Shipping Container Aquaponics: Life Cycle Assessment and comparison with conventional food production systems

Marina Casades Cornet

Bachelor Thesis for Bachelor of Engineering

Degree Programme in Energy Technology

Vaasa, Finland, 2020

DEGREE THESIS

Author: Marina Casades Cornet

Degree Programme and Place: Mechanical Engineering, Vaasa

Specialization: Energy Technology

Supervisor: Philip Hollins

Title: Shipping Container Aquaponics: Life Cycle Assessment and comparison with conventional food production systems.

Date: August 10, 2020 Number of pages: 44 Appendices: 2

Abstract

The continued and forecasted growth in food supply-demand has put increasing pressure on the Earth's ability to provide resources. New agriculture methods that assure to be more sustainable are appearing as a solution. One of them is aquaponics, a combination of hydroponics and aquaculture.

This thesis aims to undertake a full Life Cycle Analysis of an aquaponic system and evaluate its sustainability by comparing it with conventional food production systems. Firstly there was designed an aquaponic system to fit in a container. Afterwards, it was evaluated their environmental impacts using SimaPro. Finally, it was compared the sustainability significance between this aquaponics and traditional agriculture and aquaculture systems.

The findings indicate that electricity and equipment proved to be the more significant contributors to the impact categories. Although the extended use of shipping containers by aquaponic companies, it demonstrated to be the most pollutant component in most categories. Furthermore, LEDs contributed to more than 90% of all the energy impacts, which could be dispensable in aquaponics with the use of natural lighting.

The system gave better results on the sustainability performance than conventional agriculture and aquaculture carried on separately in most categories. It coincided with the literature on the improvements in land use, eutrophication and the reduction of water consumption, requiring just 14% of the water used in traditional agriculture. It differed from previous articles in consuming 50% more energy than what was expected for an aquaponic system, spending 130 times more energy than conventional agriculture.

Language: English **Keywords:** Life Cycle Assessment (LCA), sustainability, aquaponics, agriculture, aquaculture

Table of contents

List of tables

List of figures

Glossary

ABS	Acrylonitrile Butadiene Styrene
DALY	Disability-Adjusted Life Year
DWC	Deep Water Culture
EPS	Expanded polystyrene
GPH	Gallons per hour
LCA	Life Cycle Assessment
LED	Light-Emitting Diode
NFT	Nutrient Film Technique
PE	Polyethylene
pH	Potential for Hydrogen
PMMA	Poly(metryl methacrylate)
PP	Polypropylene
Ppm	Parts-per-million
PVC	Polyvinyl Chloride

1. Introduction

With the development of the agricultural revolution 12,000 years ago, hunter-gatherer lives radically changed. They abandoned their nomadic lifestyle to adopt a sedentary one. This change allowed the development of huge human civilizations (Blakemore 2019). Back then, the human population was around 4 million; increasing 1860-times until reaching the 7.8 billion people we are today. It is expected to achieve 8 billion people in 2023 and 10billion in 2057 (Worldmeters 2020; Roser et al. 2019).

With a large and growing population food supply necessarily has to increase. However, nowadays there is a wealth of data that indicates that agriculture is the cause of numerous environmental problems. It uses half of the planet habitable land and accounts for 70% of water consumed worldwide. Moreover, it is the major pollutant of water and one of the principals of land (Greentumble 2018; Ritchie & Roser 2019; OECD wy).

For these reasons, new methods of agriculture that focus on sustainability should be studied and implemented. This thesis focuses on studying the sustainability of aquaponics, a soilless method that proved to consume 90% less water and use six times less land than conventional agriculture while raising fish (Shelley 2018). A system designed to be located in Vaasa, Finland, is studied in this thesis.

2. Purpose

The aim of the thesis is to undertake a full Life Cycle Analysis of a designed aquaponic system and evaluate its sustainability by comparing it with traditional agriculture and aquaculture.

The objectives of the thesis are:

- Design an aquaponics taking as a base a prototype setup and scaling it up to fit in a container.
- Evaluate the environmental impact of the whole aquaponic system using SimaPro.
- Compare the sustainability significance between the aquaponic system and traditional agriculture and aquaculture.

3. Research

The research consists of the definition of the theoretical starting points and the explanation of the project's theoretical background. It is fully based in previous studies, definitions and normative.

3.1 Theoretical starting points

In this section, the keywords to understand the thesis are explained. Aquaponics, life cycle assessment and impact categories and endpoint characterization factors are the introduced concepts.

3.1.1 Aquaponics

Aquaponics is a method to grow fish and plants combining hydroponics and aquaculture respectively. This hybrid takes advantage of the pros of each system and reduces their drawbacks. In addition, it has been studied as a more sustainable technique to grow plants than traditional agriculture (The Aquaponic Source 2020; Nelson Pade 2018).

Figure 1 represents simply how aquaponics work. Firstly, there is a tank where fish, that can be for consuming or not, live. They are feed with fish food, and they excrete waste mainly in the form of ammonia. At high concentrations, it can be toxic for both fish and plants. Therefore, this wastewater goes through a mechanical filter, where bigger solids are removed. After it, a biofilter of bacteria transforms ammonia into nitrite, and nitrite into nitrate. This rich in nutrients water flows through the roots of the plants. They live soilless, with a part of the roots in the water to absorb the nitrates, and the other part in the air, so they can take oxygen from it. Clean water can now come back to the first tank, where the fish will excrete again their waste (Barry 2019; Doityourself 2010).

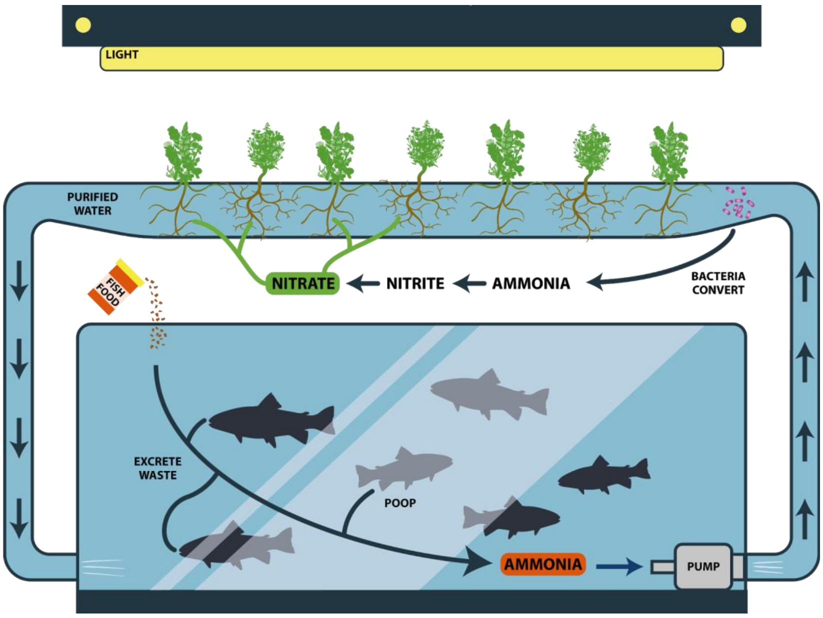


Figure 1: Functioning of an aquaponic system (Alonso et al. 2019).

Growing fish and plants in an almost closed loop solves many problems of raising them separately. On the one hand, conventional agriculture requires fertilizers and huge amounts of water. On the other hand, aquaculture has to face ammonia accumulation in water, which can be toxic for the fish. Aquaponics uses this ammonia to feed the plants and just 10% of the water required in conventional agriculture (The Aquaponic Source 2020; Rombaugh 2018).

3.1.2 Life Cycle Assessment

The Life Cycle Assessment (LCA) is a tool to evaluate the cradle-to-grave environmental performance of a product or a service in all the phases of its life. It includes the obtainment of the materials, the production, use, end-of-life treatment, recycling and the final disposal. It intends to compare, not to give absolute results, so including other stages such as packaging or transport, depends on each case. To do it, Finland is bound to implement the European Standard ISO14040. This standard defines the use that can be made from the LCA and the phases it should contain (Muralikrishna & Manickam 2017, 57-75; ISO-Norm 2006; Curran 2008; Ashby 2012, 49-75).

According to ISO-Norm (2006), there are four steps to be followed when carrying out an LCA. They can be found all throughout the thesis, where they are described. The first one is the goal and scope definition that in the end should be accomplished (see Chapter 5.2). Next, there is the inventory analysis, which describes the materials and energy flows in the system (see Chapter 5.3). Then, in the impact assessment phase, the results in the impact categories are detailed (see Chapter 6). Finally, in the interpretation step, a critical discussion is carried out and the results and sensitivity analysis are presented (see Chapter 7).

3.1.3 Impact categories and endpoint characterization factors

Each one of the materials and energy flows in the system produce consequences to the environment, named impact categories. In Chapter 6, the impacts produced by the aquaponic system are quantified. To understand them, the impacts that are not self-explicative like "land use" or "water consumption", are defined in this section.

Besides, each one of the impact categories has a unit associated depending on the damage category they affect. Human health is calculated in Disability-Adjusted Life Year (DALY). One DALY corresponds to a year of healthy life lost, so the results are the sum of the DALYs of all the population caused by the product evaluated. If the damage category is the resources, it is measured in USD2013, the dollars that these resources would cost in 2013. Finally, the ecosystems’ damage category uses the unit species.yr. It is a measure of how many living species are expected to disappear per year as a consequence of the product. The addition of all the environmental impacts which use the same unit results in the endpoint characterization factors (WHO 2013; Vieira et al. 2016; PRé et al. 2016).

Global warming is the result of the accumulation of greenhouse gases in the Earth's atmosphere. They retain the heat produced by the surface's radiation from going to space. However, global warming does not just imply melting the glaciers and the rise of the sea level, it is a cause of a generalized climate change with effects such as harder tropical storms, frequent wildfires and drought in some zones. Therefore, it affects all three damage categories (NASA 2020).

Ozone in the stratosphere filters the ultraviolet radiation from the sun, protecting humans from health problems such as skin cancer. However, if the ozone is near the ground, it may cause respiratory problems. Hence, both stratospheric ozone depletion and ozone formation are impacts that will be taken into account (EEA 2016; UK AIR 2010).

Eutrophication is the enrichment of the environment by nutrients, causing the increase of algae and plants. These harm water quality, elevating pH and CO_2 levels. These factors finally cause fish death (National Ocean Service 2017; Chislock et al. 2013).

Terrestrial acidification is a process that occurs naturally by the colonization of rock surfaces by algae and lichens. Carbon and nitrogen cycles generate acids, which are involved in dissolving rock and soil minerals, so over the time pH decreases, meaning that soils become more acidic. This process occurs naturally but is being accelerated by agriculture practices. Plants decrease their magnesium and phosphorus concentration, and as a consequence, there is a reduction in coverage, root growth and biomass. Moreover, germination and regeneration become unsuccessful and acid-tolerant species invade the soil (Robson 1989; Azevedo et al. 2013, 10-15).

Ionizing radiation is a type of energy that can cause health problems. Humans are exposed to it by natural sources in water, air and soil. Depending on the effective dose, measured with variables like the type of radiation, the potential for causing harm varies (WHO 2016).

The ecotoxicity of a chemical is the potential adverse effect that it can cause to the environment (National Research Council 2014). In the LCA made in Chapter 6, it is measured in the terrestrial, freshwater and marine environments.

3.2 Theoretical background

The framework where the study is made is the previous aquaponic system designed and built in the university; the preceding literature made by other authors, which gives an idea of the expected results of the thesis; and the location, basic to define the requirements of the system.

3.2.1 Testing setup

This thesis is a development of the initial work undertaken by European Project Semester students. Their four-month project culminated in the fabrication of an experimental aquaponics setup. This was installed in the basement of Novia University of Applied Sciences (see Figure 2). Citations used in this thesis fully acknowledge this previous work, where materials were not published they have been referenced as “unpublished work”.

Figure 2: Testing setup (Alonso et al. 2020).

3.2.2 Previous studies

The previous LCA made on aquaponic systems have shown a significant improvement in environmental performance if compared with conventional agriculture methods. Traditional agriculture accelerates eutrophication because of the use of fertilizers; while in aquaculture residues from fish are released in the water. From the combination of these techniques appears aquaponics, solving both problems by the recirculation of the water. Moreover, as the water is used in a loop, water requirements are less than 10% of what would be used in traditional agriculture. Land use is also lower than in typical agriculture due to the possibility of stacking hydroponic systems in vertical (The Aquaponic Source 2019; McGraw 2017; Delp w.y).

Therefore, as it would be expected, aquaponics proved to be more sustainable in many impact categories. It excelled in reducing water consumption and eutrophication, so these are the main expected results from this study (Ghamkhar et al. 2019; Cohen et al. 2018).

3.2.3 Characteristics of Vaasa

The system is designed to be operating in Vaasa, a city on the west coast of Finland. It is relevant knowing the characteristics of the place where it is going to be working to choose the more appropriate species and components for the system. Besides, the waste scenario of the aquaponics will depend on the residues policies taken in Vaasa.

Also, the energy source of the electricity that the system is using is an important factor to take into account. Results can vary depending on if it comes from fossil fuels or renewable energy sources. The study of where the electricity mix in Finland's grid comes is crucial, but as there are libraries that provide this data to the program that calculates the environmental impacts, SimaPro, it is not necessary to do previous research.

Climate

The climate in the place where the aquaponic system is located is important to know if artificial lighting and heating are required. Besides, depending on if the climate is cold or warm, different species will be more or less adequate for the system. Firstly, the daylight and sunshine daily hours depending on the month are shown in Figure 3. In June, there is daylight 20h/day, in contrast with the less than 5h/day in December. This means that species that can adapt to this lighting should be chosen or artificial light has to be provided.

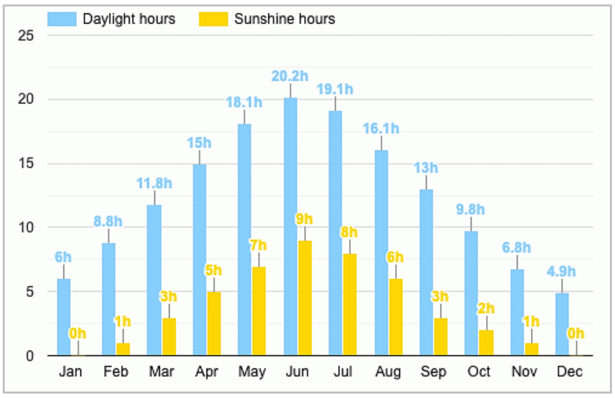


Figure 3: Daylight and sunshine hours by month in Vaasa (Weather Atlas 2017).

Next, temperatures determine which species are more adequate for the aquaponics. Additionally, the heating requirements depend on the exterior temperatures. In Vaasa, temperatures vary from -12ºC in winter to 20º in summer (see Figure 3). Therefore, cold climate species are preferable over warm ones and a heating system will be required.

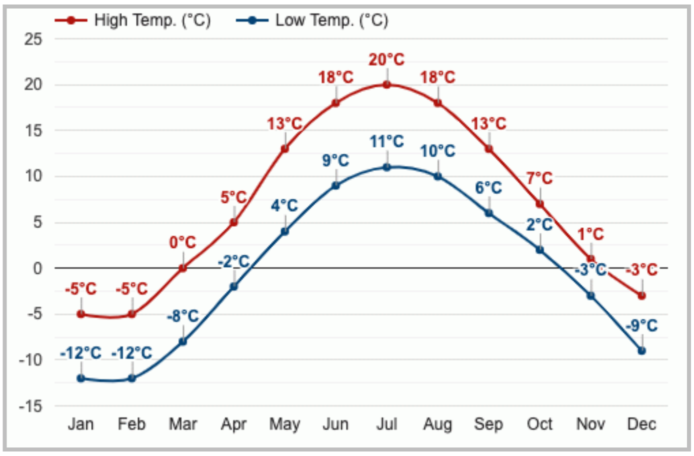


Figure 4: Maximum and minimum temperatures by month in Vaasa (Weather Atlas 2017).

To sum up, Vaasa has a cold climate and lighting is highly dependent on the season. This means that good insulation and heating should be provided. Besides, species that can adapt to cold climates and big changes in light should be chosen, or artificial light has to be provided.

Waste scenario

One of the main phases of the Life Cycle of a product is waste treatment and the disposal. For this reason, it is important to consider a realistic waste scenario that would have the aquaponic system. Finland´s Government has made a National Waste Plan for 2023 with the objective of move on a circular economy (Laaksonen et al. 2018, 11-16).

This can be seen in Figure 5, wherein 2017, just around 1% of the municipal solid waste ended up in landfills. There is a growing inclination to recover energy and, to a lesser extent, to recover material. In any case, statistics show that the disposal in a landfill is being replaced by waste recovery. For the current study, the proportions of 41% of material recovery, 58% of energy recovered and 1% of landfill sending will be considered (Statistics Finland 2019).

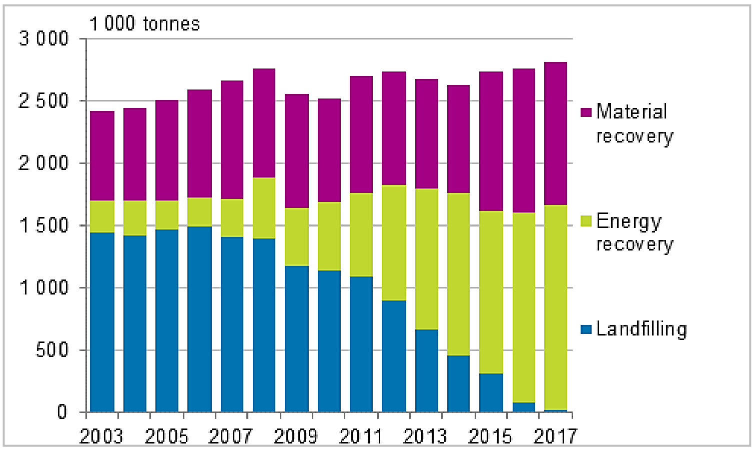


Figure 5: Amount of municipal waste by treatment from 2013 to 2017 (Statistics Finland 2019).

Waste-to-Energy is the name that receives the recovery of energy from residues. It is known that one of the plants from Finland, the Riikinvoima Ekovoimalaitos Waste-to-Energy plant, generates 180GWh of district heat and 90GWh of electricity from 145000tones of municipal solid waste (Making Future 2017). With the respective conversions, this means 1241Wh/kg of district heat and 620Wh/kg of electricity generated from residues.

It is useful to know the evolution of the waste scenarios in past years and the intentions in a close future because the aquaponics will be used for 15 years. The actual ones do not seem too optimistic if taking a look into the evolution. Consequently, the actual ones will be considered for the study.

4. Design of the aquaponic system

In this section, each one of the elements that compose the aquaponic system is explained. The design is made component by component, so depending on the previous ones selected; the characteristics of the following ones are restricted.

4.1 Container

Having an aquaponic system in a container has some benefits: it is portable, easy to customize and stackable. Some companies have already installed aquaponic systems in containers such as Growtainer (2012), who personalizes and sends them around the world or GrowUp Urban Farms (2018) that produced 20,000kg of salads and 4,000kg of fish in a year. Even EDEN ISS (2019) has a container with plants in Antarctica to test if it would be a good solution to grow food safely in the space. For the current study, it is advantageous that it was tested before, so the aquaponic system will be designed to fit in a 20ft shipping container.

