Final Report

A report submitted in partial fulfilment of the requirements for the course of
Innovation and Group Design Project (MECH0049)

Flat Iron Group

Alba Valle Espinedo
Alessandro Stringari
Nikolaos Troullinos
Edoardo Gambacorta
Frankie Leung
Ziyu Mao

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Faculty of Engineering Sciences
University College London
United Kingdom

Executive summary

This report concludes the progress and results of Flat Iron Group's weed removal robot project for the root crop farming industry in the Andean region of South America. It highlights the current agricultural practices in the region and explores the market needs, as well as the cultural, societal, and environmental aspects relevant to the development of the weed removal robot. A market gap for an affordable alternative specific to the root crop industry has been identified through the evaluation of existing products. Key design requirements include crop-weed differentiation, weed control without crop damage, and additional desirable characteristics. After evaluating six design proposals, a 'dig and grab' mechanism has been selected for further development. Upon analysing its complexity, cost, and market suitability, an earth auger-based mechanism has been deemed advantageous due to its simplicity and lower costs.

With the aid of FEA and other modelling tools, through analysis and design iterations, the design process concludes with an earth auger-based weed removal robot which eradicates weeds by the rotation of the earth auger. Its vertical and horizontal movements are supported by two separate rack and pinion systems. An Artificial Intelligence (AI) algorithm, based on Python and YOLOv3, has been developed to detect weeds among crops. The algorithm utilizes a dataset for machine learning to differentiate weed appearances. In this stage, the focus has been on identifying coriander as the target plant, and the algorithm has successfully demonstrated real-time identification of coriander presence. The design calls for the integration between the AI recognition system and the control of the auger, thus allowing the robot to scan the field, identify, target, and eliminate weeds automatically. The design also calls for the development and integration of a self-driving system that allows the robot to roam around the premises freely with minimal human intervention and supervision.

As the weed removal mechanism was considered the focal point of the project, a prototype of this was developed subsequently. The prototype was fully functional and was able to successfully demonstrate and execute the vertical, horizontal and rotational movement of the earth auger as intended. Even though the AI was capable of accurately identifying designated plants independently, due to the insufficiencies in computing power of the chosen microcontroller, the AI weed recognition algorithm was unable to be integrated with the control of the auger. The prototype consists of purchased parts and parts that are machined in-house. The lump sum of purchasing totals £474.02, reaching approximately 94.8% of the allocated £500 funding.

The manufacturing plan for RootSlice has been carefully considered, particularly on the specific requirements and sustainability aspects. The plan entails sourcing a mix of standard components and customized parts from trusted suppliers, while implementing effective inventory management and rigorous quality control processes. Additionally, the plan involves identifying skilled manufacturers capable of producing custom parts tailored to our design specifications. The manufacturing, processing, supply chain and production locations were also briefly discussed. In which, it was concluded that the robot shall be manufactured in the UK at an early stage, due to its established infrastructure, highly skilled labour force, and advanced technology.

A robust business plan has also been developed, comprising market research, marketing strategy, financial projections, and risk analysis. It has been projected that RootSlice can sell around 140 units in the first year and grows to around 340 units in sales with £1.5 million in revenue in year 4. Selling the product at £4,500 at a profit margin of 30%, it has been estimated that the farmer would be able to break even after 16 months of operation. Subsequently, the feasibility and practicality of the product were discussed alongside with feedback from a Peruvian and Chinese farmer. Proposed future actions are also outlined.

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1 Introduction

The global population has seen a positive trend for the past century, with 8.05 billion people in 2023, and it is expected to increase even further in the coming years (1). On the other hand, the global food resource is not growing as fast (2). Chemical products have become more popular in the agricultural sector to increase yield and control weed growth. However, these can be expensive and damaging for both the environment and crops (3). Weed removal is a time-consuming and labour-intensive process. This can be experienced especially in countries where technological advancement is limited due to poverty, such as Ecuador (4). Developing a low-cost and efficient product, which could help farmers to limit the growth of weeds, would help to solve and ease this difficulty. Within this report, problems related to the agricultural sector in Ecuador are researched and analysed to design and develop an autonomous robot. A detailed modelling analysis is completed, followed by a physical prototype fabrication and testing process, to later present a final design of the unique selling point. The prototyping process is described, showcasing a full list of parts to manufacture and outsource. The electronics of the weed remover are analysed, with detailed schematics for the AI system. However, only a partial section of these is implemented in the prototype due to the limited budget. A full material and manufacturing process selection is completed to identify the most efficient way of producing the product and the environmental impacts that this might have. The design is shown to potential clients both in South America and Asia, to gather feedback for future improvements. Finally, the business plan is developed, understanding the market that this product could have.

2 Project management

2.1 Group members and roles

- Alba Valle Espinedo: research, interview, modelling & analysis, and prototyping.
- Alessandro Stringari: project management, design, electronics, and prototyping.
- Edoardo Gambacorta: research, prototyping, and business plan.
- Frankie Leung: design, interview, prototyping, manufacturing.
- Nikolaos Troullinos: modelling & analysis, prototyping, and supply management.
- Ziyu Mao: electronics, interview, and prototyping.

2.2 Gantt chart

The project start date was 17/10/2022. A detailed Gantt chart was developed to have a clear overview of the project's tasks and the timeline. The chart was regularly updated, enabling an effective tracking process which guided the group towards competition. A buffer time of two weeks was allocated at the end of the project to mitigate the risk of not completing the work on time due to unforeseen events. During the project time, this was successfully used to accommodate delays encountered with the delivery of some prototyping components from an external supplier. The following milestones were identified:

1. Initial research complete - 06/11/2022
2. Final concept - 20/11/2022
3. Design approval - 27/11/2022
4. Video submission - 18/12/2022
5. Advanced research complete - 08/01/2023
6. Final design complete - 29/01/2023
7. Electronics complete - 05/02/2023
8. List of parts and costs - 19/02/2023
9. Mid-report submission - 03/03/2023
10. Prototype assembled - 23/04/2023
11. System functioning - 30/04/2023
12. Feedback implemented - 07/04/2023
13. Client interviews completed - 05/06/2023
14. Manufacturing analysis completed - 21/05/2023
15. Business plant completed - 28/05/2023
16. Final presentation concluded - 06/06/2023
17. Final group report submission - 10/06/2023
18. Project complete – 10/06/2023

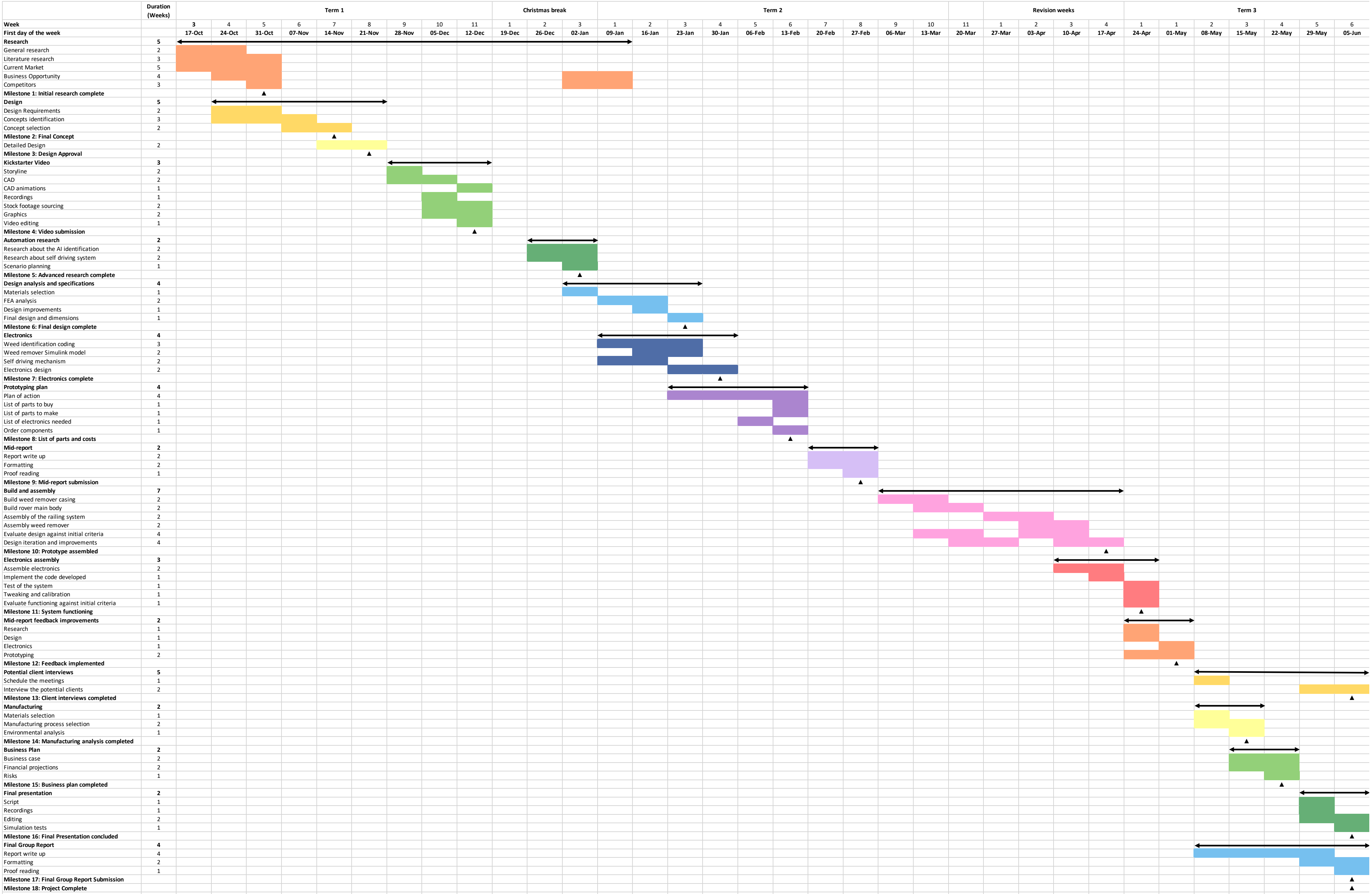

Figure 1 – Gantt chart

3 Research

3.1 Technical background

More than 90,000 farmers grow potato crops in Ecuador on over 60,000 hectares of agricultural land. It is highlighted the importance that the introduction of the autonomous weeding robot RootSlice fits in with the agricultural practices and traditions that farmers in Ecuador have adopted for thousands of years (5). Potato production in Ecuador occurs in the Andean region, with over 4,000 different varieties of native potatoes (6). These are one of the main crops produced in Ecuador and crops require an effective and sustainable weed control solution as on average, weeds decrease the yield by 54.8% in every harvest (7). Moreover, the design of the robot can work with other root crops such as carrots, sweet potatoes, and cassava, potentially helping over 14 million small-sized farmers in different developing countries including Colombia, Peru, Ecuador, and Brazil. RootSlice aims to help small/mid-size farmers as previous studies suggest most potato farms in Ecuador are less than 2 hectares of agricultural land and the potato crops are commonly grown 2,900-3,300 metres above sea level (8). The robot is thus designed to operate in accordance with these dimensions.

Moreover, the potato plant growth can reach up to 100 cm in height (9). Ridges created around the stems of the potatoes reach a height between 20-30 cm (10). Although weeds found in potato crops, *Galinsoga parviflora*, are commonly around 30 cm in height, they can grow up to 60 cm high (11). Clearance between the robot and the potato crop ensures there is no negative interference in the potato crop growth. RootSlice is thus designed with a clearance of one metre in accordance with the dimensions found in both potato crops including the height of the ridge, and their weeds. Potato trenches commonly have a width of approximately 15 cm (12), and the spacing between rows is approximately 60 to 90 cm, with 60 cm benefitting the soil by avoiding high soil temperatures through shading (13).

Furthermore, there are several technical considerations in the final design of the robot for sustainable weed control given the complex agricultural environment (14). The previously mentioned crop characteristics alongside terrain adaptation are crucial considering the characteristic high-altitude found in the Andean region (8). Autonomous weeding robots are thus designed to maximise both the automation aspect alongside the precision with machine learning and AI, crucial for the sustainable development of the agricultural sector (14). Moreover, durability alongside energy efficiency including renewable energy is employed to cover for the predicted operational time of the weeding robot.

3.2 Market research

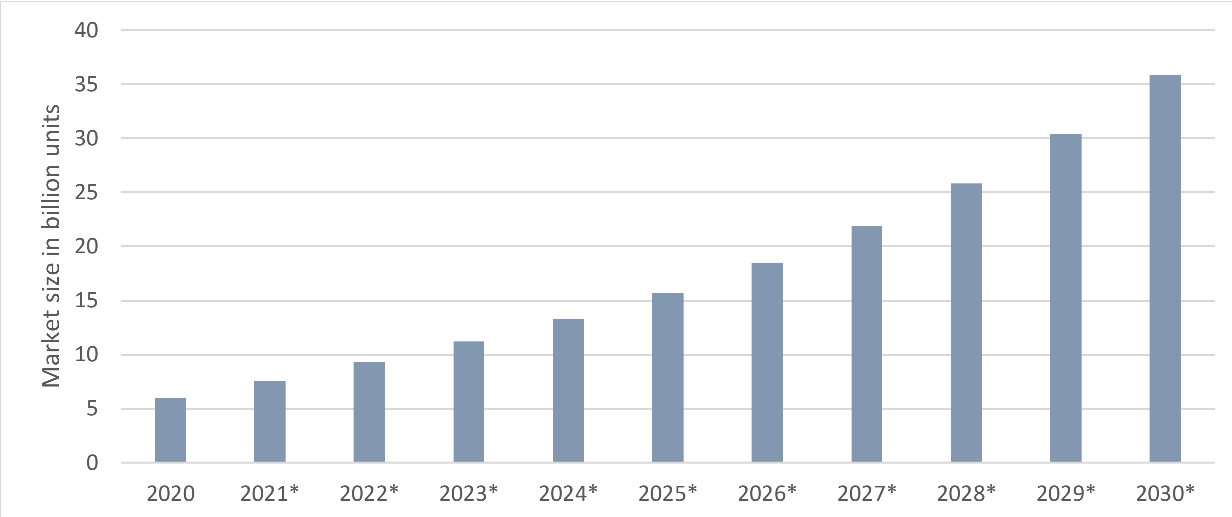

Figure 2 – Size of the of the autonomous robot for agriculture market Global market volume of agricultural robots from 2020 to 2030 (15)

The agricultural robot industry is expected to experience significant growth in the coming years, with a current market size of 11.2 billion units, projected to reach 35.9 billion units by 2030 (15). This can be attributed to a variety of factors. Firstly, there has been increasing interest in precision agriculture, a strategy used to manage crop production inputs in an environmentally friendly way, allowing farmers to reduce waste and make better use of their resources (16). Secondly, labour shortages in the agricultural sector, mainly due to migration, are driving up the demand for agricultural robots (17). Implementing automated systems can compensate for the shortage of human labour and increase productivity. Lastly, the rising global population and increasing demand for food have created a need for more efficient agricultural practices. All these factors combined, with recent technological advancements in robotics and AI are encouraging the development of highly advanced agricultural robots. This presents an immense opportunity for RootSlice, which aims to target autonomous weed removal in potato crops situated in developing countries including Ecuador, Peru, Brazil, and Columbia. Going ahead of this period of growth RootSlice would become a key player in the industry of this rapidly expanding market.

In 2017 Ecuador produced 377k tons of potatoes and 4k tons of sweet potatoes. Over the past decade, production has fallen from 450k to 377 (18). For this reason, RootSlice aims to target Ecuadorian farms as our primary goal, to help bring back or improve previous rates of productivity. Implementing weed removal robots in Ecuadorian potato crops presents a radical shift as the country's potato production is becoming more commercially oriented. In terms of the amount produced, Peru has the largest share, with an output of 4,776k tons of potatoes, followed by Brazil, with 3,656k tons (19)(18).

Table 1 – Potato and sweet potato production (tons) for 2017 *(17–20)*

Country	Potatoes Production (tons) - 2017	Sweet Potato Production (tons) - 2017
Ecuador	377,243	4,002
Brazil	3,656,850	776,285
Columbia	2,819,030	N/A
Peru	4,776,290	256,434

Having a large area of harvesting does not necessarily account for higher production. For example, Peru produces potatoes over an area of 310,000 hectares, which is more than double Brazil's harvested area(19,20). In the last decade, the harvested area in Columbia has shrunk from 170,000 to 149,000 hectares and similarly, this has occurred in Ecuador, where the cultivated area was reduced from 65,000 to 50,000 hectares(18,21).

Table 2 – Potato and sweet potato area harvested (ha) for 2017 (18–21)

Country	**Potatoes Area Harvested (ha) - 2017**	**Sweet Potato Area Harvested (ha) - 2017**
Ecuador	29,532	2339
Brazil	118,030	53,480
Columbia	149,060	N/A
Peru	310,400	14,167

This significant shrinkage of area harvested in potato crops is related to various factors including labour shortages, and inefficiencies in the harvesting process. Thus, implementing RootSlice into potato, cassava and sweet potato crop production in the countries mentioned above, will boost productivity and yield. The autonomous weed removal system can work continuously and accurately, relieving human resources. Introducing a mechanical solution to eradicating weeds will reduce the use of harmful herbicides, which will benefit both farmers and consumers.

3.3 Cultural, societal, diversity & inclusion factors

The sustainable introduction of autonomous weeding robots into the agricultural sector in Ecuador aims to deeply consider the cultural, societal, diversity and inclusion factors for technology with the potential to overcome the challenges within the agricultural sector (22). Cultural factors include traditional agricultural practices that Ecuadorian farmers have adopted for thousands of years. This is part of their culture and thus the design of the agricultural robot is aimed to preserve their traditions. Furthermore, inclusion factors are considered in detail, comprising the need for a robot design that is widely accessible to farmers in developing countries (22). For the design of RootSlice, an initial interview with a local farmer from Ecuador is thus conducted in order to assure the agricultural product is in line with the small-midsized Ecuadorian farmer's needs (5). Thus, to ensure the wide adoption of the product, the design of the robot focuses on user-friendliness, allowing farmers with no technical background to easily operate and maintain the robot. Societal factors with the introduction of RootSlice include the potential job reduction considering there are over 90,000 potato Ecuadorian farmers. This negatively affects the local economy given agriculture in Ecuador is one of the main sectors of employment (5). Political issues may thus arise from the integration of weeding technology, potentially leading to the implementation of policies aimed to protect employment and make sure benefits are equally distributed amongst local farmers (23). Furthermore, there is a strong correlation between climate change and agriculture, with greenhouse gases leading to extreme weather events (23). This can directly have a negative effect on agricultural yields and consequently impact local market prices (23). Moreover, consideration of diversity factors in developing countries such as Ecuador is crucial, given the population is diverse in terms of both different cultural and educational backgrounds. Different traditions, as well as languages, highlight the importance of designing an agricultural robot that is accessible to small-midsized farmers with different backgrounds (22).

3.4 Review of the environmental sustainability

The agricultural robot market holds the potential to become environmentally sustainable in the future and promote sustainable practices. Although there are currently several challenges associated, regulatory bodies, manufacturers, and consumers are increasingly aware of implementing sustainable technologies. The development of environmentally sustainable products alongside emerging new technologies in the agricultural sector is in turn encouraged by this existing socio-politically driven trend. Sustainable agriculture encompasses the reduction of pesticide use and in turn benefitting the quality of both soil and water (24). Moreover, the disposal of batteries at the end of the autonomous weeding robot lifecycle alongside material recycling is a problem commonly left unresolved. A sustainable approach should be taken in order to maximise the sustainability of the product sector (24). Furthermore, agricultural robots powered by renewable energy, in a country where reliable electricity access can be a challenge, can significantly contribute to a reduction of carbon emissions and align with the sustainable development goals (25). The use of recyclable materials during the first stages of the design is not only a unique selling point but can potentially positively contribute to the percentage of recyclable materials at the end of the product lifecycle (25). Thus, deepening the understanding of the strong interconnection between market demand, sustainability and technology is crucial for thriving in the weeding robot market.

3.3 Interview and feedback from the target market

RootSlice has carried out an initial interview with a potato farmer located in Peru in order to gain valuable knowledge from the farmers in a developing country and turn tailor the product to the market needs. Following the feedback gained from the interview, RootSlice is designed to be as lightweight as possible to avoid impacting the soil, as well as contain pH and humidity sensors.

