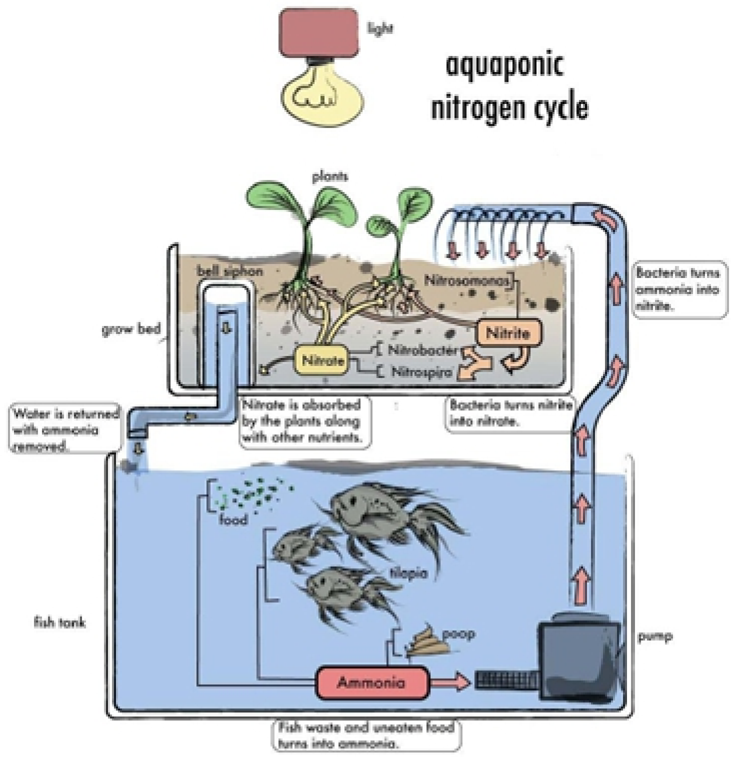

Figure 2. Work principle of an aquaponics system (Aquaponics Plans, 2009)

2.1.3 Types of Aquaponics systems

There are three main types of aquaponics systems (Backyard Aquaponics, 2012):

- Media filled beds are the simplest form of Aquaponics. They use containers filled with media of expanded clay or similar (Figure 3). Water from a fish tank is pumped over the media filled beds, and plants grow in the media. This style of system can run with a continuous flow of water over the rocks, or by flooding and draining the grow bed, in a flood and drain or ebb and flow cycle.
- Nutrient Film Technique (NFT) is a commonly used hydroponic method, but is not as common in Aquaponics. NFT is only suitable for certain types of plants, generally leafy green vegetables as larger plants will often have root systems that are too big and invasive.
- Deep Water Culture (DWC) suspends plants, allowing the roots to absorb nutrients from the underlying water. This method is one of the most commonly practiced commercial methods.

Figure 3. Grow bed with clay pebbles (Japan Aquaponics, 2015)

The designed prototype is a media based system since it is the most reliable and the simplest method of Aquaponics. Additionally, this kind of set-up requires the least maintenance in comparison to the types presented above (Backyard Aquaponics, 2012a).

2.1.4 Cycling the system

Although there are many approaches to develop a successful media based Aquaponics system, it is necessary to ensure that it is a 'cycle' system, i.e., that a population of bacteria is established in the system to convert the ammonia into nitrates, allowing plants to grow.

Ideally, it would be beneficial to use an existing tank where natural bacteria had already grown and developed, but when creating a new system time must be allowed for the bacteria to grow so that it can alter the ammonia into nitrites and nitrates, allowing the plants to feed. Without these bacteria, fish cannot be introduced in the system. It is possible to encourage the establishment of these bacteria with specific grow bed media. It is therefore a good idea to allow the system to run about a day or two before the introduction of fish or before making long-term plans, mainly because it must be ensured that the system works well and that there are no leaks or other potential problems that can be harmful to the fish.