The external dimensions of a standard 1C freight container are 6058x2438x2438mm (length x width x height). They are commonly known as 20ft containers because this is their nominal length. The minimal internal dimensions of this type of container are 5867x2330x2197mm (ISO-Norm 2013). Shipping containers can be made of many materials; however, they are mainly made of steel (Wankhede 2019).

The system will be installed in a cold climate, so insulation is a crucial part to have the desired temperature inside the container. The team that worked in building the aquaponics setup in the university modeled a 20ft container and the insulation required to install it in any part of Finland. From the study, it was deduced that 150mm of EPS in every wall with 40mm of radiant barrier (air) would produce effective insulation. The floor insulation should not include radiant barrier as there is no radiation through the ground. In addition, it is recommended to paint the outside with anti-radiant paint (unpublished work).

4.2 Hydroponic systems

An aquaponic system is the symbiosis of hydroponics and aquaculture. Hydroponics is defined as a technique for growing plants without soil, with the roots with direct contact to a nutrient-rich solution (Fullbloom Hydroponics 2011). A first draft about the number of plants and the occupied space will determine the size and characteristics of the other components.

Before distributing the system, the objective of building it should be defined. Most of the companies specialized in aquaponics do not obtain their benefits just from selling products related to aquaponics (components of the system, fish or plants). Most of them offer courses to teach the method (Aquaponics Iberia w.y; Nelson Pade 2018). Besides, Mauriceri et al. (2018) reported the benefits of teaching a wide variety of subjects using an aquaponic system. Thereby, the design of the study will be distributed in a way that allows having visitors.

There are many types of aquaponic systems, but just the ones that have been tested in the university will be included in the design because they performed well. These are deep water culture (DWC) and nutrient film technique (NFT) towers, which will be explained in this chapter. A draft of the design can be seen in Figure 6.

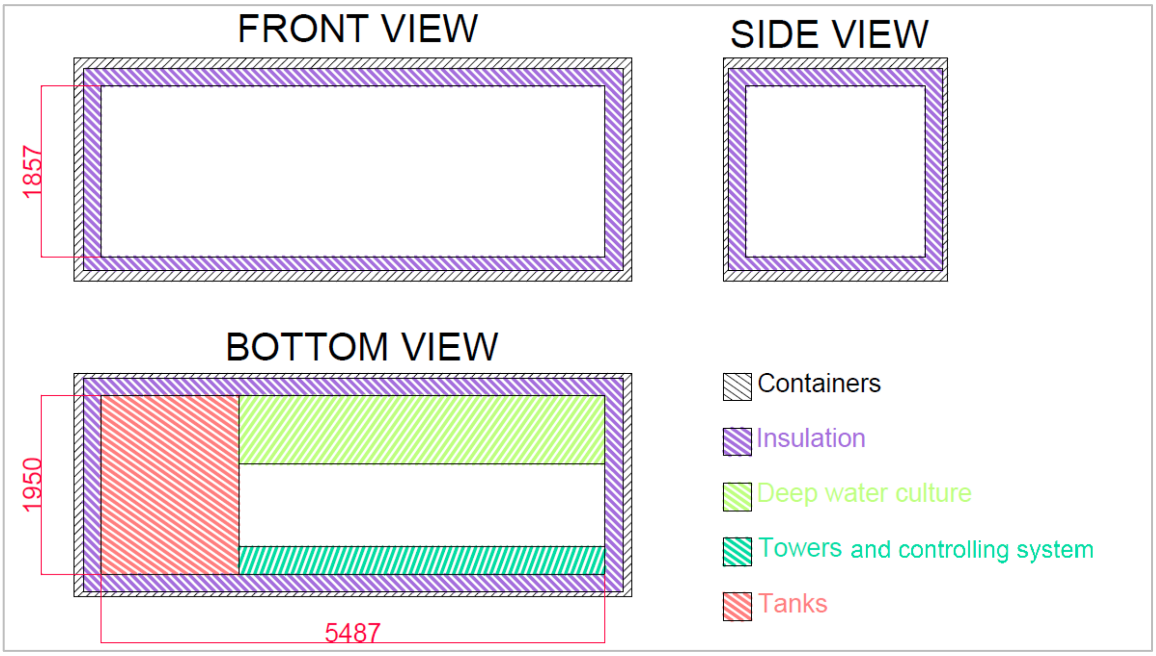


Figure 6: Draft design of the aquaponic system (in mm).

4.2.1 Deep water culture (DWC)

Deep water culture technique is considered the easiest and the most effective method of hydroponics. Plants are held in a recipient with an amount of water sufficient to maintain the density of nutrients almost constant. The plants have their roots sunk in the water continuously oxygenated. This can be accomplished with airstones connected to an air pump as shown in Figure 7 (Green and Vibrant 2019).

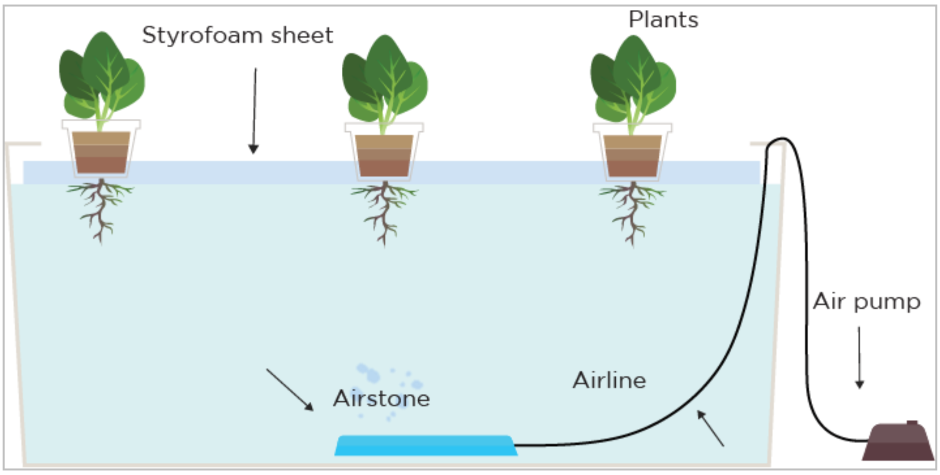


Figure 7: Deep Water Culture System (Green and Vibrant 2019).

Many companies used this method for their hydroponic systems. In Figure 8, the interior of the EDEN ISS container is shown. A similar design, also with steel shelves and four rows will be made.

Figure 8: EDEN ISS interior of the container (Haeckels 2019).

The final DWC design of the hydroponic systems consists of three rafts as the one shown in Figure 9 displayed in one long side of the container. Plants are held up by plant pots in each one of the holes. As there are 4 levels, 12 rafts are required. They are made out of expanded polystyrene so they float in the water. Each one of them has the place to grow 24 plants, so in total there will be growing 540 plants.

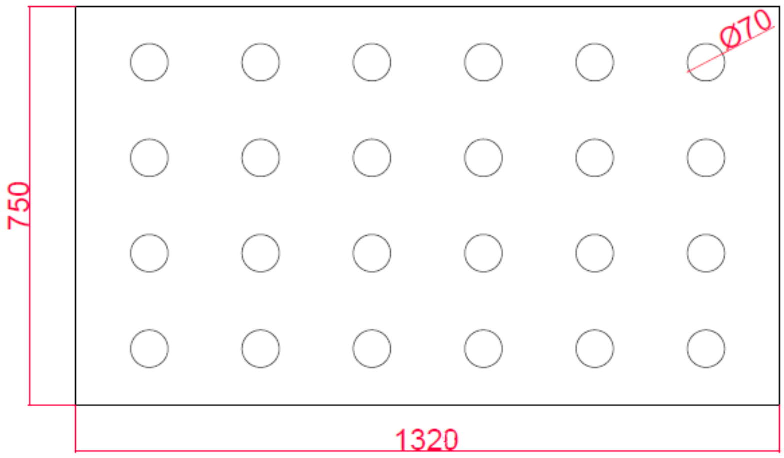


Figure 9: Design of the raft.

4.2.2 Nutrient film technique (NFT) towers

The second system is made of PVC pipes with some holes and inorganic foam with a very low density inside. The plants crop up from the holes and are hold by the foam (see Figure 9). Water is dropped from above the tube and it goes through the roots, which absorb the nutrients from it. Then, water is collected by funnels to a pipe. The setup built in the university performed well until plants died because of low maintenance. Water got evaporated from the biofilter tank, and consequently, there was no water available for the plants. As a result, they dried in a few hours unlike the plants in the DWC, which had enough reservoirs of water in their tanks to survive. Although the bad experience with this design, with more maintenance, many authors used it successfully (Alonso et al. 2020; Freightfarms 2019).

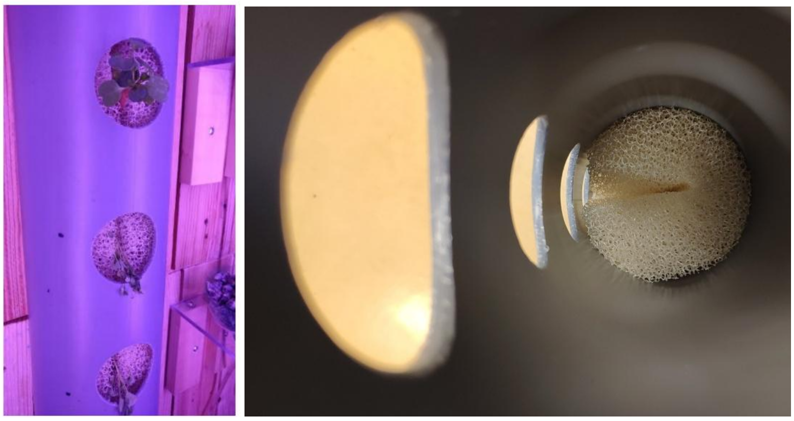


Figure 10: Subjection of the plants and interior of the vertical towers (Verburgh et al. 2020 & unpublished work).

In essence, it is a type of nutrient film technique (NFT), a method of hydroponics used basically for leafy plants. It is the most popular technique, probably because it uses little space and a wide variety of designs can be selected. A thin layer of nutrient solution flows through the roots of the plants, which absorb the nutrients while being oxygenated (Hydroenv 2014).

The design can be seen in Figure 11 and it will consist of 15 towers with 9 spots for lettuce each of them, letting 135 spots for plants. The space in the left, painted with pink stripes, is left for the tanks, and the one in blue, for the controlling system.

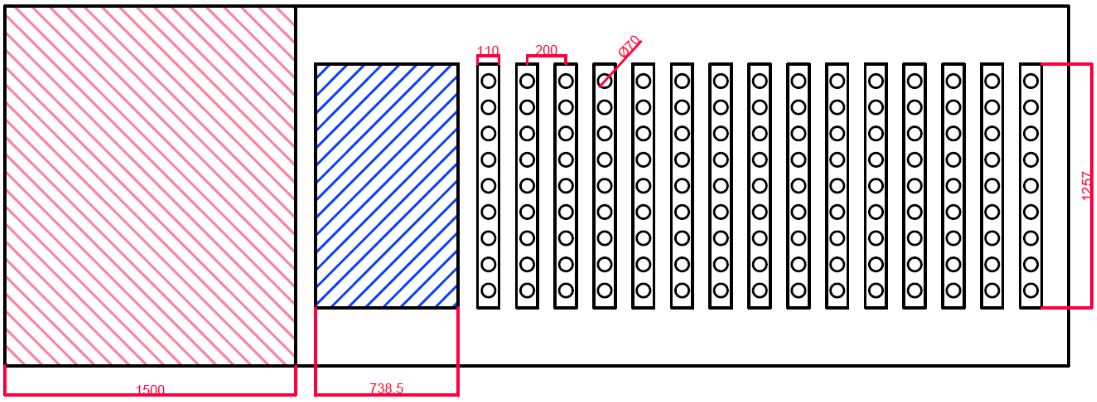


Figure 11: Design of the towers.

4.3 Plants

Almost any type of plant can grow well in an aquaponic system. However, some are more suitable than others. For example, tomatoes, leafy greens and peppers are good options (Mattson 2016).

Combining different species in the same aquaponics is an attractive option because when incorporating the adequate plants in the same system, they benefit from each other. An example is when a plant that produces chemicals that repeal certain insects is planted next to one that is highly affected by pests (Somerville et al. 2014, 119). However, as matching the required parameters of different species can be challenging, for the investigated system just one type of plant will be chosen.

Next, the type of the plants should be decided. Fruity plants, leafy greens and roots are the main types of plants that are used in aquaponics. They should grow in the hydroponic systems selected, but the towers are not suitable for heavy plants, so leafy ones are preferred. Besides, fruit plants require a higher nutrient concentration and more light (Somerville et al. 2014, 92). Therefore, the aquaponic system from the current study will just include one type of vegetable which does not bear fruit.

In the setup from the university, there were six types of plants, all of them leafy ones: lettuce, arugula, spinach, Swiss chard, parsley and basil. All of them had similar behavior. However, from these, in 2018 the most imported product was lettuce, representing 2.19% of all the value trade of vegetable imports in Finland (OEC 2020). Moreover, lettuce is one of the most used and studied plants for aquaponics and hydroponics (Cohen et al. 2018; Freightfarms 2019).

4.3.1 Lettuce characteristics and parameters

Lettuce (*Lactuca sativa*) is a type of leafy plant, which in general has a low nutrient and light demand (Somerville et al. 2014, 92; Encyclopædia Britannica 2008). This means that with the same amount of fish, more lettuce than other types of plants can grow in the aquaponics. In Table 1 some parameters that lettuce needs to grow are presented.

Table 1: Required parameters for lettuce.

Parameter	Value	Reference
Tolerable water temperature	15-22ºC	(Somerville et al. 2014, 171)
Air temperature during the day	17-28ºC	(Somerville et al. 2014, 171)
Air temperature during the night	3-12ºC	(Somerville et al. 2014, 171)
Optimal p.H levels	5.8-6.2	(Somerville et al. 2014, 171)
Tolerable p.H levels	5.8-7.0	(Somerville et al. 2014, 171)
Dissolved Oxygen	7-8ppm	(Mattson 2016)
Calcium	90ppm	(Mattson 2016)
Maximum plant densities	20-25 heads/m^2	(Somerville et al. 2014, 171)
Growth time	24-32 days	(Somerville et al. 2014, 171)

Many elements are required by the plants, but just calcium is shown in Table 1 because a common problem when growing lettuce in a hydroponic system is tip burn of the inner leaves, caused by calcium deficiency. The young leaves develop necrosis, and as a consequence, they grow deformed and with hooked tips. The plants uptake and distribute Ca by active xylem transpiration, but when humidity is too high, leaves cannot transpire. Therefore, this can be avoided by providing more airflow to the plants (Somerville et al. 2014, 88; HortiDaily 2019).

4.4 Fish

Once the plants of the system have been decided, the types of fish that can be selected are restricted. The water in the aquaponics is the same for the plants and the fish and consequently, the required parameters for the fish and the plants must be similar. Other conditionings to choose the type are the priority of local fish and the suitability for living in aquaponics.

Nile tilapia (*Oreochromis niloticus*) is the most common fish in aquaponics, but it cannot be fished near Vaasa. In Finland, there are more than 60 fish species that can be usually found in its waters, and even more, if considering occasional visitors (Encyclopædia Britannica 2011; FishinginFinland 2014). Some of them such as perch and trout have been used for many authors in their aquaponics systems (Leaffin 2019c; Brooke 2019b; Weldon 2019; Brooke 2018), so much information about how to grow them in aquaponics is available. Both fish species are possible candidates for the system of the study, but there is a priority in choosing perch because of the experience in the testing setup in the university.

4.4.1 Yellow perch characteristics and parameters

Yellow perch (*Perca fluviatilis*) is a warm type of coolwater fish (Leaffin 2019c), but it is also categorized as freshwater fish (Brooke 2019b; Encyclopædia Britannica 2020). It can live in a wide range of temperatures and pH levels (see the values in Table 2), making it suitable for aquaponics. Besides, it quickly adapts to the available food source (Brooke 2019b).

Table 2: Required parameters for yellow perch.

Parameter	**Value**	**Reference**
Tolerable range of temperatures	18,3ºC-26,7ºC	(Brooke 2019b)
Optimal range of temperatures	20ºC-25,6ºC	(Brooke 2019b)
pH levels	6,5-9,2	(Weldon 2019)
Dissolved Oxygen	3,5mg/L to saturation	(Weldon 2019)
Ammonia	<0,0125mg/L	(Weldon 2019)
Nitrite	<1,0mg/L	(Weldon 2019)
Calcium	10-160ppm	(Weldon 2019)

However, before choosing any fish, it is necessary to assure that it can live with lettuce. If comparing the parameters that are important for both plants and fish, which can be found in Table 1 and Table 2, Figure 12 is obtained.

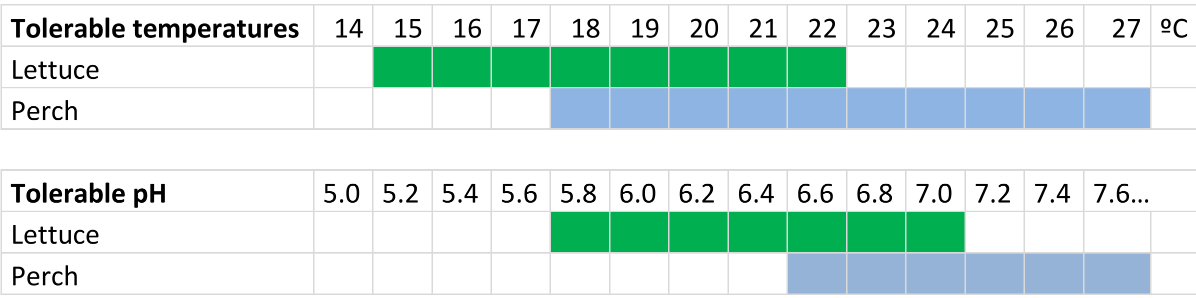


Figure 12: Lettuce and perch parameters comparison.

As it can be seen in Figure 12, lettuce and perch share an interval of temperatures and tolerable pH where they both can live. Consequently, they can grow together in an aquaponic system.

4.4.2 Fish ratios

When designing an aquaponic system, all the parts are dependent on the rest of the system. For example, depending on the surface available for plants, the amount of fish is restricted. In this chapter, the required biomass of fish will be calculated following the order that can be seen in Figure 13.

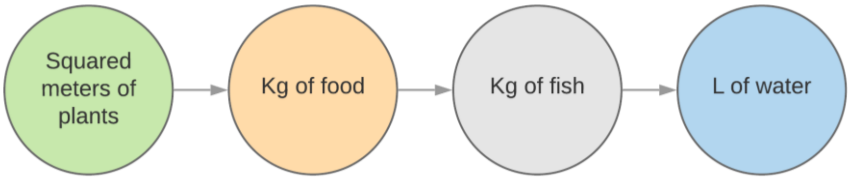


Figure 13: Order of calculations to follow when sizing an aquaponic system.

The water should remain in a range of nutrients concentration that allows plants to have enough nutrients without letting them accumulate in the water. In other words, it should be a balance between the production of nutrients and the uptake of them (Leaffin 2019a; Tidwell et al. 2012, 364-366). For this reason, the amount of plants restricts the amount of fish.

