Delft University of Technology

Msc Mechanical Engineering - Biomechanical Design Thesis - ME51035

Developing and Evaluating a Mechanical Leaf Removal Design for a New Broccoli Variety

J.A. Brabander 4480112

Supervisors:
M. Sempf (Rijk Zwaan supervisor)
Dr. Ir. G. Smit (TU Delft supervisor)

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Abstract

Automation within an industrial sector has now for years been an obvious factor. Everywhere mechanical instruments and sensors are implemented for fast and precise processes. The agricultural sector is some steps behind in relation to other sectors. Reason being that there are many irregularities which in other sectors have been made into uniform variables. One of the problems that needs to be tackled within the agricultural sector is having the leaves of crops removed.

Rijk Zwaan has created a new variety of broccoli and to make this commercially viable, a harvest machine is required. One of the aspects of this harvesting process is removing the leaves. This has to be achieved in one continuous session, with at least a ground speed of 1 km/h, while the broccoli's are still in the field. With a focus on the best performance for the least destructive working principle. After listing all the requirements, ideas are structured in a morphological overview. A weighted criteria table will be used to select three ideas, which will be made into prototypes.

Results from the initial testing period will reveal the best concept, which will be optimised. This was the Metal Wire design, which exist of multiple stainless steel wires attached perpendicular to a rotating shaft. An important aspect that boosted the performance was the unravelled ends of these wires. These rotating shaft had the wires removing the leaves, while beating the leaves down from both sides.

After optimization, the current prototype could ensure a 60% of the top section and 80% of the middle section with 20% of the broccoli's destroyed. Which was not enough to satisfy the goal, however the promising results could be improved with an upgraded machine. A clear trade-off was found between the performance and destruction. Significant improvements in results could be achieved by incorporating additional features such as a funnel and designing a more robust structure with fewer obstructions, controllable ground/rotational speed, and better alignment with the beds. Therefore at the current state the leaf removal machine operates substandard, but has potential to be developed into the desired product.

Contents

1 Introduction

1.1 Need for Innovation

Since its existence, the agricultural sector has played an important role in people's lives. Still to this day agriculture has not only the role of fulfilling the primary needs, but also plays a key role in the global economy. These influences will be expected to grow due to the increasing population in the coming years. This will also cause urbanization and lead to a a reduction in cultivable land, requiring effective agricultural development [1, 2].
In addition there is an increasing influence from environmental and food safety concerns, which pushes this sector into a certain more restricted direction. Agricultural workers are getting more difficult to be found and retained. With an increasing demand for fresh and processed vegetables, this puts more pressure on the vegetable industry. Which already deal with government regulations, large food processors and suppliers, and increasing global competition [3, 4].
There is a shortage of labor and the remaining is becoming more costly. Resulting in relatively high production costs and therefore increasing demand for mechanical harvesting or even full automation. Technical developments, such as automated harvesting techniques, are lacking which is also the key issue for the production cost. Productivity and efficiency losses due to inefficient farming methods could be improved by implementing a decrease in required labor [2, 5, 6]. In addition, there are upcoming technologies for autonomous robots in agriculture with GPS, vision based navigation, sensor connected to actuators and soil analysis [7, 8].
There are still many improvements needed in the step before this, namely the mechanical harvest. Due to the lack of uniform products in agriculture, mechanical solutions pose a great challenge. The addition of sensors to read yield, plant structure, spatial variation or even extending to selective harvesting could help. The downside is that this will also lead to a more costly design. For selective harvesting, this will in most cases have additional time as important aspect. On the other hand, single-pass mechanical harvest could have high losses. A loss of 10-20% is not very uncommon for single pass harvesting, the natural variability will require trimming or discarding [9–12].
Stochastic variations in crop development play a key role in the feasibility and whether the mechanical harvesting system will succeed or fail. Trials for size/ time variations could be implemented for information gathering in words of structural characterization [4, 13]. In addition to these challenges, sometimes prior actions have to be conducted to make the mechanical harvest easier or even possible. Leaf removal is such a step that could be considered. Broccoli is part of the brassica genus and these deal with a lot of excess material.
Leaves could be an obstruction for the growth of a product, but could also just be in the way of harvest. There is however not a singular solution to deal with leaves and as more often in agriculture, challenges will represent themselves with all the different solutions. Inconsistent variables or simply lack of uniformity continue to affect productivity.
When it comes to leaf removal specifically for broccoli, the requirement of removing leaves without harming the broccoli head presents one of the biggest challenges. This is crucial for high-value crops like broccoli, since even minor damage to the head can significantly lower the crop's market value. The use of specialized equipment for removing leaves from broccoli can help improve the harvest process and make it more efficient.
Overall, there is a need for innovation in the field of mechanical leaf removal for broccoli to improve the efficiency, precision, and safety of the process while reducing labor costs.