The following methodologies can be used to improve the cycling of the system:

- Use of a urea-based fertilizer: a method to add a source of ammonia to assist in the establishment of the beneficial bacteria colonies is to use urea fertilisers, generally available in gardening, hardware stores or nurseries. It is a fairly simple method, but it requires careful dosage and regular water tests.
- Ammonia: household ammonia may come from several different sources. As with urea, it requires special precautions with the dosage. The selected ammonia must not affect food quality, since there are many industrial ammonia sources for cleaning that tend to be scented or contain other additives.
- Dead fish/crustacean: it involves placing a small rotten fish or crustacean in the system to allow ammonia emission to feed the bacteria. This is a simple, natural source of ammonia.
- Fish food: it is possible to start an Aquaponics system cycle by introducing fish food. The food will begin to break down on the bottom of the basin and this release of ammonia will cycle into the grow beds and allow bacteria to grow.
- Urine: it is possible to start the cycle of an Aquaponics system by adding urine. Urine contains urea and urea breaks down into ammonia. This method is not suitable if any medical substances are currently being taken.

2.2 Related work

The state-of-the-art survey analysed several prototypes under development as well as existing commercial aquaponics systems. Currently, it is possible to find on the market many aquaponics systems (Mesas Llauradó et al., 2014) but, from the research conducted, no commercial producers of aquaponics systems were found in Europe. However, if the intended market is specified as being the Indoor Aquaponics then the market shrinks vastly. This market can be further reduced by adding the term 'Designer' to the aquaponics system, as many consumers are reluctant to buy unattractive objects for their homes. Overall, this search identified only one real competitor in the household aquaponics market which can be seen in Figure 4. All other systems reviewed lack the necessary appealing design to be placed indoors as an adornment.

2.2.1 Back to the roots

Back to the Roots is a US company established by a group of Berkeley students. In their online shop they offer for sale two products: one is the Mushroom Kit (to grow our own mushrooms) and the other one is the Aquafarm (Figure 4), which they describe as a "Self-cleaning fish tank that grows food" (Back to the Roots, 2015b).

Figure 4. Aquafarm (Back to the Roots, 2015a)

The Aquafarm is a simple set-up product that enables the consumer to have a small Aquaponics system at home. The design is basic and simple to manufacture, however it is prone to failing after a short period of time due to its design. The difference between the proposed system and the Aquafarm is that it is able to monitor parameters within the water to ensure the fish's safety, and uses a traditional aquarium, with a simple LED system, to enhance the viewing of the tank.

2.2.2 Backyard Aquaponics

Backyard Aquaponics is a leading edge aquaponics company launched in Western Australia. Initially it was just offering support and information for people interested in aquaponics. Today, the company, which is still a well-known provider of books, magazines and DVD on aquaponics, has an online store offering a wide range of aquaponics systems. Backyard Aquaponics provides worldwide shipping for some of their products (Backyard Aquaponics, 2012b). The cheapest and the smallest system offered by this company is the balcony aquaponics for 995 USD, depicted in Figure 5, which is definitely not an adornment for the living room.

Figure 5. Backyard Aquaponics balcony Aquaponics (Backyard Aquaponics, 2012b)

2.2.3 Nelson Pade's shop

Nelson Pade's Shop is a USA family company that has been designing aquaponics systems for nearly 25 years. They launched their online shop in 2005 and are still expanding. The shop does not ship their products outside of the USA (Nelson Pade's Inc., 2015). Their smallest and cheapest product is an aquaponics system for home or school for approximately 3000 USD, shown in Figure 6.

Figure 6. Nelson Pade's aquaponics system for use at home or school (Nelson Pade's Inc., 2015)

This system is already a "small supermarket" – it can produce about 50 kg of fish and almost 1500 heads of lettuce a year, but it's not a pretty solution to be indoors.

2.3 Components

During the materials procurement phase, the students became acquainted with the characteristics of the electrical components and materials needed for the construction of aquaponics systems (namely power sources, actuation systems, sensors, and controller systems), in order to understand their differences and make a sensible choice of the materials to use in the prototype. Additionally, the system requires a tank, a grow bed, a pump, tubing, plants and fish.

2.3.1 Fish tank

Apparently any waterproof packing container can be used as water-tight, food-safe and fish safe. The material must be resistant to water, avoid to contaminate or not impart colour to water and be transparent (and its transparency should not change over time), at least for the major part of the container.

Its size depends on the number of fish to accommodate and on the size of the grow bed. To build this prototype the team chose a 28 l tank, made of acrylic glass (Plexiglas). Its shape should facilitate spontaneous constant cleaning of the transparent area (Rasmussen, Laursen, Craig & McLean, 2005).

2.3.2 Grow beds and growing medium

An aquaponics media filled grow bed is simply a suitable container filled with a growing media such as gravel, hydroton (expanded clay) or lava rock. It performs four separate functions:

- provides support for the plants and for the roots to take hold;
- is responsible for mechanical filtration;
- is a source of mineralization; and
- is a biological filter (support for biofilm).