Manuel Choqque Bravo is a fourth-generation farmer, his family farm is located in the Peruvian Andes, where he grows over 300 different varieties of potatoes. Manuel is employing manual cross-pollination techniques on his potato farm and has recently successfully produced wine from his potatoes with the highest sugar content (26). The interview dialogue with Mr Manuel Choqque Bravo is enclosed in Appendix B. In the interview, he discussed the labour-intensive and environmentally harmful methods of weed control and the urgent need for a lightweight and easy-to-use system that could measure soil pH, nutrient levels, and humidity. He emphasised the importance of tailoring the robot to fit in with ancestral techniques and tools.

4 Design

4.1 Design methods

As outlined in the design brief, the primary objective of the project is to develop an autonomous robot that assists local farmers in effectively managing and reducing weed growth. Based on careful consideration, the robot is expected to meet the following essential requirements:

- *Detection and Differentiation:* The robot must possess the ability to accurately detect and differentiate between crops and weeds. This functionality is crucial for effective weed control.

- *Weed Population Management*: The robot should be equipped with mechanisms to control the weed population either through weed eradication or by deterring weed growth. This capability ensures that weed interference is minimised.
- *Crop Protection*: It is imperative for the robot to carry out weed control operations without causing any harm to the crops. This feature ensures the preservation and health of the desired crops.
- *Adaptability to Local Terrain and Environmental Conditions:* The robot must be designed to withstand and operate effectively in the diverse terrains and environmental conditions present in Ecuadorian potato fields. This adaptability is essential for successful implementation.
- *Low Toxicity*: The use of environmentally friendly and low-toxicity methods for weed control is a key consideration. The robot should prioritise methods that have a minimal negative impact on the environment and human health.
- *High Durability*. Given the demanding nature of agricultural operations, the robot should be built to withstand harsh conditions, ensuring durability and longevity.
- *Long Operating Range*: The robot should have a sufficient operating range, capable of continuous operation for at least 12 hours. This feature ensures that the robot can cover a substantial area in a single operational cycle.

Furthermore, the project team has identified several additional features and characteristics that would be advantageous for the robot to possess:

- Easy to operate as it may be used by farmers with limited literacy and numeracy.
- Highly automated operation with minimal need for human input and intervention.
- High energy efficiency.
- Low maintenance frequency, while being easy to maintain.
- Suitable for encountering a large variety of weeds.
- Affordable to low-income farmers in developing countries.
- Enabling remote control and internet connection.
- Off-the-shelf components.
- Utilising sustainable and recyclable materials, with a low carbon footprint during manufacturing.
- The operation sequence is adjustable to the user.
- Low noise pollution.
- Equipped with built-in machine learning and AI to optimise operating sequences.

Following the initial ideation phase, several ideas were proposed for weed control, including a rover equipped with a hot wire cutter, a gantry system-based weed picker, and a 'dug and grab' mechanism to be integrated with a rover.

4.2 Evaluation criteria

Subsequently, the ideas were further developed and evaluated using a set of predetermined criteria with varying weightings (Table 3). The evaluation process involved assessing each idea against the established criteria to determine its suitability and potential effectiveness in meeting the project objectives. The criteria considered factors such as cost, feasibility, efficiency, crop compatibility, and adaptability to the Ecuadorian potato field environment. By assigning different weightings to each criterion, the evaluation process ensured that the most critical factors were given appropriate consideration during the decision-making process. This approach enabled the project team to objectively assess and compare the ideas, ultimately identifying the most promising concepts for further development. The evaluation and weighting of criteria provided a structured and systematic approach to ensure that the selected idea or combination of ideas aligned with the project goals and constraints. This data-driven decision-making process serves as a valuable tool in determining the most viable and effective solution for the weed control robot.

Table 3 – Weighted Scoring Matrix

*Rating **(Weighted rating)**	**Weighting**	Hot Wire cutter rover		Chemical sprayer rover		'Dig and grab' rover		Blade rover		Gantry system weed picker.		Herbicide spraying Drone	
Safety	**5**	1	**(5)**	2	**(10)**	5	**(25)**	2	**(10)**	4	**(20)**	1	**(5)**
Level of automation	**5**	3	**(15)**	3	**(15)**	4	**(20)**	3	**(15)**	3	**(15)**	4	**(20)**
Sustainability	**4**	1	**(4)**	1	**(4)**	4	**(16)**	3	**(12)**	3	**(12)**	1	**(4)**
Energy needed	**4**	1	**(4)**	4	**(16)**	3	**(12)**	3	**(12)**	2	**(8)**	1	**(4)**
Maintenance difficulty	**4**	3	**(12)**	2	**(8)**	3	**(12)**	3	**(12)**	2	**(8)**	2	**(8)**
Expected capital cost	**4**	3	**(12)**	3	**(12)**	3	**(12)**	3	**(12)**	2	**(8)**	2	**(8)**
Expected operational cost	**4**	4	**(16)**	2	**(8)**	4	**(16)**	4	**(16)**	2	**(8)**	2	**(8)**
Mechanism Efficiency	**4**	2	**(8)**	1	**(4)**	5	**(20)**	2	**(8)**	4	**(16)**	1	**(4)**
Mechanism complexity	**3**	4	**(12)**	3	**(9)**	3	**(9)**	3	**(9)**	2	**(6)**	1	**(3)**
Range of weeds	**2**	3	**(6)**	4	**(8)**	3	**(6)**	3	**(6)**	3	**(6)**	4	**(8)**
Range of crops	**2**	3	**(6)**	2	**(4)**	3	**(6)**	2	**(4)**	4	**(8)**	4	**(8)**
Efficiency/ Time needed	**2**	3	**(6)**	3	**(6)**	3	**(6)**	3	**(6)**	2	**(4)**	3	**(6)**
Weighted total score		-	**(106)**	-	**(104)**	-	**(160)**	-	**(122)**	-	**(119)**	-	**(86)**

After careful evaluation, the concept of a rover integrated with a 'dig and grab' mechanism emerged as the top-scoring idea. This concept received high ratings, particularly in the areas of safety and mechanism complexity. It offers a balance between effectiveness and feasibility, making it a promising solution for weed control in potato fields. This choice sets the stage for further development and refinement of the selected idea, bringing us closer to delivering an efficient and safe weed removal solution for Andean region farmers. Restrictions on time and physical resources did not allow the prototyping and testing process to be conducted to compare the various weed removal mechanisms proposed.

4.3 Concept designs

The top-scoring idea, a rover integrated with a 'dig and grab' mechanism, has shown great promise, particularly in terms of safety and mechanism complexity. The mechanism has been developed, including a preliminary concept CAD (Figures 3 and 4). The rover is equipped with a shovel and two metal plates with horizontal blades. The process involves a sequence of motions: the shovel digs underneath the weed, lifts it towards the blades, the blades engage and cut the weed, and finally, the shovel returns to its starting position, dropping the weed back to the ground. The gantry system ensures accurate positioning based on the image-based weed recognition algorithm.

Figure 3 – Initial CAD of the rover with the 'dig and grab' mechanism (open position).

Figure 4 – Initial CAD of the rover with the 'dig and grab' mechanism (close position)

However, further analysis identified significant drawbacks with this mechanism. It requires additional motors for the shovel and blades, adding complexity and cost. The actuation system and mechanical configuration are intricate, leading to concerns about maintenance and repair, as well as increased power consumption. In light of these concerns, an alternative, simpler mechanism was explored: a single helical auger drill bit, similar to those used in earth auger machines.

The market for potato farming and other root vegetables in South America is substantial and plays a crucial role in global food security. However, weed overgrowth has been a persistent and costly issue for farmers in the region, leading to a demand for an autonomous robot that can effectively discourage weed growth. In an interview with Mr. Manuel Choqque Bravo, an Andean potato farmer, several challenges faced by farmers in the region were highlighted. The labour-intensive nature of weed removal has led many farmers to abandon their farms, while the use of herbicides has resulted in soil contamination. Mr. Choqque expressed the need for a lightweight robot that can remove weeds from their roots by generating holes in the soil. Soil compaction is a concern, as it can negatively impact potato yields by reducing water uptake. Additionally, the robot should be easy to operate, keeping in mind that farmers in the Peruvian Andes adhere to traditional agricultural techniques and tools. Mr. Choqque also mentioned the importance of the robot being able to measure soil properties and humidity, particularly due to recent drought problems in the area. Potato farms in the Andes vary in size and are slightly inclined, further emphasizing the need for a weed-removing robot tailored to the specific needs of farmers in Peru and other developing countries.

Maintenance and repair of the robot are crucial considerations for farmers. To address this, modularisation shall be implemented, allowing the robot to be disassembled into smaller independent clusters for easy maintenance (14). Reliability and autonomy are also important factors, considering the unstructured farming conditions (27) Effective weed recognition that can operate under varying weather and lighting conditions is deemed beneficial (28). Currently, K-means (29), random forest (RF) (30), SVM (31), Bayesian decision (32), and k-nearest neighbour (KNN) (33) are the most common classifying methods for weed and crop identification. In addition, the deep learning methods used for weed recognition would mainly be supervised learning (34). Row guidance systems can be implemented on farms to assist with the identification process (35). In the existing market, there are no known weed-removing robots specifically designed for the root crop field market, with the majority of robots being developed for paddy fields and vegetables (36). Common physical weed removal methods include mechanical intra- and inter-row cultivation, thermal weed control, abrasion, and mowing. This highlights the potential market opportunity for a specialised weed removal robot for the root crop farming sector (37).

4.4 Final design

Figure 5 illustrates the outlook of the robot, while Figures 6, 7 and 8 detail the design of the weed remover mechanism. This works by positioning the auger left and right through a pinion and linear gear rack system. Once the auger is correctly positioned, it is lowered into the ground through another pinion and linear gear rack system. Approaching the ground, a motor spins the auger, thus eliminating the weed underneath. The auger needs to be programmed to go a few millimetres below ground, to ensure the roots are removed. Having completed this process, the auger is retracted while spinning in the reverse direction, without leaving any holes in the soil. A sliding mechanism was designed to ensure that the weed remover would remain in place while working the ground. A notch on each side of the supporting elements and a matching lip on the boxes containing the motors do not allow a vertical motion for the motor container. The simplicity of the machine allows the parts to be replaced and maintained easily. Similar to the previous design of the rover, this is fitted with sensors and microcontrollers to allow weed recognition and self-driving.

Figure 5 – Robot model without accessories, showing the overall dimensions


Figure 6 – Weed remover system

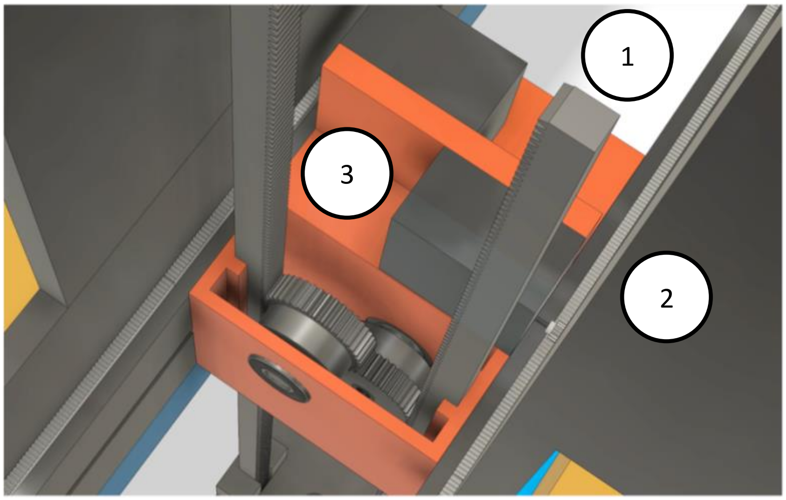

Figure 7 – Close view of the gears box system

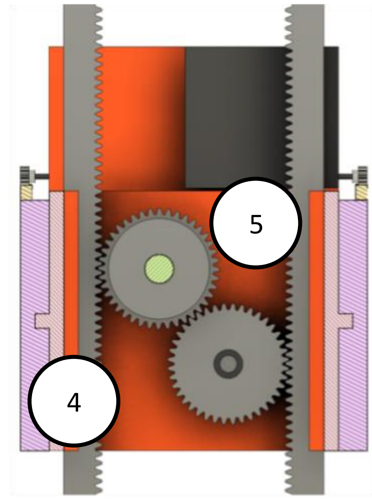

Figure 8 – Section view of the up and down mechanism

Table 4 – Features list

Number	Component
1	Up and down racks
2	Left and right racks
3	Left and right motors
4	Section view of the sliding support
5	Up and down gears

5 Modelling and Analysis

5.1 Weed killing mechanism design analysis

An Excel model was developed in order to determine the most appropriate weed-killing mechanism both in terms of cost and energy efficiency. The model was used to capture and predict the whole mechanism's movement, from being pulled out of the soil until it was entirely out of the ground and returned to its initial position. It was essential to consider the gravitational force acting on the auger until this reaches its rest position. The simulator could produce valuable results and graphs for each motor selection, such as displacement/rotation and energy consumed against time. Therefore, the optimal motor solution with the lowest possible energy consumption could be identified and assist in the research for the most affordable available motor selection.

Through physical equations and laws, the model's results were based on the relationship between object movement and the motor's speed-torque ratio. The simulation process was split and divided into concise timesteps. An overview of the model's calculating approach is depicted in Figure 9. It was assumed that the acceleration of the moving object was constant during each timestep. Therefore, as illustrated in

Figure 9, the acceleration of the previous time step was used to calculate linear velocity and displacement through Equations 1 and 2, respectively.

Equation 1 – Linear Velocity

$$V = \alpha \cdot t$$

Equation 2 – Displacement

$$X = V \cdot t + \frac{1}{2}\alpha \cdot t^2$$

Where α is the acceleration of the previous timestep, t is the time of each timestep, V is the velocity, and X is the distance covered.

Furthermore, the object's velocity was directly related to the motor's rotational speed since the same gear connected them. Also, since the motor was fully powered at all times, torque production was linearly affected by the rotational speed, as shown in Equation 3. Therefore, both forces acted by the motor on the object and energy consumed for each timestep could be estimated from Equations 4 and 5, respectively.

Moreover, in the context of pulling out tools such as the auger from the ground, soil resistance, also known as "pullout" resistance, is a critical factor that must be considered. It is affected by several factors, such as soil type, moisture content, burial depth, and the object's size. Hence, a simplified linear decreasing model has been used to estimate soil resistance as the auger is pulled out, shown in Equation 6, where A is the area of the Auger, H is Auger's length and K is the soil coefficient. The soil coefficient, K, is a frictional forcing factor affected by soil type and moisture content and will be estimated for various soil applications from real experimental observations.

Finally, based on Newton's second law, since forces acted on the moving object have been calculated, the acceleration of the current time step was estimated through Equation 7.

Equation 3 – Torque of motor

$$T = T_M - \omega \cdot \frac{T_M}{\omega_M}$$

Equation 4 – Lifting Force

$$F_m = \frac{T}{r}$$

Equation 5 – Energy consumed

$$E = T \cdot \omega \cdot t$$

Equation 6 – Soil Resistance

$$F_s = A \cdot K \cdot (H - X), \qquad for\, X < H$$

Equation 7 – Acceleration

$$\alpha = \frac{F_m - F_s - F_g}{m}$$

T is the motor's torque, ω is the angular velocity, T_M and ω_M are the maximum motor's torque and angular velocity, F_m is the motor's force acting on the object, r is the connecting pitch radius, E is the energy, and F_g is the gravitational force on the object. However, in the very first timestep, before the object started moving, all the boundary conditions were known as the motor's maximum torque and the mass of the moving objects was specified in the model. Therefore, the above process was repeated for 25,000 timesteps.

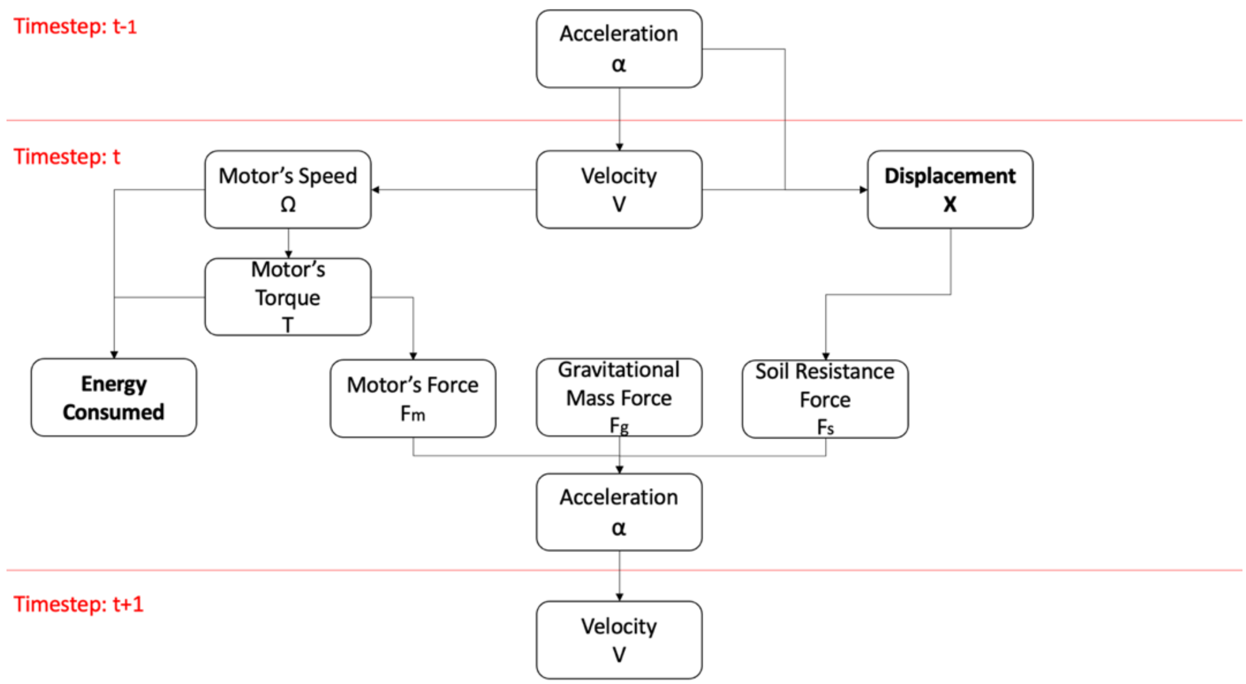

Figure 9 – Simulation Model Progress Overview

Regarding time efficiency, the prototype aims for a 20-second weed removal process. All steps of the mechanism activation are included within this time range, such as lowering the auger, eradicating weeds and raising the auger function. Therefore, it was calculated that a maximum of 5 seconds could be spent on the drilling mechanism lifting process. According to the above model, a lifting simulation of the drilling mechanism was pursued based on the RS PRO Brushed Geared DC motor (19.8 W, 12 V dc, 98 Ncm, 120 rpm), the RootSlice design specifications and an ideal non-measured soil coefficient. As depicted in Figure 10, the motor is capable of lifting the drilling mechanism in approximately 4.6 seconds, while less than 13 Watts will be consumed. Furthermore, design specifications and time/energy goals may be altered for the actual product and inputted into the simulation model for an updated motor selection.

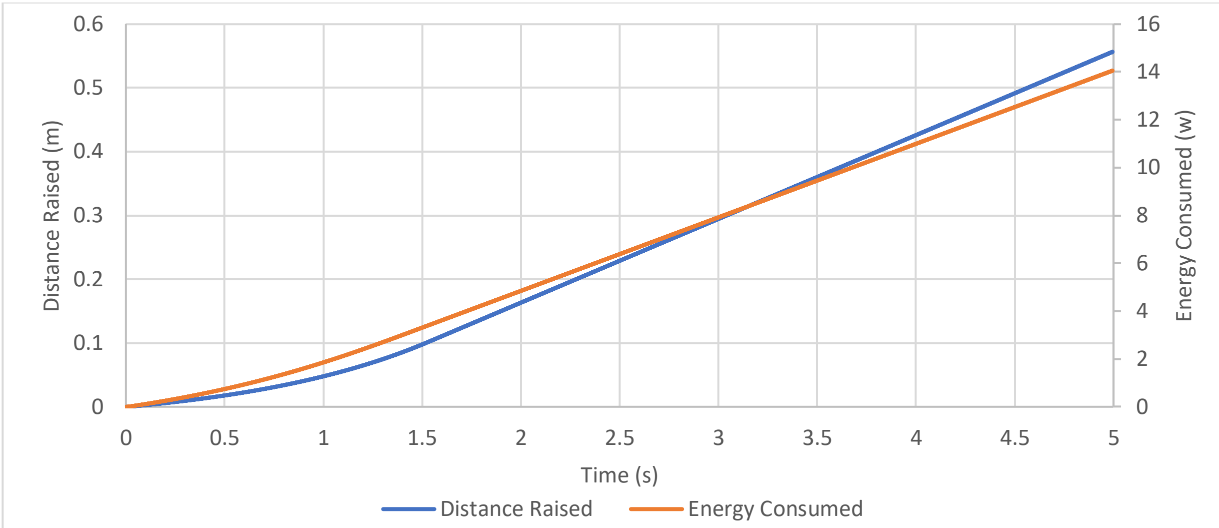

Figure 10 – RS PRO Brushed Geared DC Motor Initial Results

5.2 Materials selection

Material selection is crucial to ensure the performance of the robot, in which each part would have its own specific material properties requirements, further discussed in Section 8.2. Based on the given material properties requirements, three materials were proposed for each custom part to be investigated. A comprehensive Finite Element Analysis (FEA) was carried out on the RootSlice to gauge its structural resilience. FEA, a computational technique, is pivotal in estimating the stress, strain, and displacement experienced by materials and structures due to internal and external forces. This specific analysis involved executing an FEA for each component detailed in Table 5, using three different materials for each. The evaluation considered various load factors, including the mass of the materials and components, unexpectedly increased vibrational force, and a safety margin of 20%. This methodical approach thoroughly examined the product's structural integrity under various loading conditions.

