Treball de Fi de Grau

Grau en Enginyeria en Tecnologies Industrials

Analysis of the environmental impact of an agricultural robot for data capture and comparison with the alternative of using fixed sensors

MEMÒRIA

Autor: Guillem Haro Peña
Director: David Caballero Flores
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ETSEIB

Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona

Resum

El treball ha estat dissenyat per comparar l'impacte ambiental que tenen un robot agrícola autònom i el seu equivalent amb sensors fixes, intentant demostrar que l'alternativa del robot és més viable a nivell ambiental.

Amb un primer pas de recerca d'informació sobre la situació actual, la informació proporcionada per l'equip del CDEI sobre el robot i buscant informació addicional sobre sensors fixes i les seves característiques, s'han elaborat dos Anàlisis del Cicle de Vida amb el software obert OpenLCA, un pel robot i l'altre pels sensors. Aquests dos resultats s'ha comparat mitjançant gràfics per veure si la implementació del robot és ambientalment viable o no.

Finalment, s'ha conclòs que la solució proposada del robot agrícola autònom és millor enfront dels sensors fixes, recomanant l'ús daquests en projectes similars.

Resumen

El trabajo ha sido diseñado para comparar el impacto ambiental que tienen un robot agrícola autónomo y su equivalente con sensores fijos, intentando demostrar que la alternativa del robot es más viable a nivel ambiental.

Con un primer paso de investigación sobre la situación actual, la información proporcionada por el equipo del CDEI sobre el robot y buscando información adicional sobre sensores fijos y sus características, se han elaborado dos Análisis del Ciclo de Vida con el software abierto OpenLCA, uno para el robot y el otro para los sensores. Estos dos resultados se han comparado mediante gráficos para ver si la implementación del robot es ambientalmente viable o no.

Finalmente, se ha concluido que la solución propuesta del robot agrícola autónomo es mejor enfrente de los sensores fijos, recomendando el uso de este en proyectos similares.

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Abstract

The project has been designed to compare the environmental impact of an autonomous agricultural robot and its equivalent with fixed sensors, aiming to demonstrate that the robot alternative is more environmentally viable.

With an initial research step on the current situation, information provided by the CDEI team about the robot, and seeking additional information about fixed sensors and their characteristics, two Life Cycle Analysis have been developed using the open-source software OpenLCA, one for the robot and the other for the sensors. These two results have been compared using graphics to prove if the implementation of the robot is environmentally viable or not.

Finally, it has been concluded that the proposed solution of the autonomous agricultural robot is better compared to the alternative of fixed sensors, recommending its use in similar projects.

Summary

Glossary

- *AMR:* Autonomous Mobile Robot.
- *CFC:* Chlorofluorocarbonus gases.
- *EF:* Environmental Footprint database.
- *EPA:* United States Environmental Protection Agency.
- *LCA:* Life Cycle Analysis.
- *NDVI:* Landsat Normalized Difference Vegetation Index.
- *NMVOC:* Non Metanous Volatile Organic Compounds.
- *OEF*: Organization Environmental Footprint methods.
- *OpenLCA:* open software for Life Cycle Analysis.
- *PA:* Precission Agriculture.
- *PEF*: Product Environmental Footprint.
- *SETAC:* Society of Environmental Toxicology and Chemistry.
- *WSN:* Wireless Sensor Network.

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1. Preface

1.1. Project origin

Robotics in the industrial field is highly developed, but in agriculture, it is still an emerging market. Many agricultural robots are being developed, and there is a trend towards modernization and an increasing need to automate many tasks in this sector.

This project began on the need of finding new solutions to the environmental problems at the agricultural fields. It is needed to find new alternatives that have lower energy consumption and less polluting products emissions. These are some of the objectives of Symbiosyst project, which the Industrial Equipment Design Centre (CDEI, Centre de Disseny d'Equips Industrials) is developing an autonomous agricultural robot for this bigger project.

In this attempt to find an alternative to the current procedures to monitor data, this project will try to find if an agricultural robot is a better solution than the use of fixed sensors.

1.2. Motivation

The motivation on doing this project is the necessity of knowing and developing better possible eco-friendly alternatives to the classic solutions on the agricultural fields to control all the data that affects them, like soil moisture or its temperature.

It is well known that nowadays that environmental situation is getting worse, so we must invest on new proposals to reduce the impact that most of the agricultural activities have on the environment.

Currently, 71% of farmers identified data management as a major challenge in precision agriculture, which includes handling data form fixed sensors, according to a survey conducted by the American Society of Agronomy. Also, according to a survey by Purdue University, initial costs associated with purchasing and installing sensors, data management systems, and connectivity infrastructure were identified as barrier to adoption by farmers.

So, demonstrating that developing an autonomous robot is more environmentally efficient and more convenience than a fixed sensors network on agricultural fields is the main goal of this project and its biggest challenge.

2. Introduction

2.1. Project objectives

The basic purpose in this project is to study the environmental impact that an agricultural autonomous robot has and compare it to the impact that has a fixed sensors network in the same field. In order to do that, this project will analyse which solution has a better environmental impact.

Other specific objectives can be distinguished in this project:

- Another is to be aware of that there are many solutions to the same problem, and that all of them have benefits and disadvantages.
- The last is to identify the variables that most affect the solutions and try to minimize those, in order to find the variables that affect the most to the results.

2.2. Scope of the project

This project tries to demonstrate if an agricultural robot is capable of monitor and capture agricultural data more effectively than fixed sensors placed all over the field.

To answer this question, an open software to analyse the life cycle will be used, in order to quantify the impact of these solutions and to be able to compare and decide which one is better.

The design of the robot and the fixed sensors it is not on the scope on the project, but it will be explained because it results in necessary data for the calculations.

The robot's information will be provided by CDEI, including all the robot materials, sensors, and specifications. Fixed sensors information is limited. Due to this lack of information, the analysis of the environmental impact for the sensors will be an approximation, trying to find a way to do it as accurately as possible.

It will only be studied one case specifically, which in this case is a vineyard, that will be explained further in the Practical Framework section. Maybe in other types of agricultural fields, such as greenhouses or corn fields, the robot has not the same benefits, and to introduce fixed sensors is the best option. Also, the results depend on the field size, because in a bigger field the robot may not be as useful and efficient as sensors, or it is needed two robots to have the same impact as sensors. In this particular case, it is going to try to demonstrate that the robot is a better option than fixed sensors.

2.3. Symbiosyst

Symbiosyst is an agricultural European project which investigates innovative systems to try to go beyond the idea of solar energy production and agriculture as two different sectors, finding a new synergy where the fields and photovoltaics have a mutually beneficial relationship. [1]

Figure 1: Symbiosyst logo. Source: [2]

This project has emerged from the need to achieve net zero emissions by 2050, as a goal set by the EU. The activity is centred around the agrovoltaic initiative, denominated agri-PV, consisting of the double use of the soil for agricultural purposes and solar energy generation. To achieve this, a great technification is required in the agricultural sector. It will also promote the production of low-carbon and low-water footprint foods, as well as high-value-added products linked to the territory. [2]

There are so many objectives in this project [1]:

- Demonstrating the feasibility of agri-PV and social acceptance.
- Limiting the impact of PV on crop yield.
- Digitalizing farming tools.
- Improving systems for water supply and mitigation of climate change impact.
- Conducting sustainable agriculture.
- Involving local organizations.

- Enhancing biodiversity.

To make this happen, different organizations are researching multiple solutions. One of those is the proposed by the Centre de Disseny d'Equips Industrials (CDEI). CDEI will develop an agricultural robot, capable of omnidirectional movements and equipped with multiple sensors, which will send real-time data to a decision-making system. This data will allow to adjust some variables, like adjusting the angle of the solar panels to optimize the energy generation. This solution will represent a lower ambient impact based on only one robot instead of installing a network of sensors all over the field. [2]

Figure 2: example of a greenhouse where a robot can be working. Source: [2]

The comparison of these two solutions will represent the "Practical Framework" in this Final Degree Project, trying to demonstrate that the robot is a better alternative than the sensors.

3. State of Art

In the ever-evolving landscape of agriculture, where technology continues to revolutionize the way we cultivate crops, a new era of innovation has emerged with the advent of agricultural autonomous robots (AMR). AMRs have the potential to tackle numerous challenges faced by farmers, ranging from labour shortages to precision farming requirements.

In this section, it will be necessary to provide context on the data collection methods currently available, with special emphasis on sensors used in agriculture and AMRs.

3.1. Agriculture Sensors

There are plenty of different sensors in the industry that measure multiple variables. Most of them are used in Precision Agriculture to know if the values of these variables are the appropriate ones.

These sensors can be portable, fixed on the field or even attached to vehicles or machinery, like tractors. They are also installed on satellites and drones.

It is important to mention some of their utilities, such as measuring the moisture of the soil, measuring the ambient temperature, air quality and so much more.

There are so many benefits in the usage of this type of technology in the agricultural industry. One could be that sensors send alerts to the farmers when a measurement reaches a pre-set value, something that enables rapid responses and actions. Another example is that the agricultural industry is responsible for 70% of global freshwater usage. This could be reduced by using these sensors and managing the time to irrigate the plants, doing it only when it is necessary, optimizing the waste of water.

Even though sensors make a great impact on agriculture, there are some disadvantages when using them: this method requires continuous internet connection, something that is not available in all places, like developing countries. Also, a basic infrastructure is needed, such as smart grids, traffic systems and cellular towers. [3]

3.2. Agricultural Robots

The use of robots in agriculture can improve both productivity and working conditions for farmers. Also, can increase the environmental sustainability of their fields. [4]

In one hand, there are a lot of advantages using robots. For example, they are usually capable of spraying pesticides and other chemical products only on the plants that need them, instead of wasting these products spreading them all over the field and contaminating the ground and water near them. With sensors' help, they can also identify crop conditions, inform the farmer, and reduce production losses.

On the other hand, there is one principal inconvenience, which is positioning the robot. It requires lots of effort trying to program the machinery on the field to work autonomously. It is very difficult to identify for the robot itself and where it is going. The *Figure 3* shows a little about this problematic.

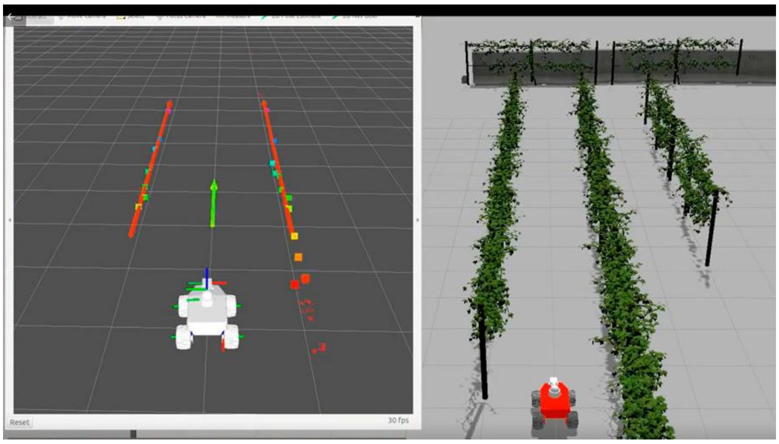

Figure 3: robot trying to position itself on the field. Source [4]

3.3. Current situation

First of all, it is needed to know which is the current situation and to know why this project is for.

Conventional agriculture systems are being replaced or reinforced with new methods due to technological development. There are lot of innovative ways to extract data from agricultural fields, some of them are going to be described in the next sections:

3.3.1. Monitoring with satellites

This type of data obtention is used mostly for tracking process and spotting problems in the fields before symptoms appear, securing a successful harvest. This technology allows to capture images of the fields from the satellites that are around the world in a simple way, which makes it an affordable and useful. [5]

In addition, some businesses had created an app for mobile, like Agrio, which you can install it in your device, select on a map the area where your field is, and periodic images will be sent to you. These images will show the status of the field, displaying some variety of colours which indicate the areas that require more attention and other that are just good. An example of this is shown in the *Figure 4*:

Figure 4: Examples of some satellite's images. Source: [5]

One of the problems with this way of data controlling is that the resolution and precision of the images is quite bad (as shown in the image above), due to the large gap between the surface of the Earth and the satellites.

Another one is that these free applications do not offer a lot of services and you must pay a monthly fee to have access to those premium services, which do not solve the problematic of having low quality images.

3.3.2. Drone tracking

This method has a lot of similarities with the previous one. The only difference is that the images of the field are taken with a drone that flies above the field. These images are sent to a mobile app (Cloud or Edge server, typically) where all the rest of the information can be found. [6]

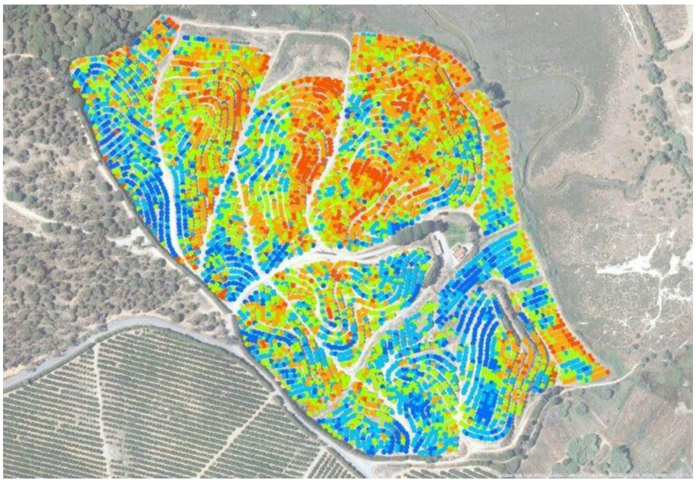

Figure 5: Example of images taken with a drone. Source: [6]

The issues of using this technology are very much alike to those seen for the monitoring with satellites. A high-resolution camera installed on the drone is needed, as well as paying a subscription to the app for the premium services.

3.3.3. Pivot irrigation

It is an autonomous farming technology which, via some cameras installed on watering machines (see *Figure 6*), can control the situation of the plants all over the field. These cameras send images to the server, where it is processed, and then are sent to the farmer's computer or smartphone, who can check the plantation and decide what to do in any moment. [7]

Figure 6: irrigation machines. Source [7]

These machines can pivot around a point by drawing a circle to cover the whole field and irrigate the areas that need water.

3.3.4. Manual data collection

This is the most time-consuming and labour-intensive process. It involves individuals physically visiting the fields to record information such as crop health, yield estimates, pest and disease observations, soil conditions, and other relevant data points. This method is prone to human error, inconsistencies, and delays in data processing and analysis. [8]

However, manual data collection does have some advantages. It allows for direct observation and assessment of the field condition, enabling farmers to make real-time decisions based on their firsthand observations. It also provides an opportunity for farmers to have a deeper understanding of their crops and engage in hands-on management.

Nevertheless, advancements in technology have led to the emergence of more efficient and accurate alternative to manual data collection in agriculture. Remote sensing technologies can collect large-scale data quickly and provide valuable insights into crop health and field conditions. Additionally, sensor-based systems installed directly in the fields can continuously monitor various parameters, such as temperature, humidity, and soil moisture.

4. Methodology

In this section, the tools used to obtain the results in this project are going to be explained, focusing on the Life Cycle Analysis and the software used to perform it, OpenLCA.

4.1. Life Cycle Analysis

A Life Cycle Analysis (LCA) is a methodology used to assess the environmental impacts of a product or service throughout its entire life cycle, from raw material extraction and manufacturing to distribution, use, and disposal. The purpose of an LCA is to identify and evaluate the potential environmental burdens and impacts associated with a product or service, including its consumption of energy and resources, emissions of pollutants and greenhouse gases, and generation of waste.

Other possible definitions to LCA can be the ones provided by [9]:

- ISO 14040: “Consecutive and interrelated stages of a product system, from the acquisition of raw materials or generation from natural resources to final disposal”.
- National Risk Management Research Laboratory of the EPA: "LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by:
    - Compiling an inventory of relevant energy and material inputs and environmental releases.
    - Evaluating the potential environmental impacts associated with identified inputs and releases.
    - Interpreting the results to help you make a more informed decision".
- UNE 150-040-96: "Life Cycle Assessment is a collection and evaluation of the inputs and outputs of matter and energy, and the potential environmental impacts directly attributable to the function of the product system throughout its life cycle.”

Secondly, here are listed the four stages that an LCA typically involves [9]:

1. Goal and scope definition, where the purpose and boundaries of the analysis are established.

2. Inventory analysis, where data is collected on the inputs and outputs associated with each stage of the life cycle.

3. Impact assessment, where the environmental impacts of the product or service are quantified and characterized based on the inventory data.

4. Interpretation, where the results of the analysis are evaluated and communicated to stakeholders.

Finally, LCA can be used to compare the environmental performance of different products or services, identify opportunities for environmental improvement, and inform decision-making in product development, procurement, and policymaking.

4.2. OpenLCA

OpenLCA is an open-source, free and professional software tool for Life Cycle Analysis. LCA is a methodology used to evaluate the environmental impacts of a product or service throughout its entire life cycle, from the extraction of raw materials to the disposal of waste. [9]

OpenLCA allows users to model and analyse life cycle inventories, impact assessment methods, and scenarios. The software provides a user-friendly interface for creating and managing LCA projects, defining inventory flows, running impact assessments, and generating reports.