Although a grow bed can be made of a variety of materials, care should be taken to make sure it fulfils certain criteria. First and foremost, it should be safe to use and should be made of materials that will not leak unwanted chemicals into the water, or that will affect the pH of the water (Japan Aquaponics, 2015).

The grow bed was built from 5 mm acrylic and filled with small plant pots to hold the expanded clay pebbles as they are the lightest and the cheapest media available. This grow bed must allow the water to leak back into the fish tank in cascade form, to promote the water oxygenation.

2.3.3 Pump

A water pump is needed to circulate the water from the fish tank through the grow bed and back to the tank. The velocity of the water flow must be sufficiently fast so as to periodically renew all the fish tank water but cannot be too fast to allow the microorganisms to adhere to the growth bed – usually, a good estimation is 5 m^3/d to 23 m^3/d (Endut, Jusoh, Ali, Nik & Hassan, 2010). The selected pump was the Syncra Silent 0.5 Multifunction Pump.

2.3.4 Tubing

Tubing is needed to carry the water through the system. Water pumps generally use half inch tubing while air pumps are set up for quarter inch tubing. Plastic tubing is available in both clear and black; black tubing deters algae from growing and clogging the tube.

2.3.5 Plants

The growth rate of plants in Aquaponics systems can be quite phenomenal. The advantage of the Aquaponics vegetables over vegetables grown in soil is that during the warm season plants get water as much as they need due to regular flooding of the grow beds, whereas in regular farming the land could go dry for an extended period of time.

Plants grown in the ground can use water around their roots very quickly in hot weather, which leads to wilting if there is a lack of water on a hot day. In an Aquaponics system, plants are watered continuously, so that they always have water, regardless of the ambient temperature.

Grow beds with gravel or clay balls seem to be the most effective for the cultivation of a wide range of plants, and it seems that most of the herbs and vegetables adapt well to Aquaponics. Of course, some plants will not work as well as with other methods. There are over 300 different aquaponics plants. The major group that will not grow are root vegetables (Endut et al., 2010; Aquaponics How To, 2015). Since the Aquaponics System is described as a small kitchen garden, it is recommend growing common herbs such as basil, thyme or rosemary.

As with all gardens, deficiencies in plants can occur, but, in general, they are easily treated. Algae extract is an excellent way to compensate for the shortcomings of all minerals that may be lacking in an Aquaponics system. As algae extract exists in many different forms, it is important to select one free of harmful additives because it will end in the fish, bacteria, plants and, ultimately, in the final consumer. It is also possible to use powdered minerals. Minerals are easy to find in many compounds, but, again, it is wise to pay special attention to their ingredients. The best way to address deficiencies is to use a good quality fish feed, i.e., fish food with a bi-product containing many minerals and trace elements.

2.3.6 Fish

Fish are the driver of the Aquaponics system, since they provide nutrients for vegetables/plants and, when edible, protein. Raising fish can be a little intimidating, especially those without any previous experience, but it is simpler in an Aquaponics system than in an aquarium.

Climate and available supplies are the major factors that need to be considered before choosing the type of fish for an aquaponics system. The fish and plants selected for the Aquaponics System should have similar needs as far as temperature and pH. There will always be some compromise between the needs of the fish and plants, but, the closer they match, the biggest the success (Nelson and Pade, Inc., 2015). In Australia, for example, Aquaponics Systems are widely used and it is not uncommon to see the farming of trout in winter and Barramundi or Tilapia in summer. There is also the possibility to use only one species that can live both in summer and in winter, but these fish take in general more time to grow. In France the Trout keeps steady growth throughout the year. Worldwide, the most used fish are Tilapia, the Barramundi and Nile perch. These three species require heated water.

The number of fish in the system is a constant subject of debate among people who practice aquaponics. Levels of fish stocks in a system can be as high as in intensive aquaculture, but if the density rises, the probability that things go wrong increases. In high density aquaculture it is needed to monitor all parameters of the water to be sure that the conditions are maintained at the optimum level. With lower quantities of fish stocks, the risk is reduced. The growth rate of plants in the slightly dense systems may still be very impressive. Therefore, to ensure the safety of fish and plants, the parameters of the water should be frequently controlled and the level of fish stock should be adjusted to the tests' results (Buzby & Lin, 2014).