Upon examination of RootSlice, as illustrated in Figures 11 and 12, it was noted that the main body's components, including the main case, case divisor, battery supports, lidar supports, and upper covers, sustained either no or minimal negligible deformation across all conceivable load scenarios and material combinations. A safety factor exceeding 10 was derived from the tests on these components. Within the context of FEA, this term accommodates a safety margin surpassing the theoretical design capacity, offering a buffer for any unexpected variables (38). It signifies a quantifiable measure of a system's structural capacity exceeding anticipated or factual loads. It establishes a ratio between the material's strength and the maximum stress present within the design. Generally, safety factors are understood to commence from a value of 1.5, and can extend up to 6, contingent upon the criticality of the specific application (39).

In the current scenario, the extraordinarily high safety factors of the components may suggest a viable opportunity for minimising the volume of material utilised in the design. This has the potential to curtail production costs effectively.

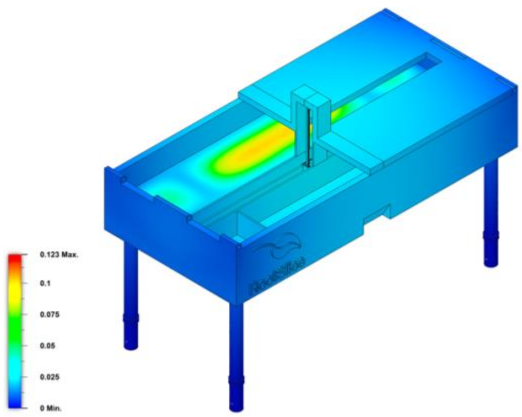

Figure 11 – FEA Assembly Results with Working Materials.

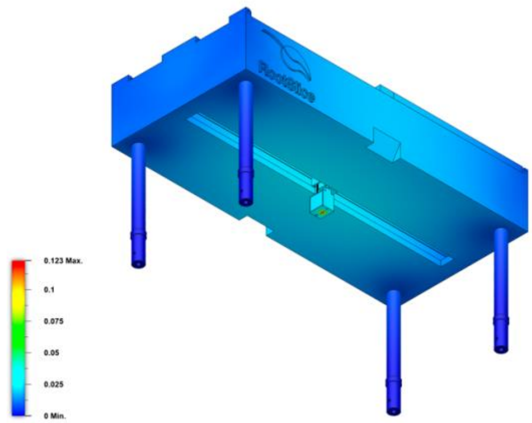

Figure 12 – FEA Assembly Results with Working Materials.

Nonetheless, as depicted in Figure 13, the point of interest within the main body was identified in the drill case. Although the current design of the case delivered acceptable deflections for all proposed materials under the anticipated loading conditions, with a measurement of 0.2362mm for the most cost-effective material, Polypropylene (PP), in Figure 14, a marginally adequate safety factor of 5.4 was determined for PP. Consequently, it is recommended to initiate additional laboratory testing specifically for the drill case in order to evaluate its structural integrity more thoroughly.

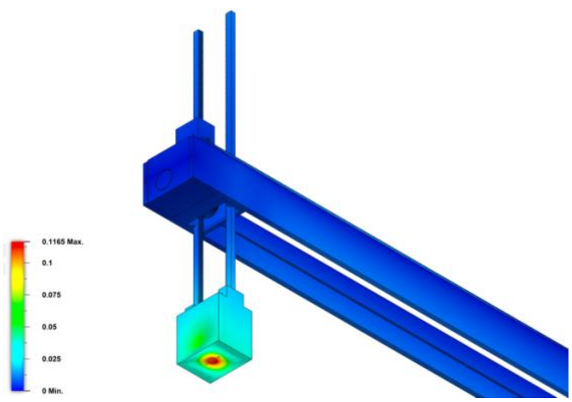

Figure 13 – FEA Mechanism Assembly Results

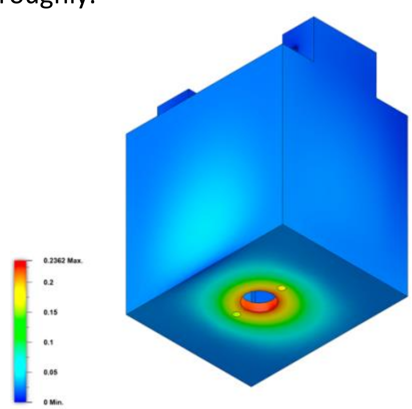

Figure 14 – FEA Results of a PP Drill Case

Furthermore, regarding the vertical standing elements of the RootSlice, an FEA was also carried out on the legs and the wheel shafts. As depicted in Figures 15, 16, and 17, where shafts of Polypropylene (PP), aluminium, and stainless steel were subjected to the loading conditions, only the stainless steel proved resilient, maintaining its original form. Conversely, the PP and aluminium shafts exhibited substantially higher deformations at the points of interest, registering inadequate safety factors of 3.89 and 5.12, respectively for this application.

Similarly, as evidenced by Figure 18, the Polyvinyl Chloride (PVC) legs failed to meet the required structural integrity standards under the anticipated loading conditions, resulting in a significant deflection of 2.617 mm. Consequently, aluminium was identified as the more viable solution due to its superior performance in maintaining structural stability.

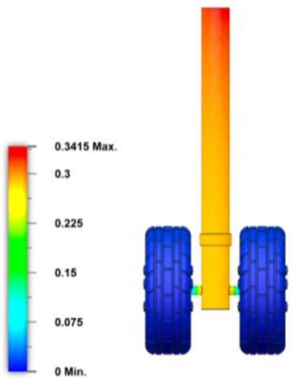

Figure 15 – FEA Results of PP Shaft and Aluminium Leg

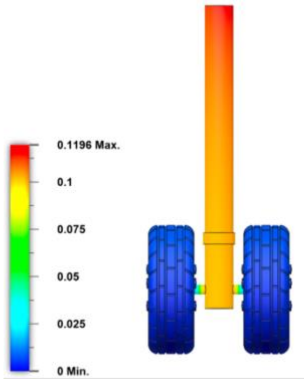

Figure 16 – FEA Results of Aluminium Shaft and Leg

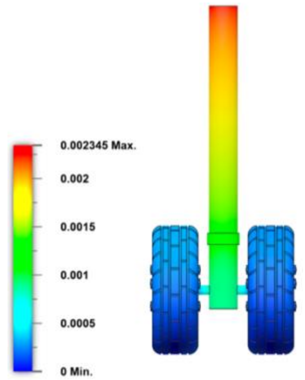

Figure 17 – FEA Results of Stainless-Steel Shaft and Aluminium Leg

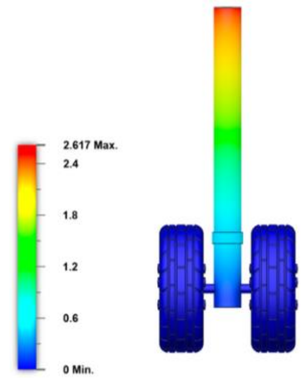

Figure 18 – FEA Results of PVC Leg and Stainless-Steel Shaft

As shown above, most of the proposed materials are able to withstand the expected mechanical stress. Thereupon the materials are decided by comparing between their relative manufacturing cost, cost of raw materials and density as shown below in Table 5. For instance, although ABS has a slightly lower raw material cost than PP, PP has a relatively lower manufacturing cost and density, thus it was concluded that PP would be a more suitable material for the manufacture of the case. On the other hand, for parts such as the case divisor and battery support, both PP and PE have a low manufacturing cost, while PE has a slightly lower raw material cost than PP, but PP has a slightly lower density than PE. Be that as it may, PE generally has a lower carbon footprint than PP (Figure 19), thus PE is regarded as a more appropriate material for the case divisor and battery support.

Table 5 – Material selection process (40,41)

Component	Materials required	Pass FEA?	Suitability for Manufacturing	Manufacturing Cost (£/kg)	Raw Material Cost (£/kg)	Density (g/cm³)
Case	Stainless Steel	Yes	Yes	4.00	2.16	8.03
	Aluminium	Yes	Yes	3.00	1.52	2.7
	ABS	Yes	Yes	1.50	0.76	1.05
Legs	Aluminium alloy	Yes	Yes	3.00	1.44	2.7
	Stainless Steel	Yes	Yes	4.00	2.16	8.03
	PVC	No	Yes	1.50	1.2	1.2
Case divisor	PP	Yes	Yes	1.20	0.88	0.9
	PE	Yes	Yes	1.20	0.8	0.92
	ABS	Yes	Yes	1.50	0.76	1.05
Battery support	PP	Yes	Yes	1.20	0.88	0.9
	PE	Yes	Yes	1.20	0.8	0.92
	ABS	Yes	Yes	1.50	0.76	1.05
Lidar support	Aluminium	Yes	Yes	3.00	1.52	2.7
	Stainless Steel	Yes	Yes	4.00	2.16	8.03

	PP	Yes	Yes	1.20	0.88	0.9
Upper covers	Aluminium	Yes	Yes	3.00	1.52	2.7
	Stainless Steel	Yes	Yes	4.00	2.16	8.03
	ABS	Yes	Yes	1.50	0.76	1.05
Axes (shaft)	Aluminium alloy	No	Yes	3.00	1.44	2.7
	Stainless Steel	Yes	Yes	4.00	2.16	8.03
	PP	No	Yes	1.20	0.88	0.9
Gear and drill cases	PP	Yes	Yes	1.20	0.88	0.9
	Aluminium	Yes	Yes	3.00	1.52	2.7
	Stainless Steel	Yes	Yes	4.00	2.16	8.03

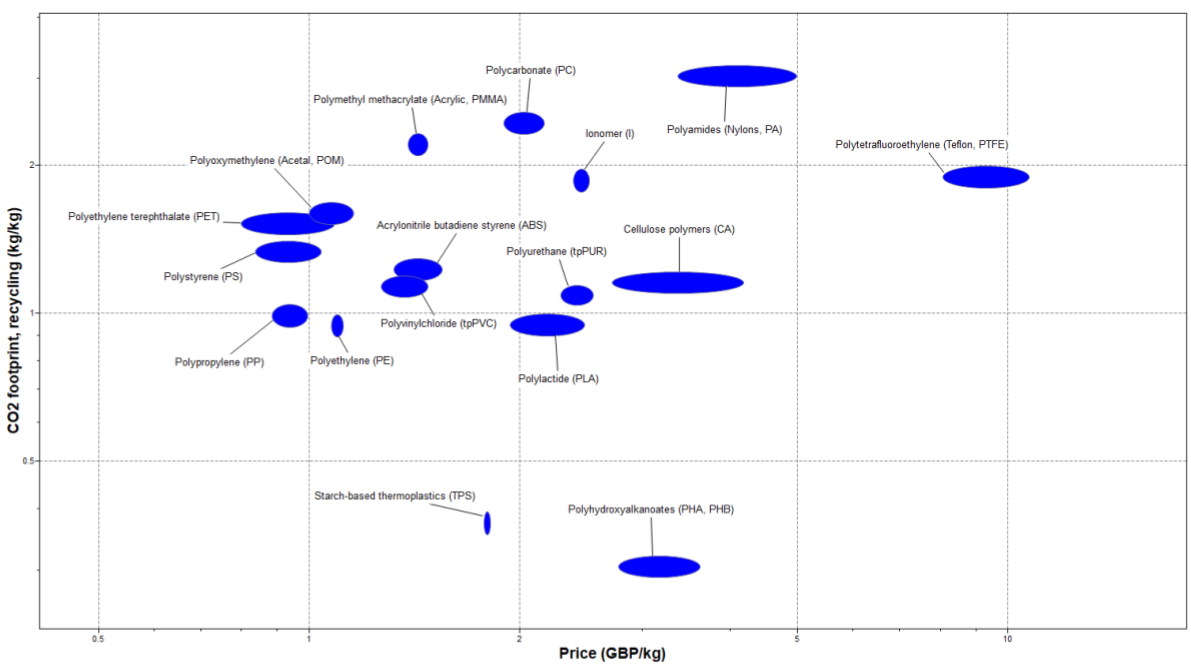

Figure 19 – Material selection graph - polymer (Carbon footprint against density)

6 Electronics

6.1 Microcontroller and sensors

To control an autonomous system, a computer is required. On the other hand, these can be expensive and may need specific requirements depending on the system which needs to be controlled. As this project is targeted at low to mid-income countries (LMICs), it is important to keep the production costs as low as possible. Microcontrollers can be found on the market at a low price and are designed for embedded computer control applications (42).

It is important to have a closed-loop system to control and have the desired output. This information is captured by sensors which enable the system to operate safely and efficiently. Ultrasonic sensors are suitable for detecting obstacles located at a close distance, up to 10 meters, at a small cost. A similar result can be achieved with radar sensors, which are preferred to detect bigger objects. Instead, optical sensors can be used for both long and short distances (43,44). Lidar sensors are a popular option for autonomous vehicles. This is due to their ability to detect very distant objects precisely, even with low visibility. They can calculate the distance from an object, as well as its shape, size, and speed (44). For the weed removal system, ultrasonic sensors will be used to detect the position both laterally and vertically. By applying a sensor on each side of the gears' container, the system will be able to understand its displacement from the centre. Likewise, by applying another ultrasonic sensor to the case of the drill motor, it will be possible to estimate its vertical location.

Designing and programming an autonomous system for a robot requires both time and resources, as well as developing skills. To make the development of the robot more efficient, it was decided to assign this task to an external company. On the other hand, this would only be possible later in the development, after the first round of funds is raised from the Kickstarter.

6.2 Actuators

Electric motors are manufactured in various sizes and capacities for different applications. The two most common types of electric motors are AC motors and DC motors. These are used in most applications, where they are adjusted to satisfy product requirements. A low power upon start-up is needed for controlled acceleration so AC motors can maintain a constant speed and performance. In addition, AC motors are a very durable type of electric motor, as they are brushless and divided into synchronous and induction(45,46). DC motors can also be used for various purposes, especially for high-torque applications requiring speed control. Therefore, they are used widely when lifting heavy loads is required in various conditions. DC motors can be manufactured both brushed and brushless. Generally, brushless electric motors, where magnets are mounted around the rotor, have higher efficiency because speed is not lost due to brushes and, therefore, have a more silent operation. They also include specialised circuitry to control both speed and direction. However, even though they have lower efficiency and require more maintenance, brushed motors are frequently used in many industrial applications as they introduce a more affordable option (46,47).

RootSlice requires a motor to move the weed-killing mechanism. The motor must be able to rotate in two directions, as it will need to lift the object and push it down to the ground during the weed drilling process. Therefore, a DC motor is the most suitable as it can be implemented to rotate in both directions while lifting or pushing down an object.

A rough estimation under normal conditions is that brushed DC motors can reach approximately 1,000 to 3,000 working hours on average. At the same time, brushless can achieve tens of thousands of working hours, as there are no brushes to wear (48,49). Hence, brushed DC motors were selected for the prototype as a cheaper option where repairing frequency was not an issue. In contrast, brushless DC motors are preferred to be installed in the actual product design in order to achieve a more sustainable solution. However, operating errors and exposure to unideal environmental conditions, such as water or dust, can adversely affect the motor's components, particularly the bearings, which play a critical role in a brushless motor's lifespan. Water, for instance, contains tiny particles, as is often the case in natural bodies of water or even rain, that can infiltrate in the motor and cause damage to the bearings over time (50). Therefore, it is crucial that the actual robot's design can provide a solid insulation space from dust and water for the motors.

6.3 AI Identification

An existing artificial intelligence (AI) algorithm was adapted to accurately identify and remove weeds in between potato plants, without damaging the yield. The algorithm has a flexible design, meaning that a high number of weed types can be stored (51). On the other hand, training the system is a lengthy process which requires high processing power. As a result, for testing purposes, the AI was trained to identify coriander as a weed to target, through real-time video images. This is because coriander can be easily bought at a local supermarket on the day of the simulation compared with Ecuadorian weeds, which are hard to source in the UK. The system is coded using Python as the language and PyCharm as the IDE for programming (Appendix D). A data set with a sample size of 880 coriander pictures was downloaded from the internet and labelled. After completing the labelling, with the help of labelme2voc, the JSON file was converted into a dataset in the VOC format. Thereafter, by using OpenMMLab, it was possible to build a neural network and train it. Using the neutral network architecture of "mobilenet v2"(52), the backbone network of the artificial intelligence algorithm was optimised. This reduced the number of calculations in the program while maintaining accuracy. Finally, YOLOv3 (53) was selected as the target detection algorithm. As a result, the system can now detect coriander for the simulation, and it would be ready for any type of unwanted weeds by uploading a database with sufficient pictures.

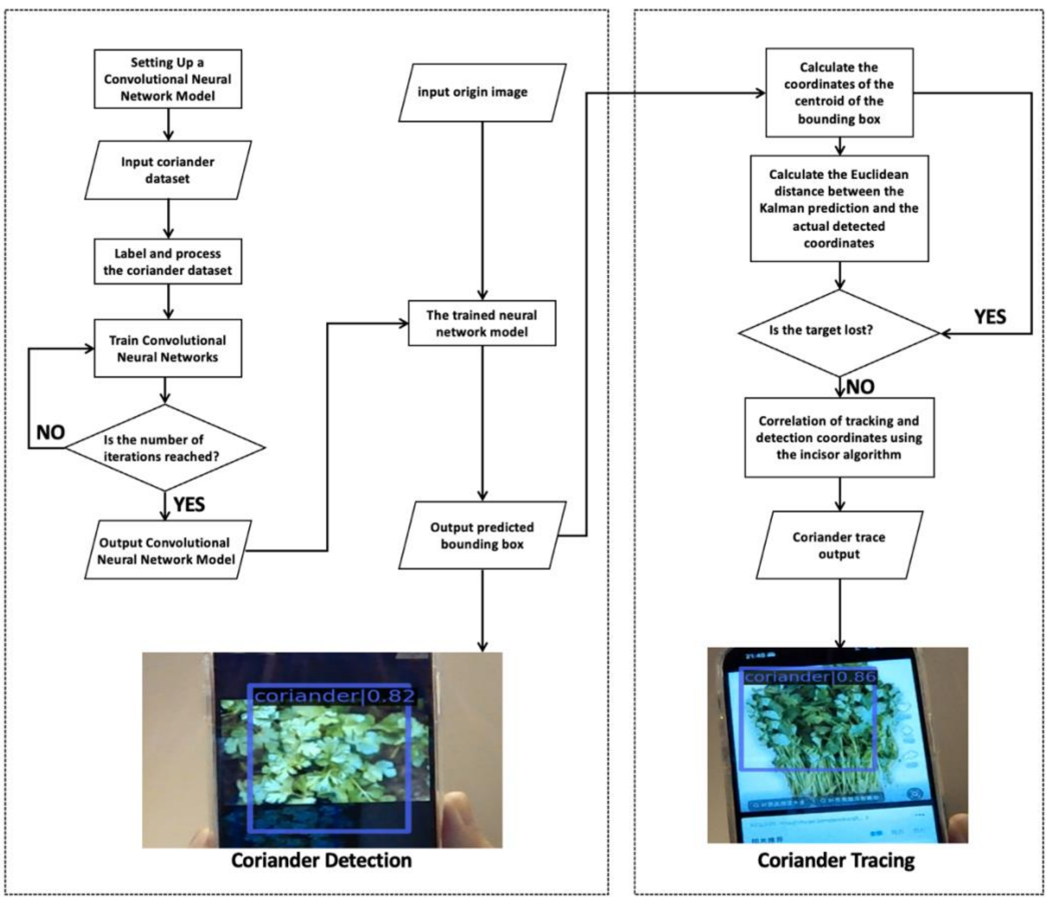

Figure 20 – AI system block diagram

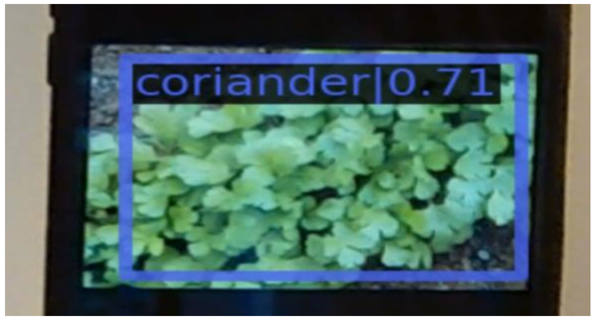

Figure 21 – AI algorithm detecting a picture of coriander through live vide

For the AI identification system to be implemented with the robot, the following components are required:

Table 6 – AI components

Module name	Provider	Function	Price
Jetson Nano B01	Taobao Yabo intelligent flagship store	Data processing, master control centre. NVIDIA's entry-level AI master control kit. Affordable price and reliable performance	£113.40
STM32F405R GT6 development board	Taobao Qinyuansheng flagship store	Bottom centre control panel	£13.80
Huan'er 16-way servo control board	Taobao Huan'er flagship store	Receive instructions from the lower computer to control the robot steering gear	£3.60
Astra Le'tv camera	Taobao Somatosensory of China flagship store	Acquire each frame of image in real time for target detection	£200.40

6.4 Additional features

Following the interview with Manuel Choqque Bravo, it was identified that measuring the soil parameters is a key task that farmers need to perform regularly. As a result, RootSlice was fitted with a sensor capable of measuring the soil temperature, humidity, and pH, automating another duty that farmers would otherwise need to perform manually. For this application, the YIGU YGC-SM Soil All-in-One Sensor was found to be the most suitable (54). This is because of it:

1. Provides high measurement accuracy, fast response, and good interchangeability.
2. Is less affected by the salt content of the soil and can be applied to various soil types.
3. Contains electrodes made of specially treated stainless-steel material, which can withstand strong external impact and is not easy to be damaged.
4. Is completely sealed, resistant to acid and alkali corrosion, and can be buried in soil or directly put into water for long-term dynamic detection.
5. Has a modular design which can be selected arbitrarily according to needs and can monitor up to 8 soil elements.