In general, to feed 1m^2 of plant growing area, 100g of fish food should be daily input. However, lettuce has a low nutrient demand, and just 40-50g of fish food a day will be enough to fulfill their needs. From the fish food, 80% is used by the fish, and the rest is excreted as waste (Leaffin 2019a; Tidwell et al. 2012, 364-366; Somerville et al. 2014, 124).

In total, there are 17,4m^2 of plants in the system. Consequently, between 696g and 870g of fish food should be daily input in the system (see Eq.1). Fish eat 1-2% of their body weight a day depending on their growth stage: young fish eat more than older (Somerville et al. 2014, 124; Aller-aqua 2018). Consequently, 34.8kg – 87.9kg of fish are required in the aquaponics (see Eq. 2.1 and Eq. 2.2).

$$17.4m^2 \cdot \frac{40-50g\ fish\ food/\ day}{1m^2} = 696-870g\ fish\ food/day \quad [Eq.1]$$

$$696g\ fish\ food/day \cdot \frac{100g\ fish}{1-2g\ fish\ food/day} = 34.8-69.6kg\ of\ fish\ biomass \quad [Eq.2.1]$$

$$870g\ fish\ food/day \cdot \frac{100g\ fish}{1-2g\ fish\ food/day} = 44.0-87.9kg\ of\ fish\ biomass \quad [Eq.2.2]$$

The maximum stocking density is 20kg of fish per 1000L of water. However, high densities are the first cause of fish stress and it complicates the control of the aquaponics (Somerville et al. 2014, 125). To avoid that, just 15kg per 1000L will be grown in the fish tank.

The common plants used in aquaponic systems can grow in a wide range of nutrient density (Tidwell et al. 2012, 364-366). For this reason and because of the variability of fish food that perch eat, the amount of fish that can be input in the system varies from 34.8kg to 87.9kg. An amount of fish in the middle of the range will be selected to avoid complications. If considering 60kg of fish, 4000L of water is required.

The number of fish obtainable from the weight depends on their size when input in the system. The information related to their sizes, weight and ages can be found in Table 3.

Table 3: Length and weight of perch according to their age.

	Time	Length	Weight	Reference
Perch fingerlings	1-2 months	2,5-3,5cm	-	(Weldon 2019; The Fish Site 2007)
Harvest size	12-18 months	10-15cm	0,23-0,34kg	(Brooke 2019b)
Final grow	10 years	25-30cm	1kg	(Brooke 2019b)

To obtain fish all the year-round, yellow perch in different growth stages will be contained in the fish tank. Every three months, fish in the harvest size should be collected and the same amount of fingerlings should be added (see Table 4). From it, it can be deduced that the medium fish sizes 0.23kg. As there are 60kg of fish, there are approximately 260 fish. If every three weeks one fifth can be harvested, 52 fish can be collected.

Table 4: Average lengths and weights of the perch in the system according to their age.

Age in the beginning	After 3 months	Age in the harvest time of the oldest	Average lengths	Average weights
2 months	→	5 months	3.5cm	0.09kg
5 months	→	8 months	7cm	0.18kg
8 months	→	11 months	10cm	0.23kg
11 months	→	14 months	12.5cm	0.29kg
14 months	→	17 months	15cm	0.34kg
		Average	9.6cm	0.23kg

To sum up, perch will be the fish of the system. It is a suitable fish to grow in aquaponics and it can be fished in Finland. For the number of plants that need to be feed, 260 fish weighting together 60kg is required. To avoid stressing them, they will live in a 4000L fish tank.

4.5 Fish food

One of the reasons yellow perch are a good selection for aquaponics is because it is easy to adapt them to alternative diets. Some authors recommend alimenting them with the same feed than trout or salmon. It can be explained because both fish share many characteristics. They are between freshwater and cold water carnivore fish (Brown et al. 1996, 171-174; Brooke 2019b; Leaffin 2019b; Encyclopaedia Britannica 2020). This fact is an advantageous coincidence for the project because fish food labels do not display the exact amount of each ingredient, but in the SimaPro libraries, there is already trout feeding as a material that can be directly inputted to the LCA.

It is recommended to have fish in mixed grow rates to harvest regularly (Leaffin 2019a). However, for every fish length, it is preferred choosing a different size of fish food (Aller-aqua 2018). As in the tank of the current study, there are fish from mixed lengths; the middle size of fish food should be chosen. From the test in the university, it was proven that perch prefer flakes than granulated fish food. They are thin enough for the small fish, so they can eat them. As a consequence, trout feeding in the shape of a flake will be used.

4.6 Fish tank

The fish tank is a crucial element in the aquaponic system. To grow healthy fish and plants, the right one should be chosen (Green and Vibrant 2019).

On the one hand, any fish tank that can support the weight of the water will work. Therefore, if taking into account the objective of building the aquaponic system, having a transparent tank, the fish would be seen and it would be more visual for the students coming to visit it. Also, it is recommended having cylindrical tanks to make it easier cleaning it. In rectangular tanks, fish waste gets stuck in the corners and water does not flow as well as in tanks with round walls (FAO 2015; Green and Vibrant 2019).

Although glass is the most common material in aquariums, if the objective is having a cylindrical tank, it will be more expensive than rectangular ones. Besides, due to its dimensions, it will be heavy and it is not easy finding the desired shape and size. Another option that is gaining popularity is acrylic fish tanks. This material is stronger and lighter than glass, but over the time it loses quality due to the yellowing and the easy apparition of scratches, and it is also expensive (Fish Geeks 2016; Glasscages 2007; Glasscages w.y).

As reported in Chapter 4.4.2, the required volume to fit the needed amount of fish is 4000L. If just taking into account the best option for the fish, big tanks help the maintenance of a stable system (Green and Vibrant 2019). However, big transparent tanks are expensive and there is less availability. For further studies, the economic part and the opportunity of finding the tank should be considered, but for the current one, just the best tank for the fish will be chosen. As a result, a bit oversized acrylic and cylindrical tank with a diameter of 1.6m, the height of 2.2m and wide of 20mm will be selected.

A complete acrylic tank would be too expensive and difficult to manufacture. Therefore, 80% of the tank will be made of polyethylene (PE) and the rest of acrylic. This amount should be enough for the students to see the fish.

4.7 Filtration

In the aquaponics systems, two types of filtration are required. Mechanical filtration is responsible for accumulating and removing waste. Whereas biological filtration dissolves some particles and makes easier for the plants to absorb the nutrients (Somerville et al. 2014, 44-48).

4.7.1 Mechanical filtration

Mechanical filtration is one of the most delicate parts of the design. Many issues can affect both the health of the living species and clogging the system if a proper waste removal is not accomplished. For these reasons, some mechanical filtration methods will be discussed in this chapter (Somerville et al. 2014, 44-48).

In small-scale aquaponics, clarifiers can remove 60% of the solids and as a consequence, they are the most recommended method. Clarifiers are tanks designed in a way that makes the water flow slower. When this happens, particulates suspending in water accumulate in the bottom, where they can be removed, so clarifiers perform as settlers. To collect the waste, they are connected to the bottom of the fish tank by a pipe that sucks the wastewater (Somerville et al. 2014, 44-48; Brooke 2019a).

There are two main types of clarifiers: the ones that make the water flow slower by making it swirl and the ones with baffles inside. Solids should be periodically removed by connecting a pipe with a minimum diameter of 30cm to the bottom. To assure the collection of waste, the tank uses to have a conical shaped bottom (Somerville et al. 2014, 44-48; Brooke 2019a).

A general rule recommends using a tank six times smaller than the fish tank, but the optimal design will depend on the rest of the system (Somerville et al. 2014, 44-48). This approximation is enough for the design, so a cylindrical container with a conical bottom with a capacity of 667L will be used in the system of the study. This can be achieved with the design shown in Figure 14. Many fish tanks are made of polyethylene (Green and Vibrant 2019), so this is the material that will be considered for it.

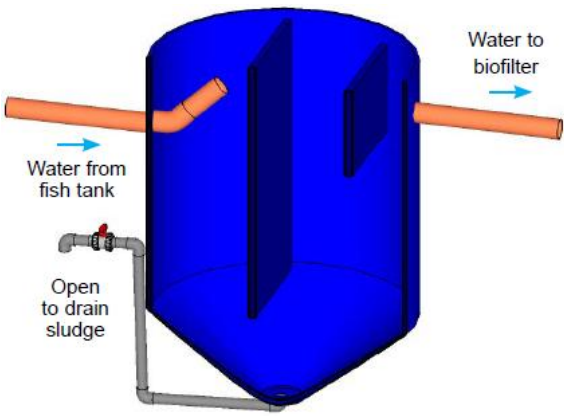


Figure 14: Conical clarifier with baffles (Somerville et al. 2014, 45)

4.7.2 Biological filtration

Mechanical filtration dissolves the biggest waste particles that are remaining in the water. However, some of them dissolve or are too small to be captured in this way and biological filtration is required. Besides, the nitrite and the ammonia in the water should be converted into nitrate also by biological filtration to simplify the plants the uptake of nutrients. This is why another tank where the majority of the bacteria live should be integrated into the system (Somerville et al. 2014, 44-48).

The characteristics that this tank should accomplish to have healthy growing bacteria is having a large surface area and oxygenated water. To increase the surface area, bioballs are commonly used. They are usually made of plastic and have a considerable surface area if taking into account their small volume (Somerville et al. 2014, 44-48). They can be seen in

Figure 15. In the testing setup, the research group improved the designs available in the shops and on the Internet and 3D printed them. They were made of ABS and there will be 200 of them in the system. The tank size uniquely depends on the available space in the container (see the sizes in Appendix 1 Data collection).

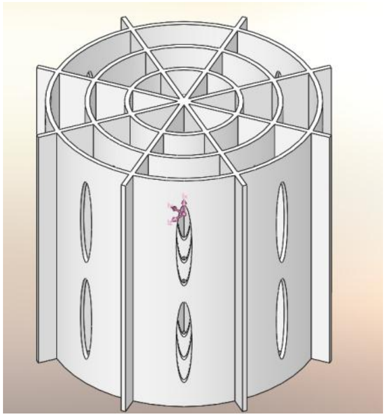


Figure 15: Design of the bioball used in the testing setup (unpublished work).

4.8 Pump

The sizing of the pump is a key issue for the normal operation of the aquaponic system. Having the wrong size of the pump can result in giving excessive or insufficient nutrients to the living parts of the system. The objective of having the correct pump is maximizing the effectiveness of aquaponics (Castelo 2018).

There are two main types of pumps: the submersible and the inline ones. The first type should be situated in a water tank. They are usually used in small commercial aquaponics that do not need to more than 1200GPH (gallons per hour). The inline pumps are used for big aquaponic systems with more than 50 towers (Castelo 2018; Storey 2016). Therefore, as the aquaponics has to fit in a container, and there are few towers and rafts, the optimal pump is the submersible.

Knowing the type of pump, the required size can be calculated. The first step is determining the GPH or LPH (liters per hour). Generally, all the water should circulate through the system every two hours (Castelo 2018; Storey 2016). As the system from the current study contains approximately 5240L of water, the pump should pump at least 2620L of water each hour, which is the same than 692GPH.

The next step is measuring the heat height. This is the distance between the water level in the grow beds or the towers and the level in the sump tank where the pump is situated (Castelo 2018; Storey 2016). In the case of the current study, the maximum distance that can be between the levels is 1.8m, or which is the same, 5.9 feet.

Finally, each manufacturer provides some charts that in one axis contain the GPH and the other one, the heat height. With this information, the pump related to the line that matches the operation of the system should be chosen (Castelo 2018; Storey 2016). In Figure 16, the heat height and flow rate chart from the pumps from ActiveAQUA, a company that produces components for aquaponics, can be seen. The red cross shows the conditions that the pump should reach according to the studied system.

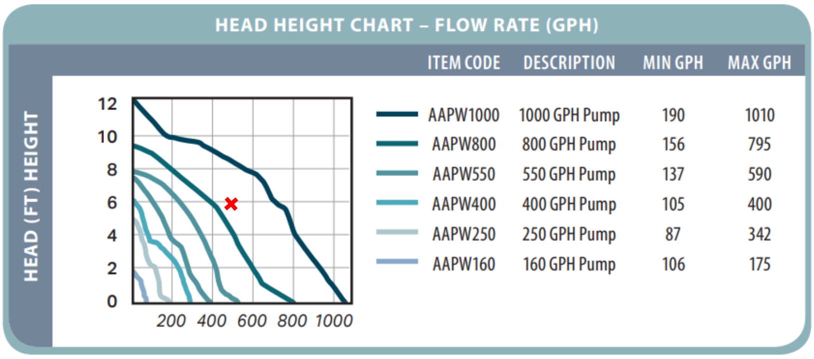


Figure 16: Heat height and flow rate chart from ActiveAQUA pumps (ActiveAQUA 2016).

From the characteristics that should meet the pump, the selected one is AAPW1000, available in Amazon. Its weight is 8.62 pounds, or 3.9 kg, of mixed materials. As the amount of each one of the materials is not easy to know, and the total weight is low compared to other components, just the power consumption in its operation will be considered. It can supply up to 92W (Amazon w.y).

4.9 Water

Aquaponics is a system where the water is conserved; it flows through the different components and loses are almost irrelevant if comparing with other methods of agriculture. However, as they are produced every day, they become significant, and water should be introduced periodically. The principal reasons for water escaping the system are evaporation and leaks, but also wastewater from the clarifier can have an impact (Baptista 2014; Somerville et al. 2014, 44-48).

Plants use the water in the evapotranspiration and they retain it in their tissues. Besides, water is directly evaporated from the tanks. In general, depending on the system characteristics, an aquaponics has a daily water loss of 1-3% (Baptista 2014; Somerville et al. 2014, 29)

The system of the study should be built in a closed container and in a cold climate, factors that reduce the evaporated water. For these reasons, the lower value from the normal water use ranges will be considered. This means that 1% of the water in the system should be introduced every day. As in the system of the study, there are approximately 5240L of water, everyday 52.4L of water should be input.

Despite this, for the study, no water outputs will be considered. This is because any of the processes where water is output from the system has a significant ecological impact. Firstly, when the water is evaporated, it will return to the Earth’s surface as rainwater. Secondly, water is absorbed by the plants, which is already considered in the LCA. Finally, water and solids are removed from the bottom of the clarifier. These contain high densities of nutrients and can be used as precious fertilizers (Somerville et al. 2014, 44-48).

In an improved system, it would be interesting to include a rainwater collection system. Rainwater is perfect for aquaponics because it usually has neutral pH and low salinity. Besides, it will improve the sustainability of the system and reduce costs (Somerville et al. 2014, 30).

4.10 Lights

Both plants and fish require light to live. Coldwater fish need light between 8h/day and 12h/day. As it has to be tested to know the optimal amount of light hours, the upper value in the range is going to be chosen to not obtain too optimistic results. A slow transition from darkness to light and the other way round replicating natural cycles will help the fish to do not stress (Waithaka 2019).

Though, plants need more specific requirements. Firstly, they demand a defined combination of colors in each stage of its life for an optimal grown. Next, according to the plant species, the intensity required is different. In the case of lettuce, low intensity is enough. Finally, different species require different periods of light. Some sources assure that lettuce requires from 14h to 18h/day of light (D'Anna 2019; Richards 2019), while some others explain that 10h to 12h/day is enough (Allman 2013; NoSoilSolutions 2018). Again, testing will say, but for the moment, 14/day is supposed.

4.11 Controlling system

The correct operation of the system requires having the ambient conditions prepared for the living species. A controlling system connected to several sensors and actuators should be installed to achieve it. For the LCA, the consumption of a Raspberry Pi and an Arduino board is considered (Alonso et al. 2019).

4.12 Final design

To sum up, the final design consists of a 4000L fish tank and two different types of hydroponics: DWC, with 12tanks, and the NFT, with 19 towers. The used plants are lettuce, and the fish, perch. It also includes complementary components such as the required for the filtration, for connecting the components and the controlling system.

5. Life Cycle Assessment of the aquaponic system

In this chapter, some of the phases of the LCA of the previously designed aquaponic system are made following the ISO 14040 standards. It includes the explanation of the software and the method used, SimaPro and ReCIPe 2016 (H), the goal and scope definition and the inventory analysis.

5.1 SimaPro and ReCiPe 2016 (H)

The software used in this study is SimaPro, the computer program leading LCA for 30 years in more than 80 countries. There is a variety of licenses for companies and education institutions in a range of prices from 350€ to 7000€. It follows ISO 14044 and 14040 standards and contains libraries with information that reduces the amount of data that the user has to introduce. It has been used in many LCA investigations by researchers and several companies used it to evaluate their products and services (PRé 2016).

Many methods can be used for the LCA, but for this investigation, ReCiPe 2016 Endpoint (H) method is chosen as the most suitable. It analyzes 21 impact categories, more than many of the methods, and some authors used it before for their LCA on aquaponics, so it simplifies comparisons with literature (PRé 2019; PRé 2016).

The user can select any of the three variants of the ReCiPe Endpoint method according to the objective of the study. For a time horizon of 20 years, the Individualist perspective (I) should be used. On the contrary, for considering long-term impacts that may not be fully established and pessimistic future socio-economic developments, the Egalitarian perspective (E) is the best variant. For the studies where the most frequent policy principles are taken into account, the Hierarchy perspective (H) should be selected (ReCiPe manual). For this study, the default variant (H) is used (PRé 2019).

5.2 Goal and scope definition

The LCA is carried on to evaluate the environmental impacts of the whole aquaponic system and compare it with the ones caused by conventional agriculture and aquaculture. This is made using the same functional unit as the other studies, in this case, 1kg of fish.

It includes the phases from the extraction of the material to its disposal, including the transport of the components from the factory that produces them to Vaasa. However, it is excluded the transport of the materials from its extraction location to the factory. The packaging is neither considered. All the contemplated components are explained in their respective sections in Chapter 4 and Appendix 1 Data collection, with their forming materials and amounts.

Breeding and seeding are out of the boundaries of the system, so perch fingerlings and lettuce sprouts should be bought. With perch avoiding breeding is easy because they require temperatures to about 7ºC for at least a month and having mature fish, which is not going to happen in the system (Brooke 2019b).

5.3 Inventory analysis

Collection of data is a crucial part of the project. The LCA results will fully depend on the considerations and assumptions taken on this part. It is supposed that the system will last 15 years, and after it, it will be disposed in the typical waste scenario in Finland (see Chapter 3.2.3). Long operation times will reduce the impacts made by equipment comparing with the other assembly groups (see them in Chapter 6.1). As can be seen in Figure 17, the inputs are the components and the operation of the system, and the outputs, the fish and the lettuce. In the sections of each one of the components, the taken data are explained (see Chapter 4), but the exact information introduced in Simapro is explained in Table 6, Table 7, Table 8 and Table 9; found in Appendix 1.