In the Aquaponics System, the tank will be stocked with Convict Cichlids (*Amatitlania nigrofasciata*) (Figure 7) since they do not require much space and are easy to take care (Wikipedia, 2015a).

Figure 7. Convict Cichlids (Wikipedia, 2015a)

3 PROJECT DEVELOPMENT

This section presents the design and development of the Aquaponics System, including the mechanical and electrical architecture, and the definition of its set of functionalities.

3.1 Eco-efficiency measures for sustainability

The design and development of an Aquaponics System emphasizes the eco-efficiency measures for sustainability considered. During the project, the team had to address the three spheres of sustainability, namely the environmental, economic and social impacts associated with the product they purpose to develop, as well as its lifecycle analysis (Mesas Llauradó et al., 2014).

In the Energy and Sustainable Development module, the team addressed the set of eco-efficiency measures for sustainability to take into account during the project development and latter industrialization and commercialization. It is of particular importance to state that the economic impact of aquaponics can be extremely large if done correctly. As with regular farming, aquaponics requires land in order to set-up the system. Initially aquaponics is very expensive with its set-up costs compared to agricultural farming due to the need for tanks, piping, media, etc. But this initial cost is reduced by larger profit margins due to aquaponics allowing plants to grow faster and is an organic system with the plants being healthier than unnaturally fertilized plants. Coupling the fast, healthy growth of plants with large fish farming, aquaponics is a two in one system. Also, organic foods are on the rise across the world with people looking to healthy alternatives to cheaply manufactured/processed foods. Furthermore, Aquaponics reduces the strain on resources by allowing the user to both farm and eat the fish within the system and grow/harvest the plants that are produced. This system is not fully sustainable, but has a large reduction on key resources such as water, requiring only 10 % compared to agricultural farming.

Through sustainable manufacturing and the use of recycled materials (glass, plastic, etc.) the team goal was to create a product with little impact on the environment. This footprint would be continuously kept low by the correct use of the system which would need up to 90 % less water than traditional farming and the only real input would be the energy to power the electronic system and food for fish.

3.2 Marketing plan

In parallel with this study, in the Marketing and Communication module, the students defined the market plan for the product. They researched the market and identified the customer's requirements to define a product matching those needs. This knowledge allowed the team to create a customer oriented marketing strategy and to develop an integrated marketing program. With this purpose, the team performed an environmental analysis, consisting of a Political, Economic, Social and Technological analysis (PEST-Analysis) of the macro-environment and of the micro environment, and a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis, defined the strategic objectives for the project, performed the market segmentation, defined the positioning of the product and, finally, defined the marketing mix.

Based on the market analysis, the team decided to target the household market, as a small system would be easier to control and keep sustainable compared to a large (small farm) sized system (Mesas Llauradó et al., 2014). Such a system would also allow creating an aesthetic product for the home, an easier control over the environment and would require a smaller electronic system. Even though there are many large scale aquaponics systems, there are not many for indoors usage, making this area an interesting target market. With the recent increase in both sustainable products and the purchase of organic foods, there is a large market share available for quality aquaponics systems.

The students also concluded that there are three regions in the world where organic food production gained popularity during the last 15 years - the USA, Australia and countries of the European Union. Since the main competitors are operating within the Australian and American market, the team chose the countries of the EU as their target region.

To fully achieve these objectives, the design was focused on creating an aesthetic and attractive look for a modern indoor Aquaponics system.

3.3 Ethical and deontological concerns

Finally, in the Ethics and Deontology module, the students analysed the ethical issues surrounding the product as well as more general ethics on a wider range of issues. In several cases, ethical conflicts and difficulties are encountered in the process of developing, launching and selling a new product. These conflicts can often be complicated and, in order to be able to find the right solution and have everyone's best interests at heart, it is needed to adopt a concrete set of ethics. Regarding the ethical and deontological concerns faced by the students while developing the aquaponics system, they addressed aspects related with engineering ethics, sales and marketing ethics, academic ethics, environmental ethics, liability aspects, and intellectual property rights.

Regarding environmental ethics, i.e., the relationship that humans have with the natural environment, many environmental aspects had to be taken in account by the team in the design of the aquaponics system. The main objective was to make the environment adequate for fish and plants to live. The team identified the following aspects as deserving a special attention:

- Meet the nutritional requirements of the fish species.
- Clean water frequently.
- Tank size - fish retrieve the oxygen from the water, therefore, it is essential to have a tank with appropriate dimensions (larger rather than a small tank).
- Correct pH.
- Right temperature.
- Good light.
- Decoration. Habitat complexity plays a much larger role in shaping aggressive behaviour than most other factors.