Firstly, a flow must be created, indicating the number of materials that are needed of each substance. Secondly, processes must be created which connect the inputs and outputs of the flows, creating a system. Finally, a product is created, and by means of the software, calculations to determine the impact of each flow an element on the environment.

Figure 7: LCA photo

Thereafter, the elements that conform to OpenLCA and which are needed to make the studies will be explained.

4.2.1. Databases

A database is a structured collection of data that is usually stored in an informatic system and organized in a way that allows for easy retrieval, modification, and management of information. Databases are developed by public and private institutions. [9]

In the case of LCAs, databases are fed with information about the practices of exploiting raw materials, construction product systems, agriculture, electronics, among others. To be able to perform the analysis, databases must be accompanied by impact categories, which will be presented later.

In OpenLCA portal, named Nexus, offers access to different databases, some of which are free, and everyone can download it. Of this range of possibilities, there are some that collect information from a single country, others that only cover a small region, and others that have a more continental scope. It is only going to be explained the one used for this project, the Environmental Footprint (EF) database.

Environmental Footprint Database

The EF database contains data on the environmental impacts of a wide range of products and services, including food, construction materials, clothing, and transportation. It includes the following data [9]:

- Agricultural products.

- End-of-life treatment: energy and material recycling, landfill disposal, renewable fuels, and wastewater treatment.
- Materials production: agricultural production, glass and ceramics, inorganic and organic chemicals, metals and semimetals, plastics, water, wood, renewable food and raw materials, paper and cardboard and other mineral materials.
- Systems: Construction, packaging, electrical and electronic, non-specific parts.
- Transport services: by air, train, ship, and road vehicles.

The database provides all this data to make an analysis on factors such as greenhouse gas emissions, water use, land use, and resource depletion, and is designed to be used in conjunction with the Product Environmental Footprint (PEF) and Organization Environmental Footprint (OEF) methods.

One of the key features of the EF database is that it is based on a common framework and set of rules, which ensures consistency and comparability across different product categories and regions within the EU. It also incorporates a wide range of data sources, including industry-specific databases, national inventories, and scientific studies. [9]

The database is constantly evolving and being updated as new data becomes available and as the methodology for environmental footprinting is refined.

Overall, the EF database is an important resource for companies, governments, and other stakeholders who want to understand the environmental impacts of their products and services and make informed decisions about how to reduce their environmental footprint.

4.2.2. Impact categories

Impact categories are used to quantify and evaluate the potential environmental, social, and economic impacts associated with a product, process, or service over its entire life cycle. [9]

An impact category is a broad and standardized environmental or social issue that is used to organize and quantify the potential impacts of a product or process. Examples of impact categories include climate change, human toxicity, ozone depletion, water use, land use, and biodiversity.

The selection of impact categories depends on the goal and scope of the LCA study, as well as the stakeholders' interests and concerns. Impact categories are typically chosen based on their relevance to the product or process being assessed, their potential significance, and the availability of reliable data and methods to assess them.

Once the impact categories are selected, the LCA practitioner uses a variety of models, data, and tools to quantify the potential impacts in each category. The results are then aggregated and interpreted to provide insights and recommendations for improving the environmental and social performance of the product or process. [9]

In summary, impact categories are an essential aspect of LCA and provide a structured framework for evaluating the potential impacts of a product or process on the environment and society.

The main impact categories which are going to be used are resumed in the table below, commonly used and defined by the Society of Environmental Toxicology and Chemicals (SETAC):

Table 1: Environmental Impact Categories. Source: [10]

Categories of Environmental Impact		Reference Units	Characterization Factor
Global Warming	The phenomenon observed in temperature measurements that shows an average increase in the temperature of the Earth's atmosphere and oceans in recent decades.	Kg. Eq. CO_2	Global Warming Potential (GWP)
Energy resource consumption	Energy consumed in the extraction of raw materials, manufacturing, distribution, use, and end-of-life of the analysed element.	MJ	Quantity consumed
Ozone layer depletion	Negative effects on the ability to protect against solar ultraviolet radiation of the atmospheric ozone layer.	Kg. Eq. CFC-11	Ozone Depletion Potential (ODP)
Eutrophication	Excessive growth of the algae population caused by the artificial enrichment of river and reservoir waters as a result of the massive use of fertilizers and detergents, which causes high consumption of oxygen in the water.	Kg. Eq. N	Eutrophication Potential (EP)
Acidification	Loss of the neutralizing capacity of soil and water as a result of the return to the earth's surface, in the form of acids, of sulphur and nitrogen oxides discharged into the atmosphere.	Mol H+ Eq.	Acidification Potential (AP)
Material consumption	Consumption of materials extracted from nature. Specifically, minerals and metals.	Kg. Eq. Sb	Quantity consumed
Formation of photochemic	Formation of precursors that lead to photochemical pollution. Sunlight hits these precursors, causing the	Kg. NMVOC Eq.	Photochemical Ozone Creation Potential

al ozone	formation of a series of compounds known as photochemical oxidants (e.g., Ozone-O3).		(POCP)

4.2.3. Impact Assessment Methods

Impact assessment methods are used to convert the inventory data into meaningful impact indicators that represent the potential environmental or social impacts associated with a product or process. [9]

There are various impact assessment methods available, and the choice of method depends on the goal and scope of the LCA study, as well as the availability of data and the preferences of the stakeholders. Some commonly used impact assessment methods include [9]:

- ReCiPe: This is a widely used impact assessment method that uses the midpoint and endpoint approaches to assess the potential impacts in different impact categories. The midpoint approach quantifies the potential environmental impacts of a product or process in terms of intermediate environmental indicators, while the endpoint approach translates the intermediate indicators into endpoint impact categories such as human health, ecosystem quality, and resource depletion.

- CML: This is another commonly used impact assessment method that uses the midpoint approach to assess the potential environmental impacts in different categories, such as climate change, acidification, and eutrophication.

- Eco-Indicator 99: This method combines the midpoint and endpoint approaches to assess the potential environmental impacts in different categories, such as human health, ecosystem quality, and resources.

- Social LCA: This method assesses the potential social impacts of a product or process, such as human rights, labour practices, and community well-being.

The choice of impact assessment method can significantly affect the LCA results, and it is important to select a method that is appropriate for the study's goal and scope. The LCA practitioner must also ensure that the data used in the assessment are accurate and representative, and that the methods used to convert the inventory data into impact indicators are scientifically valid and transparent.

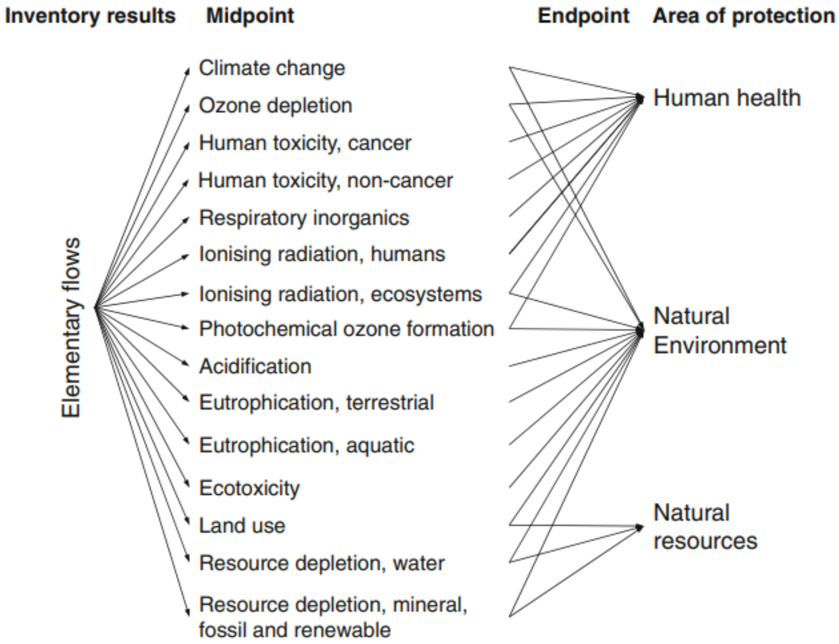

Figure 8: Framework of the impact analysis structure. Source: [11]

Midpoint

The midpoint approach used in impact assessment methods quantifies the potential environmental impacts of a product or process in terms of intermediate environmental indicators such as emissions to air, water, and land; consumption of resources; and generation of waste. These indicators are selected based on their relevance to the product or process being assessed and are typically expressed in physical units such as kilograms of pollutants or cubic meters of water. [9]

Endpoint

The endpoint approach used in impact assessment methods translates the intermediate environmental indicators into endpoint impact categories that are easier to understand and compare, such as human health, ecosystem quality, and resource depletion. These impact categories are selected based on their relevance to the stakeholders' concerns and interests and are typically expressed in units such as disability-adjusted life years, species loss, or fossil fuel equivalents. [9]

Comparison

The difference between the midpoint and endpoint approaches is that the midpoint approach focuses on the direct and measurable environmental or social indicators, while the endpoint approach considers the indirect and less tangible impacts that may be more relevant to the stakeholders. The midpoint approach is more suitable for technical experts who are interested in understanding the underlying environmental mechanisms, while the endpoint approach is more suitable for decision-makers and stakeholders who are interested in the overall impact on human health, ecosystem quality, or resource availability.

To sum it up, the midpoint and endpoint approaches are complementary and are used to provide a comprehensive assessment of the potential environmental or social impacts associated with a product or process. The choice of approach depends on the goal and scope of the LCA study, as well as the preferences of the stakeholders.

4.2.4. System limits

The LCA are usually studies “from the cradle to grave”. This means that it is analysed the life of the product since the raw materials are collected up to when the whole product is recycled or thrown away. There are also several limitations that should be considered [9]:

1. Data availability and quality: LCA relies heavily on accurate and reliable data throughout the life cycle stages of a product or process. However, obtaining comprehensive and high-quality data can be challenging, especially for emerging technologies or complex supply chains. Limited data availability can lead to uncertainties and assumptions in the assessment.

2. System boundaries: Defining the boundaries of the LCA system is a crucial step. Decisions need to be made regarding which processes or inputs to include or exclude. This boundary setting can be subjective and impact the results and comparability of different LCAs.

3. Simplified models and assumptions: LCA often involve using simplified models and assumptions to estimate impacts. These simplifications can be necessary due to data limitations, or the complexity of the system being assessed, but they may introduce uncertainties and limitations in the results.

4. Interpretation and weighting: LCA involve assessing multiple environmental impact categories, such as climate change, resource depletion, and toxicity. Assigning relative importance or weighting to these impact categories is subjective and can vary based on stakeholder perspectives. Different weighting methods can lead to varying conclusions and interpretations.

5. Scope and boundaries of analysis: LCA generally focuses on environmental impacts but may not consider other important factors such as social or economic aspects. Additionally, it may be challenging to capture indirect or downstream impacts associated with the product or process being assessed.

These limitations can also be classified this way [10]:

- “From Cradle to Gate”: Partial product life cycle, including resource extraction, material transformation, entry into manufacturing, and exiting the manufacturing plant.
- “From Gate to Gate": When only the inputs/outputs of the manufacturing system (manufacturing processes) are considered.
- “From Cradle to Grave": Total product life cycle, including the extraction of raw materials, processing of necessary materials for component and product production, transportation, storage and distribution, product use, and finally, recycling and/or waste disposal (end of life).
- “From Cradle to Cradle": It is acknowledged that the outputs from waste disposal in the system can be considered as raw materials and/or inputs for the same or another system.

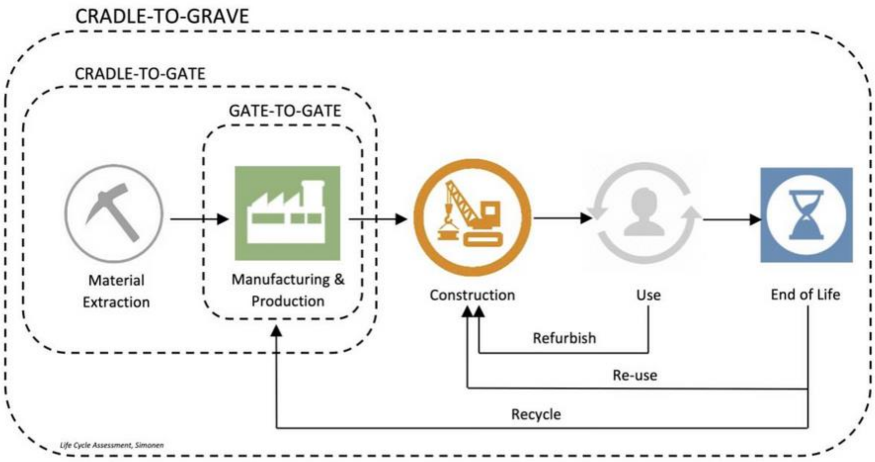

Figure 9: Sketch of system’s limitations. Source: [12]

4.3. Case of study

A possible solution to the problem explained in previous sections is the one that is going to be the object of the study and the one that will be dealt with more extensively in this project: an Autonomous Mobile Robot (AMR).

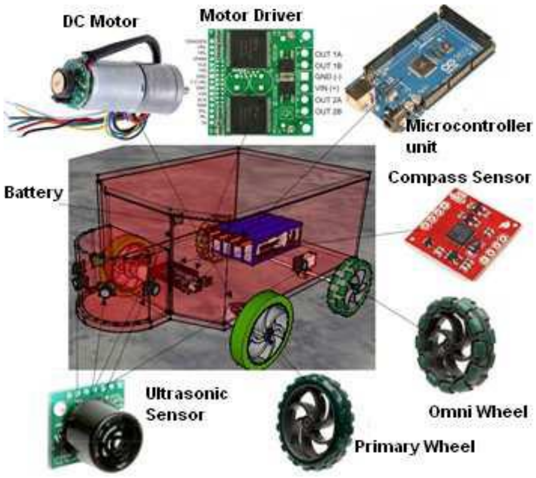

Figure 10: parts of an AMR. Source: [13]

This machine (as seen in the last section above) can do many things, such as collecting data from different plants all over the field or spreading pesticides on plants that need it. This section will describe what the robot looks like and what kind of things it can do.

The use of automated robots in agriculture to monitor crops is currently a technically viable solution that has been quite validated by some experts. For example, in labour-intensive tasks, agricultural robots can handle physically demanding tasks that require repetitive actions or precision, such as pruning or thinning crops. Also, they can work tirelessly for extended periods, reducing the need for manual labour and increasing overall efficiency.

However, in this work, it will be assessed whether it truly makes sense environmentally to use this solution instead of fixed sensors.

4.3.1. Robot elements

The different parts, seen in *Figure 10*, that make up a robot need to be defined, because they will have to be incorporated in the OpenLCA to make a Life Cycle Analysis (LCA). It must be said that some materials have not been known exactly, either because of the vendors do not have this information available or also because of the limitations of the OpenLCA software in not including all the materials. So, for these reasons the study done is just an approximation and done with the most accuracy, due to that robot's design is not final.

The robot materials and each quantity have been provided by CDEI:

Table 2: robot's materials and quantities.

	Materials	Mass (kg)
SM 500 V1.1	STEEL	111.368428
	ALUMINIUM	33.298789
	MOTOR STEEL	8.068144
	BATTERIES	7.504558
	ELECTRIC COMPONENTS	5.48532
	DX1100 (PC)	4.504431
	SLIP RING	3.265577
	REDUCTION STEEL	3.098118
	SCANNER	2.801366
	PLASTICS	1.694062
	CONNECTOR CABLE	0.961794

Table 2 has been used as a reference to carry out the analysis.

a. Steel

Is the majority component and makes up the largest part of the structure, either of the outer sheets or of the inner structure. The total amount of steel used in this robot is approximately 120 kg.

Of this 120kg, 8kg are for the 4mm sheets that make up the robot motor. 3kg are for the motor's gear, which is forged steel. The approximately 110kg remaining is steel electrogalvanized coil used for inner structure, like a support for the motor, the upper disk or for the wheel rim flanges.

These values were provided by the constructors of this robot, which decided how much steel to use in each part of the robot.

Steel is commonly used in AMR due to its various beneficial properties and characteristics. Here are some reasons why steel is suitable for such robots:

- Strength and Durability: Steel is known for its exceptional strength and durability, making it well-suited for robust applications in agricultural environments.

- Rigidity: Steel offers high rigidity, which is crucial for maintaining stability and precision in AMR.

- Protection: Agricultural environments can be demanding, with potential exposure to impacts, debris, and other hazards.

- Weldability: Steel is highly weldable, allowing for easy assembly and modification of the robot's structure.

- Cost-effectiveness: Steel is a cost-effective material, readily available in large quantities.

While steel offers many advantages, it's worth noting that AMR may also incorporate other materials in their construction, depending on specific design requirements. Keeping in mind that the robot total weight is around 180kg, steel plays an important role in the calculation of the LCA. This means that steel may be one of the major contributors to pollution effects, but this must be checked with the OpenLCA.

b. Aluminium

Aluminium is another major component of the robot, not as much as steel, but also has a big impact in it. It is used in the housing of the robot, to give robustness while giving lightness.