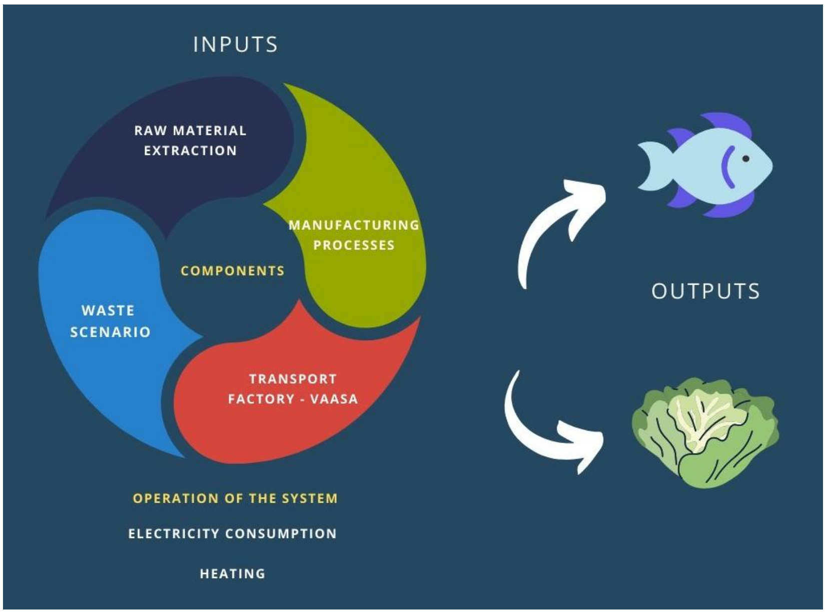


Figure 17: Inputs and outputs of the system.

6. Results

After introducing the data to SimaPro, the impacts of the described aquaponic system are calculated using the method ReCipe 2016 (H). This chapter contains an explanation of the process tree and the assembly groups, the impact assessment and the comparison of the results from other aquaponics, traditional agriculture and aquaculture.

6.1 Process tree and assembly groups

Some authors in the literature had divided the components and processes into groups to identify the main causes of each impact or damage categories. The same groups have been used in the current study to easily compare the results. These are equipment, heating, electricity and fish food (Ghamkhar et al. 2020). These assembly groups exclude tap water, perch fingerlings and lettuce sprouts. However, their impacts can be neglected because the defined groups produce more than 93% of the impact in all categories of characterization.

Table 1 is the process tree with all the processes and components of the aquaponic system. Each one of them has assigned a color that classifies them to their corresponding group. Note that the waste scenario is included in the equipment group.

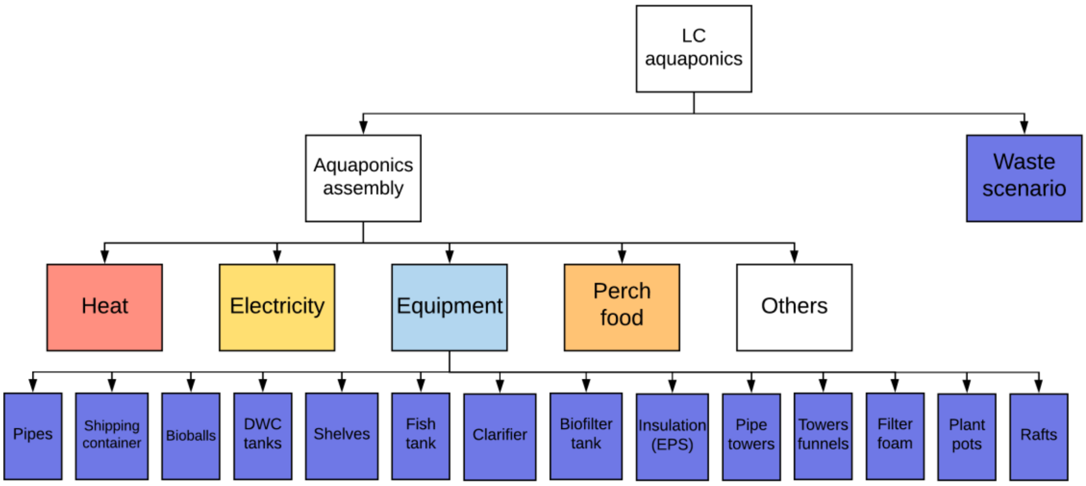


Figure 18: Process tree diagram of the life cycle of the aquaponic system and assembly groups.

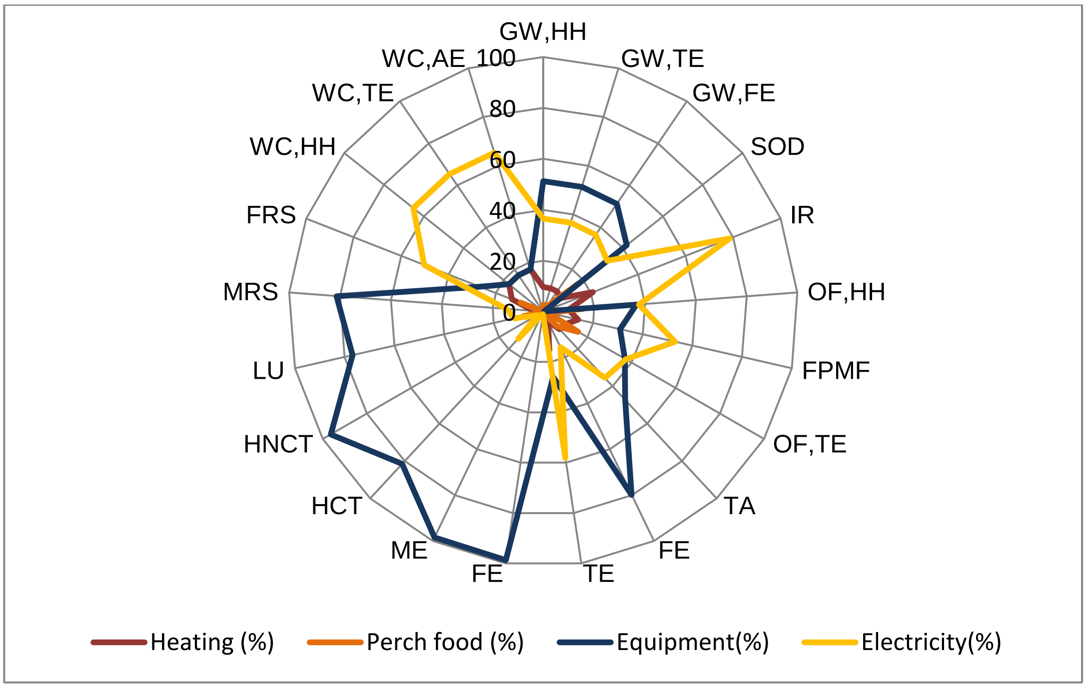
Figure 18 is a simplification of the real process tree. Each one of the components data used for the calculations includes many processes, materials, emissions, etc. such as the manufacturing processes and the transport (see Appendix 1 for the exact data).

6.2 Impact assessment

The impact assessment phase is made to understand the significance and importance of the potential environmental impacts in the whole life cycle of the designed aquaponic system (ISO-Norm 2006). There will be explained and illustrated the characterization and the damage assessment of the aquaponics. Moreover, the results will be compared with those obtained by other authors in similar studies.

6.2.1 Characterization

The characterization is an essential step according to ISO. To know the relative contribution of a substance to an impact category, they are multiplied by a characterization factor (PRé 2019, 1-2). By this way, knowing the substances that appear in the life cycle of the aquaponic system, it is known their contribution to a specific impact category (See Chapter 3.1.3 for the explanation of the impact categories). Figure 19 is the characterization graph by assembly groups, created from Table 11, and this one from Table 10, directly outputted from SimaPro. Both tables are found in the Appendix 2. Lines in Figure 19 correspond to the assembly groups, and the relative percentage of contribution of each one of them is shown in the net.



Where: Global warming, Human health (GW,HH); Global warming, Terrestrial ecosystems (GW,TE); Global warming, Freshwater ecosystems (GW, FE); Stratospheric ozone depletion (SOD); Ionizing radiation (IR); Ozone formation, Human health (OF,HH); Fine particulate matter formation (FPMF); Ozone formation, Terrestrial Ecosystems (OF,TE); Terrestrial acidification (TA); Freshwater eutrophication (FE); Terrestrial ecotoxicity (TE); Freshwater ecotoxicity (FE); Marine ecotoxicity (ME); Human carcinogenic toxicity (HCT); Human non-carcinogenic toxicity (HNCT); Land use (LU); Mineral resource scarcity (MRS); Fossil resource scarcity (FRS); Water consumption, Human health (WC,HH); Water consumption, Terrestrial ecosystem (WC,TE); Water consumption, Aquatic ecosystems (WC,AE).

Figure 19: Characterization by assembly groups.

From Figure 19, it highlights that in many categories, the element that produces a higher impact is equipment, followed by electricity. Whereas, the impact produced by heating and perch food is minimal if compared with the other two.

Ghamkhar et al. (2020) made a similar LCA of a cold-weather aquaponic system in Stevens Point, Wisconsin. However, the results they obtained are different. In their study, the parameters with a major significance were heat and electricity. It cannot be explained by weather differences, because as shown in Figure 20, in general, Vaasa has lower temperatures than Stevens Point. Therefore, the difference in results must be explained in another way. There are many types of aquaponics, so it is an option that Ghamkhar et al.

(2020) made the study on an aquaponic system that requires much less equipment. The current study includes a whole shipping container, the transport of the components from the company where they are manufactured to Vaasa and the waste scenario for each of them. Besides, it is considered that the shipping container is well insulated with EPS, which lowers the energy consumption invested in heating. As it is not known the considerations that were used for the other study, no conclusions can be made.

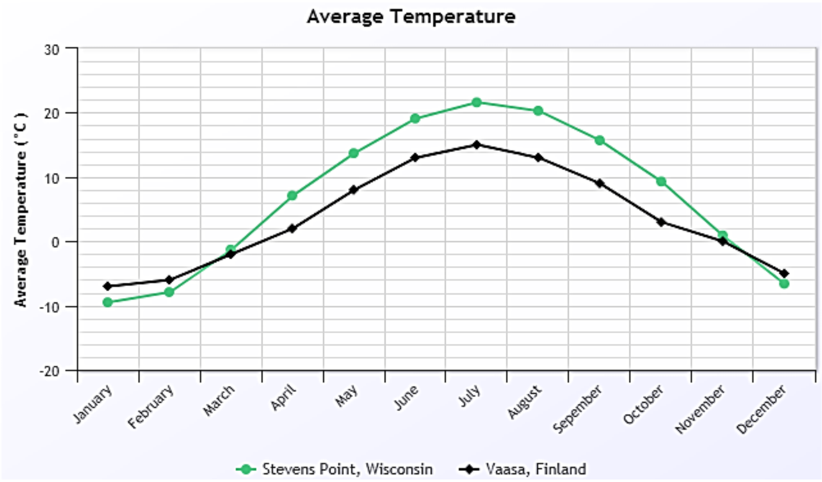


Figure 20: Temperature average comparison of Vaasa and Stevens Point (Weatherbase w.y)

6.2.2 Damage assessment

In the damage assessment step, the impact category indicators expressed with the same unit are added in a common damage category. ReCiPe 2016 (H) uses three endpoint characterization factors to classify the impact category indicators: human health, ecosystems and resources (See the explanation of the impact category indicators in Chapter 3.1.3) (PRé 2019, 1-26). Figure 21 is the damage assessment by assembly groups obtained from Table 12 in the Appendix 2.

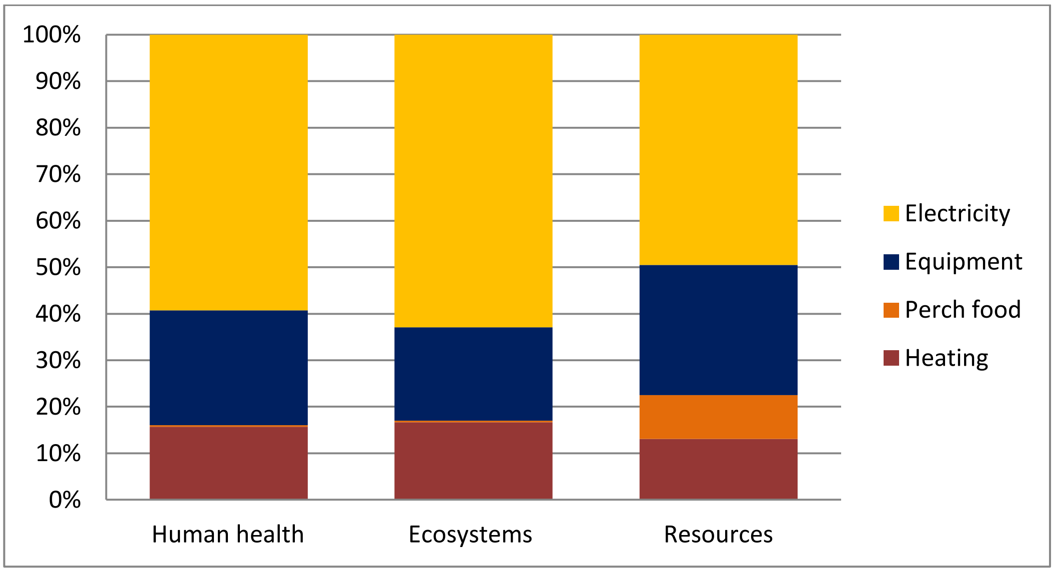


Figure 21: Damage assessment by assembly groups.

It can be seen that although in the characterization (Figure 19) energy is not the main contributor in most of the impacts when just looking at the damage assessment graph

(Figure 21), it is consolidated as the most damaging parameter. This is because in Figure 19 the impact categories where energy has a higher percentage, the environmental impacts are high (it has elevated values of DALY, species.yr or USD 2013). Per contra, in the impacts equipment has a higher percentage, the environmental impacts are low (see the exact data in Appendix 2).

Thus, in all the categories the factor that has a higher significance is electricity, followed by the equipment. Closely next to it there is the heating and with a lower impact, perch food.

Similar results were found by Maucieri et al. (2017) that built a micro aquaponic system for educational proposes with recovered materials. He found that electricity is the most significant impact on the aquaponic system, while water consumption was the lowest. It is remarkable the low effect that produced the equipment in their study, which produced less than 16% of the impact in all categories. This can be explained by the use of recovered materials, which demonstrated to be a major sustainable choice.

6.3 Impact assessment ignoring the effects of the shipping container

If just taking a look in the equipment assembly group, it highlights that the sipping container is the main contributor in 15 of the 21 impact categories. This is calculated without ignoring the waste scenario because shipping container contributes to it too. See Figure 22 for the relative contribution of equipment, without taking into account the waste scenario, to all the studied impact categories with and without shipping container. It is created from Table 13 in the Appendix 2.

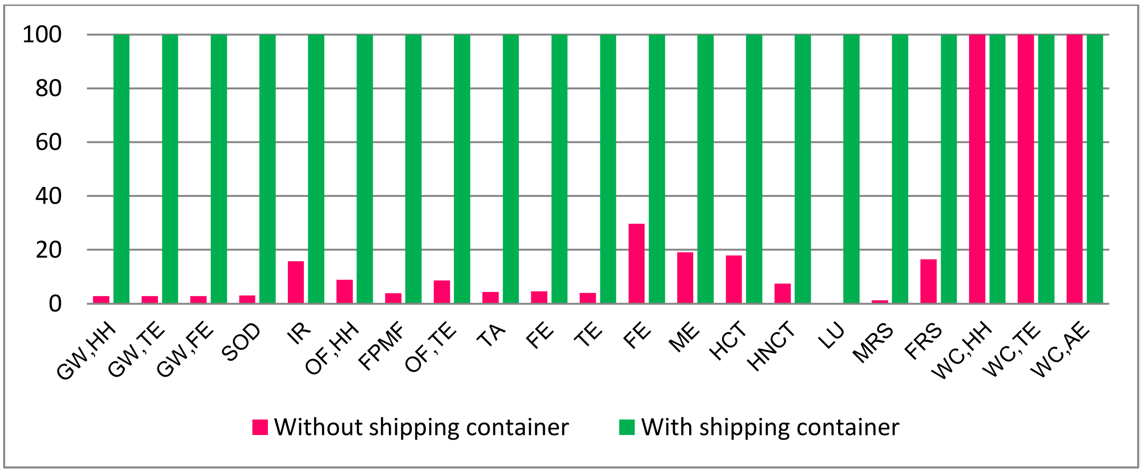


Figure 22: Relative contribution to the impact categories of the equipment with and without the shipping container ignoring the effects of the waste scenario (%).

Knowing the importance of the shipping container, it is interesting to evaluate if the results would be similar without it. Both characterization and damage assessment will be calculated again. Figure 22 is the characterization graph calculated with these new conditions (see the complete name of the impacts in Figure 19). Now electricity is the main contributor, gaining in 6 more categories than Figure 19 where it produced the major significance in 9 of 21 categories. It is obtained from the data from Table 14 in the Appendix 2.

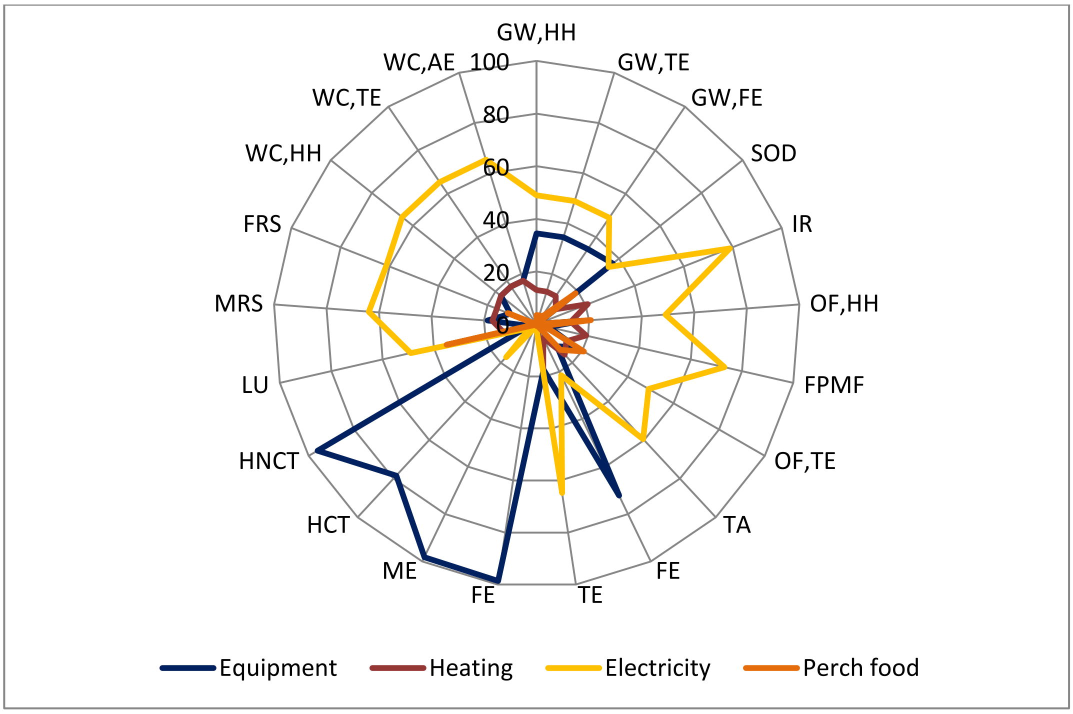


Figure 23: Characterization graph by assembly group without including the container.

If looking at the new damage assessment in Figure 23, made using the data from Table 15 in the Appendix 2, important reflections can be made. If the container is excluded from the calculations, the percentage of damage in the ecosystems and human health caused by heating now gets closer to the caused by equipment (compare with Figure 19). Even more interesting is looking at the resources damage column, where both perch food and heating overcome equipment damage. With this consideration, electricity gets largely considered as the main contributor causing more than 60% of damage to each category.