7 Prototyping

7.1 Description of your prototype

Due to the limited budget available for the prototyping section of the project, it was decided to focus on having a single working part of the robot, the weed removal system. By doing so, it is possible to present the working principle of the selling point of RootSlice to potential investors, and use the funds raised to later develop the rest of the robot. Likewise, this approach enables to analyse of the efficiency and optimises the weed removing system, through practical tests.

To reduce the waiting time and optimise the prototyping process, the majority of the bespoke components were built by the group using the university facilities. Instead, standard components were sourced from trusted university partners to avoid possible delays and problems.

7.2 Parts list

Table 7 shows the components which were manufactured in the university's workshop. Most of the supporting structure required for the prototype was built using Acrylic. This is because this material can be cut precisely into shape using a laser cutter. Although this process requires an energy input, it must be considered that it is both more efficient and precise than for instance, cutting plywood by hand. Instead, components which required a more sophisticated shape were manufactured using a 3D printer. This device is capable of creating PLA-based objects with complicated shapes and cavities, by building supporting material which can be later easily removed.

Table 7 – List of built prototype components

Component	Quantity	Material	Machinery	Estimated time	Work required beforehand
Supporting structure for simulation	1	Acrylic	Laser cutter	2 days	Dimensions
Scaled side supports	2	Acrylic	Laser cutter	½ day	Dimensions
Casing containing the gears	1	PLA	3D printer	1 day	3D printer compatible CAD file
Casing containing the motors	1	PLA	3D printer	1 day	3D printer compatible CAD file
Casing containing the drill	1	PLA	3D printer	1 day	3D printer compatible CAD file
Legs supports	8	PLA	3D printer	1 day	3D printer compatible CAD file
Supporting legs	4	Waste wood	Saw	1 day	Dimensions

Figure 34 in Appendix C shows the detailed technical drawings of the gears, motors and drill casings which were made for the prototype and maintain the same design and dimensions for the final design.

The components outsourced were chosen according to the requirements previously analysed. The parts were identified considering costs, reliability of the merchants and availability. It was important to receive the right components on time, otherwise, the project could be delayed.

Table 8 – List of parts purchased for the prototype

Component	Code	Quantity	Shop	Price per unit	Price
Arduino UNO kit	K000007	1	UCL Market (Onecall)	£98.98	£98.98
Cables Arduino	791-6463	1	RS UK	£3.74	£3.74
Ultrasonic Sensor HC-SR04	46130	4	RS UK	£2.52	£10.08
L298N (pack of 4)	-	1	Amazon	£11.99	£11.99
12 V Battery	-	1	Amazon	£25.99	£25.99
Left and right motor	238-9636	2	RS UK	£9.01	£18.02
Left and right gear	101281012FAR	10	UCL Market (Onecall)	£0.55	£5.52
Left and right rack	104281602FAR	8	UCL Market (Onecall)	£4.31	£34.46
Up and down motor	454-0883	1	RS UK	£44.24	£44.24
Up and down gear	521-6339	2	RS UK	£28.72	£57.44
Up and down rack	876-2412	2	RS UK	£55.13	£110.26
Bearing	234-6873	1	RS UK	£6.83	£6.83
Weed remover motor	-	1	Amazon	£28.89	£28.89
Auger	-	1	Amazon	£10.59	£10.59
Black Paint Spray	-	1	Grays Inn Hardware	£6.99	£6.99
				Total	**£474.02**

At the end of the build and assembly of each component, time was allocated to evaluate the design against the initial criteria. Table 3 shows the design criteria that the final product needs to fulfil. As the prototyping section is only focused on building the weed remover, it was possible to only evaluate the criteria related to this component. Some examples include safety, level of automation, efficiency, complexity, and costs. The design was only deemed successful once these criteria were fully satisfied. For this reason, during the prototype building process, it was essential to follow the plan and consider how any changes may have an impact against the evaluation criteria.

7.3 Prototype electronics

Due to the limited budget, it was not possible to implement a sophisticated controller for the prototype. As a result, to test the system and understand the requirements that the bespoke controller will need to have, an Arduino UNO board was installed. This device was programmed using MATLAB, with Simulink, to manually operate the motors from an external laptop. The input and output pins on the motherboard were used to establish a connection with the motors and sensors (55). Likewise, since the motors will be only used for prototyping, requiring no maintenance, brushed motors were chosen as a cheaper alternative to brushless ones. L298N motor drive modules were fitted between the microcontroller and the actuators. These devices enable to control the rotational speed and direction of the motor, through the PWM signal coming from the microcontroller (56).

7.4 Prototype electronics diagram

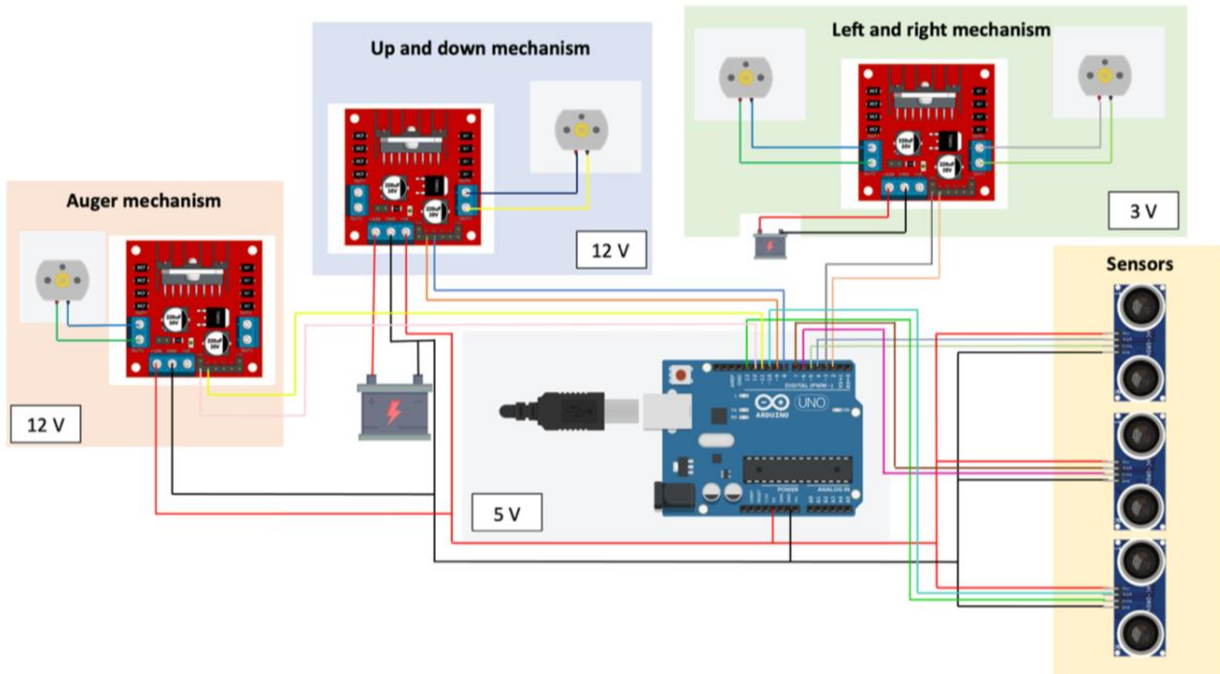

Figure 22 – Diagram of the weed remover prototype electronics

7.5 Tests and simulations

The testing of the prototype focused on the three main movements of the weed remover system: lateral, vertical, and rotational. Overall, the mechanism was able to successfully move both laterally and vertically. Instead, it was identified that rotating the auger produces an amount of vibration significantly higher than expected. For this reason, the box containing the auger motor initially designed was not able to withstand this amount of stress, failing at one of the rack anchoring points. To solve this problem, the design of the component was altered, now featuring different brackets for the racks. As a result, the new box is now capable of tolerating a higher frequency of vibration, enabling the auger to eradicate the weeds (Figure 24).

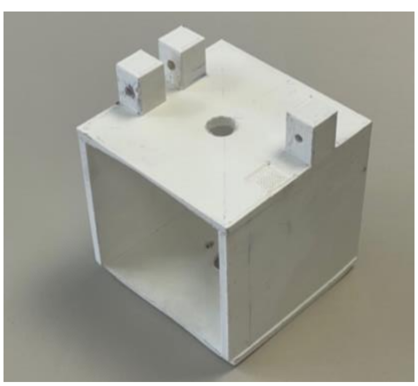

Figure 23 – Failed drill case design

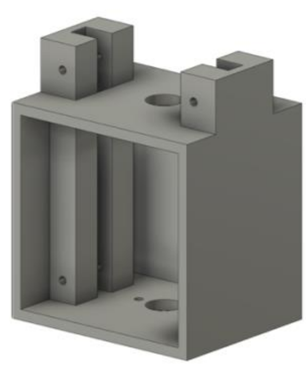

Figure 24 – New drill case design

Moreover, the prototype underwent an extensive series of additional examinations and assessments centred around the performance capabilities of the system's motors. More specifically, as highlighted in

Section 5.1, for the system to meet the desired performance standards, the motor ought to be capable of elevating the auger mechanism in less than 5 seconds.

In alignment with the lifting process model detailed in Section 5.1, given an ideal soil coefficient of 70×10^3, it is anticipated that the RS PRO Brushed Geared 19.8 W/12 V DC motor should facilitate the lifting of the auger in approximately 4.6 seconds. However, following a comprehensive series of tests examining the prototype's efficiency within a natural soil application experiment, the average time to completion amounted to approximately 6.45 seconds. Hence, a more robust motor is required to be selected for the robot.

Also, due to these observations, it was imperative to refine the simulation model by updating the soil coefficient to ensure coherence with the experimental findings. Consequently, a soil coefficient of 83.3×10^3 was implemented into the system. As evidenced in Figure 25, this adaptation produced time results that are virtually identical to those measured in the laboratory. The precision of the soil coefficient will undergo further enhancements as it continues with more experimental tests of the prototype. This will be completed under numerous environmental and soil conditions to improve the simulation model's accuracy.

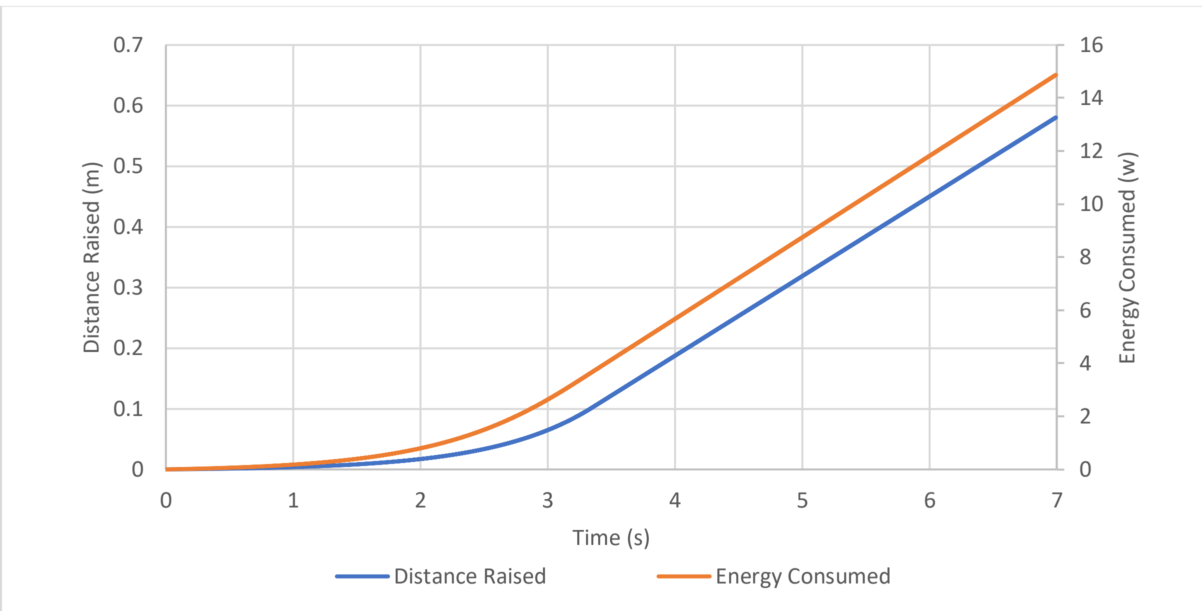

Figure 25 – RS PRO Brushed Geared DC Motor Updated Results

Figure 26 – Testing of the left and right mechanism

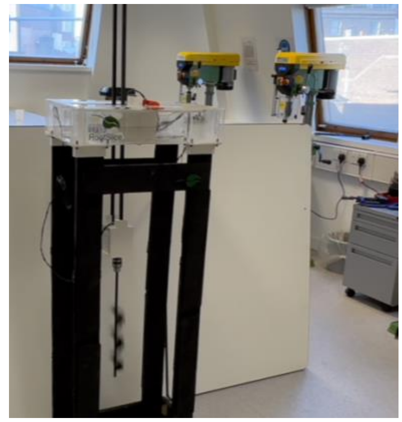

Figure 27 – Testing of the up and down/auger mechanisms

7.6 Sustainability of the prototype

The prototype is designed with close consideration for sustainability, safety and efficiency whilst addressing the unique needs of the local potato farmers. To reduce the chance of failure and the probability of design improvements required throughout the prototyping section, the physical prototype was only started once the FEA analysis was completed and the design was adjusted accordingly. Recycled materials were prioritized, using wood scraps available at the workshop for temporary and/or non-essential components such as the legs. Likewise, priority was given to renewable materials, for instance, PLA for the 3D printer. Similarly, each group member made sure to switch off machinery and tools after completing a task throughout the whole prototyping phase. An in-depth risk analysis was conducted to identify drawbacks and mitigation strategies to ensure the long-term sustainability and success of the prototype. Moreover, the prototype's modularity and easily sourced components ensure easy maintenance for local farmers with limited engineering knowledge. Overall, the sustainability of the prototype is attained through risk mitigation strategies, modularity, farmer-feedback design, and safety features.

8 Manufacturing

8.1 Manufacturing requirements

The manufacturing plan for the weed removal robot encompasses a diverse range of materials and parts, including both off-the-shelf components and custom parts that are tailored to the specifications. Standard components like gears, motors, and sensors, which adhere to industry standards, can be readily sourced from external suppliers with established supply chains. These components are widely available and fulfil the necessary requirements for the robot's functionality.

On the other hand, the production of custom parts, such as the chassis and exterior cover, necessitates adherence to stringent manufacturing protocols. These parts are designed to meet the detailed requirements of the robot's design and must be fabricated to precise specifications.
For custom build components, the manufacture would either be a) outsourced to external specialised manufacturers for batch production, or b) manufactured in-house directly from raw materials for mass production when the production scale is sufficiently large to justify the substantial capital cost. As the

quoting for the cost of outsourced manufacture can vary drastically between countries, locations, companies, and other factors, it would be difficult to obtain an accurate quote. For this reason, at this instance, the calculation is suited for a long-term scenario where all the custom parts are to be manufactured in-house.

By carefully balancing the use of readily available standard components and the manufacturing of custom parts, the manufacturing plan for the weed removal robot will ensure optimal performance and quality while also considering cost-effectiveness and efficiency. In order to maintain the expected level of quality, rigorous quality control procedures shall be implemented throughout the manufacturing process. This involves meticulous attention to detail, regular inspections, and adherence to quality assurance protocols to ensure that each component meets the defined quality standards.

8.2 Materials

The material properties requirements for the robot are essential to ensure its durability, functionality, and performance in the demanding agricultural environment. The robot will be subjected to various operational conditions, including exposure to moisture, soil, and mechanical stresses. Therefore, the chosen materials must possess specific properties to withstand these challenges. Additionally, the selected materials should be compatible with the manufacturing processes employed, ensuring ease of fabrication, assembly, and integration of various components. This will contribute to efficient production and enable cost-effective manufacturing. With regards to the materials selection process, once all the basic requirements are fulfilled, the minimisation of cost and weight shall be taken into account. Moreover, the sustainability and recyclability aspects should also be considered (57).

In detail, for the case and upper covers, their primary role is to protect the internal components from external objects and outdoor conditions. While they do not need to withstand large amounts of stress, they should be suitably rigid to provide sufficient protection while not adding unnecessary weight to the robot. In addition, it is important that they are resistant to outdoor conditions such as moisture, UV radiation, and temperature fluctuations.

The legs of the robot bear the weight of the entire system, and as such, they need to be strong and rigid to ensure stability and support during operation. Similar to the case and covers, they should also possess resistance to outdoor conditions to withstand potential environmental factors.

The case divisor does not need to experience significant stress, but it should be lightweight and compatible with the overall design. Its purpose is to separate internal components efficiently while contributing to the overall structural integrity of the robot. Components such as the battery support and LIDAR support require materials that can withstand the weight of the respective components they hold. They should be designed to provide sufficient support and stability without being affected by outdoor conditions.

The shafts and wheels play a critical role in transmitting mechanical force and motion. They need to survive significant mechanical stress and should be rigid to ensure efficient operation. Additionally, they should possess resistance to outdoor conditions to maintain their performance in varying environments.

For components like gears and racks, their primary requirement is to withstand significant load. While they do not need resistance to outdoor conditions, they should be durable and capable of transmitting force effectively. Lastly, the auger, which plays a crucial role in the weed removal process, needs to withstand significant torsion while exhibiting resistance to outdoor conditions. The materials of each part are summarised below in Table 9.