The total amount of aluminium in the robot is approximately 33kg, which all of them is in sheet parts, used in the robot casing.

Aluminium is commonly used in AMR and other vehicles for several reasons:

- Lightweight: Aluminium is significantly lighter than steel while still providing adequate resistance.

- Corrosion resistance: Agricultural environments often involve exposure to moisture, fertilizers, pesticides, and other corrosive substances.

- Thermal Conductivity: Aluminium has high thermal conductivity, meaning it can efficiently dissipate heat generated by the robot's electronics or power systems.

- Machinability: Aluminium is highly machinable, enabling easy fabrication of complex shapes and structures.

It must be said that aluminium is not inherently pollutant, but the production of this material can have environmental impacts. The primary environmental concern associated with aluminium production is the extraction and refinement of bauxite ore, which is the main source of aluminium.

Additionally, the refining process requires a significant amount of energy, often derived from fossil fuels; and generates waste materials, like red mud. However, is highly recyclable. Requires significantly less energy compared to primary production. Therefore, recycling aluminium is an effective way to minimize the environmental footprint of this material. But, in this project, it is considered that all the aluminium originates from primary sources.

c. Plastics

Plastics play a significant role in the design and construction of agricultural robots. Here are some key aspects of plastics in agricultural robots:

- Structural Components: Plastics are commonly used for manufacturing the structural components of agricultural robots. They offer a combination of strength, durability, and light weight.

- Wiring and Cable Management: Plastics are used for cable management and other electrical and electronical components within agricultural robots.

- Sensor Housings: Agricultural robots often integrate various sensors for tasks such as soil analysis, crop monitoring, and obstacle detection.

- Weight Reduction: Agricultural robots often operate in dynamic environments and may need to traverse uneven terrain or delicate crops.

- Cost-Effectiveness: Plastics generally offer a cost-effective solution for agricultural robot construction compared to other materials like metals or composites.

The advent of 3D printing technology has further expanded the use of plastics in agricultural robotics. 3D printing allows for the rapid prototyping and fabrication of custom parts, including intricate designs and geometries. Plastics like PLA (Polylactic Acid) and ABS are commonly used in 3D printing agricultural robot components.

The total amount of plastics in the robot does not reach even 2kg, which means that probably will not have a lot of impact in the LCA.

It's worth noting that the selection of plastics and their specific applications in agricultural robots can vary depending on factors such as the robot's intended tasks, environmental conditions, and desired performance characteristics.

d. Batteries

Batteries are a crucial component of autonomous mobile robots (AMRs), as they provide the power needed to run the robot's motors, sensors, and computing systems. The choice of battery for an AMR depends on several factors, including the robot's power requirements, operating environment, and budget.

The total weight of the battery in this robot is barely 7.5kg, which is not actually a very heavy battery.

Here are some key considerations when choosing a battery for an AMR:

1. Capacity: The battery capacity determines how much energy the battery can store and how long the robot can operate before the battery needs to be recharged.

2. Voltage: The battery voltage determines the amount of power that can be supplied to the robot's motors. Most AMRs use batteries that provide a voltage of 12V or 24V.

3. Chemistry: The chemistry of the battery determines its energy density, weight, and cost. Common battery chemistries used in AMRs include lead-acid, nickel-cadmium (NiCd), nickel-metal-hydride (NiMH), and lithium-ion (Li-ion).

4. Charging time: The time it takes to recharge the battery can impact the robot's uptime. Some batteries can be charged quickly, while others require a longer charging time.

5. Battery management system: A battery management system (BMS) is used to monitor the battery's state of charge, temperature, and other parameters. The BMS helps to prolong the battery's life and prevent damage to the battery or the robot.

Overall, selecting the right battery for an AMR requires careful consideration of these factors and others specific to the application. It is important to choose a battery that is reliable, efficient, and provides the necessary power for the robot to operate optimally.

e. Wheels

The wheels of the AMR are an important component of the robot because they are the only element that is all the time in contact with the surface of the terrain.

So, taking into consideration the fact that agricultural fields are not very levelled, but is very uneven, the wheels shall be larger and with treads, just to have a better adaption to the terrain.

The manoeuvrability of the robot is also important. If the robot must turn in tight spaces, omni-directional wheels or swivel wheels may be considered.

The type of wheel affects at the speed of the robot. If the robot has to be fast to collect data, it is preferred to have smaller wheels, while heavier and larger wheels are better for slower speeds.

They shall be easy to maintain and replace when necessary. The ones with removable treads or with modulars design are easier to maintain. This keeps relation with the cost of the wheels, which is probably the factor that will determine the wheel that it will be bought.

In resume, in the selection of the optimum wheel, all these factors must be in balance. The better option for an off-track wheel may be ones that are bigger than if they were for smooth surfaces, with treads and easy to maintain.

In the object of the study, two of the wheels have a diameter of 8”, have a maximum speed of 25 km/h and weight 3 kg.

Figure 11: wheels of the robot. Source: [14]

There is also another wheel used as a support, can withstand up to 450kg and it weights approximately 11.5kg, due to that it also has a small structure of steel. [15]

Figure 12: support wheel of the robot. Source: [15]

f. Routers

Routers on agricultural robots are used for multiple purposes related to connectivity and communication. Here are some examples:

- Remote Control and Monitoring: Routers enable remote control and monitoring of agricultural robots. They allow operators to send commands to the robot and receive real-time feedback on its status.

- Data Transmission: Agricultural robots generate a significant amount of data related to crop health, soil conditions, weather, and other relevant information. Routers facilitate the transmission of this data to the cloud or a central server, where it can be processed and analysed for decision-making purposes.

- GPS and Navigation: Routers often play a role in the integration of GPS systems for navigation. They help establish a reliable connection to satellite-based positioning systems, allowing the robot to determine its location accurately and navigate through the fields or orchards.

- Fleet Management: In cases where multiple robots are deployed in a coordinated manner, routers can facilitate fleet management. They enable communication and coordination between the robots, ensuring they operate efficiently, avoid collisions, and optimize their tasks collectively.

In the developed robot are installed two types of routers: the RUTX11, which allows reliable, fast connection and high data transmission [16]; and the TSW110, which enables industrial high-bandwidth applications with a reliable connection [17]. The two of them weigh approximately 0.3kg.

Figure 13: photo of RUTX11. Source: [16]

Figure 14: photo of TSW110. Source: [17]

g. Sensors

Sensors are used in agricultural robots for a variety of reasons. They play a crucial role in collecting data and providing essential information for decision-making and autonomous operations. Here are some reasons why sensors are used in agricultural robots:

- Crop Monitoring: Sensors are used to monitor various parameters related to crops, such as soil moisture, temperature, humidity, nutrient levels, and pH. This information helps optimize irrigation, fertilization, and overall crop management practices.

- Weed and Pest Detection: Sensors can detect the presence of weeds, pests, and diseases in agricultural fields. Optical sensors, thermal sensors, or multispectral/hyperspectral sensors can identify variations in vegetation or detect specific signatures associated with pests or diseases.

- Navigation and Obstacle Avoidance: Sensors, particularly proximity sensors, ultrasonic sensors, LiDAR (Light Detection and Ranging), or cameras, are essential for navigation and obstacle avoidance in agricultural robots.

- GPS and Localization: Global Positioning System (GPS) sensors are used for accurate localization and mapping of agricultural robots. GPS enables precise navigation, path planning, and tracking of the robot's position in the field.

- Environmental Monitoring: Sensors are used to monitor environmental factors that impact agricultural operations, such as temperature, humidity, wind speed, and solar radiation.

- Harvesting and Sorting: Sensors are employed in agricultural robots to assist in harvesting and sorting operations. Vision-based sensors can determine the ripeness of fruits or vegetables, allowing the robot to selectively harvest ripe produce.

These are just a few examples of how sensors are used in agricultural robots. The specific types of sensors utilized depend on the application and the data required for optimal farm management and automation.

With all this information, the selected sensors are:

i. Thermal Camera

One thermal camera will be installed in the robot. The model is the Optris Xi 400 [18].

These types of cameras detect and measures the infrared energy from objects. This data is converted in an electronic image which shows the surface temperature of the object. On the robot, this camera is going to be used for measurement of the temperature of crops to determine plant water stress.

Figure 15: photo of the Optris Xi 400 thermal camera. Source: [18]

ii. RGB-D Cameras

Two RGB-D cameras will be installed in the robot. The model is the INTEL RealSense Depth Camera D455 [19].

An RGB-D camera is a sensor that both provides depth (D) and colour (RGB) data as the output in real-time. Depth information is retrievable through a depth map/image which is created by a 3D depth sensor. The depth map allows to pinpoint objects more effectively for pattern recognition or detection. [20]

On the robot, these cameras are going to be used one for measuring plant strength and crop yield, and the other one for the robot navigation.

Figure 16: photo of the INTEL RealSense Depth Camera D455. Source: [19]

iii. NDVI Sensor

One NDVI sensor will be installed in the robot. The model is the Crop Circle ACS-214 Active Crop Canopy Sensor [21].

The Landsat Normalized Difference Vegetation Index (NDVI) is used to quantify vegetation greenness -which refers to the overall health and vigour of the vegetation- and is useful in understanding vegetation density and assessing changes in plant health. Often assessed based on the intensity or abundance of green colour in the plant foliage. It can be an indicator of plant growth, photosynthetic activity, and overall plant health.

On the robot, this camera is going to be used to calculate crops biomass.

Figure 17: photo of the ACS-214 Active Crop Canopy Sensor. Source: [21]

4.3.2. Characteristics summary table

Below there is a summary table with the components of the robot and which characteristics have each one:

Table 3: Summary of characteristics of robot's elements

Characteristic	Steel	Aluminium	Plastics	Battery	Wheels
Resistant	✔	✔	✔	✔	✔
Durable	✔	✔	✔	✔	✔
Cost-effectiveness	✔		✔		✔
Corrosion resistance		✔	✔	✔	✔
Lightweight		✔	✔		
Machinability	✔	✔	✔		

4.4. Fixed sensors

Agriculture requires new technological advances to increase productivity while reducing the environmental impact, by reducing the use of agro-chemical or other pesticides. At the same time, if costs can be lowered this could be an acceptable solution. [22]

Sensor technologies are trying to reach this goal. Precision agriculture (PA) has become indispensable in monitoring the fields to increase productivity. PA uses information technology to ensure that crops receive the optimum inputs when needed for improving their health and productivity. To do it, it is necessary to know real-time data about the conditions of the crops, information recollected by sensors, which can give information about moisture of the soil at different depths, air temperature and many other useful information. [23]

PA and smart farming are emerging areas where sensors-based technologies play an important role. For this reason, it is important that these technologies are efficient and present cost reductions.

For achieving these goals, a Wireless Sensor Network (WSN) must be considered. It consists of multiple sensors distributed in the study field, connected by the internet. These sensors -called nodes- will send the data they collect to the base station, where processing, analysis and storage of this data will be done.

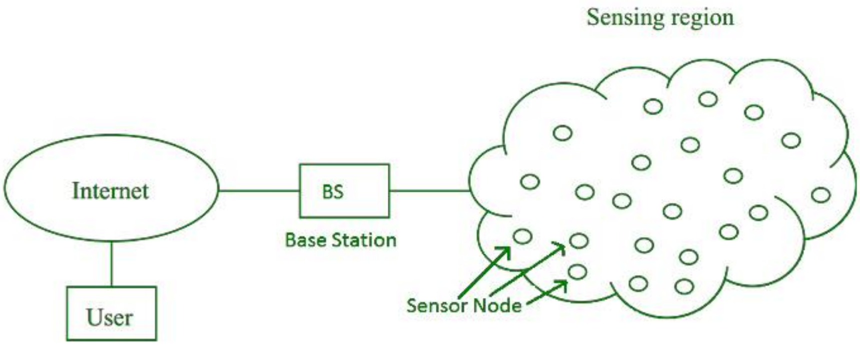

Figure 18: Sketch of a WSN. Source: [24]

In one hand, here are some advantages of WSN are:

- Low cost. WSNs consists of low-cost sensors that are easy to deploy.
- Wireless connections, which can be cost-effective to install and maintain.
- Real-time monitoring. WSNs enable real-time monitoring data for decision-making and control.

In the other hand, there are some disadvantages:

- Limited range, which can be a challenge for large fields.
- Data security. WSNs are vulnerable to security threats.
- Interference. Wireless communication is susceptible to interference from other wireless devices or radio signals. [24]

This sensor network will be compared to another possible solution: the agricultural robot. The robot can also present these advantages and disadvantages, but the comparison will be only about the environmental impact; it means that it is going to be decided which solution has less impact on the environment. How many fixed sensors are going to be used is explained in section 5.1. Below are explained which types of sensors are going to be used in the study:

4.4.1. Thermal sensors

Also known as infrared sensors or thermographic sensors, detect and measure the thermal radiation emitted by objects. They are sensitive to the infrared portion of the electromagnetic spectrum and are commonly used to measure temperature or identify variations in heat distribution. Those specifically, are used to know the temperature directly on the crops.

The main materials used to make these types of lenses are Germanium and Silicon. Mirrors can also be used as optical components for thermal imaging systems. These components have surfaces that are mainly made of metals, such as copper and aluminium. [25]

Thermal cameras weigh from a few hundred grams to a couple of kilograms. So, it is considered that an aluminium case weighs around 0.75kg, it has 0.025kg of copper of wire, and 0.225kg of silicon lenses.

4.4.2. RGB-D cameras

RGB-D cameras are used in agricultural fields to measure plant strength and crop yield. These will be installed all over the field to monitor all these data and send it to the data centre, where it will be processed.

The main materials used to make these cameras are plastics and aluminium in general, but they can also contain electronics components made of semiconductors and copper. [26]

RGB-D cameras have a usual weight from 100 to 500 grams. So, it will be considered that they have an aluminium case of around 0.2kg, 0.015kg of copper wire and 0.085kg of plastics for the lenses.

4.4.3. NDVI sensors

They are used to quantify vegetation greenness, which refers to the overall health and vigour of the vegetation. Specifically, these sensors will calculate the biomass of crops.

These sensors are typically made of semiconductor materials such as silicon or gallium. The housing is often made of aluminium. [27]

These types of sensors are lightweight to facilitate easy installation and positioning. They weigh from a few grams to a few hundred grams. For this reason, it is considered that has an aluminium case of 0.4kg, 0.025kg of copper wire and 0.125kg of silicon.

5. Practical framework

This practical component of this bachelor's thesis delves into the use of OpenLCA. This tool will help with making a Life Cycle Analysis of the robot and its contrast with fixed sensors. By the results given, it will be concluded if the robot solution it is better than the other ones.

5.1. Setup

First of all, it is needed to make some assumptions to start:

1. Robot speed is 1.5 m/s according to producer's information.
2. Considered field would be a vineyard, but this can be extrapolated to another types of plants.
3. Frequency of data recollection needed is 15 minutes approximately, according to producer's information. This is the time when the robot must pass again at the same point where it started, so the total trajectory shall be done in this time.
4. Resolution of the sensors is the following, according to producer's information:
    a. For thermal cameras, it is needed one camera every 8 meters.
    b. For RGB-D cameras, it is needed one camera per vine.
    c. For NDVI sensors, it is needed one sensor every 8 meters.
5. The LCA components of material acquisition and component fabrication have been grouped into a single process called "Manufacturing".

Making these assumptions, the next step is to calculate the surface of the field.

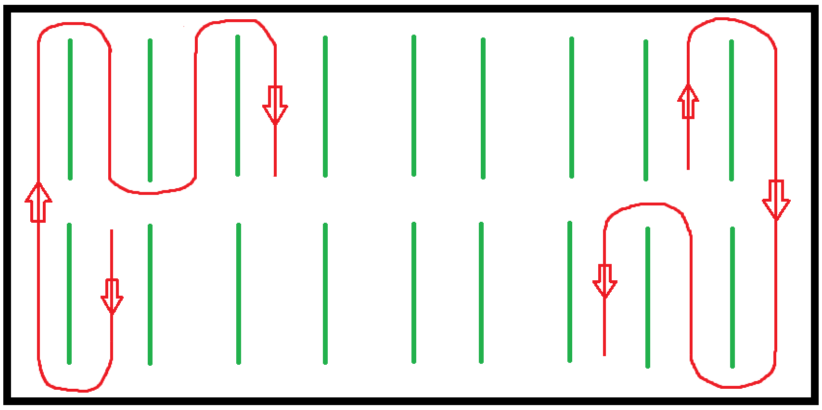

Figure 19: Sketch of the field and the robot's trajectory.

Considering that the robot must restart the same path after 15 minutes, if it goes at 1.5 m/s, the robot can traverse 1350 meters in this time. Considering that the field has a similar shape as the *Figure 19*, each vine measure 10 meters approximately and are 3 meters of space between each, it can be calculated that there are in total 104 vines, 52 vines per row.

So, the field surface shall be 52 vines x 2 rows = 104 vines in the vineyard.

The length of the field is 52 vines x 3 meters between each = 156 meters length.

The width of the field is 2 vines x 10 meters each + 5 meters between the (2) rows = 25 meters wide.

Finally, to calculate the surface, 156 meters length x 25 meters wide = 3900 m^2. This is the equivalent as 0.3900 ha.