Furthermore, environmental ethics must serve not to hinder future generations. Therefore, the team stated that they have to be responsible with natural resources that they are using. In their aquaponics system they want to use materials which can be recycled.

3.4 Design

Since the project proposal did not impose any restraints on the physical appearance of the product, the team could be creative. The initial design aim was to be sleek and simple, avoiding to be an intrusive object in the home. This is where the cylindrical shape came into the design. However, this idea was abandoned when the team concluded that the cuboid tank would contain more water, due to its corners, when compared to a cylindrical shape. This would also improve the well-being of any fish kept within the tank as fish prefer a large body of water to swim freely.

The change of shape provided a stronger base for the tank but produced weak spots at the corners. This would be tackled by metal supports hidden behind the veneer/plastic strips that would wrap around the base and top. The design would incorporate the Light Emitting Diode (LED) strips around the underside of the grow bed for aesthetic appeal (Rasmussen et al., 2005). Therefore, the grow bed design follows the shape of the cuboid tank apart from an area taken out the back middle section. This allows the pump to sit in the middle of the tank and feeding of the fish with ease. This area will often be covered from view by the plants growing within the grow bed and does not take anything away from the physical appearance of the tank itself (Figure 8).

Figure 8. Design of the system

3.5 Mechanical structure

The designed structure includes the fish tank, the plant grow bed, a bell siphon together with a fail-safe pipe and the electronic components housing.

3.5.1 Bell siphon

To ensure even and intermittent (periodically fills and empties the growing bed) flow of water throughout the grow bed, it was decided to use a simple method inspired by the bell siphon (Figure 9). This method simply involves a tube with a smaller diameter than the pump tube so that the grow bed could fill with water as the smaller tube could not expel the rising water as quickly as it was being pumped into the grow bed. This small tube would be surrounded by a similar guard/filter to stop any waste/dirt.

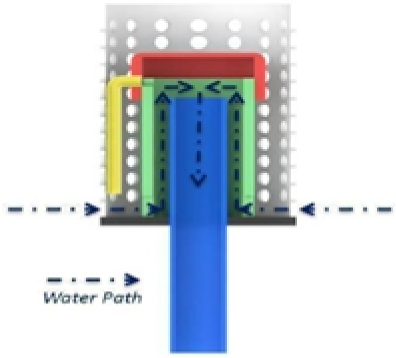

Figure 9. Bell siphon water path (Wikipedia, 2015b)

3.5.2 Fail-safe pipe

Originally it was planned and designed to have small cut outs where the pipe entered the grow bed as fail safes in-case the bell siphon/stand pipe failed. It was found that these cut outs would not direct the water directly back to the tank and this could lead to splashes over the side of the tank. The decision was to use a single pipe at a pre-set safety level. The pipe itself must be larger than the pump pipe so that outgoing water flow is faster than the incoming water flow that it does not spill over the side of the grow bed or reaches the level of the electronics casing. The fail-safe stand pipe can be seen in Figure 10 and clearly shows its large size to easily remove the water. Two holes were placed to limit the height of water in the growing bed, thus preventing the water entry into the housing with the electronics and itself spill out of the fish tank (detailed in the recess behind the electronics housing in grow bed, as depicted in Figures 11 and 12).

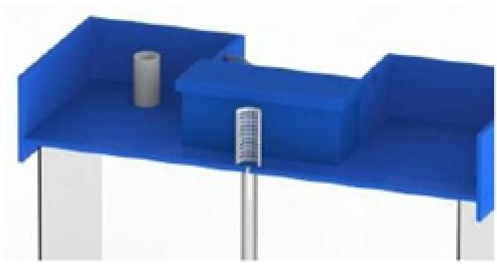

Figure 10. The fail-safe stand pipe

3.5.3 Grow bed

Much of the grow bed (Figure 11) was developed during the development phase to fit with the changing electronic and design demands.

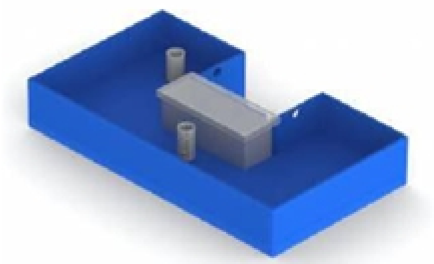

Figure 11. Final grow bed design

Cut outs were added to the bed to allow the pump tubing to go straight into the bed instead of sitting atop a side (Figure 12). The sides of the bed were increased by 10 mm to allow extra space for water. As can be seen in Figure 13, holes were added for the stand pipes, and stabilizing features were added to keep the bed in place.