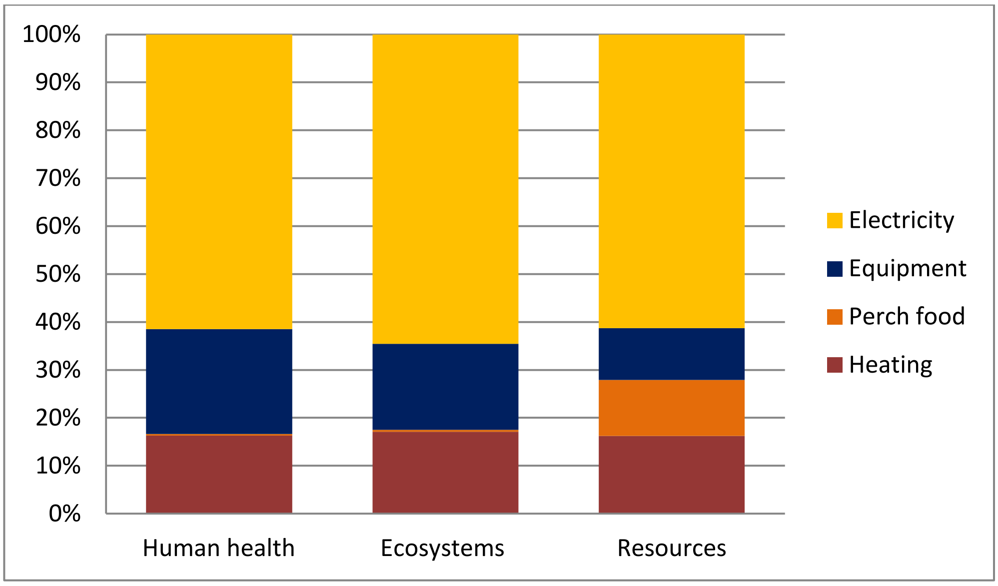


Figure 24: Damage assessment graph by assembly group without including the container.

From now, the container impacts will be omitted to understand which ones of the results are caused by the system, and not by the housing. Later on, in Chapter 7, it will be developed in greater depth.

6.4 Comparison with conventional agriculture and aquaculture

Aquaponic systems have been reported as a greener technique than conventional agriculture and aquaculture. In this section, this is going to be proved by using the available data obtained from other studies and the results from this report.

6.4.1 Comparison with conventional agriculture

The aquaponic system of the study uses 292.1 tones of water to produce 82,712 clumps of lettuce with an average weight of 100g. This means, in 15 years the system will be able to produce 8,271kg of lettuce with water use of 35L/kg of lettuce.

A study made in Yuma, Arizona in the USA by Lages et al. (2015) accounted for 250±25L/kg of lettuce grown by conventional agriculture. The investigated aquaponics system used between 12.7% and 15.6% of the water required for conventional agriculture, a value close to the 10% published in the literature (Winkler 2008; The Aquaponic Source 2020). In Figure 25 can be visually seen the difference.

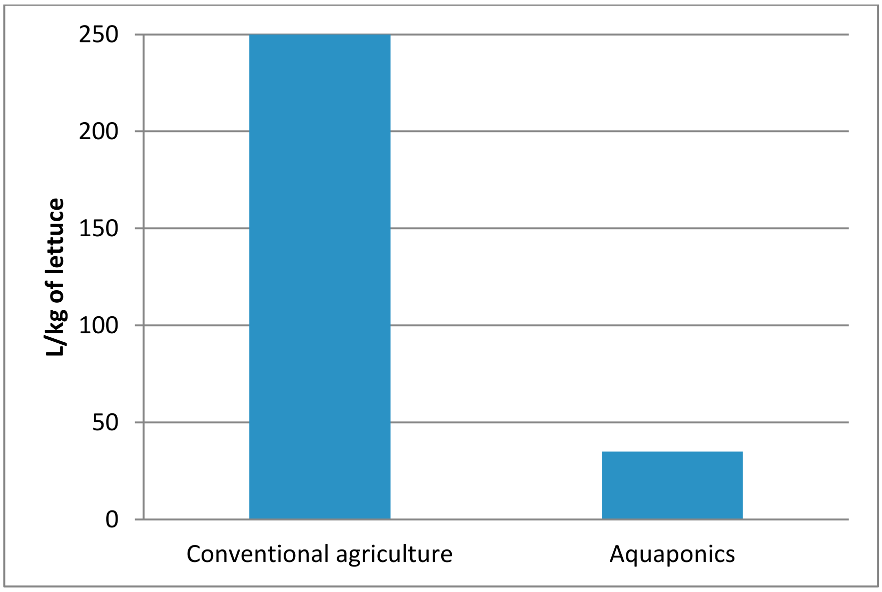


Figure 25: Water requirements comparison between conventional agriculture and aquaponics.

However, it is known than the requirements of electricity are higher in aquaponics than in other techniques, even more, if it is located in a cold climate (Hhamkhar et al. 2020). In 15 years of operation, the aquaponics from the investigation used 318,645kWh. As there were produced 8,271kg of lettuce, this means that it used 38.53kWh/kg of lettuce. Conventional agriculture uses 1,100±75kJ/kg of lettuce, while aquaponics used 138,692kJ/kg of lettuce; around 130 times the electricity required with the conventional method (see Figure 26).

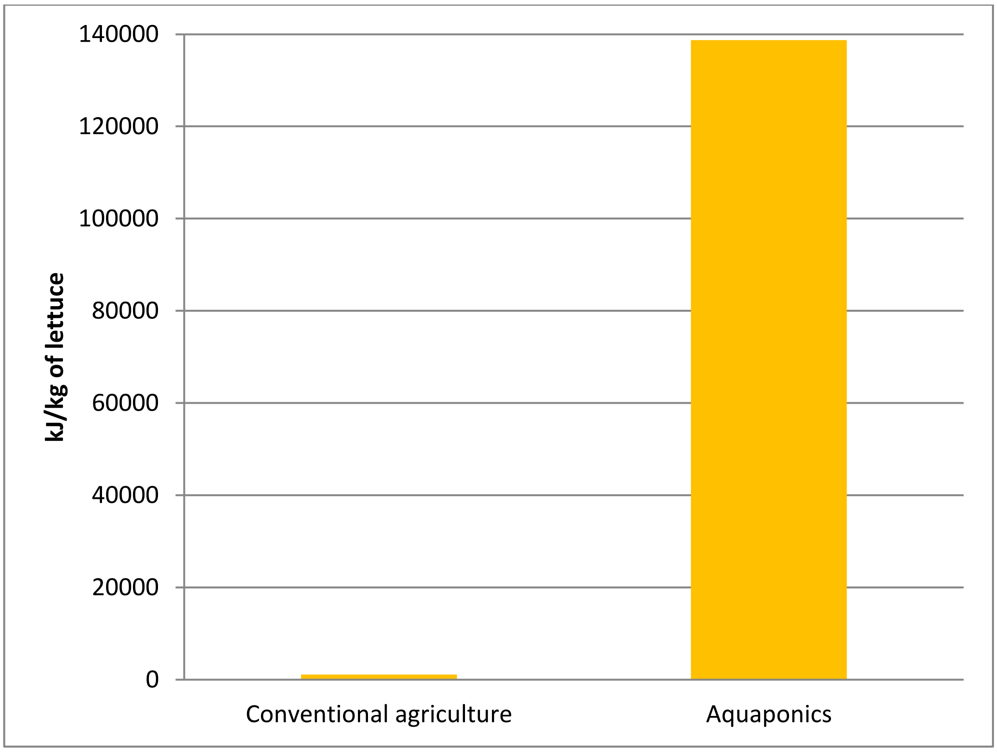


Figure 26: Energy requirements comparison between conventional agriculture and aquaponics.

This value is about 50% higher than what it was published in the literature for hydroponics. It would be expected to have a closer result because the electronic equipment necessary is almost the same. This time, the difference can be explained by heating requirements caused by the difference in temperatures (see Figure 27). In addition, the considered hydroponics system is installed in a greenhouse. This means that probably there is a natural source of light and energy requirements invested in light are much lower than in the aquaponics closed in the container, where lighting accounts for more than 90% of electricity usage (Lages et al. 2015).

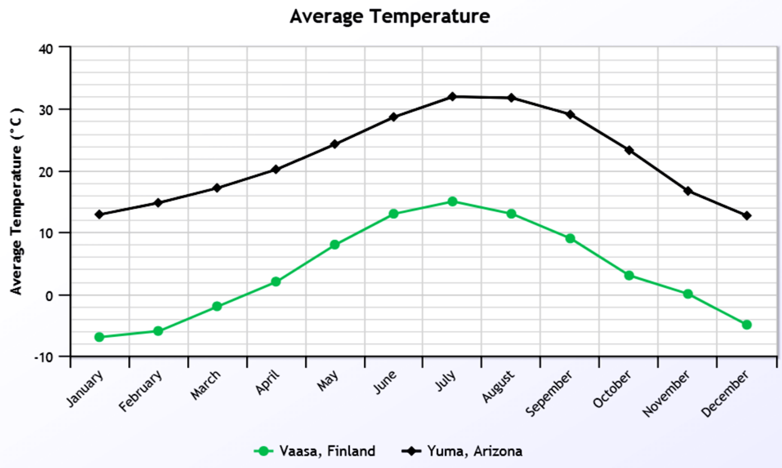


Figure 27: Temperature average comparison between Vaasa and Yuma (Weatherbase w.y)

These results can make one think that aquaponics is not as sustainable as it is reported in the literature, so in the next section it is going to be evaluated.

6.4.2 Comparison with conventional agriculture combined with aquaculture

In this study, it has been discussed a lot about agriculture, but considering the fish as a co-product of the system is essential to understand its effectiveness. In all the time of operation, the system will produce 1,101.6kg of perch. Cohen et al. (2018) made an LCA comparing conventional agriculture and two types of aquaculture with aquaponic. Their results are compared with the ones obtained in this project in Table 5. Additionally, a fourth column with the results of the current study if wind energy is used instead of the electricity mix in Finland’s grid is used. In light blue, it is indicated the less contributor system in each impact, while as darker is the blue, worst is the system performing in that category.

Table 5: Each system performance to the impact categories (Modified from Cohen et al. (2018)).

Impacts	Unit	Pond-based Aquaculture, Conventional agriculture	Lake-based Aquaculture, Conventional Agriculture	Aquaponics Cohen et al. (2018)	Aquaponics using electricity mix from Finland's grid	Aquaponics using energy from the wind
Global warming, Human health	DALY	3,75E-01	3,50E-01	7,64E-02	2,97E-01	1,01E-01
Global warming, Terrestrial ecosystems	species.yr	1,08E-03	1,06E+03	2,30E-04	8,98E-04	3,04E-04
Global warming, Freshwater ecosystems	species.yr	2,94E-08	2,88E-08	6,30E-09	2,45E-08	8,32E-09
Stratospheric ozone depletion	DALY	4,25E-05	2,73E-04	3,25E-04	1,41E-04	7,93E-05
Ionizing radiation	DALY	6,26E-05	3,80E-05	4,61E-04	1,16E-03	5,42E-06
Ozone formation, Human health	DALY	4,39E-04	4,30E-04	2,00E-04	4,85E-04	1,61E-04
Fine particulate matter formation	DALY	3,10E-01	3,06E-01	4,35E-04	1,65E-01	1,18E-02
Ozone formation, Terrestrial ecosystems	species.yr	6,44E-05	6,29E-05	2,90E-05	6,93E-05	2,30E-05
Terrestrial acidification	species.yr	3,98E-04	3,94E-04	1,40E-04	1,38E-04	2,57E-05
Freshwater eutrophication	species.yr	1,07E-04	1,09E-04	1,55E-05	1,43E-05	4,91E-06
Terrestrial ecotoxicity	species.yr	4,71E-06	4,54E-06	1,19E-06	1,40E-05	8,27E-07
Freshwater ecotoxicity	species.yr	2,75E-06	2,67E-06	5,33E-07	3,43E-05	3,21E-05
Marine ecotoxicity	species.yr	5,73E-07	5,57E-07	9,64E-08	6,82E-06	6,34E-06
Human carcinogenic toxicity	DALY	2,51E-02	2,46E-02	1,19E-02	3,87E-02	1,82E-02
Human non-carcinogenic toxicity	DALY	3,96E-02	3,88E-02	1,48E-02	2,13E-01	1,86E-01
Land use	species.yr	1,32E-03	1,32E-03	1,23E-03	8,68E-05	3,34E-05
Mineral resource scarcity	USD2013	5,57E+01	5,25E+01	1,21E+02	1,26E+02	1,80E+01
Fossil resource scarcity	USD2013	1,32E+04	1,24E+04	6,49E+03	1,03E+04	2,33E+03
Water consumption, Human health	DALY	7,50E-02	6,74E-01	1,72E-02	3,89E+00	6,35E-01
Water consumption, Terrestrial ecosystem	species.yr	4,56E-04	4,10E-03	1,05E-04	2,36E-02	3,86E-03
Water consumption, Aquatic ecosystems	species.yr	2,04E-08	1,83E-07	4,68E-09	1,06E-06	1,73E-07

From Table 5 it highlights the low impacts of the aquaponics from Cohen et al. (2018) study and from the one from this study when a renewable source of energy is used. However, the results have to be interpreted carefully.

Firstly, because the aquaponics investigated in the present study produces approximately 1kg of fish of each 8kg of lettuce, while the Cohen et al. (2018) systems produce 1kg of fish for each 5kg of lettuce. As the functional unit is 1ton of fish, the designed aquaponics is generating a higher production of lettuce with those impacts. If the functional unit would be 5kg of lettuce, then the impacts would be reduced.

Secondly, it should be taken into account that Cohen et al. (2018) are producing the lettuce in a greenhouse in Switzerland, a warmer country than Finland. It would be more interesting to compare which is the most sustainable method to obtain fresh products in Vaasa, but the study does not include the transport. As a consequence, it cannot be compared systems in cold climates with systems in warm climates, because the first one will generally have bigger impacts.

Although all this, it is enough clear that the aquaponic system which uses wind energy is the greener of the options. It showed a similar performance than Cohen et al. (2018) aquaponics, but this one did not include the transport, so it cannot be known if when the products arrive at Vaasa will pollute more or less than the ones obtained in the local aquaponics. As expected, all aquaponic systems had a better environmental performance in eutrophication, land use and water consumption. In the following chapter, all the issues found in this one will be discussed to obtain conclusions.

7. Discussion

In this chapter, it will be discussed if the initial objectives are achieved, the validity of the results in comparison with other published work, the limitations of the study and the consistencies and inconsistencies of it.

The first objective of this thesis was to design an aquaponic system taking as a base the prototype setup described in Chapter 3.2.1 and scaling it up to fit in a shipping container. By describing the components that should be in the system, sizing them and deciding its amount, this objective was met. The decisions made in the design are directly related with the impacts of the system and the credibility of the results when comparing with other studies.

The next two objectives are to evaluate the environmental impact of the designed aquaponics using SimaPro and compare it with the sustainability significance of traditional agriculture and aquaculture. Both objectives were met in Chapter 6 by using the obtained results to create graphs and tables and using the data to compare it with other articles.

Unlike other articles, this one studied the sustainability of housing the aquaponic system in a shipping container, a common practice in aquaponics companies. However, including it in the study made mask the real impacts from aquaponics, so it had to be excluded. To minimize the ecological impact of it, a reused shipping container can be restored for accommodating an aquaponics. Another option is to provide housing for the system by building a structure from less polluting or from recycled materials. Though, it should provide similar or more insulation than the shipping container to not increase the ecological cost in other categories.

This investigation coincided with other published work in the improvement of aquaponics over conventional agriculture and aquaculture in the eutrophication, land use and water consumption impacts. It highlights that electricity is the main contributor of the system, consuming 50% more energy than hydroponic systems studied.

The reason for this high value of electricity consumption can be found in its usage, contrasting with other studies in using 90% of it for the lighting. As lettuce requires little light, it should be tested if the LEDs are consuming too much power. In that case, the system would be consuming less than it was calculated. Also, it was considered that lettuce is a long-day plant, but literature reported contradictory results about it. Ideally, it should be tested the efficiency of the system with daylight between 8h and 14h, and then decide if 14h/day was too much for the optimal grown of lettuce. Besides, if another type of housing that takes advantage of the daylight in summer is chosen, much energy can be saved. For instance, LumiGrow (2018) used sensors that detect when the sunlight is intense to automatically close the lights.

Moreover, energy proved to be the major contributor when the electricity came from the mix in the grid, but not when it came from the wind, where the whole aquaponics showed the best environmental performance. Some authors investigated the consequences of using renewable energy sources instead of fossil fuels and reported that their use can reduce environmental impacts (Forchino et al. 2017). Consequently, deeper studies on the optimal source of the electricity according to the location should be made.

The low values of heating impacts comparing with other cold weather aquaponic systems can be explained by the good insulation on the system, but also by overrating the heat that the selected heater can produce. In the testing setup experiments and models made in the university, the material and the thickness of the insulation was decided, but there was omitted the use of the heater. The next step is testing the performance of various heaters to choose the best one and to concrete how much power they require.

Less important is that there have been found more efficient methods to produce the tanks than thermoforming, such as rotational molding, being PE the ideal material for this technique. It is relatively new compared to thermoforming, but more energy efficient. Nevertheless, there should be a company that produces them this way near Vaasa, and this is not the responsibility of the aquaponics builders (BPF 2015; euRECIPE 2006, 41-48).

To sum up, the objectives were achieved successfully, and in general, the results appeared to be similar than LCA made on aquaponics. Further studies on environmental housing structures, the light requirements of lettuce and energy sources should be made to improve the sustainability performance of the designed system. Besides, more reliable results would be obtained if this study was compared with more articles.

8. Conclusions

Aquaponics can be part of the solution to the climate crisis. It demonstrated to improve the environmental performance of agriculture and aquaculture before and this study is one more proof of it. This bachelor thesis presents an LCA made on an aquaponic system located in a cold-weather region in 21 impact categories. The results revealed that an optimization on equipment, focusing on the housing, and on the electricity will derive to a significant reduction on the environmental impacts.

The housing for the aquaponics was at first chosen to be a shipping container because many companies succeed using it. However, the environmental impacts caused by it were bigger than the ones produced by all the other equipment components, masking their significance. When the impacts made by the shipping container were ignored, the results are shown to be similar to the ones from other studies, especially concerning eutrophication, land use and the use of water.

Despite this, electricity usage in the designed aquaponics was much higher than in the ones from literature, being the LED lights the major consumers. To reduce their consumption, it is recommended to experiment with the intensity and the daily hours they are turned on.

Summarizing, housing and electricity are the most sensitive parameters in the aquaponic system. They are points where further investigation should focus on to optimize the sustainability of the technique. The ball is now in the court of the entrepreneurs and farming sector, that will have to decide if this technology is mature and with sufficient potential to invest in.