Taking consideration of these dimensions, the following sensors will be needed (see also Table 4):

- 1 thermal sensor per 2 vines, considering that is needed one every 8 meters, makes a total of 52 thermal sensors.
- 1 RGB-D camera per vine, makes a total of 104 RGB-D cameras.
- 1 NDVI sensor per 2 vines, considering that is needed one every 8 meters, makes a total of 52 NDVI sensors.

Table 4: comparison of sensors needed to robot.

Fixed Sensors	Robot
 x52	 x1
 x104	
 x52	

All these sensors shall be connected with copper wires to give them electricity, which traduces in 1350 meters of copper wire plus the distance needed to connect the sensors to electrical network. 150 extra meters are going to be supposed. Considering that copper wire approximately weights around 100 grams per meter, and we have 1500 meters of wire; 150 kg of copper wire is needed.

5.2. Robot LCA results

First of all, the LCA of the robot is going to be assessed. The impact categories studied are explained in point 4.2.2. In this section, is going to be seen which components of the robot have more impact and should be aware of.

5.2.1. Climate change

Climate change is measure in kilograms of CO_2 emissions to the atmosphere. The total emission for the robot is 4391.13 kg of CO_2. In the graphic below we see which process is the most impacting:

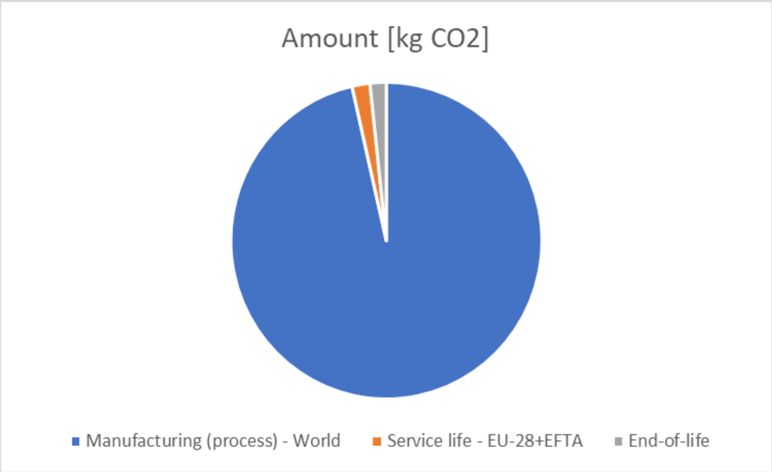

Figure 20: Graph of the robot's processes impact in climate change.

As its observed, the manufacturing of materials is the most impacting process in climate change, with the 96.45% of the impact. So, it is better to take a zoom in about this process:

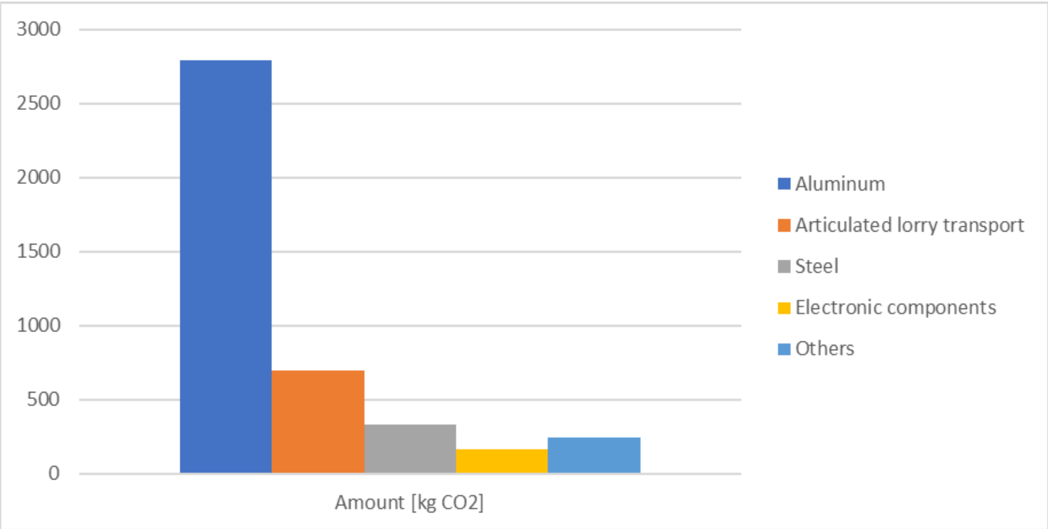

Figure 21: Graph of the robot's Processes in Manufacturing impact in climate change.

It is well observed that the Aluminium is the material that have the major impact on climate change, with an amount of 2795.35 kg of CO_2 only emitted by this material. This makes the 63.66% of the total emissions. So, in this case, the better option would be reducing the quantity of aluminium present in the robot.

5.2.2. Energy resource consumption

Energy resource consumption is measured in Megajoules (MJ). The total energy consumed by the robot is 1.21×10^8 MJ, which corresponds to 3.36×10^7 kW/h.

In the graph below, we see which process has more impact:

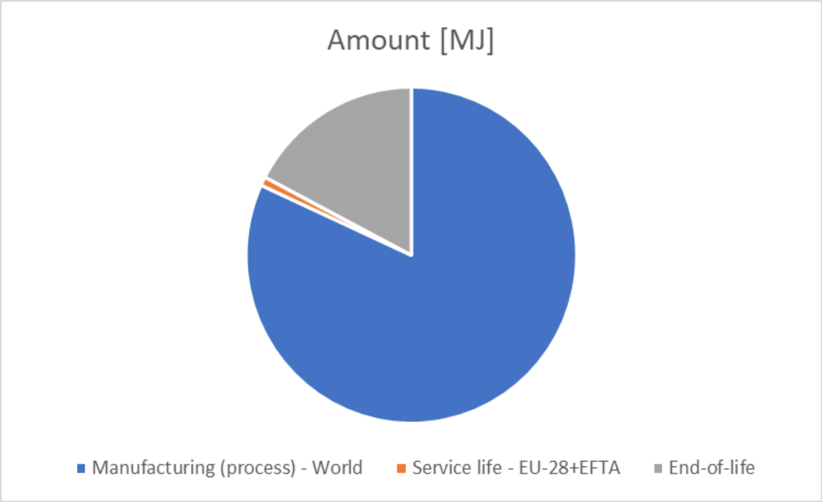

Figure 22: Graph of the robot's processes impact in energy resource consumption.

As observed, the manufacturing has the major impact in energy consumption with 81.83% of the total. Also, the End-of-life has to be considered with the 17.32% of the total impact. For the manufacturing process:

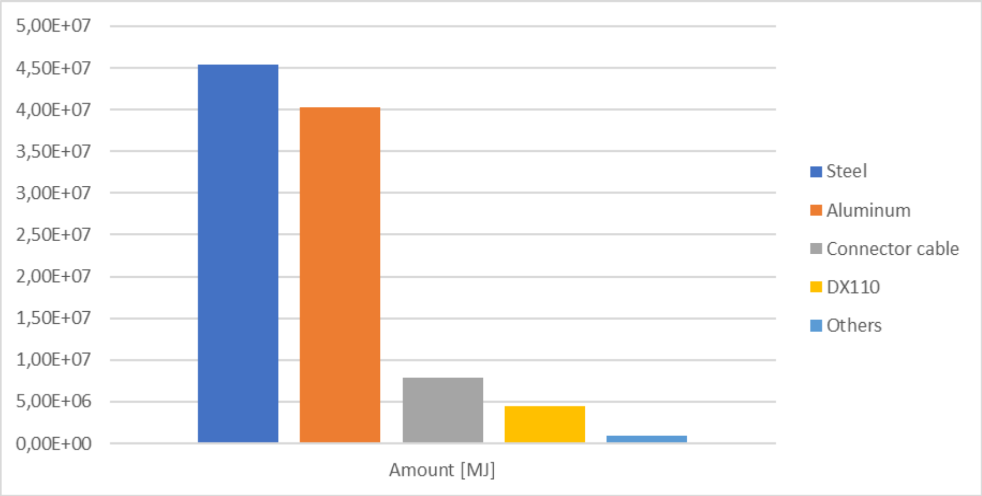

Figure 23: Graph of the robot's Processes in Manufacturing impact in energy resource consumption.

As seen, the steel and the aluminium have the major impact in energy resource consumption for the Manufacturing process, with $4.53x10^7$ MJ ($1.26x10^7$ kW/h) and $4.03x10^7$ MJ ($1.12x10^7$ kW/h), respectively. That is the 37.60% for the steel and 33.43% for aluminium of the total energy consumed.

In the other hand, for End-of-life process, the treatment of copper consumes $2.088x10^7$ MJ ($5.8x10^6$ kW/h), which means 17.28% of the total energy consumed, making it the most energy wasting item when it comes to recycling.

5.2.3. Ozone depletion layer

Ozone depletion layer is measured in kilograms of Chlorofluorocarbons (kg of CFC-11). The total amount emitted by the robot is $3.16x10^{-5}$ kg of CFC-11. Despite it seems that is not a great number of kilograms, continuous and accumulative emission of these substances can have a long-term significant impact on the ozone layer. For this reason, international regulations have been implemented to limit and gradually eliminate the use and production of these substances. To understand better what the CFC gases are, they are explained in the next point:

Kilograms of Chlorofluorocarbons (kg of CFC-11)

This measurement is used for quantifying substances that contribute to the ozone depletion layer. The emission of a significant amount of these gases shall have a very negative impact on the ozone layer and in the environment in general [28]. For example:

1. Depletion of the ozone layer: when released into the atmosphere, they rise to the ozone layer and react with ozone molecules, causing their decomposition. This results in the formation of holes or weakened areas in the ozone layer, allowing harmful ultraviolet radiation to enter.

2. Increase ultraviolet radiation (UV): excessive UV radiation can have detrimental effects on human health, such as an increased risk of skin cancer, eye damage, suppression of the immune system, and disruptions to aquatic and terrestrial ecosystems.

3. Impact on climate: CFC-11 is also a greenhouse gas, contributing to global warming. Its release into the atmosphere can contribute to climate change and long-term alterations and climate patterns.

In the graph below, we see which process has more impact on the ozone depletion layer:

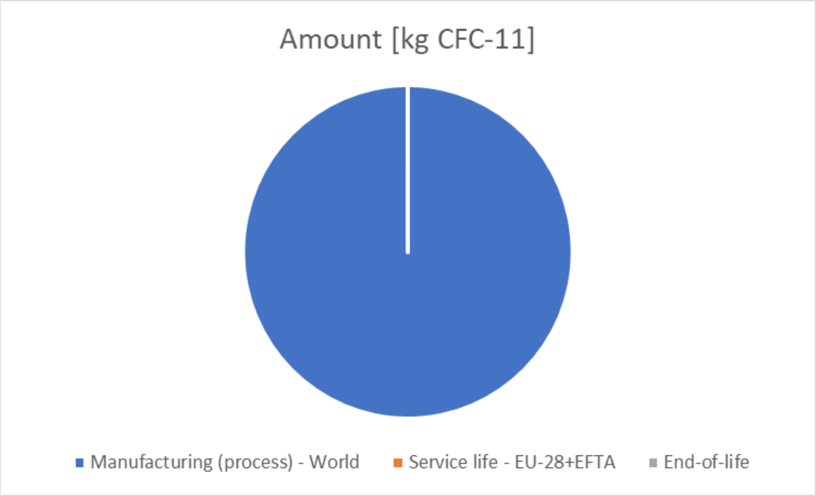

Figure 24: Graph of the robot's processes impact in ozone depletion layer.

We can observe that practically the Manufacturing process has the full impact on the ozone depletion layer, with 99.98% of the impact. That is a total of 3.16×10^{-5} kg of CFC-11. Taking a better look to this process:

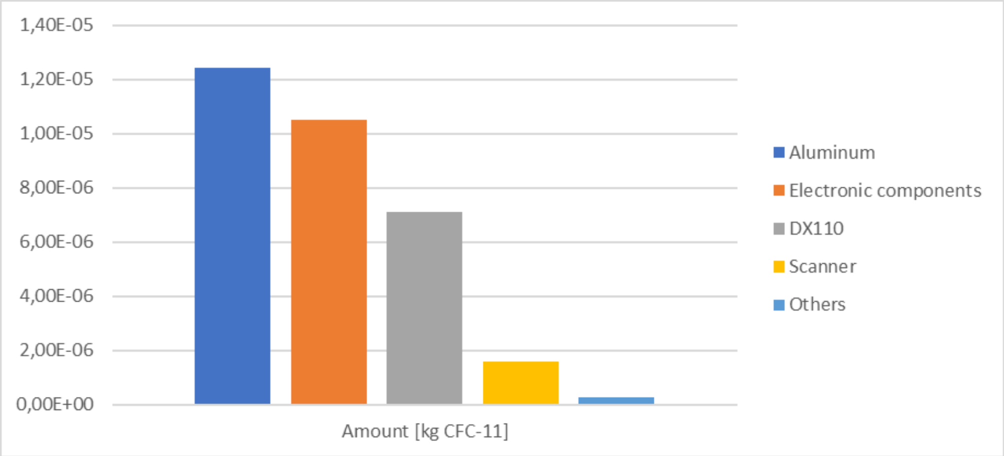

Figure 25: Graph of the robot's Processes in Manufacturing impact in ozone depletion layer.

Here, three elements have a significant impact in the emission of CFC gases. Aluminium has the greatest impact with 39.37% of the total kg of CFC-11 emissions. It is followed by electronic components and DX110, with 32.92% and 22.52% of the total kg of CFC-11 emissions each. So, CFC emissions should be reduced, and this could be done by changing the aluminium parts with other materials that have less CFC gases emissions.

5.2.4. Eutrophication

Eutrophication is measured in kg of Nitrogen equivalent. The total amount of kg of Nitrogen emitted is 6615.67 kg. Eutrophication is one of the principal causes of lakes pollution. It is produced when amounts of water receive a contribution of inorganic nutrients, mainly Nitrogen (N) or Phosphorus (P). Some kind of consequences can be: [29]

- An uncontrolled proliferation of microorganisms and plants, breaking down the environmental balance so that light can reach lower levels.
- Decreasing dissolved oxygen, caused by the absence of light, can result in an unviability for the species to keep living there.
- Loss of water quality.
- Appearance of some toxins produced by some types of algae.

In the graph below, we see which process has more impact about eutrophication:

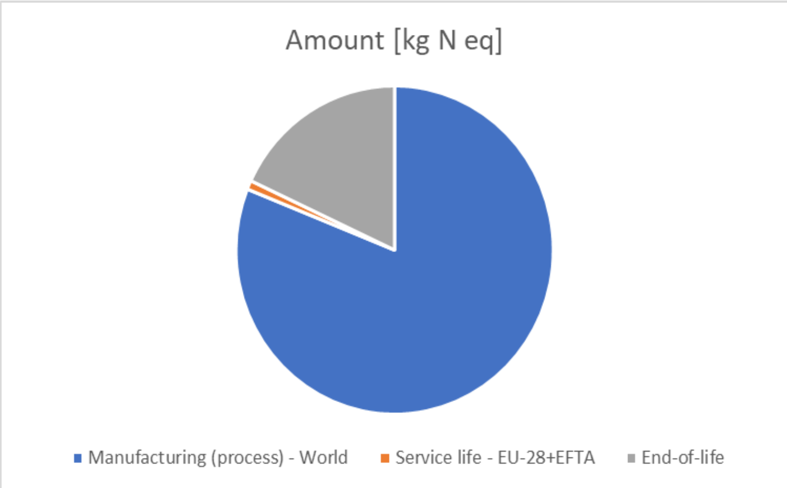

Figure 26: Graph of the robot's processes impact in eutrophication.

As it is seen, Manufacturing process is the major element that eutrophicates water, with the 81.84% of the total, which traduces in 5414.18 kg of N emitted. In addition, End-of-life process must be considered, because it represents the 17.32% of the total of N emitted. Of this percentage, the copper recycling represents the 17.26% of the total N emitted, with 1141.7 kg of N drop it into the water.

For the Manufacturing process, below there is how emissions are distributed:

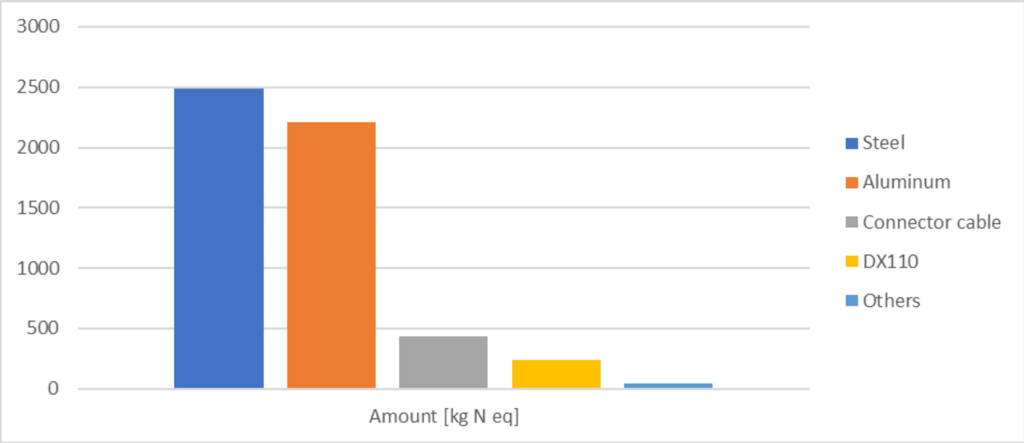

Figure 27: Graph of the robot's Processes in Manufacturing impact in eutrophication.