8.3 Parts list

Table 9 – List of parts (40,41)

Component	Custom Made?	Quantity	Materials required	Volume per unit (m^3)	Density (g/cm^3)	Weight (kg)	Material Cost per unit	Manufacture Cost per unit	Estimated cost per unit	Total
Case	Y	1	ABS	153.3	1.05	160.65	£122.09	£240.98	£363.07	£363.07
Legs	Y	4	Aluminium alloy	3.15	2.7	8.51	£12.26	£25.53	£37.79	£151.16
Case divisor	Y	1	PE	8.80	0.92	8.1	£6.48	£9.72	£16.20	£16.20
Battery support	Y	2	PE	7.88	0.92	7.25	£5.80	£8.70	£14.50	£29.00
Lidar support	Y	2	PP	2.96	0.9	2.66	£2.34	£3.19	£5.53	£11.06
Upper cover	Y	2	ABS	34.82	1.05	36.56	£27.58	£54.84	£82.42	£164.84
Shaft	Y	8	Stainless steel	0.02	8.03	0.16	£0.35	£0.64	£0.99	£7.92
Drill case	Y	1	PP	0.3	0.9	0.27	£0.24	£0.32	£0.56	£0.56
Gear case	Y	1	PP	0.86	0.9	0.77	£0.68	£0.92	£1.60	£1.60
Solar panels	N	4	-	-	-	-	-	-	£81.36	£325.44
Blinking light	N	1	-	-	-	-	-	-	£7.99	£7.99
Ultrasonic sensors	N	4	-	-	-	-	-	-	£2.52	£10.08
Lidar	N	1	-	-	-	-	-	-	£80.70	£80.70
Motherboard, cables and batteries	N	1	-	-	-	-	-	-	£200.00	£200.00
AI Identification system	N	1	-	-	-	-	-	-	£331.20	£331.20
Wheel motors	N	4	-	-	-	-	-	-	£75.00	£300.00
Steering motors	N	4	-	-	-	-	-	-	£50.00	£200.00
Wheels	N	8	-	-	-	-	-	-	£7.88	£63.04
Gear	N	4	-	-	-	-	-	-	£60.00	£240.00
Left and right brushless motor	N	2	-	-	-	-	-	-	£45.00	£90.00

Rack	N	4	-	-	-	-	-	-	£50.00	£200.00
Up and down brushless motor	N	1	-	-	-	-	-	-	£45.00	£45.00
Weed remover motor	N	1	-	-	-	-	-	-	£20.00	£20.00
Auger	N	1	-	-	-	-	-	-	£10.00	£10.00
Soil All-in-One Sensor	N	1	-	-	-	-	-	-	£35.55	£35.55
									Total	**£2,904.42**

8.4 Manufacturing

To manufacture the various parts of the robot, using CES it was found that the appropriate manufacturing and processing techniques would be as follows:

The legs made from aluminium alloy can be manufactured using CNC machining, die casting, or extrusion processes. The choice of technique will depend on the desired design, strength requirements, and production volume (58).

The case and upper cover made by ABS, as well as the case divisor made from polyethylene (PE) can be manufactured using injection moulding. This process involves injecting molten ABS/PE material into a mould cavity and allowing it to cool and solidify to form the desired shape of the component. Similar to the case divisor, the battery support made from polyethylene (PE) can also be manufactured using injection moulding. The PE material is injected into a mould to create the battery support structure (59).

The LIDAR supports, gears case, and drill case made from polypropylene (PP) can also be manufactured using injection moulding (59). This process allows a precise and efficient production of complex shapes, making it suitable for creating these components (60).

The shaft made from stainless steel needs to be manufactured using processes such as machining or turning. Machining involves cutting and shaping the stainless-steel material using tools such as lathes or mills to create the desired shaft shape. Turning specifically refers to the process of rotating the stainless-steel workpiece while a cutting tool removes material to form the shaft (61).

These manufacturing and processing techniques have been commonly used for the respective materials and parts mentioned. However, it is essential to consult with material suppliers and manufacturers to determine the most suitable manufacturing processes based on specific design requirements, desired properties, and production considerations for the RootSlice robot.

8.5 Processing

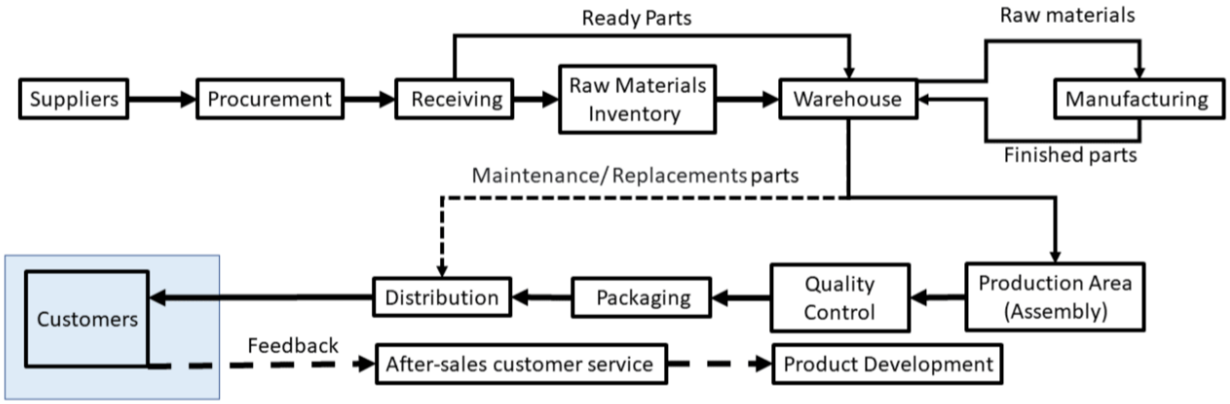

Figure 28 – Processing Block Diagram

As shown in Figure 28, the overall manufacture process involves several stages that ensure the efficient production of the robot. The process begins with procurement, where the company identifies and engages with reliable suppliers for the required materials and components, including both raw materials (i.e. polymers) and ready-made outsourced components (i.e. motors). In which, this is crucial to ensure the availability of high-quality inputs for the manufacturing process.

Once the raw materials are sourced, they are received and stored in the raw materials inventory. This inventory serves as a centralized location where all the necessary inputs are organized and managed. The warehouse department oversees the storage and retrieval of these materials, ensuring that they are easily accessible for the manufacturing process. While the components and parts that are outsourced could be stored in the warehouse directly to be utilised in the later assembly stage (62).

The manufacturing itself shall take place in a dedicated production area, specifically designed for assembly. This area shall be equipped with the necessary tools, equipment, and machinery to efficiently assemble the robot. In which the skilled workers shall meticulously follow the manufacturing instructions and assemble the various components to create the final product. Raw materials would be retrieved from the warehouse to be manufactured, once the parts are finished and machined, they will be returned to the warehouse awaiting to be assembled.

To ensure the quality and reliability of the robot, a dedicated quality control department shall be incorporated into the manufacturing process. This department conducts rigorous inspections and tests at different stages of the assembly process to identify any defects or deviations from the required specifications. By adhering to strict quality control measures, RootSlice can ensure high-quality products are delivered to its customers (63).

Once the robot passes the quality control checks, it proceeds to the packaging department. The product shall be carefully packaged, taking into consideration the necessary protective measures to ensure its safe transportation and delivery to customers. The packaging department plays a crucial role in maintaining the integrity and presentation of the product.

The distribution department takes charge of delivering the weed removal robot to customers. This involves coordinating with logistics partners to efficiently transport the packaged products to their respective destinations. In all, a reliable and streamlined distribution network shall be established to ensure timely delivery and customer satisfaction. The customers can pass on any feedback to the after-sales customer service team, and the recommendations could be further passed on to the product development team for design iterations and improvements. On the other hand, the customers could also contact the after-sales customer service team to order maintenance/replacement parts to be dispatched from the warehouse via the distribution channels (63).

In line with the commitment to environmental sustainability, efforts shall be made to explore the use of sustainable materials and production processes. This includes investigating the feasibility of utilizing recycled or biodegradable materials in the manufacturing process, which can not only help reduce costs but also minimise the carbon footprint. Furthermore, sustainable manufacturing practices aimed at reducing waste and optimising resource utilisation shall be implemented. This may involve the adoption of lean manufacturing principles, such as process optimisation and waste reduction strategies. Additionally, exploring the use of renewable energy sources to power the manufacturing facilities aligns with the goal of minimising environmental impact and promoting sustainability (64).

8.6 Supply chain

In order to ensure a smooth and efficient manufacturing process, RootSlice recognises the importance of establishing strong partnerships with reliable suppliers and manufacturers. This entails carefully identifying and screening potential suppliers, as well as entering into contractual agreements that outline expectations and standards. Building a robust supply chain is crucial to ensure the timely availability of high-quality materials and components required for the production of the weed removal robot.

RootSlice shall adopt an agile supply chain strategy, which allows for flexibility and responsiveness to changing market demands. The nature of the agricultural industry, particularly in remote areas with diverse environmental conditions, requires the ability to adapt quickly to varying customer requirements and emerging trends. An agile supply chain will enable RootSlice to swiftly adjust production volumes, respond to customer needs, and introduce new product variants as necessary (65).

Furthermore, the lean supply chain approach may also be suitable for RootSlice. Lean principles focus on minimising waste, reducing lead times, and improving overall efficiency. By implementing lean practices, RootSlice can optimise its manufacturing operations, eliminate non-value-added activities, and improve productivity. This will help in reducing costs and enhancing customer satisfaction by delivering products quickly and efficiently (66).

However, it is essential to anticipate potential disruptions in the supply chain. External factors such as natural disasters, political instability, or economic fluctuations can lead to delays or interruptions in the supply of materials and components. To mitigate these risks, RootSlice should adopt proactive measures. This includes diversifying the supplier base to reduce dependency on a single source, establishing backup suppliers, and maintaining buffer inventory to accommodate unexpected disruptions. Regular communication and collaboration with suppliers can also help in addressing potential issues and finding alternative solutions (67).

Furthermore, technological advancements can play a significant role in ensuring supply chain resilience. RootSlice should explore the use of digital platforms and advanced analytics to improve visibility, traceability, and forecasting accuracy. Real-time data monitoring and predictive analytics can aid in identifying potential bottlenecks or disruptions in the supply chain, enabling proactive measures to be taken to minimise their impact (68).

8.7 Manufacturing global options

The Andean region is a beneficial place to manufacture. First off, it boosts the local economy by generating job opportunities and promoting regional development. By enhancing the local community's standard of living, this can have a good social influence. Local manufacturing also lowers shipping costs and transportation emissions, resulting in a supply chain that is more environmentally friendly. Additionally, compared to other places, the Andean region might offer lower labour and production expenses. For RootSlice, this might mean significant cost reductions, boosting the marketability of the device. The availability of cheap labour can also help with production scalability, enabling the fabrication of larger volumes at a relatively lower cost (69).

However, there are disadvantages to manufacturing in the Andean region as well. One potential challenge is the availability of skilled labour and suitable materials. This can impact the quality and consistency of the product. To ensure high-quality manufacturing, RootSlice would need to invest in training programs to enhance the skills of the local workforce. Additionally, the limited availability of specialised materials may require importing them from other regions, potentially increasing costs and lead times (70).

Manufacturing in Mexico, a nearby country with a well-developed manufacturing industry, offers advantages such as access to an established infrastructure and expertise. The manufacturing ecosystem in Mexico is more advanced compared to the Andean region, allowing for streamlined production processes and higher production efficiency. This can lead to faster time to market and potentially lower production costs (71).

However, manufacturing in Mexico also presents challenges. Quality control may be more difficult to manage due to potential communication barriers and geographical distance. Close collaboration and effective communication channels with the Mexican manufacturers would be crucial to ensure that the desired quality standards are met. Additionally, transportation logistics, such as shipping the manufactured robots back to the Andean region, need to be considered to avoid any delays or additional costs (72).

Manufacturing in the UK offers advantages such as an established infrastructure, a highly skilled labour force, and advanced technology. The UK has a strong manufacturing sector with a reputation for high-quality production. Manufacturing in the UK can provide RootSlice with the assurance of product excellence and consistency. Additionally, the absence of language and cultural barriers can facilitate effective communication and collaboration between RootSlice and the manufacturing partners.

However, there are potential drawbacks to manufacturing in the UK. Importing outsourced components from other regions can result in increased carbon footprint and shipping costs. This needs to be carefully considered to ensure that the environmental impact remains within acceptable limits. Additionally, the higher labour and production costs in the UK compared to other regions may impact the overall cost-effectiveness of manufacturing (73).

Import taxes can be a significant challenge when manufacturing in different regions. It is important to consider the tax policies and trade agreements between the manufacturing country and the destination market. In the case of manufacturing in the Andean region, RootSlice may face import taxes when exporting the robots to other countries. To mitigate this, RootSlice could explore the possibility of establishing trade agreements or partnerships with the target markets to reduce or eliminate import taxes. Engaging in negotiations with government authorities and trade organizations can help in securing favourable trade terms (74).

Similarly, manufacturing in Mexico or the UK may also involve import taxes when importing components or exporting the final product. RootSlice can consider leveraging existing trade agreements, such as the North American Free Trade Agreement (NAFTA) for Mexico or trade agreements between the UK and target markets, to reduce import taxes (75).

Supply chain disruption is another critical consideration when evaluating manufacturing options. Disruptions can arise from various factors such as natural disasters, political instability, labour strikes, or transportation disruptions. The Andean region may be more susceptible to certain types of disruptions due to its geographical location and potential socio-political challenges. To mitigate these risks, RootSlice can implement supply chain risk management strategies such as diversifying suppliers, maintaining buffer stocks, and establishing contingency plans.

Manufacturing in Mexico or the UK may also face supply chain disruption risks, although to a lesser extent. RootSlice can mitigate these risks by thoroughly evaluating the stability and reliability of the suppliers and logistics providers in those regions. Establishing strong relationships with reliable suppliers, implementing backup plans, and regularly monitoring the geopolitical and economic climate can help in mitigating the impact of potential disruptions.

All things considered, it has been concluded that the manufacturing of the RootSlice robot at the early stage of development is suitable to take place in the UK, due to the established infrastructure, skilled labour force, and advanced technology. This ensures product excellence, consistent quality, and effective communication. However, careful consideration is needed for the higher production costs and potential environmental impact. Mitigating supply chain disruptions through risk management strategies is essential.

As the production scale grows the company producing RootSlice could consider moving the production plant to Mexico, where the labour cost is lower. This is because after a few years, a high level of automation and standardisation in the production process is expected to be reached, with a systemised structure, reducing the need for close monitoring.

8.8 Environmental sustainability analysis

To ensure the environmental sustainability of RootSlice, a comprehensive life cycle assessment (LCA) shall be conducted. This assessment shall examine various aspects, including material selection, energy consumption, waste management, supply chain, and end-of-life disposal, in order to minimise the negative impact on the environment.

In terms of material selection, preference needs to be given to sustainable and environmentally friendly materials. This may involve exploring the use of recycled materials to reduce the demand for virgin resources. Each material's environmental impact shall be carefully evaluated to make informed decisions during the manufacturing process.

The energy consumption of the manufacturing process requires also be evaluated and optimised. This may involve the use of energy-efficient equipment and implementing energy-saving measures within the production facility. Exploring the use of renewable energy sources must also be considered to further reduce the carbon footprint (76).

A waste management plan needs to be developed to minimise waste generation and maximise recycling and reuse. This involves identifying different types of waste generated during the manufacturing process and implementing strategies for their proper management. Closed-loop manufacturing processes, where waste materials are used to create new products, shall also be explored to reduce waste and resource consumption (77).

The supply chain of the product must be carefully considered, as it can significantly impact the environment. Sourcing materials locally to reduce transportation emissions and working with suppliers who prioritize sustainability in their operations needs to be key strategies to minimise the environmental footprint.

Furthermore, the end-of-life disposal of the weed removal robot shall be addressed. Electronic waste disposal can have significant environmental consequences, and thus measures must be taken to ensure responsible disposal. This may include designing the product to be easily disassembled for recycling purposes or establishing a take-back program where customers can return the product for proper and environmentally friendly disposal (78).

To promote a longer service life for RootSlice, it is designed with repairability in mind. Spare parts are readily available and easy to fit, particularly for the target audience of remote farmers. By extending the product's lifespan through easy repair and maintenance, the overall environmental impact of the product can be reduced.

The stated aim for the service life of the RootSlice robot is to ensure durability and reliability, enabling it to remain in service for a minimum of 5 years. This helps minimise waste generation and resource consumption associated with frequent product replacements.

9 Business Plan

9.1 Evaluation of business case

The developed business case was devised on the premise of offering an affordable, efficient, and sustainable solution to weed management for small-scale farmers. RootSlice takes pride in its fully mechanical solution which removes the need for harmful pesticides or other synthetic agents, that damage the state of the crops. The business philosophy of RootSlice is to provide weed management sustainably while improving productivity for farmers in the Andes and beyond.

9.1.1 Market Size

The size of the global market for potato processing was valued at roughly $31.8 billion in 2022, projected to reach $51 billion by 2030 (79). This equates to a 60% growth of the industry within the next 8 years, combined with recent advancements in agricultural automation presents an attractive opportunity for RootSlice to enter the market within this timeframe.

RootSlice aims to target potato production facilities in Ecuador, Brazil, Columbia and Peru. In 2017, Ecuador produced 377,000 tons of potatoes and 4,000 tons of sweet potatoes. Over the past decade, production in Ecuador has fallen from 450,000 to 377,000 tons (80). For this reason, RootSlice aims to target Ecuadorian farms as our primary goal, to help bring back or improve previous rates of productivity. In the Andean regions of Guayaquil and Quito, the price for a tonne of potatoes is $1810.75 as of 2023 (81). Accounting for 377,000 tons produced in 2017, this would equate to a market size of around $682 million. This is a conservative estimate, not considering the radical shift in production due to precision agriculture and advanced automation (82).

9.1.2 Customer Segments

Root crop farmers: The product aims to focus on root crop farmers in the Andean region, specifically small and medium-sized farmers in these developing countries. The common thread is farmers who often lack the resources and tools in weed removal, which can result in lower yields and profits. We identified the needs and pain points of our target customer by conducting an interview with Manuel Choqque Bravo, a potato farmer in the Andean Region. Mr. Bravo addressed how weed control is a major problem in potato production, and how farmers have been forced to abandon their crops due to the intensive labour required in their removal. RootSlice aims to solve this by focusing on providing a solution which is self-sufficient (through self-driving and image recognition) and labour-saving. Another challenge for him was to remove the need for herbicides, as these lead to soil contamination. This is why RootSlice aims to promote sustainable farming practices through mechanical weed removal. Mr. Bravo expressed concern for soil compaction, worrying the weight of the robot might impact soil health and reduce potato yield. In our design development process, we have valued lightweight components to mitigate this. Lastly, Mr. Bravo explained how farmers in this region have little knowledge/access to technology, so the development of our product involved design for repair, modularity, and an intuitive mode of operation.

By informing the design development with the customer segment's pain points, RootSlice aims to provide a tailored solution that exceeds their demands. Having identified the potential barriers to adoption (cost, lack of technical knowledge, resistance to change), the development of RootSlice and the business case were adapted to overcome these hurdles. As RootSlice grows and evolves, the aim is to tackle other developing countries where root crops are a staple, including Africa and Asia, or other regions where root crop farming is prevalent.

Agricultural co-operatives & organisations: RootSlice aims to keep contact with agricultural co-operatives and organizations, such as DGRV based in Ecuador (83). These groups often work with small-scale farmers to provide resources and support, and our product can help them achieve their goals more effectively. These organisations will act as intermediaries to promote RootSlice and help in reaching out to small-scale farmers. A potential challenge could be communicating the effectiveness and benefits of our solution and complying with the organisation's requirements and standards.

NGOs & government organisations: Lastly, NGOs and government bodies supporting agricultural development in target countries are also potential customers for our weeder robot. These institutions often have the mandate to promote sustainable agriculture practices and improve food security, which our product can help to achieve. By collaborating with these groups, we can leverage their expertise and networks to reach more farmers and make a greater impact. A key practice in product development is to align our solution with the NGO's goals and mandates. This does pose its challenges, such as potential bureaucratic hurdles, slow decision-making processes, or specific regulatory requirements.

Customer support: When targeting our key customer segments, trust and credibility are required. Excellent customer support will be offered, including regular communication and consultations to ensure that end users are satisfied with the product and address any concerns they may have. RootSlice aims to have a dedicated customer support team and schedule technicians to take routine trips to the crop farm to ensure the robot is operating to standards. Another key aspect is developing the appropriate training and educational materials for our root crop farmers, as well as gathering and responding to user feedback. Investing in strong customer relationships enables retaining existing customers and attracting new ones through positive word of mouth and referrals.

9.1.3 Competition

Formulating a business case for RootSlice involved conducting an in-depth analysis of our competitors. By evaluating the strengths and weaknesses of the existing players, RootSlice aims to strategically position itself by improving upon existing solutions and addressing the unique needs of potato crop farmers in the Andean region. Firstly, we examined Carbon Robotics, which developed a unique laser weeding technology in their robot. Its biggest strength is efficiency, able to remove 100,000 weeds per hour, and they claim this cut weeding costs by 80% (84). The downside is their robot must be towed by a tractor, so requires extra labour compared to RootSlice's self-driving technology. Furthermore, their price point is steep which may be a potential cost barrier for small-to-medium-sized farmers in developing countries. RootSlice aims to differentiate itself from Carbon Robotics by providing a solution which is more affordable for the targeted customer segment, and less energy-consuming with the use of a mechanical system rather than a laser. Nexus Robotics R2 Weed2 takes pride in its adaptability to remove weeds from multiple crops and its ability to operate 24/7 (85). It utilises machine learning algorithms to identify weeds and navigate farm fields. RootSlice's latest design makes use of motion sensors cameras and lidar enabling a self-driving mechanism and weed recognition system which aims to use 50% less computing power than Nexus. In terms of sustainability, RootSlice's innovative drilling mechanism eradicates weeds while maintaining soil health. Lastly, we inspected Small Robot Company's (SRC) robotic weeding solution named "Dick". It removes weeds by using electric charges, and while this can be a sustainable approach it is arguably more energy-consuming than RootSlice (86). "Dick" complex AI and machine vision technology can identify and remove individual weeds. While this algorithm is more advanced and effective, it is also more difficult to operate, which may be a hurdle for the customer segment of medium-sized farmers.