9. References

3dstartpoint. 2016. *3D Print Power Consumption – How Much Power Does a 3D Printer Use?* [online]. Available at: https://3dstartpoint.com/3d-print-power-consumption-how-much-power-does-a-3d-printer-use/ (Accessed: 18.03.2020)

ActiveAQUA. 2016. *The Active Aqua difference* [online]. Available at: http://www.activeaquahydroponics.com/sites/default/files/attachments/Pump_Info_Sheet_head_height_chart.pdf (Accessed: 20.03.2020)

Aller-aqua. 2018. *Perch* [online]. Available at: https://www.aller-aqua.com/species/warm-freshwater-species/perch (Accessed: 21.01.2020)

Allman, M. 2013. *Daylight Hours to Grow Lettuce* [online]. Available at: https://homeguides.sfgate.com/daylight-hours-grow-lettuce-70987.html (Accessed: 18.06.2020)

Alonso, B., Boumeester, B., Casades, M., Fernández, M., Koers, N., Lex, S., van Loon, M., Olumba, S., Trott, P. and Verheyen, L. 2019. *Aquaponics* [online]. Vaasa: Novia University of Applied Sciences. Available at: http://eps.novia.fi/assets/Sidor/2/1545/Autumn-2019-Aquaponics-Final-Report-Part-1-of-3.pdf (Accessed: 04.05.2020)

Amazon. w.y. *Hydrofarm AAPW1000 Active Aqua 1000 GPH Submersible Hydroponic Pond Aquarium Water Pumps (2 Pack)* [online]. Available at: https://www.amazon.com/Hydrofarm-Active-1000GPH-Submersible-Hydroponics/dp/B00K58OGKW (Accessed: 20.03.2020)

Amazon. w.y-a. *Hydrofarm AAPW1000 Active Aqua 1000 GPH Submersible Hydroponic Pond Aquarium Water Pumps (2 Pack)* [online]. Available at: https://www.amazon.com/Hydrofarm-Active-1000GPH-Submersible-Hydroponics/dp/B00K58OGKW (Accessed: 20.03.2020)

Amazon. w.y-b. Vornado AVH10 Vortex Heater with Auto Climate Control, 2 Heat Settings, Fan Only Option, Digital Display, Advanced Safety Features [online]. Available at: https://www.amazon.com/Vornado-EH1-0096-43-Automatic-Climate-Control/dp/B00SVIOFNG?ref_=s9_apbd_orecs_hd_bw_b28ik&pf_rd_r=VC5HBFMKCFMHAYP8QMWY&pf_rd_p=4e115bee-0729-42da-b7e5-701e201b0121&pf_rd_s=merchandised-search-11&pf_rd_t=BROWSE&pf_rd_i=510182 (Accessed: 24.03.2020)

Amazon. w.y-c. *Estantería de 4 niveles Supreme* [online]. Available at: https://www.amazon.com/-/es/Estanter%C3%ADa-de-4-niveles-Supreme/dp/B0007MHD1K?ref_=fsclp_pl_dp_2 (Accessed: 06.04.2020)

Aquaponics Iberia. w.y. *Producción de Peces y Vegetales de Forma Sustentable y en Simbiose* [online] (*in Spanish*). Available at: https://www.aquaponicsiberia.com/?lang=es (Accessed: 07.05.2020)

Ashby, M. 2012. *Materials and the Environment* [online]. Available at: https://mycourses.aalto.fi/pluginfile.php/565284/mod_resource/content/2/ME-chap3.pdf (Accessed: 19.06.2020)

Australian Urethane & Styrene. w.y. *Expanded Polystyrene (EPS)* [online]. Available at: https://www.thermalps.com.au/imagesDB/wysiwyg/TDS_Expanded_Polystyrene.pdf (Accessed: 07.03.2020)

Azevedo, L., van Zelm, R., Hendriks, A. and Huijbregts, M. 2013. *Global assessment of the effects of terrestrial acidification on plant species richness* [online]. Environmental pollution. Available at: https://www.sciencedirect.com/science/article/pii/S0269749112004782 (Accessed: 09.06.2020)

Baptista, P. 2014. *Water Use Efficiency in Hydroponics and Aquaponics* [online]. Available at: http://blog.zipgrow.com/water-use-efficiency-hydroponics-aquaponics/ (Accessed: 28.04.2020)

Barry, J. 2019. *AQUAPONICS: HOW DOES IT WORK?* [online]. Available at: https://www.accesstoaquaponics.com/aquaponics-how-does-it-work/ (Accessed: 04.05.2020)

BigSteelBoxTV. 2011. *How Shipping Containers Are Made (HD) - BigSteelBox (Extended Version)* [online]. Available at: https://www.youtube.com/watch?v=z7l6AQN1KV0 (Accessed: 02.04.2020)

Blakemore, E. 2019. *What was the Neolithic Revolution?* [online]. Available at: https://www.nationalgeographic.com/culture/topics/reference/neolithic-agricultural-revolution/ (Accessed: 08.06.2020)

British Plastics Feferation (BPF). 2015. *Rotational Moulding* [online]. Available at: https://www.bpf.co.uk/plastipedia/processes/rotational_moulding.aspx (Accessed: 30.03.2020)

Brooke, N. 2019a. *Using a Clarifier as Solids Filtration in Aquaponics Filtration in Aquaponics* [online]. Available at: https://www.howtoaquaponic.com/designs/aquaponics-clarifier/ (Accessed: 26.02.2020)

Brooke, N. 2019b. *Yellow Perch Aquaponics: Ideal fish?* [online]. Available at: https://www.howtoaquaponic.com/fish/yellow-perch-aquaponics/ (Accessed: 21.01.2020)

Brown, P. B, Dabrowski, K. and Garling, D. L. 1996. *Nutrition and feeding of yellow perch (Perca flavescens)* [online]. Berlin: Blackwell Wissenschafts-Verlag. Available at: https://www.researchgate.net/publication/229992031_Nutrition_and_feeding_of_yellow_perch_Perca_flavescens (Accessed: 30.03.2020)

Castelo, J. 2018. *Water Pumps for Aquaponics: How to Choose the Right Size* [online]. Available at: https://worldwaterreserve.com/aquaponics/water-pumps-for-aquaponics/ (Accessed: 13.03.2020)

Chislock, M. Doster, E., Zitomer, R. and Wilson, A. 2013. *Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems* [online]. Available at: https://www.nature.com/scitable/knowledge/library/eutrophication-causes-consequences-and-controls-in-aquatic-102364466/ (Accessed: 08.06.2020)

Cohen, A., Malone, S., Morris, Z., Weissburg, M. and Bras, B. *Combined Fish and Lettuce Cultivation: An Aquaponics Life Cycle Assessment* [online]. Procedia CIRP. Available at: https://www.sciencedirect.com/science/article/pii/S2212827117307989 (Accessed: 08.05.2020)

D'Anna, C. 2019. *The Basics of Hydroponic Lighting* [online]. Available at: https://www.thespruce.com/hydroponic-lighting-basics-1939224 (Accessed: 18.06.2020)

Delp, R. w.y. *The Use of Fertilizers & Eutrophication* [online]. Available at: https://homeguides.sfgate.com/use-fertilizers-eutrophication-77917.html#:~:text=Fertilizers%20provide%20essential%20nutrients%20like,vegetables%20and%20ornamental%20flowers%20grow.&text=Fertilizer%20nutrients%20left%20unused%20in,of%20excessive%20amounts%20of%20nutrients. (Accessed: 17.06.2020)

Doityourself. 2010. *How an Aquaponics system works* [online]. Available at: https://www.doityourself.com/stry/how-an-aquaponics-system-works (Accessed: 04.05.2020)

EDEN ISS. 2019. *Ground Demonstration of Plant Cultivation Technologies for Safe Food Production in Space* [online]. Available at: https://eden-iss.net/ (Accessed: 05.05.2020)

Encyclopædia Britannica. 2008. *Lettuce* [online]. Available at: https://www.britannica.com/plant/lettuce (Accessed: 18.06.2020)

Encyclopædia Britannica. 2011. *Tilapia* [online]. Available at: https://www.britannica.com/animal/tilapia (Accessed: 30.04.2020)

Encyclopaedia Britannica. 2020. *Perch* [online]. Available at: https://www.britannica.com/animal/perch (Accessed: 30.03.2020)

euRECIPE. 2006. *Low Energy Plastics Processing* [online]. Available at: http://www.tangram.co.uk/TI-Energy-Low%20Energy%20Plastics%20Processing%20(e).pdf (Accessed: 30.03.2020)

European Environmental Agency (EEA). 2016. *Stratospheric ozone depletion* [online]. Available at: https://www.eea.europa.eu/publications/signals-2000/page010.html (Accessed: 06.06.2020)

EWI Store. 2020. *EPS Insulation ($1m^2$)* [online]. Available at: https://ewistore.co.uk/shop/eps-insulation-1m2/ (Accessed: 16.04.2020)

Fish Geeks. 2016. *Choosing the right material for your custom aquarium* [online]. Available at: https://fishgeeks.com/custom-aquarium/ (Accessed: 25.02.2020)

FishinginFinland. 2014. *Fish species* [online]. Available at: https://www.fishinginfinland.fi/species (Accessed: 03.04.2020)

Food and Agriculture Organization of the United Nations (FAO). 2015. *7 rules-of-thumb to follow in aquaponics* [online]. Available at: http://www.fao.org/zhc/detail-events/en/c/320156/ (Accessed: 21.02.2020)

Forchino, A.A., Lourguioui, H., Brigolina, D. and Pastresa, R. 2017. *Aquaponics and sustainability: The comparison of two different aquaponic techniques using the Life Cycle Assessment (LCA)* [online]. Available at: https://www.sciencedirect.com/science/article/pii/S0144860916301522#fig0025 (Accessed: 12.06.2020)

Freightfarms. 2019. *Greenery* [online]. Available at: https://www.freightfarms.com/greenery#vertical-farming (Accessed: 05.06.2020)

Fullbloom Hydroponics. 2011. *Hydroponic Systems 101* [online]. Available at: https://www.fullbloomgreenhouse.com/hydroponic-systems-101/ (Accessed: 05.05.2020)

Ghamkhar, R., Hartleb, C., Wu, F. and Hicks, A. 2020. *Life cycle assessment of cold weather aquaponic food production system* [online]. Journal of Cleaner Production. Available at: https://www.sciencedirect.com/science/article/pii/S0959652619336376 (Accessed: 02.05.2020)

Glasscages. 2007. *Glass Aquariums* [online]. Available at: https://glasscages.com/?sAction=ViewCat&lCatID=2 (Accessed: 25.02.2020)

Glasscages. w.d. *Acrylic Cylindrical Aquariums (Circle Aquariums)* [online]. Available at: https://glasscages.com/?sAction=ViewCat&lCatID=75 (Accessed: 25.02.2020)

Green and Vibrant. 2019. *Deep Water Culture (DWC) – The Definitive Guide* [online]. Available at: https://www.greenandvibrant.com/deep-water-culture (Accessed: 09.05.2020)

Green and Vibrant. 2019. *The Best Aquaponic Fish Tanks - Buying Guide & Recommendation* [online]. Available at: https://www.greenandvibrant.com/best-aquaponic-fish-tanks (Accessed: 26.02.2020)

Green and Vibrant. 2019. *The Best Aquaponic Fish Tanks – Buying Guide & Recommendation* [online]. Available at: https://www.greenandvibrant.com/best-aquaponic-fish-tanks (Accessed: 25.02.2020)

Greentumble. 2018. *The Main Causes of Land Pollution* [online]. Available at: https://greentumble.com/the-main-causes-of-land-pollution/ (Accessed: 12.06.2020)

Growtainer. 2012. *A Modular State-of-the-Art Growing System Delivered to Your Door* [online]. Available at: http://www.growtainers.com/growtainer-2-2/ (Accessed: 05.05.2020)

GrowUp Urban Farms. 2018. *Commercial-scale Controlled Environment Production* [online]. Available at: https://www.growup.org.uk/about-us (Accessed: 05.05.2020)

Haeckels. 2019. *EDEN ISS* [online]. Available at: https://haeckels.co.uk/journal/eden-iss/ (Accessed: 09.05.2020)

HortiDaily. 2019. *Inner leaf "tip-burn" in lettuce* [online]. Available at: https://www.hortidaily.com/article/9091827/inner-leaf-tip-burn-in-lettuce/ (Accessed: 08.02.2020)

Hydroenv. 2014. *¿Qué es el sistema NFT?* [online] (in Spanish). Available at: https://www.hydroenv.com.mx/catalogo/index.php?main_page=page&id=101 (Accessed: 05.06.2020)

ISO-Norm. 2006. *Environmental management – Life cycle assessment – Principles and framework* [online]. Available at: https://www.iso.org/obp/ui/#iso:std:iso:14040:ed-2:v1:en (Accessed: 04.05.2020)

ISO-Norm. 2013. *Series 1 freight containers – Classification, dimensions and rating*s [online]. Available at: https://web.archive.org/web/20190331092550/https://www.sis.se/api/document/preview/916460/ (Accessed: 15.01.2020)

ISO-Norm. *2013. Series 1 freight containers – Classification, dimensions and rating*s [online]. Available at: https://web.archive.org/web/20190331092550/https://www.sis.se/api/document/preview/916460/ (Accessed: 15.01.2020)

Laaksonen, J., Salmenperä, H., Stén, S., Dahlbo, H., Merilehto, K. and Sahimaa, O. 2018. *From Recycling to a Circular Economy The National Waste Plan 2030* [online]. Helsinki: Ministry of the Environment. The Finnish Environment 01en/2018. Available at: http://julkaisut.valtioneuvosto.fi/bitstream/handle/10024/160889/SY_01en_18_WEB.pdf?sequence=1 (Accessed: 28.04.2020)

Lages, G., Daiane, F., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G. and Halden, R. 2015. *Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agriculture Methods* [online]. Available at: http://scholar.google.fi/scholar_url?url=https://www.mdpi.com/1660-4601/12/6/6879/pdf&hl=es&sa=X&scisig=AAGBfm1Ko2jmaH0tnSo8feqY2ufSgj7AhA&nossl=1&oi=scholarr (Accessed: 03.05.2020)

Leaffin. 2019a. *Aquaponics – How many plants per fish?* [online]. Available at: https://www.leaffin.com/aquaponic-fish-plant-ratio/#Factors_influencing_the_Ratio (Accessed: 14.01.2019)

Leaffin. 2019b. 9+ *Important Things to Consider when choosing Fish for Aquaponics* [online]. Available at: https://www.leaffin.com/guide-choosing-fish-aquaponics/ (Accessed: 21.01.2020)

Leaffin. 2019c. *Growing Rainbow Trout in an Aquaponic System* [online]. Available at: https://www.leaffin.com/trout-aquaponics/ (Accessed: 30.03.2020)

Lumeri. w.y. *LUMERI T8-INTEG100* [online]. Available at: https://www.lumeri-projektori.fi/lumeri-t8-integ100.html (Accessed: 10.04.2020)

LumiGrow. 2018. *Superior Fresh - Largest Aquaponics Facility in the World Uses LumiGrow LED Grow Lights* [online]. Available at: https://www.youtube.com/watch?v=87n2i2zuMsM (Accessed: 18.06.2020)

M.A. Curran. 2008. *Life-Cycle Assessment* [online]. Available at: https://www.sciencedirect.com/science/article/pii/B9780080454054006297 (Accessed: 19.06.2020)

Making Future. 2017. *Successful Waste-to-Energy Project in Finland* [online]. Available at: https://www.afconsult.com/en/newsroom/news/news/2017/successful-waste-to-energy-project-in-finland/ (Accessed: 01.05.2020)

Mattson, N. *Growing Hydroponic Leafy Greens* [online]. Available at: https://gpnmag.com/article/growing-hydroponic-leafy-greens/ (Accessed: 05.06.2020)

Maucieri, C., Forchino, A., Nicoletto, C., Junge, R., Pastres, R., Sambo, P. and Borin, M. 2018. *Life cycle assessment of a micro aquaponic system for educational purposes built using recovered material* [online]. Available at: https://www.sciencedirect.com/science/article/pii/S0959652617327634 (Accessed: 05.05.2020)

McGraw, B. 2017. *The many sides of sustainability in aquaculture* [online]. Available at: https://thefishsite.com/articles/the-many-sides-of-sustainability-in-aquaculture (Accessed: 17.06.2020)

Modulor. w.y. *Polyurethane filter foam ("plant foam"), PPI 10, large-pored 50.0 x 300 x 400 mm* [online]. Available at: https://www.modulor.de/en/polyurethane-filter-foam-plant-foam-ppi-10-large-pored-50-0-x-300-x-400-mm.html (Accessed: 20.03.2020)

Muralikrishna, I. and Manickam, V. 2017. *Environmental management* [online]. Available at: https://www.sciencedirect.com/book/9780128119891/environmental-management (Accessed: 10.06.2020)

National Aeronautics and Space Administration (NASA). 2020. *GLOBAL CLIMATE CHANGE* [online]. Available at: https://climate.nasa.gov/ (Accessed: 15.05.2020)

National Ocean Service. 2017. *What is eutrophication?* [online]. Available at: https://oceanservice.noaa.gov/facts/eutrophication.html (Accessed: 08.06.2020)

National Research Council. 2014. *A Framework to Guide Selection of Chemical Alternatives* [online]. Washington, DC: The National Academies Press. Available at: https://www.ncbi.nlm.nih.gov/books/NBK253975/ (Accessed: 09.06.2020)

Nelson Pade. 2018. *What is Aquaponics?* [online]. Available at: https://aquaponics.com/aquaponics-in-schools/aquaponics-information/ (Accessed: 03.05.2020)

NoSoilSolutions. 2018. *HOW TO GROW HYDROPONIC LETTUCE* [online]. Available at: https://www.nosoilsolutions.com/how-to-grow-hydroponic-lettuce/ (Accessed: 18.06.2020)

Observatory of Economic Complexity (OEC). 2020. *Finland (FIN) Exports, Imports and Trade Partners* [online]. Available at: https://oec.world/en/profile/country/fin/#:~:text=Its%20top%20imports%20are%20Crude,and%20China%20(%243.95B). (Accessed: 06.06.2020)

Omnexus. 2017a. *Comprehensive Guide on Polyvinyl Chloride (PVC)* [online]. Available at: https://omnexus.specialchem.com/selection-guide/polyvinyl-chloride-pvc-plastic (Accessed: 17.03.2020)

Omnexus. 2017b. *Polyethylene (PE)* [online]. Available at: https://omnexus.specialchem.com/selection-guide/polyethylene-plastic#HDPE (Accessed: 05.03.2020)

Omnexus. 2018. *Density of Plastics: Technical Properties* [online]. Available at: https://omnexus.specialchem.com/polymer-properties/properties/density (Accessed: 07.03.2020)

Organisation for Economic Co-operation and Development (OECD). w.y. *Managing water sustainably is key to the future of food and agriculture* [online]. Available at: https://www.oecd.org/agriculture/topics/water-and-agriculture/ (Accessed: 12.06.2020)

Polymerdatabase. 2018. *Poly(methyl methacrylate)* [online]. Available at: https://polymerdatabase.com/polymers/polymethylmethacrylate.html (Accessed: 25.02.2020)

PRé Consultants, Arcadis and CODE. 2016. *BIOSCOPE Methodology* [online]. Available at: https://www.bioscope.info/uploads/bioscope.info/bee_downloads/9/file/Methodology_Report_v1.compressed.pdf (Accessed: 14.05.2020)

PRé. 2016. *Introduction to LCA with SimaPro* [online]. Available at: https://www.pre-sustainability.com/download/SimaPro8IntroductionToLCA.pdf (Accessed: 13.05.2020)