It can be observed that steel and aluminium are the elements that have the major impact, with 37.56% and 33.41% of the total kg of N emitted, respectively. That represents 2484.96kg of N and 2210.61kg of N each. So, again, the use of steel and aluminium should be reduced if it is possible.

5.2.5. Acidification

Acidification is measured with the pH, which is directly related to hydrogen ions concentration (H+) that are responsible for water acidification. Water acidification can affect marine life and its development and reproduction capacity, risking their population. [30]

In this study, is going to be used the mol of H+ that are emitted to the water. In total, the robot produces 12601.9 mol of H+.

To understand better if it is a lot or not, let's see an example:

Considering 1 litre of water in neutral conditions (pH of 7 on a scale of 0 to 14, where 0 is the most acid and 14 the basest), hydrogen ions concentration (H+) and hydroxyl (OH-) is approximately $1x10^{-7}$ mol/L each. If we want to make water more acid, the concentration of H+ must rise. The following equation is needed:

$$[H+] = 10^{(-pH)}$$

To reduce the pH to 3, the hydrogen ions concentration shall be:

$$[H+] = 10^{(-3)} = 0.001 \text{ mol/L}$$

Considering that hydrogen has a molecular mass of 1 gram per mol:

$$\text{Mass} = 0.001 \text{ mol/L x 1L x 1 g/mol} = 0.001\text{g}$$

In resume, 0.001 mol/L (or 0.001g) of H+ would be required to make 1 litre of water reach a pH of 3. This is a simple calculus, in real life other factors may affect acidification of water.

So, the robot can make more acid 12602 litres of water, becoming a pH of 3 from neutral.

In the graph below, we see which processes have more impact on acidification:

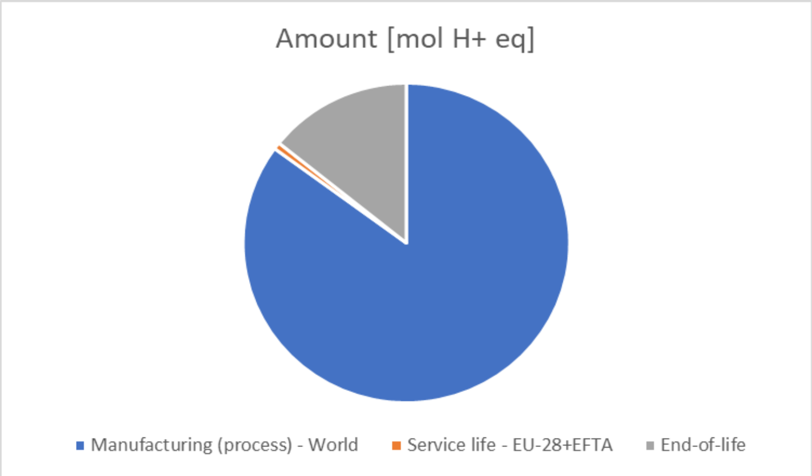

Figure 28: Graph of the robot's processes impact in acidification.

Analysing the above graph, it is seen that the Manufacturing process has the bigger impact on acidification, representing the 81.85%. End-of-life process has the 17.31% of the impact, again with the recycle of copper as the main character with 17.25% of the mol H+ emissions.

The Manufacturing process it is divided in:

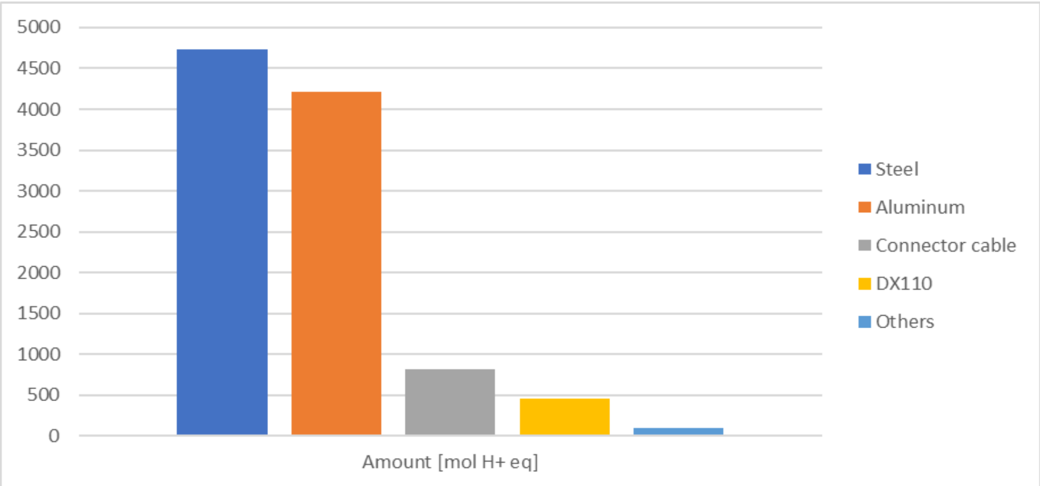

Figure 29: Graph of the robot's Processes in Manufacturing impact in acidification.

As observed, steel and aluminium have the bigger impact with 33.57% and 33.44% of the total mol H+ emitted, being 4731.07 mol H+ and 4214.1 mol H+ each. Another time, the best way to stop acidification should be by reducing the quantity of steel and aluminium.

5.2.6. Material consumption

Material consumption, especially the resource use of minerals and metals, is measured in kilograms of Substance equivalent (kg Sb eq). This common unit is because this way is easier to compare and aggregate the impacts of different substances, providing a standardized way to assess their environmental performance.

In total, the robot produces 908.3 kg Sb, and in the graph below it is seen which processes have the major impact:

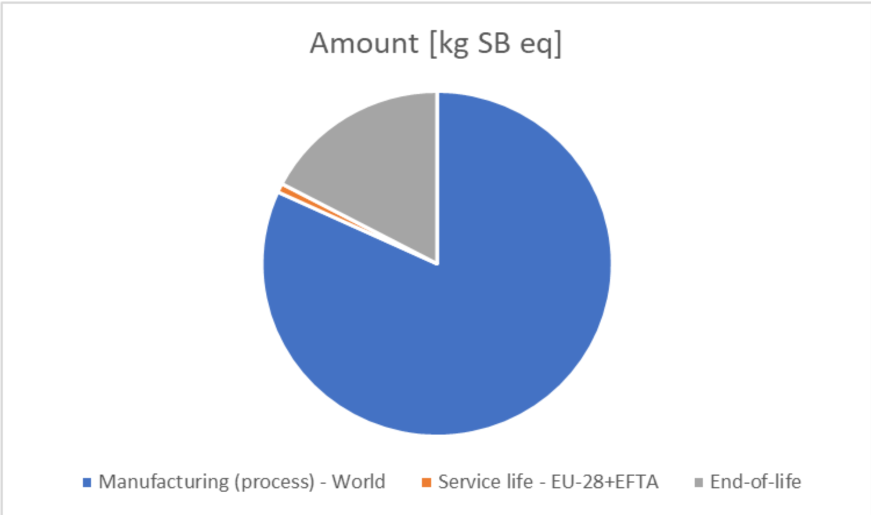

Figure 30: Graph of the robot's processes impact in material consumption.

As observed, the main process that impacts the material consumption is the Manufacturing, with the 81.83% of the impact, followed by the End-of-life process with the 17.32%, which represents in 743.28 kg Sb for Manufacturing and 157.34 kg Sb for End-of-Life. For the last one, the copper being recycled wastes the 17.28% of the total material consumed.

For the Manufacturing, here is how it is distributed:

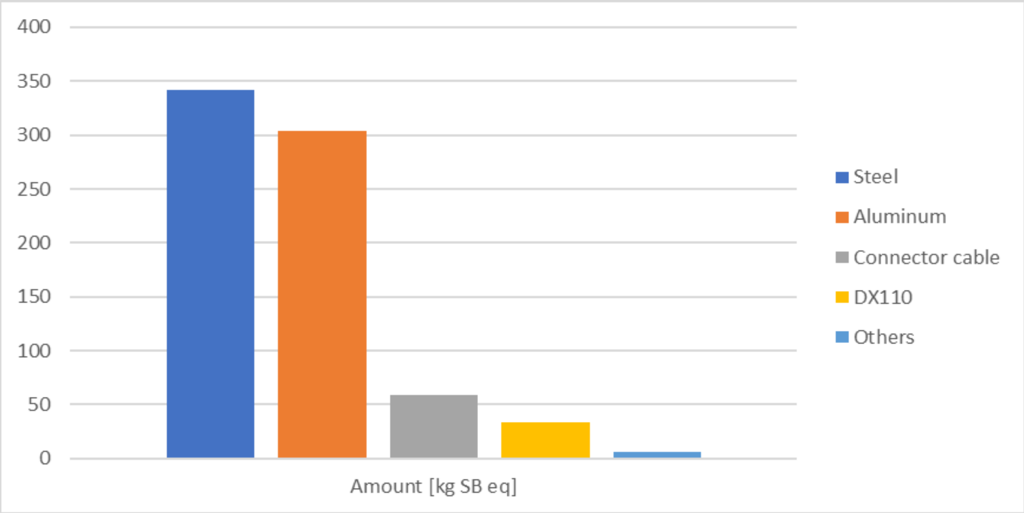

Figure 31: Graph of the robot's Processes in Manufacturing impact in material consumption.

Steel and aluminium have the greatest impacts. Steel represents the 37.61% (341.59 kg Sb) of the total material consumed, and aluminium the 33.44% (303.7 kg Sb). This is because steel and aluminium are the components that are used in the biggest quantity in all the robot.

5.2.7. Photochemical ozone formation

Photochemical ozone formation is measure in kilograms of Non-Methane Volatile Organic Compounds (NMVOC) equivalent. These compounds are chemical substances that contain Carbon and evaporate easily at ambient temperature. They can contribute to ozone formation and other photochemical pollutants into the atmosphere. It is commonly known as "smog", which is fog intensified by smoke or other atmospheric pollutants. This smog can have negative impact on human health, like respiratory problems and plant biomass decrease. [31]

The total amount of NMVOC kilograms emitted by the robot is 11109.7 kg.

Below there is the distribution of these emissions per processes:

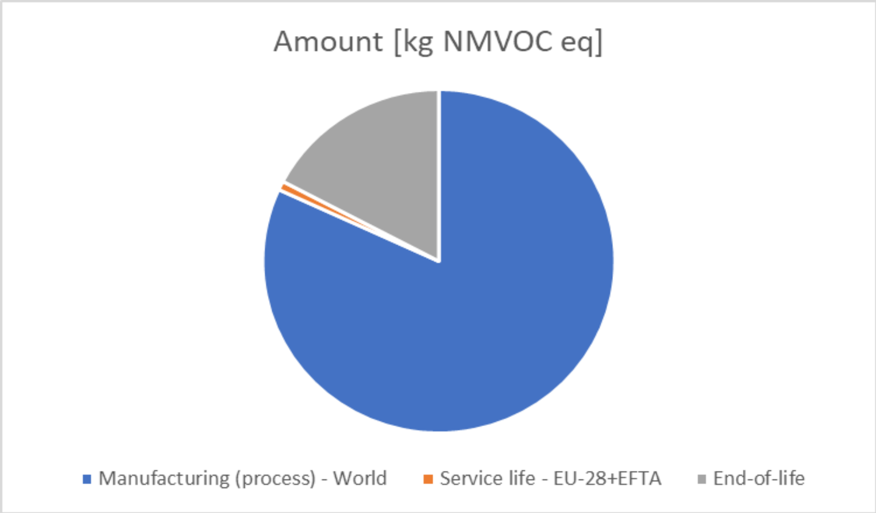

Figure 32: Graph of the robot's processes impact in photochemical ozone formation.

Again, the Manufacturing process is the one that have the major impact, representing the 81.84% of the total, emitting 9092.69 kg of NMVOC. End-of-life is the 17.31%, with 1923.16 kg of NMVOC emissions, compounded basically of the copper recycling, representing the 17.25% of the total emitted.

The Manufacturing process has the following distributions:

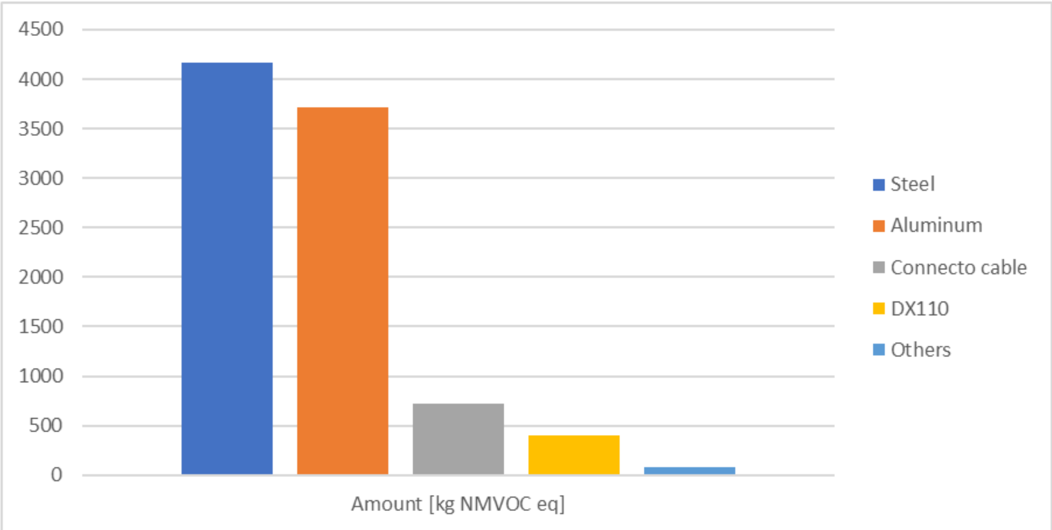

Figure 33: Graph of the robot's Processes in Manufacturing impact in photochemical ozone formation.

Once again, steel and aluminium are the main characters, representing the 37.55% and 33.42%, respectively. Steel emits 4171.6 kg of NMVOC, and aluminium emits 3713.41 kg of NMVOC. So, this emissions should be tried to minimize by reducing the use of these two components when possible.

5.3. Robot Sensibility Analysis

Sensibility Analysis is a technique used to assess the impact of variations or uncertainties in input parameters on the output or results of a model, simulation, or analysis. It helps in understanding the relative importance of different factors or variables and their influence on the overall outcome.

In this project, as seen in the previous sections, the most impacting factors are Steel and Aluminium. For this reason, it is going to be studied how impact is modified when changing these two parameters.

5.3.1. Aluminium

This material production has a very high impact on the analysis, so trying to reduce the use of aluminium can have many benefits on sustainability objectives. Instead of aluminium, magnesium can be used, keeping in mind the pros and cons of it [32]:

- Magnesium is significantly lighter than aluminium, with a density about 30% lower.
- Magnesium offers greater design freedom due to their high formability and casting capabilities.
- Magnesium is generally more expensive than aluminium, which can impact the overall cost of manufacturing.
- Joining magnesium components can be more complex than aluminium due to its lower melting point and greater reactivity.

Knowing these points, it is decided to reduce part of the aluminium used in the robot in 18kg and incorporate 15kg of magnesium. These are the results on each impact category:

a. Climate change

The total amount of kg of CO_2 emissions is 2896.68kg, by reducing only 18kg of Aluminium. That is 34% of total less emissions. In the graph below it is seen how this is distributed in processes:

Manufacturing process keeps having the major impact with 93.18% (2699.23 kg of CO_2 emitted), but it is less than before. Now it is going to be seen which processes have bigger impact in Manufacturing:

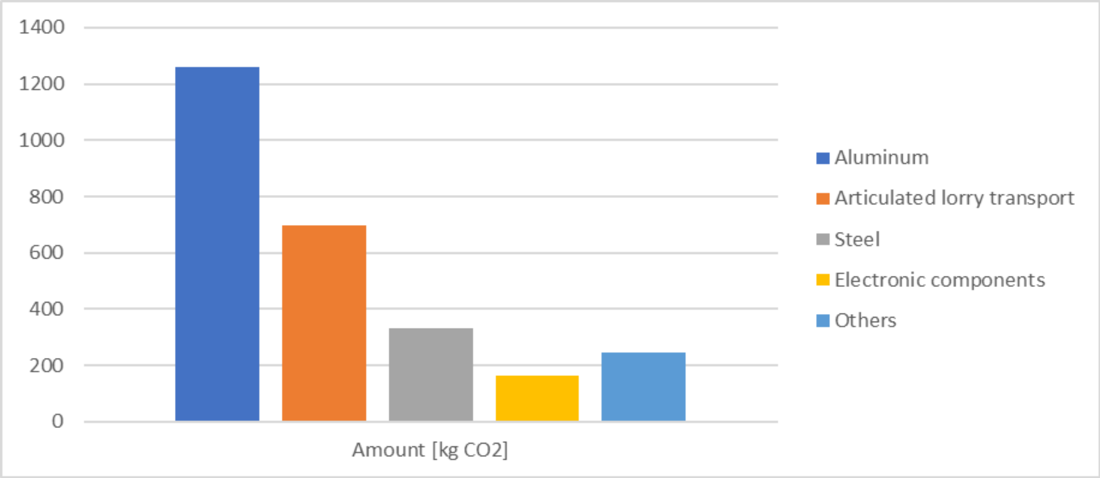

Figure 34: Graph of the Processes in Manufacturing impact in climate change (18kg of Aluminium less).