Analysing potential market players has allowed RootSlice to leverage competitive advantages, including affordability, sustainability and a design-for-repair approach which is accustomed to the needs of our target customers. Through these competitive insights, RootSlice has a more established roadmap for product development and marketing campaigns.

9.1.4 Value Propositions

As shown by the analysis above, the pioneered drilling mechanism distinguishes RootSlice from other weed removal technologies currently on the market, providing a solution which focuses on profitability and sustainability. RootSlice offers the potential to significantly increase the efficiency and productivity of farmers. From the analysis, it aims to target 6 acres of crops per hour, almost 4 times what is achievable with standard manual labour. This translates to reduced labour costs, increased savings and improved crop yields. As global food demand continues to grow, there is a growing need for efficient and sustainable farming practices. By eliminating the need for harmful chemicals and pesticides, a sustainable and environmentally friendly solution is offered. The product is designed to be easy to use and maintain, making it accessible to root crop farmers with limited literacy and technical expertise. This was done via a unique design for repair approach which embraces modularity and easy maintenance.

9.1.5 Design for Repair

Due to the nature of the targeted customer and the countries where it will operate, RootSlice has been designed with attention to repairability and longevity. Considering the remote locations of potato farmers in the Andean region, our product has been designed to be robust, reliable, and repairable with components that are affordable and readily available worldwide. This was achieved by sourcing motion sensors, motors, gears, augers, or any component that might fail within the product life cycle, to be as readily available as they can within these remote locations. The plan is to establish a procedure for efficient distribution of spare components and might involve partnering with local suppliers or distribution centres within the Andean regions. The modularity allows spare parts to be replaced with little engineering knowledge, and the help of manuals as well as instructional tutorials that will be provided to farmers and technicians along with RootSlice. Another plan is to organize training sessions with experienced engineers, allowing farmers to develop the necessary skills to maintain and repair RootSlice by themselves. The design for repair solution makes our robot cost-effective as it amortises the price point over a longer time frame. In turn extending the life span of RootSlice, reducing waste, and providing a more sustainable, affordable solution for weed management.

9.2 Finance projections

Conducting a detailed analysis of financial projections can offer an all-inclusive view of RootSlice's economic viability. This can provide crucial insights into determining the sustainability of our business model, informing strategic decisions, and establishing possible risks and strategies for mitigation. This analysis can also be beneficial for investors, providing qualitative data to establish potential return on investment. The following was achieved by specifying expected costs, projected profit/revenue, expected units sold and payback time by inspecting cumulative savings for the customer segments. It can also involve establishing key partnerships and channels, cost structures and revenue streams, as well as key resources. Through this, the aim is to highlight the financial feasibility of RootSlice, strengthening its value position as an advanced, green, and cost-effective solution in the agricultural sector.

9.2.1 Key Partnerships & Channels

Determining essential partnerships includes seeking suppliers of high-quality components and materials to ensure that products meet the highest standards of durability and reliability. Additionally, contracts with distributors and resellers in the target markets are required. This is to ensure that the robot is readily available to customers, as well as provide replacement parts and maintenance when needed, following the design-for-repair approach. Local NGOs and government organisations in the target countries will also be valuable partners in helping with distribution and training. Agricultural experts and farmers will be consulted for product feedback and testing. As for channels, social media marketing & word of mouth will be utilised to reach end users. Partnering with NGOs and government organisations will allow RootSlice to reach target markets and provide training and support to its key customer segments.

9.2.2 Cost Structure & Revenue Streams

Fixed costs include R&D, manufacturing, and logistics, ensuring competitiveness in the industry and meeting the evolving needs of the targeted user persona. Variable costs will include marketing and sales efforts, distribution costs, and customer support. The pricing strategy will be determined based on the target markets and competitive landscape. Revenue streams come from direct sales to customers through e-commerce platforms and distribution channels, as well as reseller partnerships. Additionally, the potential to offer maintenance and repair services will be negotiated with NGOs and agricultural cooperatives for potential subsidisation or funding.

Our cost structure operates on the following assumption: Revenues and profits are projected to increase as production is scaled up and marginal material and manufacturing costs are reduced, achieving economies of scale. A contingency fund allows managing of unexpected expenses or setbacks. The cash flow will be managed using a lean approach, covering expenses.

9.2.3 Key Resources:

Ensuring the success of the business model heavily relies on the availability of key resources. Skilled engineers and designers will be required to create a high-quality and efficient robot that meets specific needs, targeting all potential markets. A marketing and sales team is essential to promote the product and create brand awareness. Distribution networks could be required to ensure the product reaches the target markets efficiently. This involves creating training materials and resources that enable farmers to operate and maintain the robots with ease. Angel investors and crowdfunding platforms are explored to secure the investment capital needed in starting the business while sustaining its growth over time.

The business case was synthesised into a business model canvas, providing actionable steps in determining the structure of operations while operating with a lean approach.

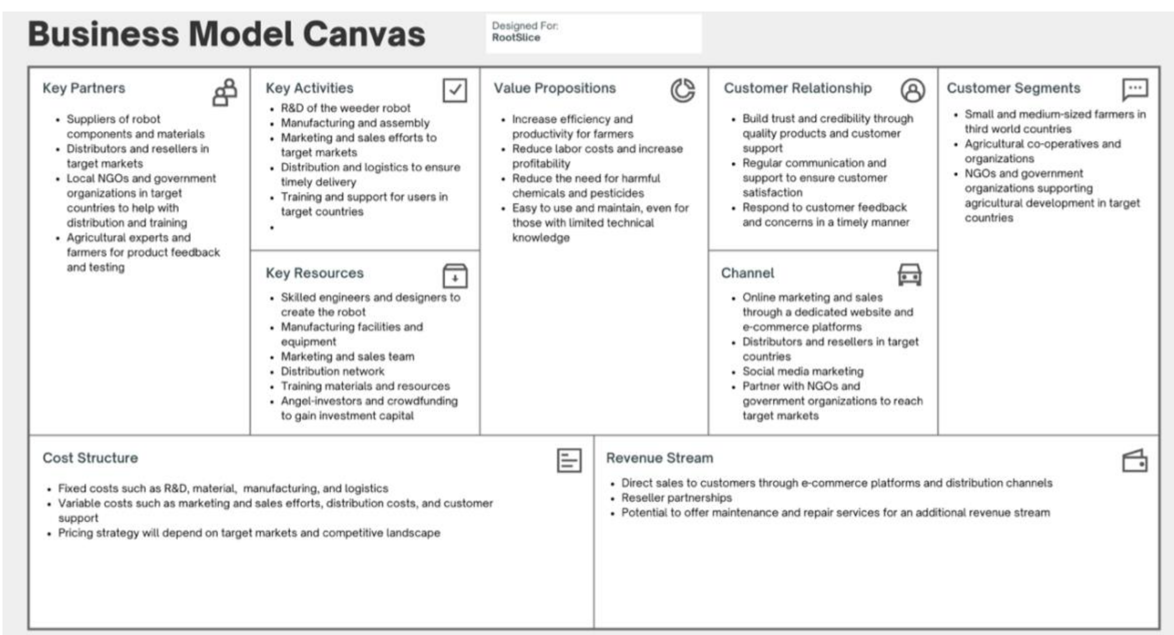

Figure 29 – Business Model Canvas

Having determined the optimal partnerships, cost structures and key resources for RootSlice has allowed for a more accurate determination of financial projections.

As determined above, the cost of RootSlice was estimated at £2900 in terms of production, materials, and assembly. This however does not consider capital costs, transportation and storage or other miscellaneous operation costs. It was assumed for these related costs to amount to 20% of the production costs. By including a profit margin of 30%, the overall retail cost of RootSlice was determined to be £4500, excluding VAT. The projected monthly revenue and profits were assumed based on the following assumptions throughout a 4-year period (June 2024-June 2027). The retail price was adjusted each year based on predicted inflation rates and Fibonacci retracement analysis (87).

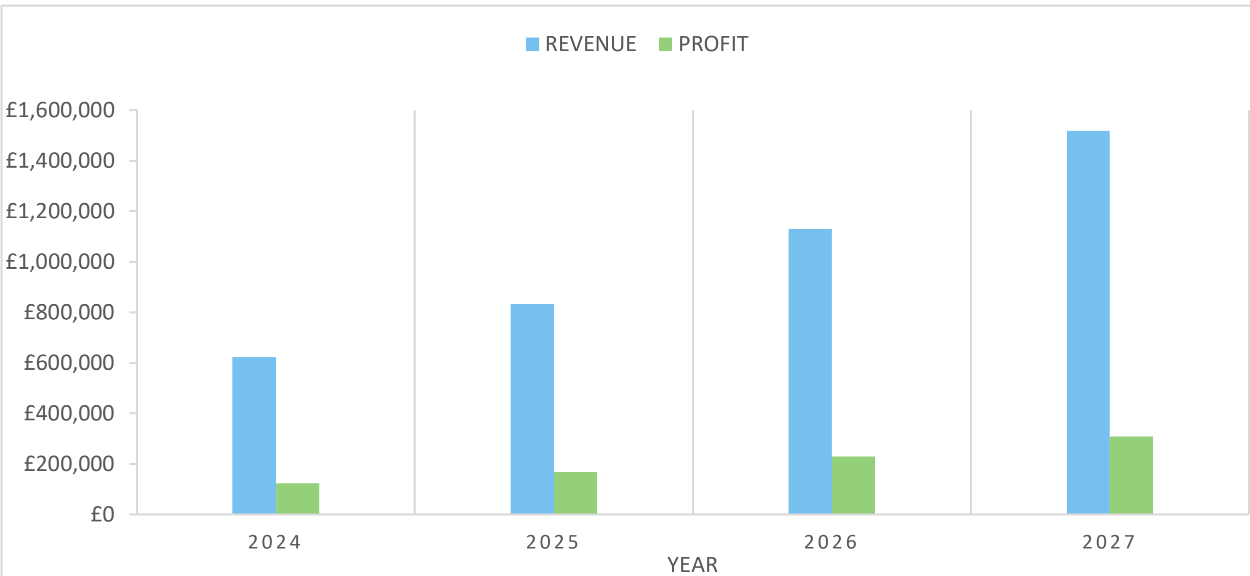

Figure 30 – Projected revenue & profit forecast 2024-2027

Projected revenues for 2024 are estimated to be £621,558, increasing to £1,517,220 by the end of 2027. This reflects on a hike in profits from £124,758 to £307,620. The margins are aimed to increase in the following years, as material costs and bulk orders reduce due to economies of scale, and production processes are optimised with higher levels of expertise.

Table 10 – Expected revenue & profit forecast 2024-2027

Year	Expected Revenue (£)	Expected Profit (£)
2024	621,558	124,758
2025	834,543	168,543
2026	1,128,375	228,375
2027	1,517,220	307,620

RootSlice is expected to enter the market by June 2024, selling 10 units, and an expected monthly growth rate of 3%. As aforementioned, the production cost will be about £2900, with a selling price of £4500, meaning a per unit profit of £900 for the company, and the investors. Based on the following assumptions, units sold by year were estimated as seen in Figure 31.

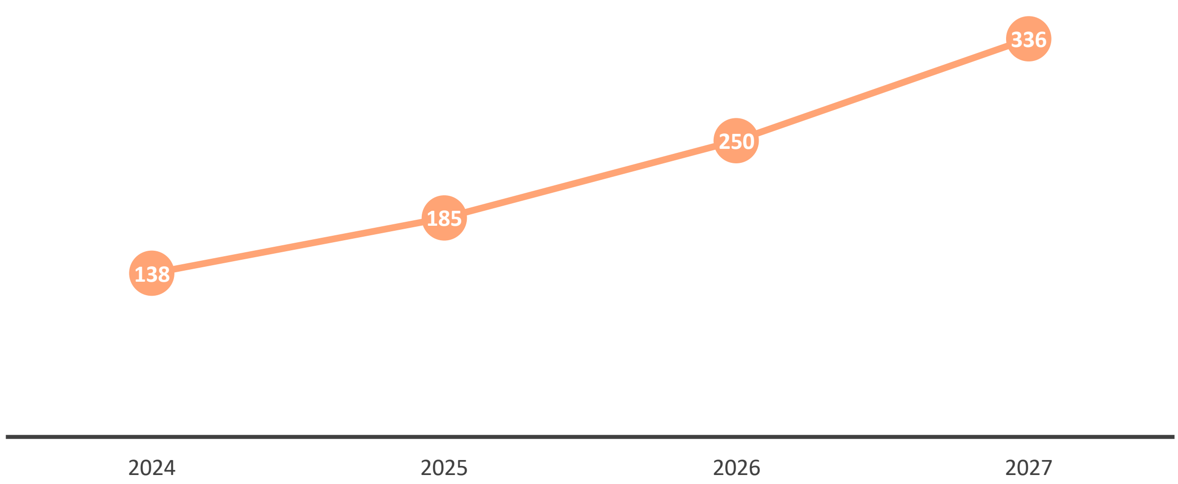

Figure 31 – Projected units sold by year, 2024-2027

In 2024, RootSlice aims to sell 138 units, steadily increasing to 185 units in 2025, 250 in 2026 and a promising 336 units by 2027. The number of units sold will heavily depend on relationships with partners, including NGOs and agricultural cooperatives, which aid in finding customers and potentially funding part of the costs.

Lastly, payback time was calculated by devising the cumulative savings provided by RootSlice. The service life of our solution is estimated to be at least 10,000 hours. Dividing our retail price £4,500/10,000 hours, we obtain £0.45/hour operating costs. When compared to the labour cost of a farmer in Peru, determined to be 2.21 £/hour, this would enable the farmer to save about £3,520 per year (88). This also provides the end user with a potential fund for any unforeseen maintenance or repair costs.

Figure 32 – Payback time in terms of cumulative savings and retail price

Dividing the potential annual savings of £3,520 by 12 months, this results in a monthly saving of £293 per month. Considering the retail price to be £4,500, this means that the farmer would recoup the initial investment of RootSlice after 16 months, as shown in Figure 32 above.

Conducting a thorough financial analysis for RootSlice has been instrumental in formulating the business case. Demonstrating its financial feasibility has proven the potential for RootSlice to be a profitable investment for stakeholders and investors, while considering its commitment to innovation and sustainable farming. Moving forward, the aim is to refine projections based on proven sales data and reports, as well as macro-economic indicators and market conditions. This guarantees RootSlice's business strategy to remain responsive and resilient in the face of changing circumstances and unexpected scenarios.

9.3 Critical analysis of the risks

The thorough development of a business use case proposal also involves a critical analysis of the risks involved. This was executed by conducting a PESTEL analysis, used to identify macro or external factors faced by an organization such as RootSlice (89). This analysis was broadened by also examining internal factors, including operational, financial & regulatory risks. A proactive approach to risk management is highly beneficial in preparing for potential drawbacks while demonstrating commitment to the successful implementation of our solution for possible stakeholders.

9.3.1 Regulatory, Financial & Operational Factors

Regulatory: These might involve a requirement for certifications to distribute RootSlice, which may vary based on the targeted developing countries. For example, OECD, the trans-governmental organization for trade facilitation, established the agricultural robotics solution must comply with the OECD tractor certification system (90). RootSlice's success in obtaining such certifications will involve compliance with relevant laws in target markets, such as Ecuador and China. Further challenges might also arise with changes in regulations impacting the deployment of agricultural robots. To mitigate this, RootSlice aims to monitor regulatory developments in emerging countries, intending to adapt the design and business plan to comply with novel requirements.

Financial: A key financial risk is not securing enough funding for the deployment and expansion of RootSlice into the mass market. According to UK Business Statistics, 42% of start-up businesses fail as there is no market need for their services and products (91). To mitigate this, RootSlice has developed a solution which closely targets our customer segments, strengthened by conducting multiple rounds of user interviews and feedback. Another solution would be to diversify sources of funding, involving government grants, angel investors, and strategic partnerships with suppliers, as well as maintaining a lean operation to keep costs low. Other risks might involve fluctuations in the exchange rate, potentially affecting the price of components and the retail price of RootSlice. A solution to diminish this risk would be to plan against inflation rate risk by ordering components in bulk and organising the cost structure of operations to account for any fluctuations.

Operational: Risk within the operation of RootSlice could arise due to many factors, including delays in the supply chain affecting production. For example, if the production of augers required for RootSlice has a 2-month delay, this would halt the assembly process and stop the overall productivity of the firm. These risks are very hard to predict as they transpire in a variety of circumstances, including issues with logistics, global events (such as the Russia-Ukraine war) or supplier problems. To diminish this concern, it is important for RootSlice to diversify the suppliers while maintaining good relationships with each, as well as developing a contingency plan and fund to account for possible disruptions. In their study on why the adoption of commercial agricultural robots is still low, Gil et al. revealed that some robotic solutions have low productivity due to the presence of defects or technical issues (92). This problem can be minimised by implementing quality control within the production process, including novel testing procedures, and creating a customer service team that promptly responds to any issues that might arise.

9.3.2 PESTEL Analysis

A PESTEL analysis for RootSlice allows for the systematic assessment of external macro-economic and social factors, including – Political, Economic, Sociocultural, Technological, Environmental & Legal. When identifying these factors, it aids RootSlice in anticipating and being prepared for risks that might occur (assessing its probability), and strategically devising mitigation strategies.

Political

Table 11 – Political Risks, with Assessed Probability & Mitigation Strategy

Risks	Assessed Probability	Mitigation Strategy
Variations in target nations' agricultural subsidies or policies	**25%** - Affected by administrative change or macro-economic conditions	Staying up to date with political developments or policy changes in selected countries
Instability of politics in target countries (i.e., Andean region)	**20%** - Stable thus far but hard to predict any unforeseen scenarios	Diversifying markets by targeting more than one developing country
Restrictions in trade or tariffs impacting the import/export of our product or relevant components	**30%** - Trade policies are generally unpredictable and vary greatly from country to country	Forming partnerships with local suppliers to dodge any potential trade restrictions
Variation in environmental regulations regarding sustainable farming practices	**40%** - New interest in sustainable farming might lead to new regulations	Embrace a culture that supports sustainable farming and agricultural innovation

The highest identified risk for RootSlice is political instability within the Andean region. As of a report published in 2021, the political stability index for Ecuador is an acceptable -0.27 where -2.5 is weak and 2.5 is strong (93). Regarding variations on environmental regulations, RootSlice tackles this by ensuring the product promotes sustainability and has a large focus on preserving the environment.

Economic

Table 12 – Economic Risks, with Assessed Probability & Mitigation Strategy

Risks	Assessed Probability	Mitigation Strategy
The global recession may affect farmer's ability to invest in RootSlice	**35%** - Macro economic conditions are unpredictable and vary across target countries	Customers are able to pay for RootSlice with flexible options including financing and monthly payments
Labour cost changes may increase the cost of manufacturing RootSlice	**30%** - These changes vary with economic conditions and regulations	Automate processes of production to minimise manufacturing costs
Inflation affecting the cost of materials	**30%** - Inflation rates tend to fluctuate	Ensure bulk purchasing materials and economies of scale to achieve lower prices

Hikes in interest rates may impact the cost of financing	**25%** - These are determined by the central bank and vary over time and across countries	Strategic partnerships with a range of investors to secure funding and maintain a strong financial position

Minimum wages in the Andean region of Ecuador have increased to 450 USD/month in 2023 compared to 340 USD/month in 2014 (94). RootSlice could save the farmer potential labour costs by having a solution which operates 24/7. Production for RootSlice will be carried out in 2024 in the UK, where it is estimated that the minimum wage will be £11.16, a 9.7% increase compared to 2023 (95). In terms of manufacturing/transportation, optimising processes and streamlining operations with a lean approach will be fundamental in hedging against inflation and rises in wages.