PRé. 2019. *SimaPro Database Manual Methods Library* [online]. Available at: https://simapro.com/wp-content/uploads/2019/02/DatabaseManualMethods.pdf (Accessed: 02.05.2020)

Richards, J. 2019. *The Difference Between Short-Day & Long-Day Plants* [online]. Available at: https://homeguides.sfgate.com/difference-between-shortday-longday-plants-67267.html#:~:text=Long%2DDay%20Plants%20Definition&text=The%20long%2Dday%20flowers%20that,the%20plant%20flowers%2C%20or%20bolts. (Accessed: 18.06.2020)

Ritchie, H. and Roser, M. 2019. *Land Use* [online]. Available at: https://ourworldindata.org/land-use#:~:text=Arable%20agriculture%20(cropland),pastures%20used%20for%20livestock%20rearing). (Accessed: 12.06.2020)

Robson, A. D. 1989. *Soil acidity and plant grow* [online]. San Diego: Academic Press. Available at: https://books.google.es/books?hl=en&lr=&id=KL8gWPuOET0C&pg=PA61&redir_esc=y#v=onepage&q&f=false (Accessed: 09.06.2020)

Roser, M., Ritchie, H. and Ortiz-Ospina, E. 2019. *World Population Growth* [online]. Available at: https://ourworldindata.org/world-population-growth (Accessed: 08.06.2020)

Rumbaugh, E. 2018. *Ammonia Control in Intensive Aquaculture Systems* [online]. Available at: https://www.biologicalwasteexpert.com/blog/-ammonia-control-in-intensive-aquaculture-systems (Accessed: 06.05.2020)

Santander. 2018. *FINLANDIA: EXPORTACIÓN DE PRODUCTOS* [online]. Available at: https://santandertrade.com/es/portal/gestionar-embarques/finlandia/exportacion-de-productos (Accessed: 16.04.2020)

Scandic Container. 2017. *Used containers* [online]. Available at: https://www.scandiccontainer.fi/en/containers/category/used-containers/ (Accessed: 16.04.2020)

Shelley, T. 2018. *Nasty Truth: Aquaponics vs. Traditional Farming* [online]. Available at: https://www.survivopedia.com/nasty-truth-aquaponics-vs-traditional-farming/#:~:text=Traditional%20Farming,-FOOD%2C%20Plants%20%26%20Gardening&text=Conventional%20aquaculture%20includes%20raising%20aquatic,in%20a%20highly%20symbiotic%20environment. (Accessed: 12.06.2020)

Skretting. 2018. *Optimized nutrition for Rainbow trout* [online]. Available at: https://www.skretting.com/en/feeds-services/rainbow-trout/?lifephase=474993 (Accessed: 16.04.2020)

Somerville, C., Cohen, M., Pantanella, E., Stankus, A. and Lovatelli, A. 2014. *Small-scale aquaponic food production* [online]. Rome: Food and Agriculture Organization of the United Nations. Report 589. Available at: http://www.fao.org/3/a-i4021e.pdf (Accessed: 08.02.2020)

Statistics Finland. 2019. *Amount of municipal waste has not grown and recovery has replaced disposal at landfill cites* [online]. Available at: https://www.stat.fi/til/jate/2017/13/jate_2017_13_2019-01-09_tie_001_en.html (Accessed: 28.04.2020)

Storey, A. 2016. *Sizing a Pump for Hydroponics or Aquaponics* [online]. Available at: https://university.upstartfarmers.com/blog/sizing-a-pump-hydroponics-aquaponics (Accessed: 10.06.2020)

Tanks Direkt. 2020. *All products* [online]. Available at: https://tanksdirekt.de/en/all-products/ (Accessed: 16.04.2020)

The Aquaponic Source. 2019. *7 Ways Aquaponics is Sustainable* [online]. Available at: https://www.theaquaponicsource.com/sustainability-in-aquaponics/ (Accessed: 17.06.2020)

The Aquaponic Source. 2020. *What is Aquaponics?* [online]. Available at: https://www.theaquaponicsource.com/what-is-aquaponics/ (Accessed: 03.05.2020)

The Fish Site. 2007. *Species Profile: Yellow Perch, Perca flavescens* [online]. Available at: https://thefishsite.com/articles/species-profile-yellow-perch-perca-flavescens (Accessed: 25.01.2020)

Tidwell, J., Allan, G., Avnimelech, Y., Browdy, C., Brune, D., Chappell, J., Ebeling, J., Fornshell, G, Hargreaves, J., Hinshaw, J., Langan, R., Leffler, J., Masser, M., Massingill, M., Mims, S., Onders, R., Rakocy, J, Ray, A., Rheault, R., Stickney, R., Timmons, M., Treece, G. and Tucker, C. 2012. *Aquaculture Production Systems* [online]. 1st edn. USA: John Wiley & Sons, Inc. Available at: https://www.academia.edu/36260785/Aquaculture_Production_Systems?auto=download (Accessed: 14.01.2020)

UK AIR. 2010. *Stratospheric ozone depletion* [online]. Available at: https://uk-air.defra.gov.uk/research/ozone-uv/ozone-depletion (Accessed: 08.06.2020)

Verburgh, A., Van de Looverbosch, F., Lorenzoni, F., Dwenger, K., Bourras, M., Grabarczyk, N., Diels, S. and Stiegler, S. 2020. *Hygrow Aquaponics* [online]. Vaasa: Novia University of Applied Sciences. Available at: http://eps.novia.fi/assets/Sidor/2/1545/Spring-2020-Hygrow-Aquaponics-Final-Report.pdf (Accessed: 05.06.2020)

Vieira, M., Ponsioen, T., Goedkoop, M. and Huijbregts, M. 2016. *Surplus Cost Potential as a Life Cycle Impact Indicator for Metal Extraction* [online]. Available at: https://www.mdpi.com/2079-9276/5/1/2/htm (Accessed: 14.05.2020)

Waithaka, E. 2019. *How Long Should You Leave Aquarium Lights On—The Light Schedule* [online]. Available at: https://aquariawise.com/how-long-to-leave-aquarium-light-on/#cold-water-fish-light (Accessed: 18.06.2020)

Wankhede, A. 2019. *How Are Shipping Containers Made?* [online]. Available at: https://www.marineinsight.com/tech/how-are-shipping-containers-made/ (Accessed: 05.03.2020)

Wankhede, A. 2019. *How Are Shipping Containers Made?* [online]. Available at: https://www.marineinsight.com/tech/how-are-shipping-containers-made/ (Accessed: 05.03.2020)

Weather Atlas. 2017. *Monthly weather forecast and climate Vaasa, Finland* [online]. Available at: https://www.weather-atlas.com/en/finland/vaasa-climate (Accessed: 16.06.2020)

Weldon, V. 2019. *Yellow Perch Aquaculture* [online]. Available at: https://freshwater-aquaculture.extension.org/yellow-perch-aquaculture/ (Accessed: 25.01.2020)

Winkler, S. 2008. *How Aquaponics Works* [online]. Available at: https://home.howstuffworks.com/lawn-garden/professional-landscaping/aquaponics1.htm (Accessed 05.05.2020)

Wish. w.y. *45L/min 25W Electromagnetic Air Compressor Aquarium Oxygen Pond Air Pump Aerator* [online]. Available at: https://www.wish.com/product/5987d924a11359712ea815f6?hide_login_modal=true&from_ad=goog_shopping&_display_country_code=FI&_force_currency_code=EUR&pid=googleadwords_int&c=%7BcampaignId%7D&ad_cid=5987d924a11359712ea815f6&ad_cc=FI&ad_lang=EN&ad_curr=EUR&ad_price=30.00&campaign_id=9527731335&gclid=CjwKCAjwkun1BRAIEiwA2mJRWenYALQ9eMRdOUeGq1H8k29ETmmQtEBK9l14w97WNLvMJrvdJ5tzuhoC5bwQAvD_BwE&share=web (Accessed: 12.05.2020)

Workshop. 2012. *Wood Density Chart* [online]. Available at: https://cedarstripkayak.wordpress.com/lumber-selection/162-2/ (Accessed: 02.04.2020)

World Health Organization (WHO). 2013. *Metrics: Disability-Adjusted Life Year (DALY)* [online]. Available at: https://www.who.int/healthinfo/global_burden_disease/metrics_daly/en/ (Accessed: 14.05.2020)

World Health Organization (WHO). 2016. *Ionizing radiation, health effects and protective measures* [online]. Available at: https://www.who.int/news-room/fact-sheets/detail/ionizing-radiation-health-effects-and-protective-measures (Accessed: 09.06.2020)

Worldmeters. 2020. *World population* [online]. Available at: https://www.worldometers.info/world-population/#:~:text=The%20current%20world%20population%20is,currently%20living)%20of%20the%20world. (Accessed: 07.06.2020)

10. Appendices

Appendix 1 Data collection

Table 6: Components

Component	Material	Size	Density	Weight	Amount	References
Fish tank	Acrylic (PMMA) (20%)	W=20mm Interior measures (cylinder): D=1.60m H=2.2m Total material: 0.27m^3 Total capacity: 4.42m^3	1.15g/mL 1150kg/m^3	62.1kg	1	(Polymerdatabase 2018)
	Polyethylene (PE) – High density (HDPE) (80%)		0.91-0.97g/cm^3 Common value: 0.94g/cm^3 940kg/m^3	248.4kg		(Omnexus 2017b)
	Total (100%)		-	310.5kg		-
Clarifier	Polyethylene (PE) – High density (HDPE)	W=20mm Interior measures (cylinder): D=0.75m H=1.4m Interior measures (cone): D=0.75m H=0.5m Total material: 0.08m^3 Total capacity: 0.692m^3	0.91-0.97g/cm^3 Common value: 0.94g/cm^3 940kg/m^3	75.2kg	1	(Omnexus 2017b)
Biofilter tank	Polyethylene (PE) – High density (HDPE)	W=10mm Interior measures (cylinder): D=0.35m H=1.5m Total material: 0.017m^3 Total capacity: 0.128m^3	0.91-0.97g/cm^3 Common value: 0.94g/cm^3 940kg/m^3	16.0kg	1	(Omnexus 2017b)

Bioballs	Acrylonitrile Butadiene Styrene (ABS)	Measures (approx. cylinder): D=74mm H=70mm Total: 14.5cm^3	1.020-1.210g/cm^3 Average value: 1.115g/cm^3 1115kg/m^3	1.617·10^{-5}kg/bioball 3.23kg	200	(Omnexus 2018)
Shipping container	Steel	-	-	30480kg	1	(ISO-Norm 2013; Wankhede 2019; Workshop 2012; BigSteelBoxTV 2011)
	Wood (oak) – used for the floor	8.86m^3	600-900kg/m^3 Average value: 750kg/m^3	6645kg		
	Total	-	-	37125kg		
Insulation	Expanded Polystyrene (EPS)	4.521m^3	11-32kg/m^3 Common value: 32kg/m^3	144.67kg	-	(Australian Urethane & Styrene w.y)
Pipe towers	Rigid Polyvinyl Chloride (PVC)	$D_{exterior}$=110mm W=5mm L=1257mm	1.3-1.45g/cm^3 Average value: 1.375g/cm^3 1375kg/m^3	2.89kg/tower 43.37kg	15	(Omnexus 2017a)
Pipes (for connecting components)	Rigid Polyvinyl Chloride (PVC)	$D_{exterior}$=50mm W=4mm L=27m (aprox.)	1.3-1.45g/cm^3 Average value: 1.375g/cm^3 1375kg/m^3	21.46kg	-	(Omnexus 2017a)
Towers' funnels	Acrylonitrile Butadiene Styrene (ABS)	33.57cm^3	1.020-1.210g/cm^3 Average value: 1.115g/cm^3 1115kg/m^3	0.561kg	15	(Omnexus 2018)
Filter foam	Polyurethane	50x300x400mm=6·10^{6}mm^3 0.006m^3/filter foam sheet Total: 0.27m^3	30kg/m^3	8.1kg	3filters/tower x 15 towers = 45	(Modulor w.y)

Plant pots	Acrylonitrile Butadiene Styrene (ABS)	$D_{exterior}$=70mm W=3mm H=70mm 70% of the surface is a hole (see Figure _) $1.616 \cdot 10^{-5}m^3$	$1.020\text{-}1.210g/cm^3$ Average value: $1.115g/cm^3$ $1115kg/m^3$	0.018kg/pot 9.73kg	540	(Omnexus 2018)
Fish food (trout feed) – Includes transportation of the ingredients to the factory	Fishmeal (47%)	-	-	1791.17kg	-	Library: LCA Food DK (SimaPro)
	Wheat (14%)	-	-	533.54kg	-	
	Rape seed oil (20%)	-	-	762.2kg	-	
	Soy meal (18%)	-	-	685.98kg	-	
	Chemicals (1%)	-	-	38.11kg	-	
	Total (100%)	-	-	696g/day x 365days x 15 years 3811kg	-	
Perch fingerlings	Trout*	-	-	0.07kg/fingerling 226.8kg	54perch x 4 times/year x 15years = 3240perch	-
Lettuce sprouts	Lettuce	-	4g/lettuce sprout	4g/lettuce sprout 330kg	423lettuce sprouts/28days x 365days x 15years = 82712	-
Shelves	Steel	1320x750x1950mm	-	54.43kg/shelf 163.29kg	3	Data adapted from (Amazon w.y-c)
Rafts	Expanded Polystyrene (EPS)	1320x750x40mm $0.0396m^3$	$11\text{-}32kg/m^3$ Common value: $32kg/m^3$	15.2kg	12	(Australian Urethane & Styrene w.y)

DWC tanks	Polypropylene (PP)	1320x750x200mm w=1mm 0.001813m^3	0.970g/cm^3 970kg/m^3	1.76kg/tank 21.1kg	12	(Omnexus 2018)
Water	Water	Initial input: 5240L Variable input: 52.4L/day	1kg/L	5240kg initial + 52.4kg/day x 365days/year x 15years 292130kg	-	-

*There is no data available for perch. Therefore, as trout is the most similar fish with available data, it is selected.

Table 7: Manufacturing processes.

Process	**Components**	**Power consumption and emissions**	**Hours**	**Energy consumption**	**Reference**
3D printing	Bioballs	50W	5h x 200bioballs	50kWh	(3dstartpoint 2016)
	Towers funnels		4h30min x 15funnels	3.38kWh	
	Plant pots		3h x 540pots	81kWh	
Thermoforming	Fish tank	The library offers a long list of emissions and energy input from different sources	-	-	SimaPro libraries
	Clarifier				
	Biofilter tank				
Corrugating	Shipping container	The libraries offer a long list of emissions, inputs and outputs	-	-	(BigSteelBoxTV 2011) SimaPro libraries
Arc welding					
Painting					

Table 8: Operation process.

Process	Components	Power consumption and emissions	Hours	Energy consumption	Reference
Pumping	Pump	92W	24h/day x 365days/year x 15 years	12,088.8kWh	(Amazon w.y-a)
Heating	Heater	750W	24h/day x 365days/year x 15 years x 0.9*	88,695kWh	(Amazon w.y-b)
Lighting	LEDs	100W x 42 stripes of LEDS = 4200W**	365days/year x 15 years x (14h/day x 39/42 + 12h/day x 3/42)	318,645kWh	(Lumeri w.y)
Controlling the system	Raspberry Pi	~10W	24h/day x 365days/year x 15 years	1,314kWh	Real data from the setup in the university
	Arduino	~24W		3,153.6kWh	
Oxygenate DWC	Air pump	25W	24h/day x 365days/year x 15 years x 2 units	6,570kWh	(Wish w.y)

* Taking into account the cold climate in Vaasa (see Chapter 3.2.3) it is considered that it will be working 90% of the time. **39 stripes for pants and 3 stripes for fish

The infrastructure of Finland for the transport of goods is well developed. It has more than commercial 50 ports, including Vaasa's port (Santander 2018). For this reason, as it can be seen in Table 9, all the components arrive to Finland by ship.

Table 9: Transport.

Component	**Company**	**Origin place**	**Method of transport**	**Distance**	**Comments**	**Reference**
Fish tank, Clarifier and Biofilter	Tanks Direkt	Rotterdam, Netherlands	Ship	114.5km	-	(Tanks Direkt 2020)
			Truck	2098.5km		
Shipping container	Scandic Container	Vaasa, Finland	-	-	As Vaasa is a port city, it is considered that it is not going to be difficult to find a used container. The company from the reference offers shipping containers in Finland.	(Scandic Container 2017)
Fish food	Skretting	Stavanger, Norway	Ship	95.8km	-	(Skretting 2018)
			Truck	1441.2km		
Perch fingerlings	-	Vaasa, Finland	-	-	Perch is a native fish from Finland (see Chapter 4.4). It would be necessary to contact with local fishermen to assure the supply of fingerlings	Chapter 4.4
Insulation (EPS boards)	EWI Store	Kingston, United Kingdom	Ship	114.5km	-	(EWI Store 2020)
			Truck	2540.5km		

Appendix 2 Results from SimaPro

Table 10: Characterization by components and processes.