As it was expected, Aluminium has lost weight compared to the previous calculations. Now it only represents the 43.47% of the total emissions with 1259.21kg of CO_2 emitted (before it was 2795.35kg). Now, transport by truck and steel production have more importance with 24.05% and 11.50% of the total emissions, respectively.

So, by only reducing Aluminium in 18kg in the robot the emissions of CO_2 have been reduced barely 1500kg in total. That is a number to take into consideration.

b. Energy resource consumption

The total energy consumed rises to $1.53x10^8$ MJ, which is approximately 26.50% more MJ than before. Let's analyse what happened:

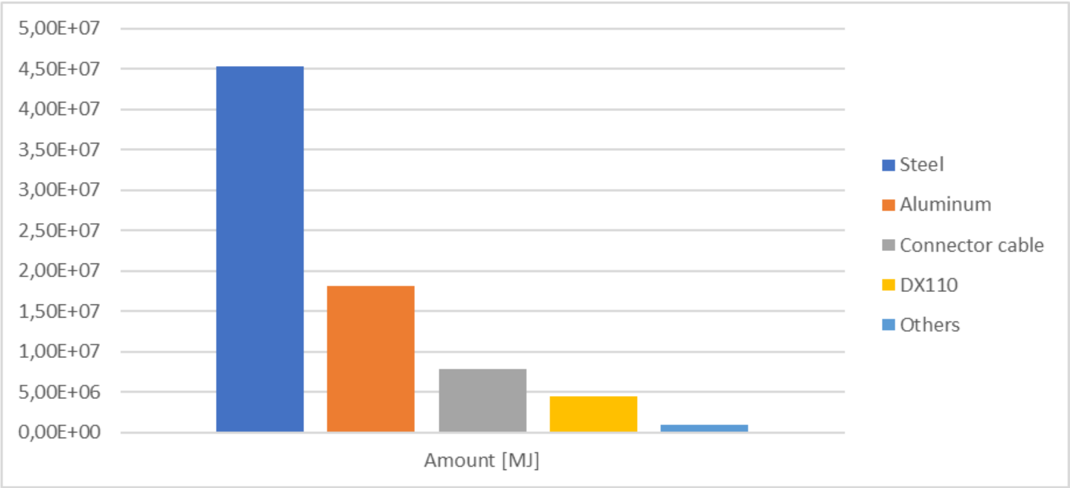

Figure 35: Graph of the Processes in Manufacturing impact in energy resource consumption (18kg of Aluminium less).

As observed, Aluminium has lost importance in energy resource consumption, wasting

$1.82x10^7$ MJ ($2.21x10^7$ MJ less than before). However, End-of-Life process gained a lot of impact, due to the recycling of magnesium, representing now a 49.18% of the total impact, with $7.50x10^7$ MJ used.

So, for energy consumption, Aluminium is a better option than Magnesium, because is has lower impact.

c. Ozone depletion layer

The total amount of kg of CFC-11 emitted now is $2.48x10^{-5}$ kg, 21.57% less kg than before. The figure below shows quantities of each component for Manufacturing process:

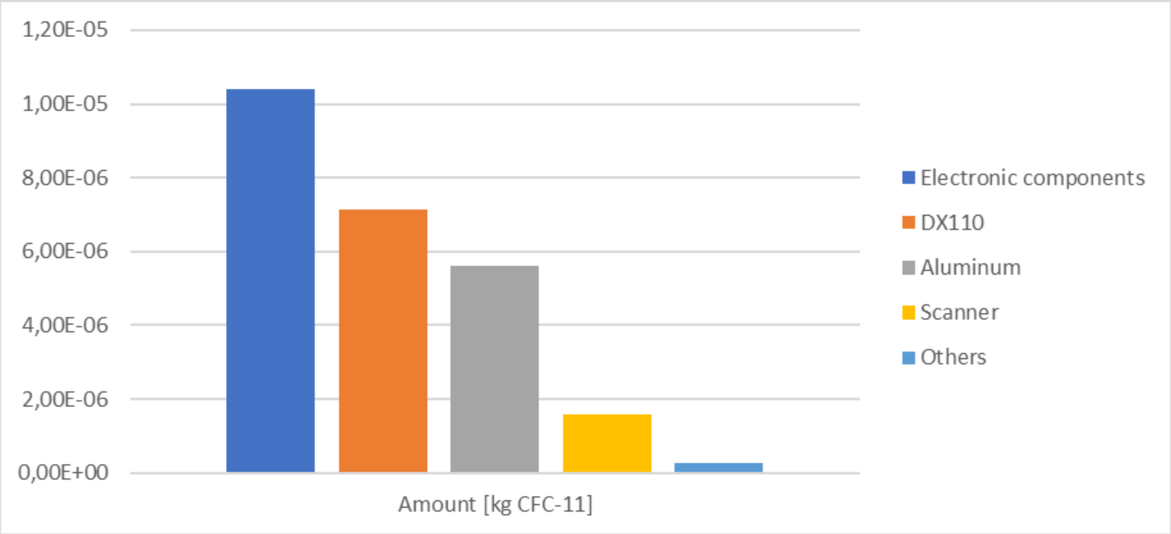

Figure 36: Graph of the Processes in Manufacturing impact in ozone depletion layer (18kg of Aluminium less).

d. Eutrophication

The total amount of kg of N produced is 8369.3kg. This is 26.52% more kg of N than before. In the figure below is seen what have changed:

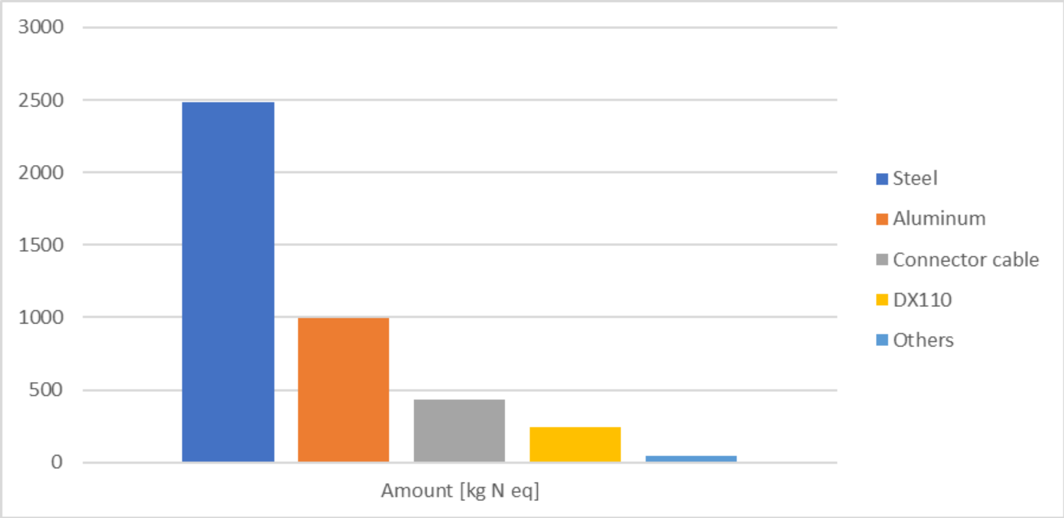

Figure 37: Graph of the robot's Processes in Manufacturing impact in eutrophication (18kg of Aluminium less).

As seen, Aluminium has reduced its impact about 55%. Despite this, the overall impact has incremented, due to the impact of the End-of-Life process, which rose to 4114kg of N because of the magnesium recycling.

e. Acidification

The total amount of mol of H+ emitted is 15937 mol, which is 26.42% higher than before. In the next graph is shown how impacts are distributed for Manufacturing process:

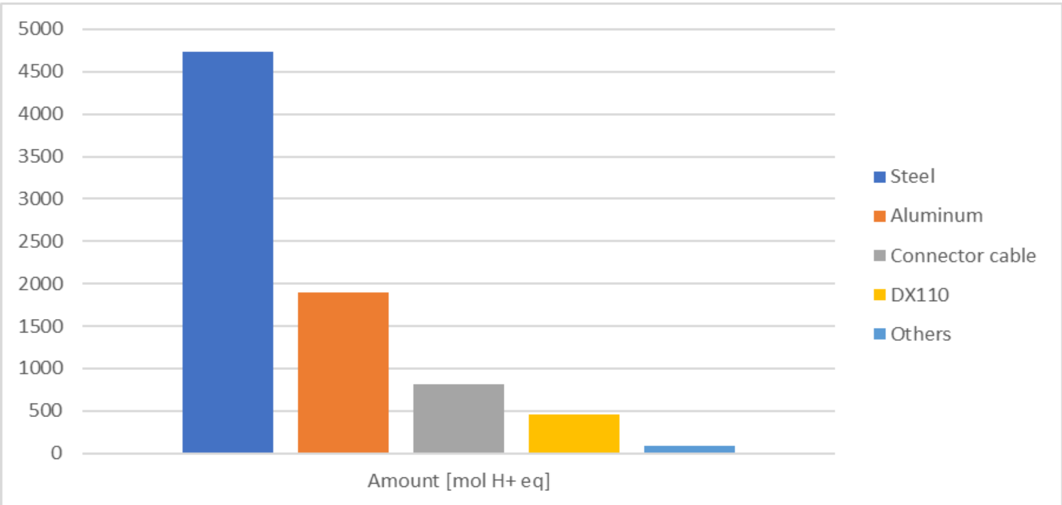

Figure 38: Graph of the robot's Processes in Manufacturing impact in acidification (18kg of Aluminium less).

As observed, Aluminium reduced its impact on 54.95%. The higher impact its due to the recycling of magnesium in the End-of-Life process.

f. Materials consumption

The total amount of kg of substances produced now is 1149.49kg, which is 26.55% more kg produced than before. In the following figure it can be observed which impacts have each element:

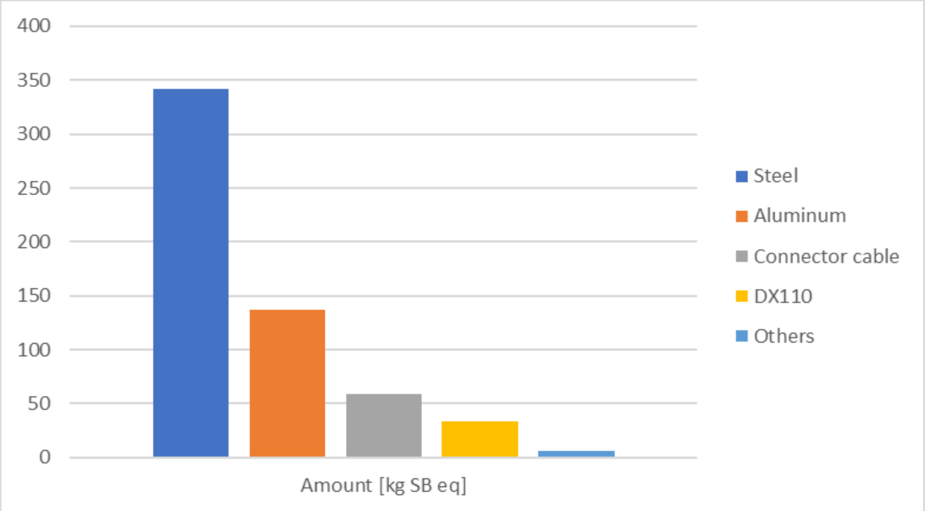

Figure 39: Graph of the robot's Processes in Manufacturing impact in material consumption (18kg of Aluminium less).

Aluminium has reduced its impact on 54.96%. However, the whole material consumption has incremented due to the recycling of magnesium.

g. Photochemical ozone formation

The total amount of kg of NMVOC produced is 14052kg, which is 26.49% more than before. Below it is shown which impacts have the different elements:

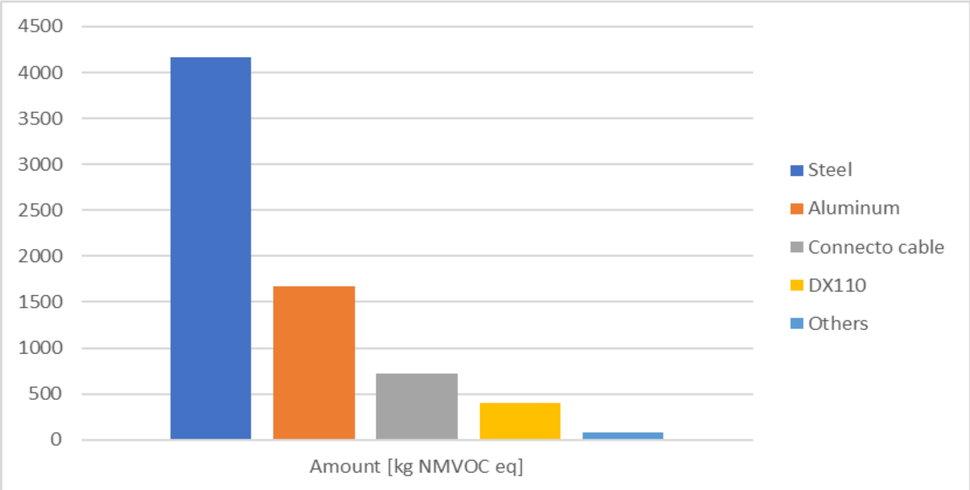

Figure 40: Graph of the robot's Processes in Manufacturing impact in photochemical ozone formation (18kg of Aluminium less).

Aluminium impact has decreased 54.95%. Although, the overall impact is higher due to the recycling of magnesium.

5.3.2. Steel

This material production has a very high impact on the analysis, so trying to reduce the use of steel can have many benefits on sustainability objectives. Instead of steel, carbon fibre can be used, keeping in mind the pros and cons of it [33]:

- Carbon fibre is more lightweight than steel.
- Carbon fibre is also stronger than regular steel and aluminium.
- Cost of carbon fibre is significantly higher than steel.

For this reason, 55kg of the steel has been removed and replaced by an equivalent of 12kg of carbon fibre. It is going to plot only Manufacturing process, because is the process that has more environmental impact in general. Here are the results obtained:

a. Climate change

The total amount of kg of CO_2 emitted now is 4225.11kg of CO_2, which is 3.78% less kg than before. The graph below shows the impacts of each element for Manufacturing process:

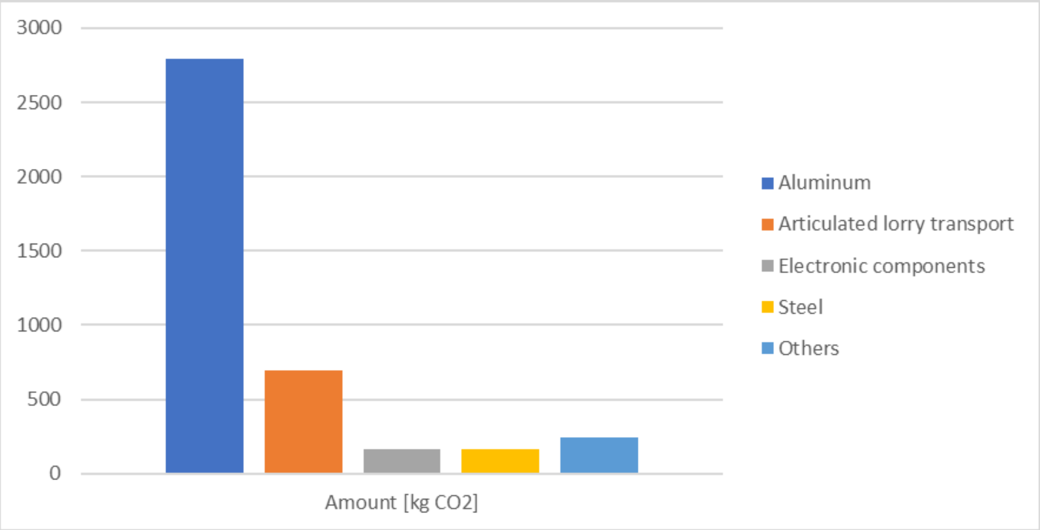

Figure 41: Graph of the Processes in Manufacturing impact in climate change (55kg of Steel less).