Sociocultural

Table 13 – Sociocultural Risks, with Assessed Probability & Mitigation Strategy

Risks	Assessed Probability	Mitigation Strategy
Target customers may have a resistance to new technology (technophobes)	30% - Farmers in developing countries may be sceptical of RootSlice	Providing easy-to-use courses and guides, including support from technicians
Lack of technical skills among target customer	35% - There may be a difficulty in introducing technical aspects	Offering training and support from on-site engineers
Negative public perspective towards commercial agricultural robots	20% - Can vary with different cultures	Promote a sustainable brand vision, and communication with public
Barriers with languages or dialects for communicating with farmers	20% - While Spanish is the main language of the Andean region, this may vary with indigenous communities	Offer training and customer support in the local language of targeted countries

The most important risk to consider would be effectively teaching technical skills in operating and maintaining RootSlice to farmers in developing countries, which may signify putting thought into how to deliver the learning material. Deichmann et al concluded that the successful implementation of communication technologies could help small-scale farmers understand how to use agricultural robots (96).

Technological

Table 14 – Technological Risks, with Assessed Probability & Mitigation Strategy

Risks	Assessed Probability	Mitigation Strategy
New technological innovations rendering RootSlice obsolete	40% - Technological advancements occur rapidly in agricultural robotics	R&D to allow continuous improvement of RootSlice to maintain relevancy in the market
Depending on technology or suppliers for manufacturing	30% - There could be disruptions in the supply chain	Diversify suppliers to not have dependencies on one
Defects or technical faults affecting the performance of RootSlice	25% - Despite QC and rigorous testing, these issues may occur	Focusing on quality control and testing to ensure reliability

While there are undoubtedly new innovations that will arise in the coming years, RootSlice has a fighting chance by constantly going through R&D to optimise the design of the robot so that it is intuitive to use and repair for the customer segment. One disadvantage new entrants may have is in building supply chains and strategic relationships with NGOs or other government organisations, essential in deploying a product like RootSlice into the mass market.

Environmental

Table 15 – Environmental Risks, with Assessed Probability & Mitigation Strategy

Risks	Assessed Probability	Mitigation Strategy
Climate change can impact farming processes and RootSlice demand	**45%** - This is an ongoing global issue which introduces future problems	Modifying current farming practices for climate change
Natural disasters affect RootSlice or supply chain productivity	**30%** - Natural disasters are difficult to predict	Creating a contingency fund that considers natural disasters
Manufacturing of RootSlice could involve pollution or waste	**25%** - Most manufacturing processes tend to generate waste	Constant exploration of energy efficient waste-free manufacturing
Energy consumption could impact the environmental footprint of RootSlice	**30%** - Energy efficiency is a growing concern globally	Use of solar panels for operation and implementing green recharging

By far the biggest concern to consider is how the ongoing global warming crisis will impact potato production. Raymundo et al. investigated applying projected climate change scenarios to potato cropping, indicating a decrease in yield by -2% to -6% by 2055, and larger declines of -2% to -26% by 2085 (97). RootSlice aims to mitigate this by constantly evolving its solution to tackle the detrimental effects of climate change.

Legal

Table 16 – Legal Risks, with Assessed Probability & Mitigation Strategy

Risks	Assessed Probability	Mitigation Strategy
Challenges with obtaining IP affecting the global distribution of RootSlice	20% - It is not uncommon for IP disputes to arise in robotics sector	Securing and actively protecting intellectual property rights
Liability concerns related to the performance or safety of RootSlice	35% - Unsafe operation of RootSlice could lead to injury	Implementing various safety standards and stopping mechanisms
Employment laws affect labour unions involved in manufacturing RootSlice	25% - Employment laws change from country to country	Comply with government laws across target countries

Curl et. al reported that farmers involved in potato harvesting are actively concerned about safety hazards or common injuries in the work field, including unsafe operation of farming machinery and agricultural robots (98). By placing stopping mechanisms near the auger and motors, RootSlice aims to minimise any related injuries caused by our solution.

By conducting a comprehensive risk analysis considering internal factors (operational, financial, regulatory risks) as well as a PESTEL analysis (encompassing macro-economic external factors) has been fundamental in defining drawbacks and forming mitigation strategies. The analysis has revealed that while there are risks evaluating and assessing, they can be appropriately managed by adopting the right strategies, giving RootSlice a chance at long-term success and sustainability.

10 Discussion

10.1 Critical analysis

At this stage, RootSlice presents several benefits and concerns which may affect the opinion of investors and/or potential clients.

Table 17 – Advantages and disadvantages of the product

Advantages	Disadvantages
Can target weeds directly from above, without affecting surrounding crops	Self-driving mechanism incomplete
Can be automated	Placement of the centre of mass high from the ground
The design developed considering easy repair	Production costs may be underestimated
Product designed closely to target customers	The selling price may be too high for developing countries, potentially affecting the financial forecasts
Solar panels provide a renewable energy source, reducing the need for external sources	The auger mechanisms may require more energy than estimated depending on the type of soil
Functional initial prototype available	Battery and recharging systems are still unknown
Robust and efficient machine learning algorithm for weed detection	Farmer's concern in buying a newly released, not fully tested product from a novel start-up
Comprehensive electronics analysis	May not be as efficient in different soil conditions or other types of crops
The prototype has undergone tests and simulations for quality assurance	This may require a learning curve for farmers who are not very familiar or sceptical with modern technology
Lightweight design with careful selection of materials for optimal performance	May not be as effective in large-scale farming operations
Flatpack assembly reduces shipping costs	The system may require maintenance and repair often to allow it to function optimally

Conducting a critical analysis of RootSlice, through examination of advantages and disadvantages can be of paramount importance in the engineering design procedure. Through this, strengths and weaknesses are not identified, but actionable insights in improving the feasibility and practicality of RootSlice in real-world scenarios are offered, informing both future design iterations and strategic decision-making.

10.2 Discussion about feasibility analysis of this product and business

Conducting a feasibility analysis for the production and release of RootSlice is pivotal in assessing the ability to carry out various aspects of the project including *product, technological, economic, operational, market and regulatory.* This will provide key insights into understanding areas of challenge and how to move forward in the development of our commercial agricultural robot.

10.2.1 Product feasibility

RootSlice's unique design encompasses a range of features. It's lightweight and intuitive, ensuring RootSlice is perfect for root crop farmers in the Andean region, an appropriate solution for a customer who may have little experience with complex machinery. The solution is equipped with soil and humidity sensors, able to measure nutrient levels. This can inform farmers with valuable data, optimizing their farming practices across all fields and not only weed removal. In the design development stage, a key consideration was designing the robot to adapt to ancestral techniques and tools that can be widely accepted among the target users. RootSlice utilises a variety of techniques optimally considered for chosen materials and components, confirming it can be feasibly manufactured and assembled.

10.2.2 Technological feasibility

RootSlice's machine learning algorithm can detect unwanted plants through live video, facilitating the detection of weeds & increasing the productivity of farmers through effective weed control. The artificial intelligence program has been enhanced using "mobilenetV2" framework, decreasing the number of calculations required, while staying accurate. The target detection algorithm was chosen to be "YOLOv3" able to target specific weeds effectively. The model was trained to recognize "Coriandrum Sativum" at first, fed with a variation of images, allowing for 95% accuracy. Feasibility is also guaranteed by choosing standardized components produced from a variety of suppliers, diversifying risks, and reducing any dependencies on the supply chain.

10.2.3 Economic feasibility

Projected revenues are estimated to be £621,558 in 2024, increasing to £1,517,220 by the start of 2028. This provides a significant profit increase from £124,758 to £307,620, providing sufficient funding for R&D and manufacturing costs. These promising figures are projected to increase as economies of scale are achieved. The total manufacturing cost is about £2,904.42, with a selling price of £4,500 guaranteeing a per unit profit of £900 per unit. Economic feasibility is backed by steady monthly growth of 3%, with units sold to increase from 138-336 in the period of 2024-2027. Lastly, RootSlice provides significant savings of £3,520 in 12 months. Farmers will recoup their investment in 16 months by only considering cumulative savings in terms of gained labour hours.

10.2.4 Operational feasibility

During the interview with Manuel Choqque Bravo, it was understood that operational feasibility could be achieved by developing an easy-to-use system along with intuitive learning materials. This allows the targeted customer segment to operate RootSlice with ease and little guidance. Other features including pH, humidity, and temperature sensors and the AI weed recognition algorithm could aid the farmers in automating tasks otherwise performed manually, drastically increasing operational productivity. Moreover, the machine learning platform is designed to learn any relevant weed types by uploading a database of pictures, highlighting its adaptability in various farming environments.

10.2.5 Market feasibility

The target market is root crop farmers in developing countries with a focus on potato farming, but can be adapted to work with cassava, sweet potato, and carrot plantations. The vision of RootSlice is to tailor to the unique needs and challenges of our customer segment. Ecuador's potato market is estimated to be worth $682 million in 2023, providing a significant customer base for RootSlice. A key factor in product development is achieving a sustainable advantage over existing competitors (Carbon Robotics & Nexus Robotics) by providing a solution that is more affordable, less energy-consuming and designed for repair. Market expansion is a possibility as RootSlice develops and adapts. A deciding factor in achieving long-term brand longevity is to build strong customer relationships, by providing consultation and periodic on-site assistance from RootSlice technicians.

10.2.6 Regulatory feasibility

Ensuring regulatory feasibility will involve complying with government regulations and policies related to agricultural robots, and staying up to date with political developments in the targeted countries. RootSlice aims to diversify its markets to reduce restrictions based on a single government policy. Another factor to consider is obtaining patents for global distribution rights, which will be mitigated by actively protecting intellectual property rights. Lastly, certifying safety standards are met is crucial in guaranteeing its performance and reliability, such as a stopping mechanism for the motor and the auger.

10.3 Comments from South American farmer

Following the initial interview that RootSlice conducted with the local farmer from Peru, a final interview took place to gain valuable feedback regarding the product's market fit. During the interview, the CAD model alongside the final Kickstarter video was shown to the Ecuadorian potato farmer. The interview concluded that the product is successfully tailored for the small-midsized farmers given its modularity and easy maintenance. Furthermore, Manuel Choqque Bravo displayed his concerns regarding whether the robot would be accessible to small farmers with limited budgets in a developing country like Ecuador. Nevertheless, positive feedback was received regarding the unique auger mechanism employed by the robot to accurately target the weeds. Overall, the local farmer showed high enthusiasm for the product as he highlighted the urgent need for a weed control mechanism that is not labour-intensive and fits in with their ancestral techniques.

10.4 Comments from Chinese professional farm operator

Mr. Hongjun Chen, a professional farm operator with more than 30 years of experience in Anhui Province, China, was invited to watch the latest Kickstarter video of RootSlice in an interview on June 4th, 2023.

Mr. Chen was impressed to see that RootSlice adopts the auger to remove weeds, which is very different from traditional robots. Usually, the cutters are rotary and a blade or a high-strength nylon rope is installed on a horizontal high-speed rotating disc to remove weeds by shearing force. Mr. Chen believes that the auger bit used by RootSlice is more suitable for potato fields than the traditional rotary blade, as these are mainly suitable for weeding large areas and flat surfaces. The new design can achieve precise weeding in a small area and uproot weeds that grow underground.

During the interview, Mr. Chen made suggested adding adjustable wheelbase and height functions to RootSlice. He explained that potatoes are often planted in rows, and farmers will determine the distance between each row of potatoes according to natural environmental factors, and there will be a certain error in the distance during actual cultivation, so the adjustable wheelbase and height would be an advantageous function necessary to make the robot better adapt to different farmlands, reduce the operation cost, and deployment time.

He also commented that using an AI technology to detect unwanted weeds could result in a problem if weeds are mixed in the area where potatoes grow. One of his main concerns was whether the artificial intelligence is accurate enough to distinguish the weeds. Moreover, he was worried about the precision of the drill and its ability to remove weeds without harming the potatoes.

Finally, he was very optimistic about the simplicity of the design and operation of the robot. He concluded by highlighting the importance of innovative products such as RootSlice due to the labour costs rising and the cost of intelligent mechanization is decreasing year by year, intelligent agricultural robots will become more and more popular.

10.5 Comments from agricultural robots' manufacturer

At the IEEE (Institute of Electrical and Electronics Engineers) Robotics and Automation Society International Conference on Robotics and Automation (ICRA) 2023 held in Excel London from 29th May to 2nd June 2023, RootSlice had the opportunity to visit the conference exhibition and talk to a number of robotics company. Notably, an interview with an industry insider, Mr Marc Jones, VP Commercial of Antobot, was conducted to seek for his professional opinion on the design and business plan of RootSlice (Figure 38). Antobot is a UK-based start-up that specialises in delivering cost-effective robotics solutions for sustainable agriculture. Their universal robot control unit® empowers farmers of all scales to access fully digitised precision farming, revolutionising the way agriculture is practised.

During the interview with Mr. Jones, he expressed his positive impressions of the design of RootSlice and found it to be both practical and achievable. He commended the team for their efforts in developing a weed removal robot specifically tailored for root crop farmers in the Andean region.

Regarding the design, Mr. Jones offered some valuable insights. He suggested that adding more earth augers to the robot may enhance the weed removal efficiency. By increasing the number of augers, the robot can cover a larger area and remove weeds quicker. This would be particularly beneficial for farmers with larger fields or those facing time constraints. Mr. Jones emphasized that efficiency and productivity are key factors in the success of any agricultural robot.

In addition, Mr. Jones shared his enthusiasm for the potential impact RootSlice could have on sustainable agriculture. He appreciated the focus on cost-effectiveness, which is crucial for farmers, especially those in developing countries. The integration of the AI weed recognition system was particularly intriguing to him, as it provides farmers with precise weed-removing techniques.

Furthermore, Mr. Jones emphasised the importance of considering scalability and adaptability in the design of RootSlice. As agriculture is a diverse industry with varying requirements, he suggested that the team explore the possibility of modular design, allowing farmers to customise the robot based on their specific needs. This flexibility would make RootSlice a more versatile solution for farmers across different regions and crop types.

Overall, Mr. Jones expressed his optimism and support for the design and business plan of RootSlice. He believes that the team has identified a significant need in the market and has developed a practical solution that could positively impact the lives of root crop farmers in the Andean region. He encouraged the team to continue refining their design, focusing on efficiency, scalability, and adaptability for the success of RootSlice.

11 Conclusion

This project focused on designing and developing an autonomous weed-removing robot for LMICs. Detailed research showed how the yield of potato crops in the Andres region, located in South America, is significantly affected by the growth of unwanted weeds. As a result, after interviewing a local farmer, it was found how essential, autonomous weed-removing robots for these locations would be, with the main requirements being reliable, efficient, affordable, and sustainable.

For the robot to be successful, it was key to find a design which did not affect the surrounding crops as well as did not require any chemicals. An intensive design selection between several different ideas enabled us to find a unique auger mechanism which targets the weeds directly and acts on their roots.

Thorough intensive modelling and analysis, combined with the motors and materials selection processes, it was possible to identify the components and materials required to provide performance and durability, while being cost-effective. Research about the electronics required to fulfil the degree of autonomy set in the main criteria was completed, revelling ultrasonic and LIDAR sensors essential for the robot. A fully functioning AI recognition system was developed and trained to detect the unwanted weeds in between the crops.

Due to the limited time and resources, it was not possible to build a prototype of the full robot. Instead, a scaled model of the weed-removing mechanism was prototyped. This enabled testing and improving the design of the selling point of the robot, which was initially found to be affected by high vibration. The testing of the auger also showed how different soils can significantly affect the efficiency of the mechanism, revealing essential to investigate this aspect further in the future.

RootSlice's manufacturing and supply chain strategy involves manufacturing the robot in the UK, leveraging its established infrastructure and skilled labour force. Material selection is based on properties such as cost, strength, and durability, with appropriate manufacturing techniques employed for each part. Close collaboration with suppliers is crucial, with measures in place to ensure high-quality materials and components. Cost considerations and sustainability practices are integrated into the strategy. By following these steps, RootSlice can achieve efficient production, cost-effectiveness, and a reliable supply chain.

The business plan is centred around providing an affordable and environmentally friendly solution for weed control to small-scale farmers. The potato processing market is globally valued at $31.8 billion in 2022, estimated to reach $51 billion by 2030, with Ecuador as a primary target market and a market size of around $682 million. Financial projections show promising growth, with revenues increasing from £621,558 in 2024 to £1,517,220 by 2027. Within the business plan is a detailed risk analysis, reflecting internal and external factors. External factors were assessed through a PESTEL analysis, whereas internal factors included operational, regulatory, and financial risks. This allowed for the formulation of key mitigation strategies to undertake, which will enforce long-term and sustainability for RootSlice.

Overall, the feedback received from farmers and a company in the robotic sector proved that RootSlice provides a unique solution to address a problem faced all over the world. The project requires further analysis and development before RootSlice can be introduced into the market, with features such as the self-driving and the AI integration essential to be implemented as the next steps. Building a second prototype which includes all the features of the robot is key in order to increase the reliability of the AI. As a result, it is necessary to find external investors, which will provide funds for the project to continue.

12 Next steps and Improvements

As mentioned earlier in the report, during the testing of the prototype, an unpredicted level of vibration was encountered. This was partially solved by altering the design of the drill case however, a significant amount of vibration is still present in the racking system. Hence, it is essential to conduct a vibration study, as over time it could lead to failure.

Furthermore, building on the observation articulated in section 5.2, substantial scope exists for optimising the utilisation of materials in the existing design. A redesign could yield a lighter, more efficient system by minimising the materials used for the casing. Such a modification could lead to significant reductions in production costs and mitigate complexity in the manufacturing process.

In addition, the system's effectiveness could be significantly augmented by integrating multiple auger mechanisms as suggested by Mr. Jones. Incorporating additional earth augers may enhance the robotic system's weed removal capacity. Therefore, the system could effectively cover a larger area, accelerating the weed eradication process. This would prove particularly beneficial for scenarios involving large fields or where time constraints are a pressing concern.

After the first investment, the aim is to develop a fully function-scaled version of the final product. This would enable to test the product in a real field and gain further feedback from farmers and potential clients. To achieve an autonomous prototype, it is essential to focus on the self-driving aspect of the robot as well as how to implement the AI with the auger system. Developing the self-driving mechanism will make it possible to identify the motors necessary for rotating and steering the wheels, as well as the size of the batteries, the solar panels, and the sensors required.

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14 Appendix

14.1 Appendix A – Portfolio of Group Notes

Date	Time	Duration	Location	Members	Tasks completed
19/01/2023	12.30	90 minutes	Robert's building (410)	Everyone	Mid-report brief reading. The group discussed the tasks that will need to be completed and allocated what section of the research everyone will need to be completed.
26/01/2023	12.30	90 minutes	Robert's building (410)	Everyone	Discussion about the progress made on the research. Highlighted some points to improve the design selection process. Defined the dimensions for the CAD model. Added some comments about the Gannt Chart and agreed that using Microsoft Project is the most professional and efficient way of doing it.
30/01/2023	14.00	30 minutes	MechSpace	Everyone	Meeting with the module coordinator and his assistant to ask some questions about the project. It was concluded that the group should focus on the selling point of the robot only for the prototyping section, instead of the whole product.
30/01/2023	16.30	90 minutes	Robert's building (basement)	Alba, Alessandro, Edoardo, Nikolaos and Frankie	The design of the weed remover system was reconsidered as a group, due to the difficulty of the originally planned one. A newer and simpler design was found, which would require fewer components to be built and should be more reliable.
02/02/2023	12.30	90 minutes	Robert's building (410)	Everyone	Everyone shared what components they require for the sections they are developing. A list of parts to order for the prototype was drafted. Likewise, it was discussed how the AI identification system will need to be

					programmed differently for the simulation in the laboratory.
06/02/2023	14.00	120 minutes	Robert's building (basement)	Alessandro, Nikolaos, Frankie and Ziyu	Further investigation about the components required for the robot was completed. The outcome of the interview that Alba had with a farmer from Peru was discussed. Ziyu shared that the machine learning process of the AI developed has been started and the system should be able to detect the weed chosen for the laboratory experiment within the next 12 days.
23/02/2023	12.30	90 minutes	Robert's building (410)	Alba, Alessandro, Edoardo, Nikolaos and Frankie	Discussion about the progress made during the reading week. Everyone presented what they completed and what requires further work. Edoardo and Nikolaos clarified some issues they had with the FEA. Instead, Alba, Alessandro and Frankie shared some potential improvements for the manufacturing and business plan sections. It was agreed with the group to complete the mid-year report by Sunday to then focus on the formatting and proofreading.
27/02/2023	13.30	90 minutes	MS Teams	Alessandro and Edoardo	In this meeting, Alessandro and Edoardo focused on reducing the length of the report as it was a few pages above the limit. Clarification was made with the module coordinator about the length of the report and adjustments were made accordingly.
28/02/2023	16.30	180 minutes	MS Teams	Everyone	All the group together went through each paragraph of the report, proofreading it and suggesting improvements.