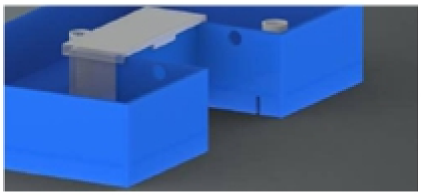

Figure 12. Cut outs in the grow bed

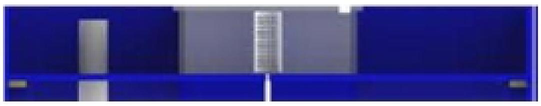

Figure 13. Grow bed cross-section

3.5.4 Electronic housing

The placement of the electronics was an area which required a large amount of time due to the safety risk between electronics and water. It was decided to create a small space within the grow bed for the electronics (Figure 14). This small area would come with a lid for easy removal of the electronics while also keeping them safe from water splashes. The housing should also include a small cut out from the back where the wires could pass through so that the lid could stay secure.

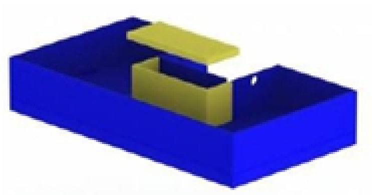

Figure 14. Electronic housing

3.6 Control

Aquaponics systems need to frequently check the water temperature and pH level (Rius-Ruiz, Andrade, Riu & Rius, 2014). Therefore, the Aquaponics System will monitor temperature, pH and the ability of oxidation / reduction potential (ORP) of the tank, display the results on a Liquid Crystal Display (LCD) screen and control the water flow. A microcontroller board will be responsible for performing these tasks automatically. The next step was to choose the components and assemble the electronic control system.

The motherboard chosen is the Arduino Duemilanove ARDU-004, programmable with the free Arduino software. It has 14 digital pins operating at 5 V, which can be used as an input or output, as well as 6 analog inputs. The selected LCD module, which is small and cheap, is connected to the power supply (5 V) and to the Arduino motherboard. The temperature sensor chosen is the DS18B20. It is waterproof, has a temperature range sufficient for the application and is powered by the data line to the Phidget Interface Kit 8/8/8 Model: PHD-1018_2. The ASP2000 pH sensor was selected to measure the pH level from 0 to 14. It requires a pH/ORP adapter (PHD-1130) to connect to the motherboard. Since all selected components need 5 V power supply, the choice was the INM-0761 power supply, which outputs sufficient current for the whole control system (2.5 A). Finally, a relay commanded by the microcontroller board works as a switch to connect and disconnect the water pump.

In the following electronic schematic (Figure 15) are presented the main electronic components, how they are set up and how they connect with each other.

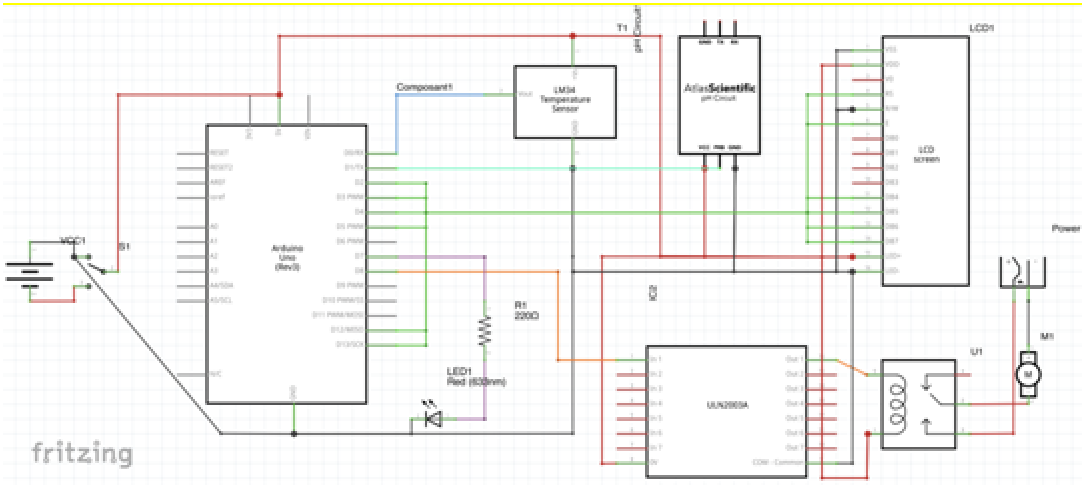

Figure 15. Schematic diagram of the entire electronic circuit

3.7 Functionalities

The Aquaponics System operates as following:

- The water from the fish tank is pumped in the grow bed by the water pump. The pump is controlled by the Arduino, manipulated by the relay and programmed to switch on/off at predefined intervals.
- When the water level reaches the upper limit of the siphon bell, the grow bed must be emptied and refilled. This process first provides the plants with necessary nutrients and then allows the water to flow back into the fish tank through a small pipe.
- Sensors within the tank send information to the Arduino, which is then displayed on the LCD screen.

If, for an unknown reason, the siphon bell does not work, or is not sufficient to discharge the water at the same rate that the pump fills the grow bed, the two side outputs must ensure that the water level inside the grow bed does not increase and overflow the aquaponics system.

4 EXPERIMENTAL TESTS AND RESULTS

Prior to the ultimate test (whether or not the integrated aquaponics system works), the team specified the following set of functional tests to be completed by the end prototype in order to be considered functional: (i) the water must be pumped from the tank to the grow bed with a time interval defined by the Arduino, (ii) the water must then slowly drain from the grow bed over a set period of time, (iii) the fail-safe pipe must remove all water in case of a pump malfunction, (iv) sensors must relay information to the user at all times through the screen, and, finally, (v) both plant and fish culture must live together safely in a symbiotic environment.

Tests were performed to ensure that all components would be safe within the electronic system. Additionally, were completed tests to check three different areas of the electronics:

- relay
- current driver, and
- sensors.

All these tests were accomplished successfully.

Figure 16 depicts a photo of the assembled Aquaponics System. As it is possible to see, at a later stage of the project implementation, it was decided to build an external box for holding all the electronics and also the water pump.

Figure 16. Photo of the assembled system

Figure 17 shows the contents of the electronics box, including the LCD display with the pH and the temperature of the water.

Figure 17. Photo of the control system and LCD

The system has been running successfully for more than a year. It has sustained six Cichlid (*Amatitlania nigrofasciata*) fishes together with two ornamental plants: maidenhair fern (*Adiantum capillus veneri*) and creeping fig or climbing fig (*Ficus pimila*). During this period, the plants had to be pruned several times due to extensive growth.

5 CONCLUSION

The main objective was to create a working system that supported both fish and plant cultures and the team has, through research, teamwork, brainstorming and development, achieved the objective and produced a low cost aesthetically pleasing prototype. The tests conducted showed that the electronics monitor the water temperature and pH parameters permanently. In terms of optimal sustainability of the system, the pump should run at 15 min to 30 min intervals. This allows saving power compared to a continuous system and provides plants extra oxygen in order for quicker growth. The students state that "*we have completed the requirements and also expanded so that the system will be successful within the intended target market due to an aesthetic design and simple functionality*." (Mesas Llauradó et al., 2014).

Regarding the process, the team reports that: "*After moving swiftly through the design stages and using all aspects (ethics, marketing, etc.) to create a quality design, we found that it was possible to create a simple product that fitted our needs. However, the technology/electronics that would be incorporated in the system* *also affected the final design due to restraints regarding size and placement. Taking this into account we developed an attractive system that combines art and technology together. Through development we were pushed to change many features of the design and many of these simplified the final product and led to an overall cheaper and easy to manufacture prototype. Overall, we found that from the initial brainstorming to the final renders, our ideas of a successful and quality aquaponics system had changed vastly. This knowledge was gained mostly through research and we believe that this led to the creation of a desirable and functioning system that fits well into the intended markets*." (Mesas Llauradó et al., 2014).

In the end of this project, the team members gained new multidisciplinary knowledge and increased their team work and cross-cultural communication skills, which are competencies difficult to acquire in traditional capstone/internship projects.

Aquaponics is a climate smart agriculture system that allows people to bring nature into the comfort of their homes. Regarding future developments, it would be interesting to create a cheaper product, using recycled materials, for shipping or manufacturing in third world countries. The benefits of aquaponics systems in these countries would be immediately felt due to the increase in both food and water resources.

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