Steel emissions has been reduced by 50.61%, and also has overall impact.

b. Energy resource consumption

1.02×10^{8} MJ (2.83×10^{7} kW/h) is the total energy consumed by the robot with 55kg of steel less than before. That is 15.70% less energy than before. For Manufacturing process, this is the distribution of elements' impacts:

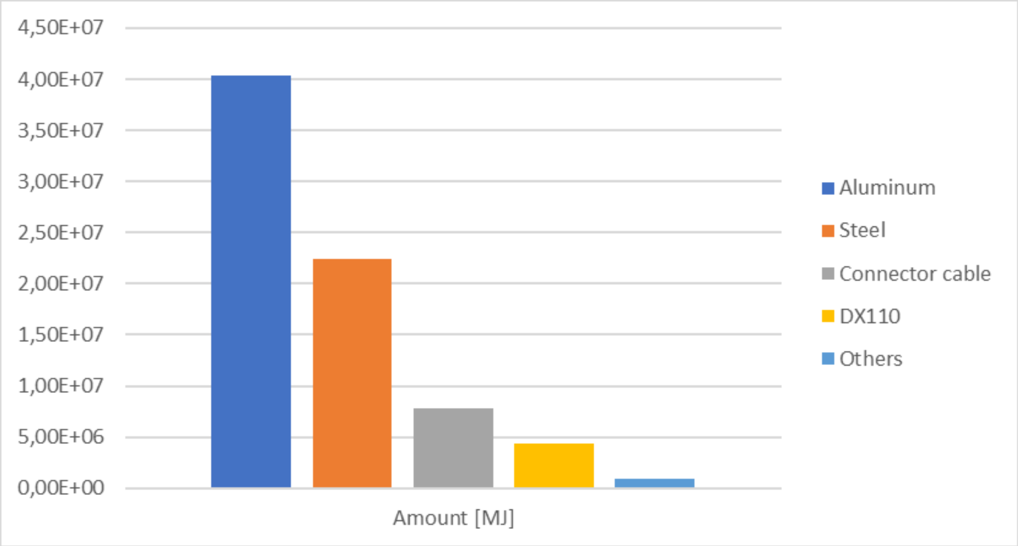

Figure 42: Graph of the Processes in Manufacturing impact in energy resource consumption (55kg of Steel less).

The energy consumed by Steel is 49.34% less than before.

c. Ozone depletion layer

The total amount of kg of CFC-11 emitted is 3.16×10^{-5} kg of CFC-11. That is the same amount as before. This is because steel have a minimal impact on this category, it only emits 2.65×10^{-9} kg of CFC-11 and carbon fibre has not also had a significant impact.

As the amount of emissions of steel is not significant, it is considered that this option emits the same amount of kilograms as the original robot.

d. Eutrophication

The overall amount of kg of N emitted now is 5586.27kg, which is 15.56% lower than before. Below there is how Manufacturing process impacts is distributed:

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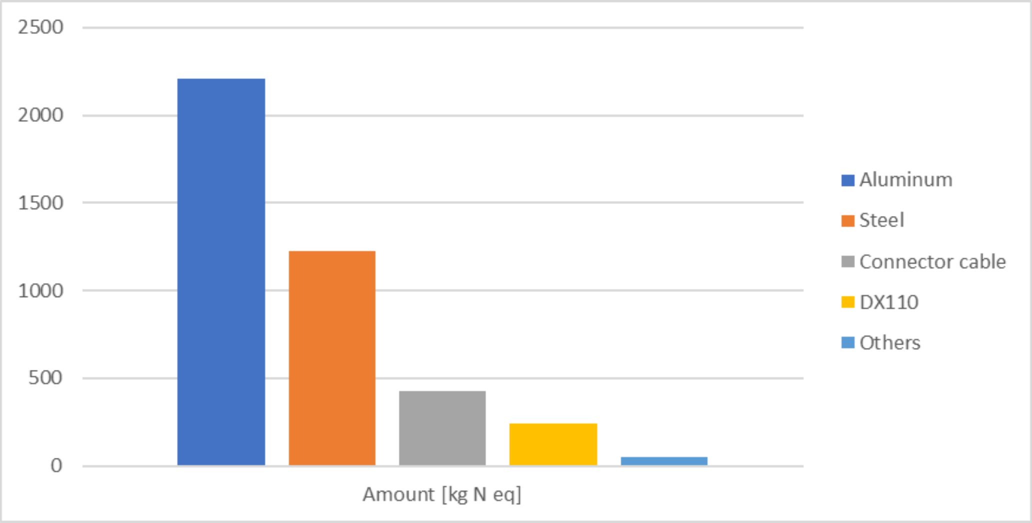

Figure 43: Graph of the robot's Processes in Manufacturing impact in eutrophication (55kg of Steel less).

Steel emissions have been reduced by 50.61%.

e. Acidification

The total amount of mol H+ produced is 10642 mol H+, which is 15.55% less mol than before. Below there are the impacts of the different elements for Manufacturing process:

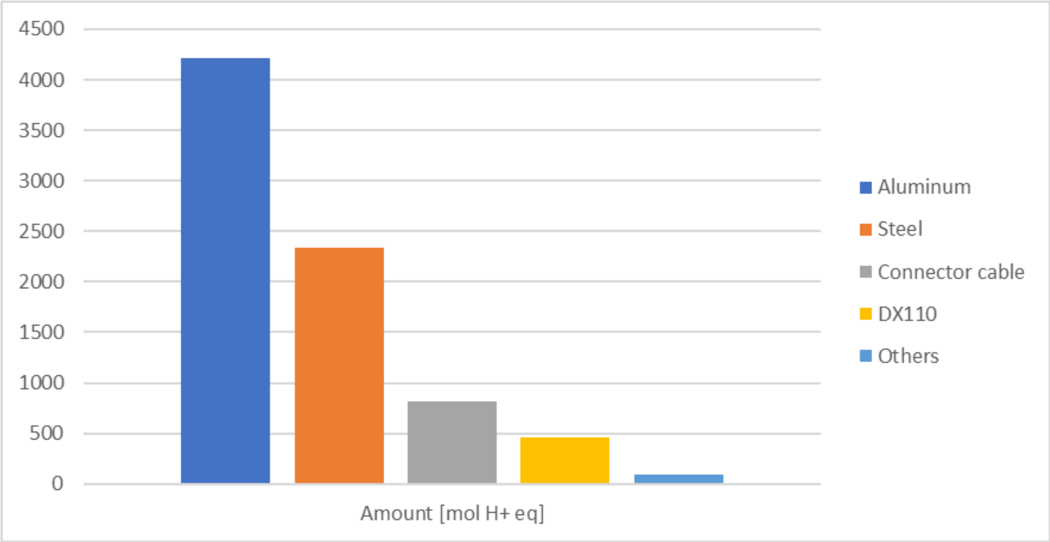

Figure 44: Graph of the robot's Processes in Manufacturing impact in acidification (55kg of Aluminium less).

Steel impact has been reduced by 51.61%.

f. Material consumption

The total material consumed by this option is 766.83kg of Substances. This is 15.57% less kg of Sb than before. Below there is the distribution for Manufacturing process:

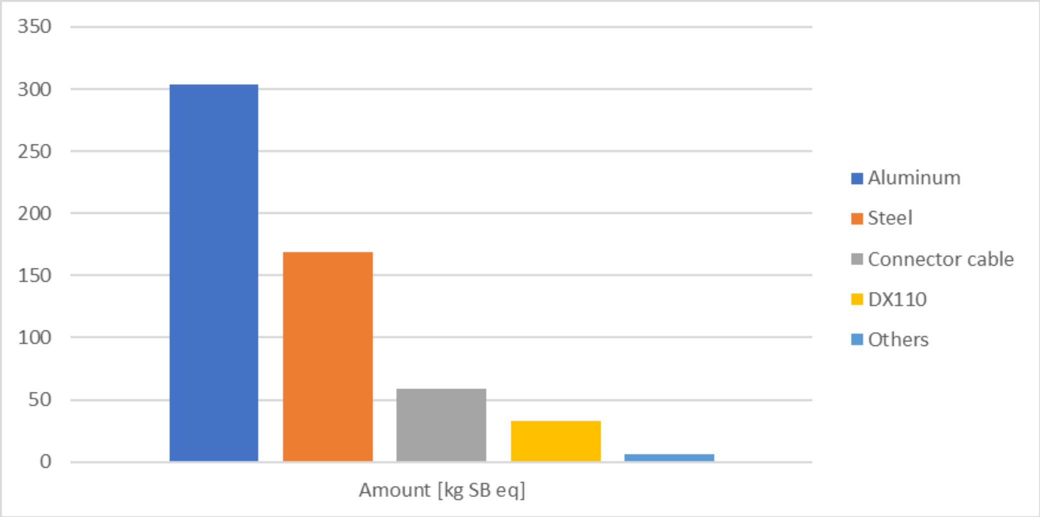

Figure 45: Graph of the robot's Processes in Manufacturing impact in material consumption (55kg of Steel less).

The total kg of Sb of Steel has been reduced in 51.61%.

g. Photochemical ozone formation

The total amount of kg of N emitted now is 9381.62kg of N. This is 15.55% less than before. The Manufacturing process has the following impacts:

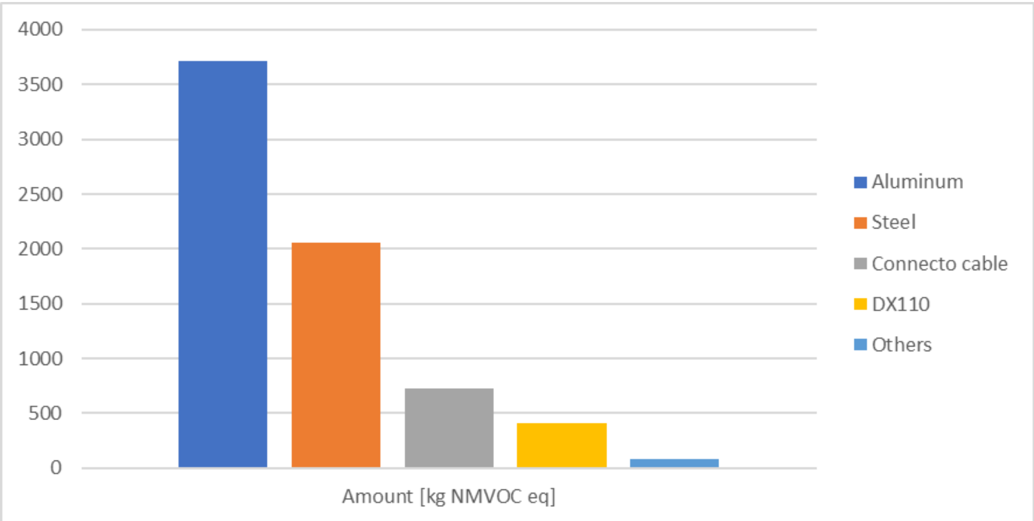

Figure 46: Graph of the robot's Processes in Manufacturing impact in photochemical ozone formation (55kg of Steel less).

Steel impact has been reduced by 51.61%.

5.3.3. Summary chart

Below there is a summary chart where it is summarized the impacts of reducing both aluminium and steel and being replaced by other materials. Considering that the original robot is 100% of the impact, here are the results:

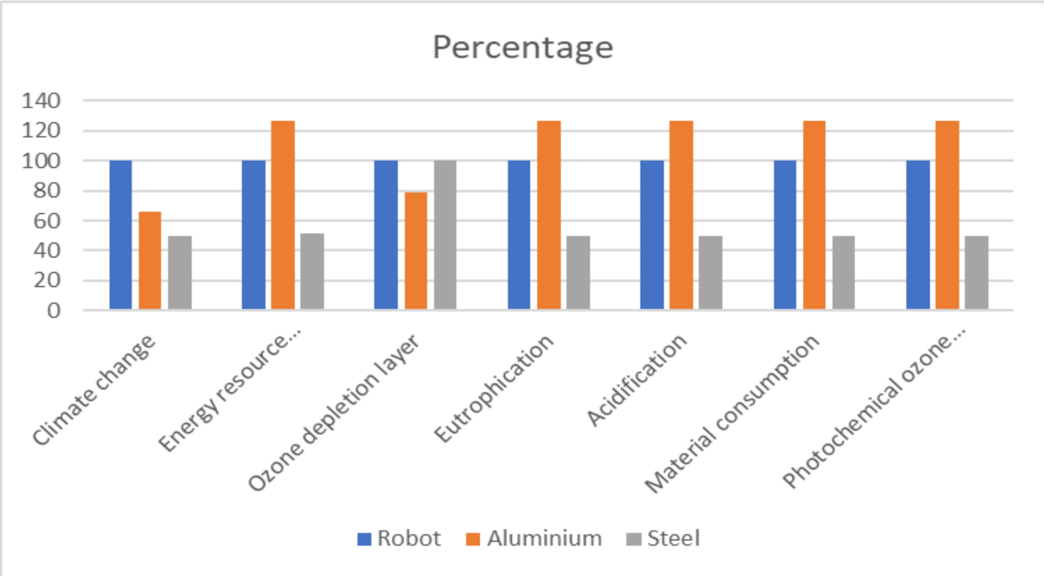

Figure 47: summary chart of sensibility analysis

As observed, for Aluminium, the environmental impact is only reduced in climate change and ozone depletion layer. So, for this material maybe it is better to keep Aluminium.

For Steel, it is seen that all the impacts categories are reduced. So, it should be better replacing Steel for Carbon Fiber, in this particular case.

5.4. Sensors LCA results

After assessing the robot's impact, it is time to analyse the impact that fixed sensors have.

5.4.1. Climate change

The total amount of kg of CO_2 produced by the fixed sensors is 143995.6kg. This is around 25 times greater than the CO_2 emissions of the robot. In the figure below it is seen how is distributed:

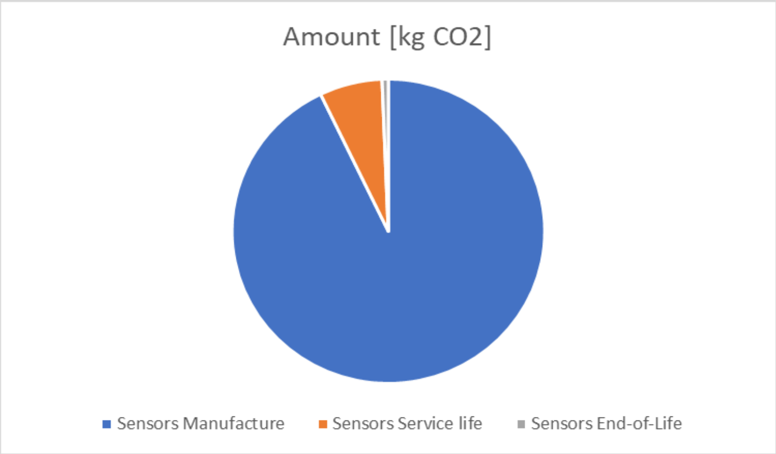

Figure 48: Graph of the sensor's processes impact in climate change.

As observed, sensors' manufacture represents the 92.86% of the total impact, with 134000kg of CO_2 emissions. This quantity is due to the manufacturing of all the copper wire needed to connect all the sensors to the data centre.

5.4.2. Energy resource consumption

The total energy consumed by sensors is 6.55x10^6 MJ (1.82x10^6 kW/h). That is sensibly less than the robot, being around 95% energy saving. Below there is the distribution of this energy:

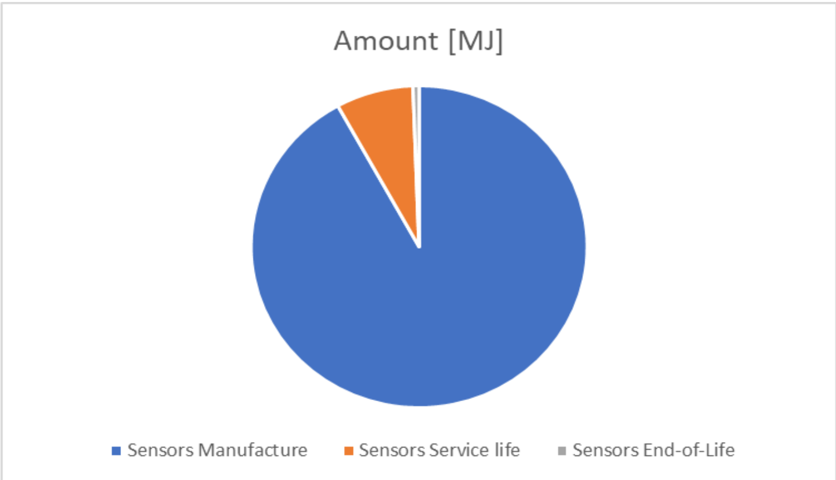

Figure 49: Graph of the sensor's processes impact in energy resource consumption.

As now seen, sensors' manufacturing process is the major contributor, representing the 91.96% of the total impact.

This energy reduction can be possibly due to that sensors don't have steel, which is a material that its manufacturing requires a lot of energy (between 20 to 50 MJ per kg).

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5.4.3. Ozone depletion layer

The total amount is 0.00324kg of CFC-11. That is approximately 100 times more kg of CFC-11 than the robot, which is a considerably amount. As seen in previous section 5.2.3, despite not being big quantities, it can have a great impact.