Impact category	Unit	Waste scenario	Fish tank	Clarifier	Biofilter tank	Bioballs	Shipping container	Insulation (EPS)	Pipe towers	Pipes for connecting components	Towers funnels	Filter foam
Global warming, Human health	DALY	9,78E-02	8,72E-04	1,35E-04	2,87E-05	2,49E-05	7,74E-02	6,29E-04	1,41E-04	6,96E-05	2,80E-06	2,47E-05
Global warming, Terrestrial ecosystems	species.yr	2,95E-04	2,63E-06	4,07E-07	8,66E-08	7,52E-08	2,33E-04	1,90E-06	4,24E-07	2,10E-07	8,45E-09	7,46E-08
Global warming, Freshwater ecosystems	species.yr	8,06E-09	7,19E-11	1,11E-11	2,37E-12	2,05E-12	6,38E-09	5,18E-11	1,16E-11	5,73E-12	2,31E-13	2,04E-12
Stratospheric ozone depletion	DALY	5,76E-05	7,46E-08	1,81E-08	3,84E-09	2,03E-09	5,57E-06	4,10E-08	1,73E-09	8,55E-10	1,37E-10	2,05E-08
Ionizing radiation	DALY	1,60E-06	2,26E-07	5,46E-08	1,16E-08	8,60E-09	2,20E-06	8,52E-08	0,00E+00	0,00E+00	5,81E-10	1,75E-09
Ozone formation, Human health	DALY	6,85E-05	4,58E-06	9,45E-07	2,01E-07	3,29E-08	1,21E-04	4,61E-06	2,37E-07	1,17E-07	5,68E-09	3,66E-08
Fine particulate matter formation	DALY	4,55E-03	9,44E-04	1,66E-04	3,52E-05	1,43E-05	4,65E-02	2,73E-04	7,66E-05	3,79E-05	1,59E-06	5,43E-06
Ozone formation, Terrestrial ecosystems	species.yr	9,75E-06	6,52E-07	1,35E-07	2,86E-08	4,72E-09	1,77E-05	6,60E-07	3,36E-08	1,66E-08	8,10E-10	5,43E-09
Terrestrial acidification	species.yr	8,75E-06	1,24E-06	2,14E-07	4,55E-08	2,05E-08	6,12E-05	6,33E-07	1,09E-07	5,41E-08	2,40E-09	8,85E-09
Freshwater eutrophication	species.yr	4,84E-06	6,76E-08	1,44E-08	3,06E-09	5,79E-13	1,80E-06	7,17E-10	8,41E-10	4,16E-10	3,91E-14	1,19E-10
Terrestrial ecotoxicity	species.yr	7,64E-07	5,87E-09	1,42E-09	3,02E-10	4,60E-11	3,69E-07	7,53E-10	2,80E-10	1,39E-10	3,11E-12	8,12E-11
Freshwater ecotoxicity	species.yr	3,66E-05	7,69E-09	1,86E-09	3,96E-10	9,82E-13	2,71E-08	1,34E-09	1,33E-11	6,56E-12	6,80E-14	2,49E-12
Marine ecotoxicity	species.yr	7,23E-06	1,53E-09	3,71E-10	7,90E-11	3,91E-13	9,95E-09	3,05E-10	2,73E-12	1,35E-12	2,64E-14	2,42E-12
Human carcinogenic toxicity	DALY	2,02E-02	3,72E-05	8,79E-06	1,87E-06	1,89E-08	1,75E-03	1,63E-06	2,19E-04	1,08E-04	1,37E-09	1,30E-07
Human non-carcinogenic toxicity	DALY	2,12E-01	3,98E-05	9,64E-06	2,05E-06	6,31E-08	1,16E-03	2,94E-05	1,08E-07	5,32E-08	4,26E-09	1,35E-06
Land use	species.yr	2,58E-06	1,06E-07	2,46E-08	5,23E-09	9,69E-10	2,66E-04	0,00E+00	0,00E+00	0,00E+00	1,46E-10	1,51E-08
Mineral resource scarcity	USD2013	9,23E+00	1,70E-01	4,06E-02	8,63E-03	9,24E-04	1,93E+02	2,94E-02	7,49E-03	3,70E-03	9,29E-05	1,13E-02
Fossil resource scarcity	USD2013	7,08E+02	1,34E+02	3,18E+01	6,76E+00	1,99E+00	1,99E+03	1,46E+02	2,02E+01	1,00E+01	2,50E-01	5,10E+00
Water consumption, Human health	DALY	1,32E-03	3,29E-04	7,78E-05	1,66E-05	2,37E-01	2,34E-04	4,39E-04	7,72E-06	3,82E-06	1,60E-02	3,46E-05
Water consumption, Terrestrial ecosystem	species.yr	8,05E-06	2,00E-06	4,73E-07	1,01E-07	1,44E-03	1,42E-06	2,67E-06	4,69E-08	2,32E-08	9,74E-05	2,10E-07
Water consumption, Aquatic ecosystems	species.yr	3,60E-10	8,94E-11	2,12E-11	4,50E-12	6,45E-08	6,37E-11	1,20E-10	2,10E-12	1,04E-12	4,36E-09	9,41E-12

Impact category	Unit	Plant pots	Perch food	Trout	Lettuce	Shelves	Rafts	DWC tanks	Water	Electricity	Heating
Global warming, Human health	DALY	5,50E-05	9,11E-03	3,80E-04	1,18E-03	1,52E-04	3,43E-05	7,59E-05	4,49E-05	1,26E-01	3,34E-02
Global warming, Terrestrial ecosystems	species.yr	1,66E-07	2,75E-05	1,15E-06	3,57E-06	4,58E-07	1,04E-07	2,29E-07	1,35E-07	3,81E-04	1,01E-04
Global warming, Freshwater ecosystems	species.yr	4,54E-12	7,51E-10	3,13E-11	9,75E-11	1,25E-11	2,83E-12	6,26E-12	3,70E-12	1,04E-08	2,76E-09
Stratospheric ozone depletion	DALY	3,28E-09	2,64E-05	1,49E-06	4,07E-07	7,33E-10	3,35E-09	2,49E-09	1,08E-08	4,85E-05	1,28E-05
Ionizing radiation	DALY	1,39E-08	1,65E-06	1,41E-07	1,24E-07	0,00E+00	8,94E-09	0,00E+00	7,05E-07	8,66E-04	2,29E-04
Ozone formation, Human health	DALY	9,86E-08	8,70E-05	1,64E-06	1,34E-06	6,96E-07	5,20E-08	1,69E-07	9,62E-08	2,06E-04	5,46E-05
Fine particulate matter formation	DALY	3,14E-05	3,54E-03	7,76E-05	1,10E-03	1,66E-04	1,13E-05	8,60E-05	2,56E-05	9,12E-02	2,41E-02
Ozone formation, Terrestrial ecosystems	species.yr	1,41E-08	1,25E-05	2,39E-07	1,96E-07	9,87E-08	7,79E-09	2,46E-08	1,40E-08	2,95E-05	7,81E-06
Terrestrial acidification	species.yr	4,65E-08	1,23E-05	3,27E-07	1,08E-06	2,66E-07	1,66E-08	1,12E-07	2,73E-08	5,48E-05	1,45E-05
Freshwater eutrophication	species.yr	9,38E-13	4,30E-08	2,93E-07	2,53E-07	5,00E-11	7,53E-11	0,00E+00	1,53E-09	1,31E-06	3,46E-07
Terrestrial ecotoxicity	species.yr	7,45E-11	2,79E-08	2,49E-09	1,94E-08	6,17E-09	6,80E-11	5,23E-11	1,82E-09	2,58E-06	6,82E-07
Freshwater ecotoxicity	species.yr	1,61E-12	1,93E-08	6,78E-11	9,77E-09	4,41E-11	1,19E-11	8,66E-11	9,17E-10	3,68E-07	9,75E-08
Marine ecotoxicity	species.yr	6,33E-13	4,06E-09	2,61E-11	2,11E-09	3,07E-11	5,81E-12	1,72E-11	2,01E-10	8,91E-08	2,36E-08
Human carcinogenic toxicity	DALY	3,18E-08	1,42E-05	5,33E-07	9,49E-05	4,88E-06	9,76E-08	7,74E-08	2,05E-05	3,99E-03	1,06E-03
Human non-carcinogenic toxicity	DALY	1,02E-07	3,16E-04	1,66E-06	1,10E-04	8,60E-06	1,01E-06	1,16E-06	9,51E-06	5,97E-03	1,58E-03
Land use	species.yr	2,62E-09	2,92E-05	1,63E-06	5,07E-07	7,96E-08	0,00E+00	0,00E+00	4,48E-08	4,08E-05	1,08E-05
Mineral resource scarcity	USD2013	1,90E-03	3,01E-01	2,48E-02	1,31E-01	2,22E+00	3,08E-03	0,00E+00	1,18E-01	3,67E+01	9,71E+00
Fossil resource scarcity	USD2013	4,73E+00	1,11E+03	3,66E+01	3,96E+01	1,14E+01	1,04E+01	9,04E+00	2,38E+00	5,80E+03	1,53E+03
Water consumption, Human health	DALY	3,84E-01	2,05E-03	1,69E-04	1,33E-05	4,28E-07	4,62E-05	0,00E+00	3,37E-03	2,41E+00	6,38E-01
Water consumption, Terrestrial ecosystem	species.yr	2,33E-03	1,25E-05	1,03E-06	8,11E-08	2,61E-09	2,81E-07	0,00E+00	2,05E-05	1,47E-02	3,88E-03
Water consumption, Aquatic ecosystems	species.yr	1,04E-07	5,59E-10	4,59E-11	3,63E-12	1,17E-13	1,26E-11	0,00E+00	9,16E-10	6,56E-07	1,74E-07

Table 11: Characterization by assembly groups.

Impact category	Unit	Heating	Perch food	Equipment	Electricity	Total	Heating (%)	Perch food (%)	Equipment(%)	Electricity(%)
Global warming, Human health	DALY	3,34E-02	9,11E-03	1,77E-01	1,26E-01	3,46E-01	9,65724062	2,63033785	51,2150242	36,4973973
Global warming, Terrestrial ecosystems	species.yr	1,01E-04	2,75E-05	5,35E-04	3,81E-04	1,04E-03	9,65836375	2,62936679	51,2106256	36,5016439
Global warming, Freshwater ecosystems	species.yr	2,76E-09	7,51E-10	1,46E-08	1,04E-08	2,85E-08	9,65680663	2,6299242	51,2175116	36,4957576
Stratospheric ozone depletion	DALY	1,28E-05	2,64E-05	6,33E-05	4,85E-05	1,51E-04	8,49415873	17,4707191	41,9334647	32,1016574
Ionizing radiation	DALY	2,29E-04	1,65E-06	4,21E-06	8,66E-04	1,10E-03	20,8126017	0,15021275	0,38262562	78,6545599
Ozone formation, Human health	DALY	5,46E-05	8,70E-05	2,01E-04	2,06E-04	5,49E-04	9,94013786	15,8481692	36,6455837	37,5661092
Fine particulate matter formation	DALY	2,41E-02	3,54E-03	5,29E-02	9,12E-02	1,72E-01	14,0448602	2,06264288	30,8134579	53,079039
Ozone formation, Terrestrial ecosystems	species.yr	7,81E-06	1,25E-05	2,91E-05	2,95E-05	7,89E-05	9,89716003	15,8062136	36,8929387	37,4036877
Terrestrial acidification	species.yr	1,45E-05	1,23E-05	7,27E-05	5,48E-05	1,54E-04	9,40151231	7,95435614	47,1135471	35,5305844
Freshwater eutrophication	species.yr	3,46E-07	4,30E-08	6,73E-06	1,31E-06	8,43E-06	4,11026493	0,5104856	79,8457384	15,5335111
Terrestrial ecotoxicity	species.yr	6,82E-07	2,79E-08	1,15E-06	2,58E-06	4,44E-06	15,380036	0,6277729	25,8668152	58,1253759
Freshwater ecotoxicity	species.yr	9,75E-08	1,93E-08	3,67E-05	3,68E-07	3,72E-05	0,2622741	0,05196893	98,6945591	0,99119785
Marine ecotoxicity	species.yr	2,36E-08	4,06E-09	7,24E-06	8,91E-08	7,36E-06	0,32036246	0,05513167	98,413778	1,21072792
Human carcinogenic toxicity	DALY	1,06E-03	1,42E-05	2,24E-02	3,99E-03	2,74E-02	3,85204076	0,05185687	81,5381717	14,5579307
Human non-carcinogenic toxicity	DALY	1,58E-03	3,16E-04	2,13E-01	5,97E-03	2,21E-01	0,71577853	0,14304127	96,4360877	2,70509253
Land use	species.yr	1,08E-05	2,92E-05	2,69E-04	4,08E-05	3,50E-04	3,09052028	8,35654873	76,873062	11,679869
Mineral resource scarcity	USD2013	9,71E+00	3,01E-01	2,04E+02	3,67E+01	2,51E+02	3,87086427	0,1200739	81,3801335	14,6289283
Fossil resource scarcity	USD2013	1,53E+03	1,11E+03	3,09E+03	5,80E+03	1,15E+04	13,3009783	9,64496537	26,7862811	50,2677752
Water consumption, Human health	DALY	6,38E-01	2,05E-03	6,39E-01	2,41E+00	3,69E+00	17,2889233	0,05559027	17,3170309	65,3384555
Water consumption, Terrestrial ecosystem	species.yr	3,88E-03	1,25E-05	3,89E-03	1,47E-02	2,25E-02	17,2889238	0,05559027	17,3170311	65,3384548
Water consumption, Aquatic ecosystems	species.yr	1,74E-07	5,59E-10	1,74E-07	6,56E-07	1,00E-06	17,2889232	0,05559027	17,3170313	65,3384552

Table 12: Damage assessment by assembly group.

Damages	Unit	Heating	Perch food	Equipment	Electricity	Total	Heating	Perch food	Equipment	Electricity
Human health	DALY	6,99E-01	1,52E-02	1,11E+00	2,64E+00	4,46E+00	15,6685376	0,33965114	24,777056	59,2147553
Ecosystems	species.yr	4,02E-03	9,40E-05	4,85E-03	1,52E-02	2,41E-02	16,6421462	0,38940844	20,074264	62,8941813
Resources	USD2013	1,54E+03	1,11E+03	3,29E+03	5,84E+03	1,18E+04	13,1002184	9,44218768	27,9485426	49,5090513

Table 13: Characterization comparison with and without shipping container.

Impact category	Unit	Total (including)	Total (excluding)	Difference	Difference (%)
Global warming, Human health	DALY	1,77E-01	1,00E-01	0,07736301	43,6171348
Global warming, Terrestrial ecosystems	species.yr	5,35E-04	3,02E-04	0,00023342	43,6188715
Global warming, Freshwater ecosystems	species.yr	1,46E-08	8,24E-09	6,3772E-09	43,618287
Stratospheric ozone depletion	DALY	6,33E-05	5,78E-05	5,5739E-06	8,80192373
Ionizing radiation	DALY	4,21E-06	2,01E-06	2,2012E-06	52,2672611
Ozone formation, Human health	DALY	2,01E-04	8,02E-05	0,00012101	60,1295854
Fine particulate matter formation	DALY	5,29E-02	6,40E-03	0,04654643	87,9091129
Ozone formation, Terrestrial ecosystems	species.yr	2,91E-05	1,14E-05	1,7688E-05	60,75211
Terrestrial acidification	species.yr	7,27E-05	1,15E-05	6,1156E-05	84,1506085
Freshwater eutrophication	species.yr	6,73E-06	4,93E-06	1,7975E-06	26,7112382
Terrestrial ecotoxicity	species.yr	1,15E-06	7,79E-07	3,6877E-07	32,1342784
Freshwater ecotoxicity	species.yr	3,67E-05	3,67E-05	2,7089E-08	0,07385275
Marine ecotoxicity	species.yr	7,24E-06	7,23E-06	9,9486E-09	0,13733314
Human carcinogenic toxicity	DALY	2,24E-02	2,06E-02	0,00175214	7,83872306
Human non-carcinogenic toxicity	DALY	2,13E-01	2,12E-01	0,00116008	0,54499397
Land use	species.yr	2,69E-04	2,81E-06	0,00026594	98,9534873
Mineral resource scarcity	USD2013	2,04E+02	1,17E+01	192,52147	94,2600463
Fossil resource scarcity	USD2013	3,09E+03	1,10E+03	1990,5259	64,4062537
Water consumption, Human health	DALY	6,39E-01	6,39E-01	0,00023429	0,03663673
Water consumption, Terrestrial ecosystem	species.yr	3,89E-03	3,89E-03	1,4247E-06	0,03663673
Water consumption, Aquatic ecosystems	species.yr	1,74E-07	1,74E-07	6,3743E-11	0,03663673

Table 14: Characterization by assembly groups without shipping container.

Impact category	Unit	Heating	Perch food	Equipment	Electricity	Total	Heating (%)	Perch food (%)	Equipment(%)	Electricity(%)
Global warming, Human health	DALY	8,92E-02	3,34E-02	1,26E-01	9,11E-03	2,58E-01	34,54148962	12,95785383	48,97133232	3,529324233
Global warming, Terrestrial ecosystems	species.yr	2,69E-04	1,01E-04	3,81E-04	2,75E-05	7,79E-04	34,5368121	12,95911843	48,97611417	3,527955301
Global warming, Freshwater ecosystems	species.yr	7,35E-09	2,76E-09	1,04E-08	7,51E-10	2,13E-08	34,54327284	12,95757919	48,97029496	3,528852999
Stratospheric ozone depletion	DALY	5,14E-05	1,28E-05	4,85E-05	2,64E-05	1,39E-04	36,93681756	9,225084282	34,86401706	18,97408109
Ionizing radiation	DALY	1,83E-06	2,29E-04	8,66E-04	1,65E-06	1,10E-03	0,166867642	20,85767903	78,82491524	0,150538087
Ozone formation, Human health	DALY	7,26E-05	5,46E-05	2,06E-04	8,70E-05	4,21E-04	17,27184729	12,97982511	49,05379931	20,69452829
Fine particulate matter formation	DALY	5,90E-03	2,41E-02	9,12E-02	3,54E-03	1,25E-01	4,725375999	19,34073783	73,09348515	2,840401021
Ozone formation, Terrestrial ecosystems	species.yr	1,03E-05	7,81E-06	2,95E-05	1,25E-05	6,01E-05	17,19976474	12,9856652	49,07587336	20,7386967
Terrestrial acidification	species.yr	1,05E-05	1,45E-05	5,48E-05	1,23E-05	9,21E-05	11,44898934	15,74152494	59,49102254	13,31846318
Freshwater eutrophication	species.yr	4,39E-06	3,46E-07	1,31E-06	4,30E-08	6,09E-06	72,12085458	5,685679579	21,48731732	0,70614853
Terrestrial ecotoxicity	species.yr	6,94E-07	6,82E-07	2,58E-06	2,79E-08	3,98E-06	17,42562835	17,13128622	64,74383106	0,699254366
Freshwater ecotoxicity	species.yr	3,26E-05	9,75E-08	3,68E-07	1,93E-08	3,31E-05	98,53293865	0,294745013	1,113913379	0,058402962
Marine ecotoxicity	species.yr	6,43E-06	2,36E-08	8,91E-08	4,06E-09	6,55E-06	98,2169131	0,360122404	1,360990474	0,061974021
Human carcinogenic toxicity	DALY	1,84E-02	1,06E-03	3,99E-03	1,42E-05	2,34E-02	78,38740582	4,509444695	17,04244253	0,060706958
Human non-carcinogenic toxicity	DALY	1,88E-01	1,58E-03	5,97E-03	3,16E-04	1,96E-01	95,98807249	0,805758195	3,045146493	0,161022818
Land use	species.yr	2,53E-06	1,08E-05	4,08E-05	2,92E-05	8,34E-05	3,029947113	12,95839139	48,97308565	35,03857585
Mineral resource scarcity	USD2013	1,07E+01	9,71E+00	3,67E+01	3,01E-01	5,74E+01	18,62954049	16,91601831	63,92970766	0,52473353
Fossil resource scarcity	USD2013	1,02E+03	1,53E+03	5,80E+03	1,11E+03	9,47E+03	10,78720006	16,20758423	61,25257728	11,75263842
Water consumption, Human health	DALY	6,39E-01	6,38E-01	2,41E+00	2,05E-03	3,69E+00	17,30849393	17,29070838	65,34520168	0,055596012
Water consumption, Terrestrial ecosystem	species.yr	3,89E-03	3,88E-03	1,47E-02	1,25E-05	2,25E-02	17,30849417	17,29070887	65,34520094	0,055596014
Water consumption, Aquatic ecosystems	species.yr	1,74E-07	1,74E-07	6,56E-07	5,59E-10	1,00E-06	17,30849439	17,29070826	65,34520133	0,055596013

Table 15: Damage assessment by assembly group without shipping container.

Damages	Unit	Heating	Perch food	Equipment	Electricity	Total	Heating	Perch food	Equipment	Electricity
Human health	DALY	9,41E-01	6,99E-01	2,64E+00	1,52E-02	4,30E+00	21,89812173	16,26820421	61,48102379	0,352650272
Ecosystems	species.yr	4,22E-03	4,02E-03	1,52E-02	9,40E-05	2,35E-02	17,95610953	17,08318861	64,5609735	0,399728364
Resources	USD2013	1,03E+03	1,54E+03	5,84E+03	1,11E+03	9,53E+03	10,83447922	16,21185517	61,26871691	11,68494869