07/03/2023	13.00	300 minutes	MechSpace	Alessandro, Edoardo, Nikolaos and Ziyu	The components ordered online were rigorously checked and counted. It was found that one of the main racks was missing from the box and some of the components were in back order. The prints of the gears and drill cases was started.
13/03/2023	14.30	210 minutes	MechSpace	Everyone	The prints started last week were collected. The drill case showed some defects due to the bed of the machine not being perfectly calibrated. However, the component is still suitable for testing. Later supports were also glue together from scrap plywood laser cut into shape. The 3D printed parts were worked with the tools to remove the support material.
20/03/2023	14.30	210 minutes	MechSpace	Everyone	The components in back order and the missing rack arrived and these were collected. As a group, we started the assembly of the gears case. We ran into some difficulties as the gears were not aligning as designed due to the tolerance of the 3D printer. Shafts for both the motor and the bearing were made. By the end of the day, all the components were press-fitted together and the gears box was complete.
02/04/2023	14.30	210 minutes	MechSpace	Alba, Alessandro, Edoardo, Frankie and Ziyu	The acrylic case for the prototype was laser cut. This process took a significant amount of time due to some initial CAD files incompatibilities and the numerous components needed. Also, it was found that the pocket supports was not perfectly cantered and these needed to be recut. Before leaving the workshop, it was possible to make an initial assemble of the case. It was found that to simplify the gluing process and improve the aesthetics of the prototype, it was

					better make the supports of the gears box with acrylic as well, instead of plywood.
18/04/2023	15.00	60 minutes	MS Teams	Everyone	The group had an online meeting to discuss the brief of the final report which was recently released. We decided how to split the sections of the report and analysed together the feedback from the midyear report. Due to the exams approaching at different dates for each group member, it was decided not to set any specific deadline.
28/04/2023	11.00	300 minutes	MechSpace	Alba, Edoardo and Ziyu	Adjustments were made to the acrylic case, in particular the pocket of the top plate needed to be wider. The side supports were laser cut using acrylic and glued together. Also, the rails for the left and right mechanism were glued onto the supports. Work was started to create 4 legs, using waste wood, which will keep the box at 1 meter from the group for the testing of the prototype.
09/05/2023	14.00	30 minutes	MS Teams	Everyone	A meeting was help with the module coordinator and his assistant to discuss about the midyear report feedback. Also, clarification was made about how the final year report needs to be structure and the requirements for the final presentation. Overall, both the module coordinator and his assistant were happy with the feedback and any doubt was cleared.
25/05/2023	13.00	240 minutes	MechSpace	Alba, Edoardo and Frankie	The legs of the case were completed. 8 supports were 3D printed to attach the legs to the acrylic case and give balance to the overall prototype. The group members glued the acrylic box together.

26/05/2023	14.00	240 minutes	MechSpace	Edoardo, Nikolaos and Frankie	The drilling case was assembled and tested. An unexpected amount of vibration was experienced resulting in a component failure. In particular, the drill box case requires to be redesigned with particular attention to the rack supports.
30/05/2023	10.00	480 minutes	MechSpace	Alba, Alessandro, Edoardo, Nikolaos and Ziyu	The full up and down mechanism was finalised, including drilling holes in the racks mounting it within the gears and drill-case. The motors were linked to the MATLAB simulation.
01/06/2023	10.00	480 minutes	MechSpace	Everyone	Left and right mechanism assembly were installed by gluing final components to the plastic case, allowing the drill-case to move. The motors were linked to the MATLAB simulation.
02/06/2023	10.00	480 minutes	MechSpace	Everyone	The whole system was tested, ensuring everything worked optimally and to standards, performing little tweaks on the motors and full mechanism.
05/06/2023	10.00	480 minutes	MechSpace	Everyone	The wooden legs were painted black, the wiring was organized together, any other issues were fixed. Kickstarter video was recorded.
06/06/2023	10.00	120 minutes	MechSpace	Everyone	The group met at the MechSpace, disassembled, and transported the prototype to the Wilkins Building for the final presentation.
09/06/2023	11.00	360 minutes	MS Teams	Everyone	The group met over teams and throughout a 6-hour call proofread the entire report. Any grammatical errors were resolved, and last references as well as formatting was added.

14.2 Appendix B – Initial Interview dialogue with Mr Manuel Choqque Bravo

This section provides a translated transcript of the interview, which was carried out in Spanish.

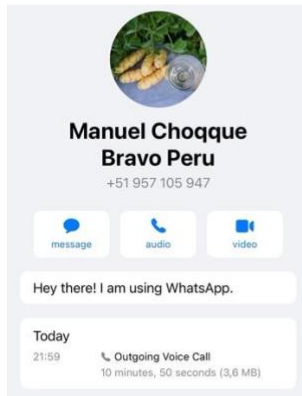

Figure 33 – Proof of the interview

RootSlice: Do you think weed control is an important aspect in potato crops in a country like Peru?
Manuel Choqque Bravo: There is a big problem regarding weeds in potato farms and many farmers have abandoned their farms as a lot of intensive labour is required to remove the weeds. It is a very important problem, and many farmers take immediate actions such as the use of herbicides, which is the fastest method, but these herbicides cause soil contamination.
RootSlice: What are the current techniques utilised in Peru for weed control in potato crops?
Manuel Choqque Bravo: Where my farm is located in the Peruvian Andes, potato farmers are the most affected by weeds. The large majority farmers remove weeds manually and a minority use herbicides, there are no farmers with access to weed-removing robots.
RootSlice: Do you think a robot that generates holes in the soil in order to remove the weeds from the roots will cause any problems to the field?
Manuel Choqque Bravo: I don't think any problem will be caused by this, removing weeds including the roots is beneficial and would be ideal. I am more concerned with the weight of the robot as this impacts how compact the soil is. Large heavy agricultural tractors are no longer used as many farmers are concerned with compact soil as the potato yield is significantly reduced under these conditions.
RootSlice: Thus, from this, the autonomous robot should be designed as lightweight as possible not to impact the soil.
Manuel Choqque Bravo: Yes, as lightweight as possible as compact soils have been seen to reduce the potato yield by reducing the water uptake by the potato crops.
RootSlice: How big are potato farms in the Andes?

Manuel Choqque Bravo: Where I am located, in the Peruvian Andes, the largest farms reach up to 5 hectares and the small ones are around 3000 sqm.
RootSlice: Is it important that the robot fits in with the agricultural practices and traditions that farmers in Peru have adapted for many years?

Manuel Choqque Bravo: Yes, I believe so, in the Peruvian Andes the farmers preserve ancestral techniques and tools and thus an easy-to-operate and maintain robot is ideal.
RootSlice: Are terrains inclined?

Manuel Choqque Bravo: Yes, they are slightly inclined they are not completely flat.
RootSlice: What other feature do you think would be beneficial for the robot to have aside from weed removal?

Manuel Choqque Bravo: Soil pH would be very beneficial as well as the number of nutrients in the soil.
RootSlice: What nutrients are beneficial for potato crops?
Manuel Choqque Bravo: Nitrogen, phosphorus, and potassium are the most important macronutrients that potato crops require in large quantities as well as the micronutrients of zinc, iron, and magnesium.
RootSlice: You mentioned previously it is important how compact the soil is, would it be therefore beneficial that the robot is able to measure the humidity of the soil?
Manuel Choqque Bravo: Yes, the humidity of the soil is very important, we have been having problems for the past years with droughts and measuring soil humidity would definitely be beneficial for potato crops.
RootSlice: Thank you so much for your time and experience Manuel, this feedback from you is very beneficial to be able to design and tailor the robot to the needs of potato farmers in Peru or other developing countries.
Manuel Choqque Bravo: I can tell you it is a very important issue; potato farms are being left abandoned here in Peru as there are not enough farmers for the labour-intensive job of removing a large number of weeds. This is why a weed-removing robot is very beneficial as I can assure you it is a very important concern.

14.3 Appendix C – Technical drawings of the gears and drill cases

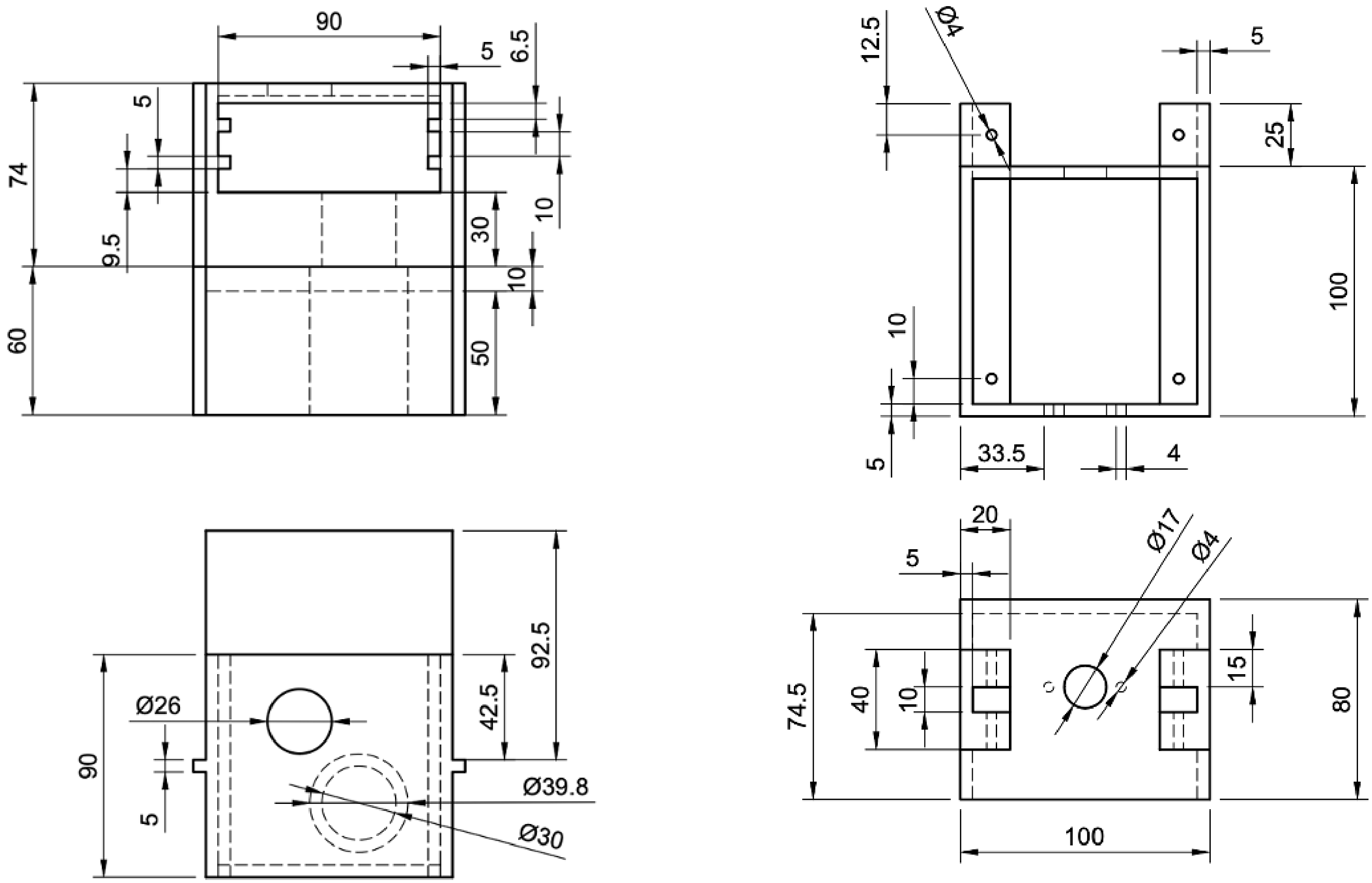

Figure 34 - Technical drawings of the gear box (left) and the drill container (right)

14.4 Appendix D – AI weed identification code (excerpt)

```
checkpoint_config = dict(interval=1)
log_config = dict(interval=50, hooks=[dict(type='TextLoggerHook')])
custom_hooks = [dict(type='NumClassCheckHook')]
dist_params = dict(backend='nccl')
log_level = 'INFO'
load_from = None
resume_from = None
workflow = [('train', 1)]
opencv_num_threads = 0
mp_start_method = 'fork'
auto_scale_lr = dict(enable=False, base_batch_size=192)
model = dict(
  type='YOLOV3',
  backbone=dict(
    type='MobileNetV2',
    out_indices=(2, 4, 6),
    act_cfg=dict(type='LeakyReLU', negative_slope=0.1),
    init_cfg=dict(
      type='Pretrained', checkpoint='open-mmlab://mmdet/mobilenet_v2')),
  neck=dict(
    type='YOLOV3Neck',
    num_scales=3,
    in_channels=[320, 96, 32],
    out_channels=[96, 96, 96]),
  bbox_head=dict(
    type='YOLOV3Head',
    # num_classes=80,
    num_classes=1,
    in_channels=[96, 96, 96],
    out_channels=[96, 96, 96],
    anchor_generator=dict(
      type='YOLOAnchorGenerator',
      base_sizes=[[(220, 125), (128, 222), (264, 266)],
            [(35, 87), (102, 96), (60, 170)],
            [(10, 15), (24, 36), (72, 42)]],
      strides=[32, 16, 8]),
    bbox_coder=dict(type='YOLOBBoxCoder'),
    featmap_strides=[32, 16, 8],
    loss_cls=dict(
      type='CrossEntropyLoss',
      use_sigmoid=True,
      loss_weight=1.0,
      reduction='sum'),
```

```
        loss_conf=dict(
            type='CrossEntropyLoss',
            use_sigmoid=True,
            loss_weight=1.0,
            reduction='sum'),
        loss_xy=dict(
            type='CrossEntropyLoss',
            use_sigmoid=True,
            loss_weight=2.0,
            reduction='sum'),
        loss_wh=dict(type='MSELoss', loss_weight=2.0, reduction='sum')),
    train_cfg=dict(
        assigner=dict(
            type='GridAssigner',
            pos_iou_thr=0.5,
            neg_iou_thr=0.5,
            min_pos_iou=0)),
    test_cfg=dict(
        nms_pre=1000,
        min_bbox_size=0,
        score_thr=0.05,
        conf_thr=0.005,
        nms=dict(type='nms', iou_threshold=0.45),
        max_per_img=100))
# Edit to VOC
dataset_type = 'VOCDataset'
data_root = 'data/'
img_norm_cfg = dict(
    mean=[123.675, 116.28, 103.53], std=[58.395, 57.12, 57.375], to_rgb=True)
train_pipeline = [
    dict(type='LoadImageFromFile'),
    dict(type='LoadAnnotations', with_bbox=True),
    dict(
        type='Expand',
        mean=[123.675, 116.28, 103.53],
        to_rgb=True,
        ratio_range=(1, 2)),
    dict(
        type='MinIoURandomCrop',
        min_ious=(0.4, 0.5, 0.6, 0.7, 0.8, 0.9),
        min_crop_size=0.3),
    dict(type='Resize', img_scale=(320, 320), keep_ratio=True),
    dict(type='RandomFlip', flip_ratio=0.5),
    dict(type='PhotoMetricDistortion'),
    dict(
```

```
        type='Normalize',
        mean=[123.675, 116.28, 103.53],
        std=[58.395, 57.12, 57.375],
        to_rgb=True),
    dict(type='Pad', size_divisor=32),
    dict(type='DefaultFormatBundle'),
    dict(type='Collect', keys=['img', 'gt_bboxes', 'gt_labels'])
]
test_pipeline = [
    dict(type='LoadImageFromFile'),
    dict(
        type='MultiScaleFlipAug',
        img_scale=(320, 320),
        flip=False,
        transforms=[
            dict(type='Resize', keep_ratio=True),
            dict(type='RandomFlip'),
            dict(
                type='Normalize',
                mean=[123.675, 116.28, 103.53],
                std=[58.395, 57.12, 57.375],
                to_rgb=True),
            dict(type='Pad', size_divisor=32),
            dict(type='DefaultFormatBundle'),
            dict(type='Collect', keys=['img'])
        ])
]
data = dict(
    samples_per_gpu=2,
    workers_per_gpu=2,
    train=dict(
        type='RepeatDataset',
        times=3,
        dataset=dict(
            type=dataset_type,
            ann_file=[
                data_root + 'VOC2007/ImageSets/Main/trainval.txt',
            ],
            img_prefix=[data_root + "VOC2007/"],
            pipeline=train_pipeline)),
    val=dict(
        # can not infer year
        type=dataset_type,
        ann_file=data_root + 'VOC2007/ImageSets/Main/test.txt',
        img_prefix=data_root + "VOC2007/",
```

```
        pipeline=test_pipeline),
    test=dict(
        type=dataset_type,
        ann_file=data_root + 'VOC2007/ImageSets/Main/test.txt',
        img_prefix=data_root + "VOC2007/",
        pipeline=test_pipeline))
evaluation = dict(interval=1, metric='mAP')
optimizer = dict(type='SGD', lr=0.003, momentum=0.9, weight_decay=0.0005)
optimizer_config = dict(grad_clip=dict(max_norm=35, norm_type=2))
lr_config = dict(
    policy='step',
    warmup='linear',
    warmup_iters=4000,
    warmup_ratio=0.0001,
    step=[24, 28])
runner = dict(type='EpochBasedRunner', max_epochs=30)

evaluation = dict(interval=1, metric=['mAP'])
find_unused_parameters = True
work_dir = 'work/coriander_yolov3_mobilenetv2'
gpu_ids = [0]
```

14.5 Appendix E – Feedback dialogue with Mr Hongjun Chen

RootSlice: After watching the promotional video of our weeding robot, what is your first impression?

Hongjun Chen: I first noticed that the knife head part of the weeding robot you designed is spiral. Most of the cutter heads of traditional weeding machines are rotary. Generally, blades or high-strength nylon ropes are installed on a horizontally rotating disc, and weeds are quickly removed in a large area by shearing force. Combined with the use scene of applying the new robot in the potato field in your promotional video, I think your design is very suitable and creative, which is very good. Because traditional herbicides are only suitable for weeding on a large area and on a flat surface, your design can precisely weed and remove the roots of weeds growing underground.

RootSlice: After watching our video, do you still have any unclear points or questions about our design?

Hongjun Chen: My biggest doubt is whether your robot height and wheelbase are adjustable? Because the shape of the robot is fixed in your video. If the size of the robot is adjustable, I think the practicability of your robot will be greatly increased, and the applicable area will be wider.

RootSlice: This is an important suggestion. The size of the prototype we made is fixed at this stage, but we will consider making it adjustable in the future.

Hongjun Chen: How do your robots weed? Is it controlled by remote?

RootSlice: Our robot uses artificial intelligence to identify weeds, automatically locate and perform weeding actions. It does not require manual operation.

Hongjun Chen: But in reality, we generally use herbicides to seal the soil before planting, and cover the land that needs to be planted. After these preliminary works, it is difficult for weeds to grow during the growth of crops. Generally, we use auxins as herbicides, such as indole acetic acid, because dicotyledonous plants have low tolerance to auxin, and most weeds belong to dicotyledonous plants. Therefore, auxin with a higher concentration has the effect of inhibiting the growth of weeds without affecting the normal growth of crops. Moreover, plant auxin will hardly pollute the environment, because it is naturally occurring, non-toxic and harmless, and can be degraded.

RootSlice: But potatoes are dicotyledonous plants, the method you said is not suitable for planting potatoes, and weeding is still required during the growth of potatoes. Another purpose of our design of this robot is to be environmentally friendly and reduce the use of chemicals as much as possible.

RootSlice: Our robot has not yet made a final quotation, but I still want to ask, if our robot can finally reach the practical stage, how much price would you be willing to buy it?

Hongjun Chen: You need quantitative data, give the workload that the robot can complete in a day, maintenance cycle and service life, and then compare it with the labour cost. But what I can tell you is that if the price is right, for me I would consider buying it. I grew ginger in Shandong Province a few years ago, and the way ginger grows is very similar to potatoes. Due to the lack of research in the early stage, the labour cost far exceeded expectations, and there was basically no benefit. Mechanized operations are very popular now, and I am very optimistic about your design, but you also need to do more research.

Hongjun Chen: Finally, I would like to add a question. I see that the main function of your weeder is to remove the weeds in the spaces around the potatoes. If weeds are mixed in the potato leaves, how should your weeder remove the weeds? Because the root system of plants is very developed, and your artificial intelligence recognition accuracy and the size of the cutter head always have working limits. It's hard to work accurately if the weeds are mixed with the crops. In response to this problem, I suggest that you go to the field to investigate and make a more reasonable optimization.

RootSlice: Thank you for accepting my interview, your comments and responses are extremely valuable. We will further research and optimize your answers.

14.6 Appendix F – Interview with Antobot

Figure 35 – Interview photo with Mr Marc Jones, VP Commercial Antobot