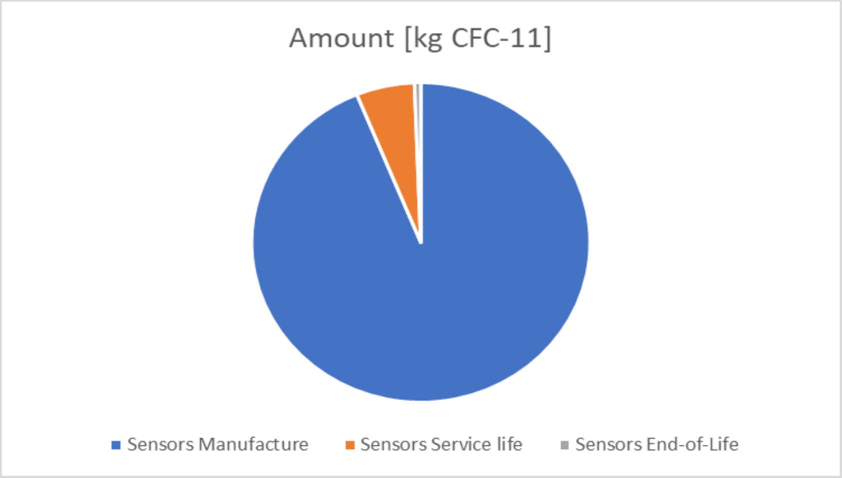

Figure 50: Graph of the sensor's processes impact in ozone depletion layer.

As seen in the graph above, the major impact is due to sensors' manufacturing, which is the 93.72%. The reason of the high increase of these gases emissions is attributed to the large production of copper to connect all the sensors.

5.4.4. Eutrophication

Fixed sensors discharge 706.53kg of N into the water. That is approximately 90% less than the quantity produced by the robot. Here is the distribution of the impact:

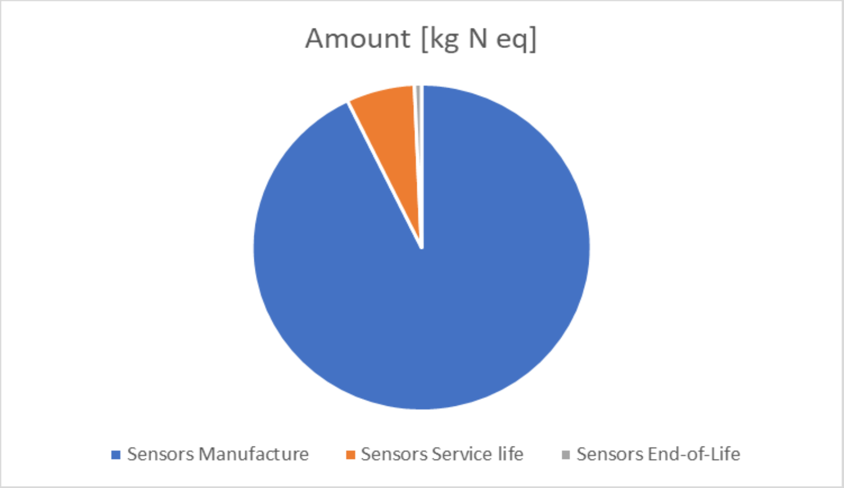

Figure 51: Graph of the sensor's processes impact in eutrophication.

Sensors' Manufacture represent 92.79% of the total impact, discharging 655.59kg of N into water.

5.4.5. Acidification

The total amount of mol H+ that is emitted to the water by fixed sensors is 1394.2 mol of H+. That is also around 90% less than the acidification produced by the robot. Below there are the processes distribution:

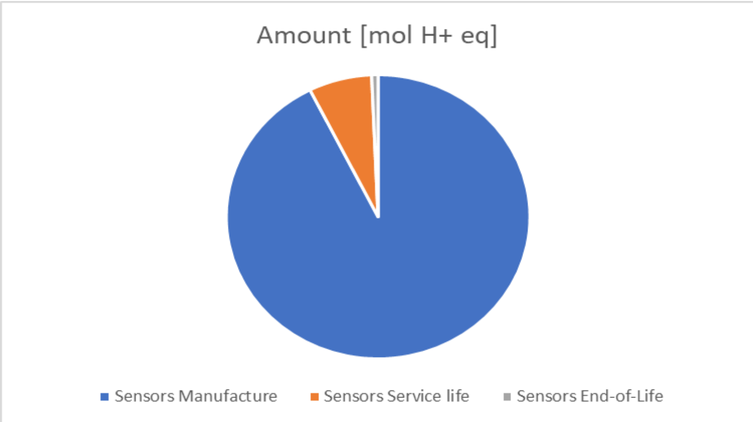

Figure 52: Graph of the sensor's processes impact in acidification.

Again, sensors' manufacture has the major impact, representing 92.60% of the total. Of this percentage, 1087 mol of H+ are produced by the copper's manufacturing.

5.4.6. Material consumption

The total kg of Substances consumed by the fixed sensors is 67.1kg. This is approximately 95% less than the robot, because the robot needs steel and aluminium, which each production consumes big amounts of substances. Below there is the distribution of the impact by processes:

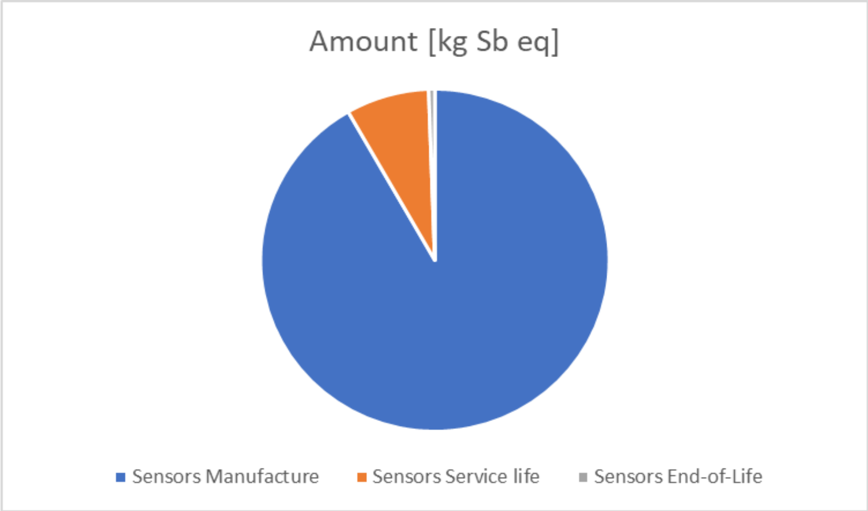

Figure 53: Graph of the robot's processes impact in material consumption.

As observed, Manufacturing process is the one that have the bigger impact, representing 91.71% of the total, again with the copper wire as the main responsible.

5.4.7. Photochemical ozone formation

The total amount of NMVOC kilograms emitted by the fixed sensors is 942.38kg, around 91% less than the quantity emitted by the robot. In the figure below is seen which processes have more impact:

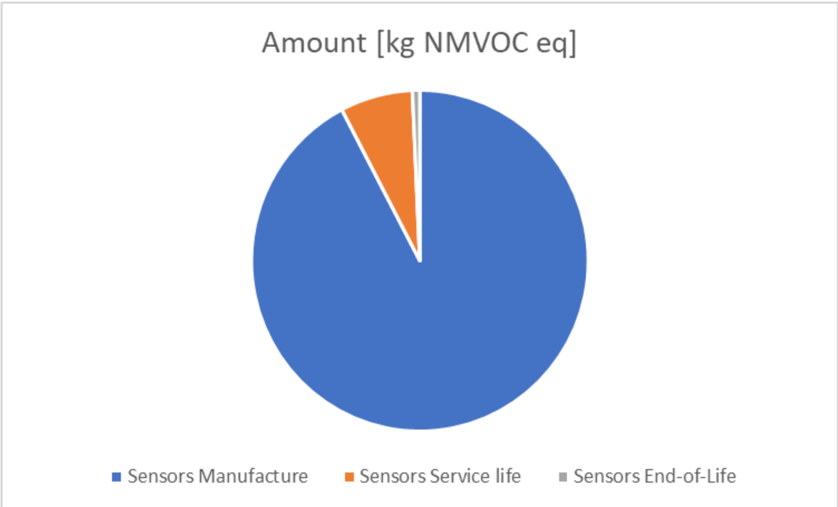

Figure 54: Graph of the robot's processes impact in photochemical ozone formation.

Sensors' manufacturing represents the 92.33% of the impact, and End-of-Life process the 6.97%, being again copper wire the process which have the biggest environmental impact, due to its large amount produced.

5.5. Summary

Overall, in the next figure it is seen in which category impacts is better the robot and where is better fixed sensors:

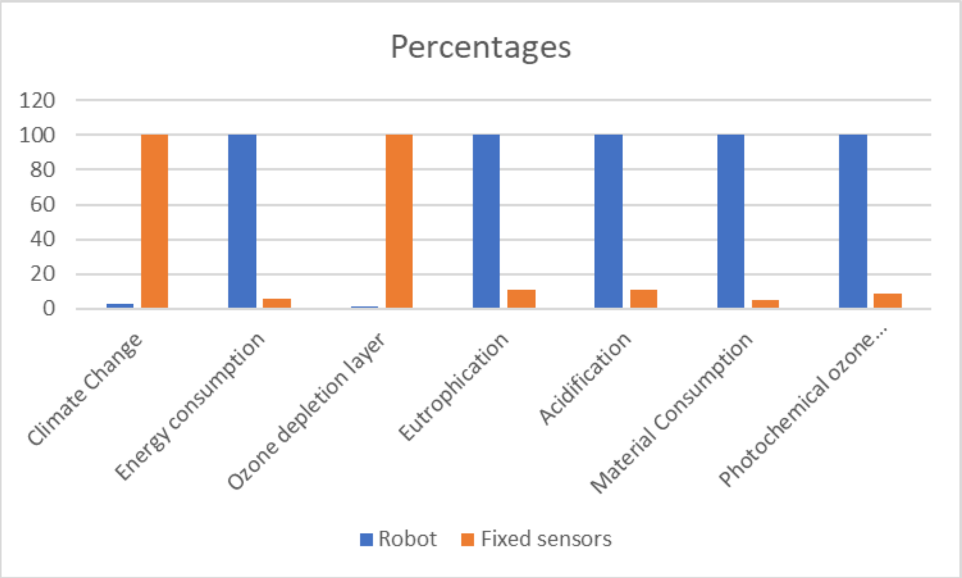

Figure 55: Summary chart of the percentages of the robot compared to the sensors.

6. Results discussion

Seeing the results obtained in Section 5, collected in Figure 55, is not easy to conclude which solution is better. Depending on which impact categories we want to minimize, robot will be better or worse.

Considering that sensors' results are an approximation and that they have been simplified and it had not been considered all the elements that conform them, they would have actually a higher impact than the currently calculated.

Focusing on climate change, which is the main category to reduce, robot has a considerably lower impact than sensors.

Then, if the energy were completely produced by renewable sources, even if the robot consumes more energy than the sensors, it would not have a great environmental impact because the energy has not been produced by polluting sources.

In addition, in the impact category "Ozone depletion layer", fixed sensors have an important quantity greater than the one emitted by the robot.

Finally, for the rest of impact categories, fixed sensors have around only the 10% of the robot's impact.

Taking all this into account and knowing all the benefits and drawbacks of each alternative, it can be concluded that the robot is a better solution. The following is a detailed explanation of why:

- Precision: robot's sensors and programming allow for precise and consistent performance, minimizing errors and reducing waste. With robots, it is possible to accurately measure data for each individual plant, while with fixed sensors, it is not possible to obtain such precision. Instead, information is known for the defined area.
- Cost-effectiveness: While the initial investment in a robot may be higher, it can lead to long-term cost savings. The robot and fixed sensors can work continuously without breaks. Also, since there are many fixed sensors, the sensors' network will require more investment in maintenance and replacements.
- Flexibility: Robots can be programmed and configured to adapt to changing needs and environments. They can easily handle increased workloads or be reprogrammed for different tasks, providing flexibility in operations.

- Convenience: With a robot, you only need to purchase it and program it to fit your specific cultivation field. In contrast, fixed sensors require purchasing them, creating infrastructure, establishing a network for device installation, and ultimately connecting them all to the electrical grid. This process can be complicated, long-lasting, and labour-intensive.

Taking all these reasons into account and focusing on the environmental impacts, it can be concluded that the robot has a lower environmental impact and therefore is a better option than fixed sensors for the particular case that has been studied.

7. Planification

A Gantt Diagram is used to explain in a visual way the planification of the project:

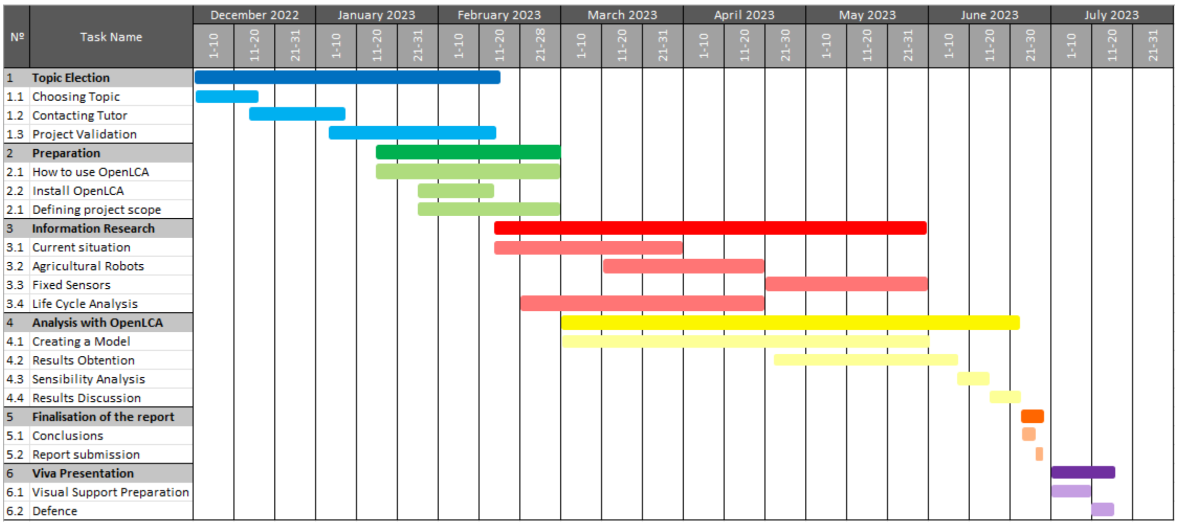

Figure 56: Gantt Diagram.

At first, is was needed to select the topic to develop the project. Once the theme was selected and validated by the tutor, it was time to start to learn how to use the OpenLCA software, which was used to make Life Cycle Analysis and to compare the two possible solutions.

Secondly, a big part of the project is to search information about the current situation and its problematics. Also, it has to be known the way the robot and the fixed sensors works.

In parallel, the robot model was generated in OpenLCA to start analysing its benefits and its environmental impact. After this, a sensibility analysis was performed to understand which elements had more impact and if they are able to be changed by others more eco-friendly or more economical. These results were compared to the ones obtained by the LCA of the fixed sensors.

Finally, conclusions were written, and the report submitted, leading to the final presentation of the project in front of the jury.

8. Studies

Economic study

The economic study of the project consists of calculating the cost of the time invested in doing all the tasks: information research, results calculation, writing the report...

Considering that this project represents 12 ECTS credits, for each credit it must be a dedication of around 25 hours and for students who are working, the minimum salary is 8€ per hour:

12 credits x 25 hours/credit x 8 €/hour = 2400 €

As the robot's design and manufacture is not considered because it is not in the scope of the project, this is the total cost of the project.

Environmental study

Although the work itself involves studying environmental impact, here we also consider the emissions produced by individuals during the execution of this work. In this way, the transportation method and route will be considered, as well as the energy consumed by computers during the project's execution.

Considering that one person consumes around 1000 kW/h by going on subway and 800 kW/h by going on bus, and we were two people going on subway, one by bus and one by bicycle, and we have had a meeting 3 times:

1000 kW/h x 2 people x 6 journeys (6 hours) = 12000 kW

And considering that a laptop consumes 0.88 kW/h and I have worked on the project around 300 hours:

0.88 kW/h x 300 hours = 264 kW

That makes a total consumption of 12264 kW.

Social and Gender equality study

From European institutions and from UPC itself, there is a call to implement objectives and promote gender equality in research and innovation, ensuring equal opportunities for men and women in scientific fields.

It is necessary to ensure that teams are composed of a diversity of genders and backgrounds, that products are designed considering the needs of all individuals regardless of their gender or abilities, and to encourage the participation of women in innovation and research by hiring more women in positions of responsibility and leadership.

Additionally, it is important to always evaluate the results from a gender perspective to ensure that there are no inequalities in the interpretation of the results.

It is necessary to close the gender and social gap in order to achieve a more just and equal society, where everyone has the same opportunities regardless of gender, background, or individual circumstances.

Conclusions

After conducting all the Life Cycle Analysis of the robot and the fixed sensors, it can be concluded that the project has successfully demonstrated the superiority of an autonomous agricultural robot solution over fixed sensors in this particular case.

As observed, the robot has a smaller environmental impact in certain relevant impact categories, thus rendering the use of fixed sensors unnecessary.

It has also been observed that by reducing the use of certain materials in the robot, its impact can be significantly reduced, indicating room for improvement.

In conclusion, the implementation of an autonomous agricultural robot is a viable option for projects with similar characteristics. Therefore, its use is recommended for future projects.

Personally, it has been a challenge to demonstrate that an autonomous agricultural robot can have a smaller environmental impact than fixed sensors, given the assumptions that had to be made in certain aspects of the project.

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