1.2 Existing Patents

Existing patents regarding leaf removal for broccoli do contain some solutions. There is a beating and a cutting mechanism to remove leaves from the broccoli, while they are still in the field. For a beating mechanism, two rotary shafts with transversely added leaf stripping means are used [14]. Another method of removing leaves, while still in the field, is done by having 4 shafts surrounding the

stem with cutting elements located below these shafts for removing the leaves [15]. While the beating mechanism is a single-pass harvest approach, the cutting is a selective harvesting solution.
Another selective harvesting that already exists for defoliating broccoli is one using a pulling mechanism. For this method the leaf removal and the harvest will be conducted at approximately the same moment. While the leaves are pushed down, an additional mechanism cuts the stem to gather the product. Therefore a pulling mechanism is used for leaf removal, while a cutting mechanism takes care of the harvest [16]. J. Kloosterman and J. Zijlstra described a machine that harvests broccoli using a cutting mechanism. While avoiding harm to the surrounding vegetation, the machine can recognize and locate the broccoli heads precisely. Using a selective harvesting method to remove the broccoli head [17].
Solutions for leaf removal could also be applied after the broccoli was removed from the soil. In one patent, the broccoli's are removed by cutting the stem using a reciprocating blade. The broccoli's with leaves still attached are then carried away while being held beneath their head. The leaves are then removed using a beating mechanism with rotating elements that only operate in the area adjacent to the stem [18].
There is a patent that kills two birds with one stone. The whole broccoli plant with leaves is removed from the soil and hang upside down. Now the head, which is the product, is cut to the desired height. In this process to finalize the size, the leaves are also removed [19].

1.3 State of the Art

Mechanical removal of broccoli leaves is a crucial aspect in the harvest of this high-value crop. The leaves of broccoli can be an obstruction during harvest and the leaf removal could lead to significant damage to the head of the broccoli, which can lower its market value.
There has been a substantial amount of research on robotic harvesting systems for several crops, including broccoli, according to a study by G. Kootstra, et al. in "Selective Harvesting Robotics: Current Research, Trends, and Future Directions." [20]. The study emphasizes the significance of creating systems that can precisely identify and harvest the crop selectively without harming surrounding vegetation.
Ishita Bhakta covers several mechanisms used in precision agriculture for crop harvesting, including vision-based systems, cutting mechanisms and gripping mechanisms in her article "State-of-the-art technology in precision agriculture: a systematic review." [21]. According to this study, cutting mechanisms are the most often used way for crop harvesting and vision-based systems are the most widely used approach for crop detection.
A method that uses 3D point clouds for real-time broccoli crop detection was presented by H. A. Montes et al. in "Real-time detection of broccoli crops in 3d point clouds for autonomous robotic harvesting." [22]. The broccoli heads can be precisely detected and located by the system, protecting the surroundings from harm.
Overall, a lot of research has been done on mechanical leaf removal for broccoli with an emphasis on creating systems that can precisely detect and harvest the crop with minimal harm to the surrounding vegetation. Further study and improvement are still required in this field, notably in creating methods for efficiently removing leaves without harming the broccoli head.

1.4 Leaf Removal Project

Rijk Zwaan is the no. 4 vegetable breeding company in the world. A family company with more than 3800 employees in 30 different countries. They develop new plant and vegetable varieties and deliver top-quality seeds all over the world. They are striving to deliver the best quality and have a continuous process where they keep innovating. Every year 30% of the turnover is invested in research and development [23]. Thriving from a professional point of view and also showing that they look out for the well-being of their employees. Proven by winning the best employee of 2017/2018.
This project is part of the department: Crop Support. The general goal of Rijk Zwaan is to make

a significant difference in the vegetable industry by introducing a new variety of broccoli. Where research and development within the brassica crops have led to the need for new developments in the harvesting of these crops. To be more precise Rijk Zwaan has made alterations to a normal broccoli; however, to make this commercially viable help was needed for the mechanical harvest. The process from a mature broccoli plant in the field to a right-sized broccoli head, could be divided into multiple parts. Removal of (residual) broccoli plant from the soil, leaf removal, cutting at the desired height and weighting/ storage. Not necessarily in this particular order. Focusing on all aspects would be too extensive for one thesis; therefore, only one part is researched.
Most considerable problem was expected to be leaf removal. In addition, the preferred order was to have the leaf removal in the field before harvesting or removing from the soil of any kind. This was not entirely a constraint, however due to multiple parties working on different aspects highly desirable.
To become a commercially viable product, there are certain constraints and requirements that should be met. These will be discussed in 2. Method and could have a large influence on the design.
In Figure 1 the process is visualized with the division into four parts. Different interested parties have their focus on different aspects. For a smooth transition from one part into another, it is recommended that this order stays approximately the same. Therefore the focus of this study, which is the leaf removal of the 'X' variety broccoli, will be adjusted to this part in the process.

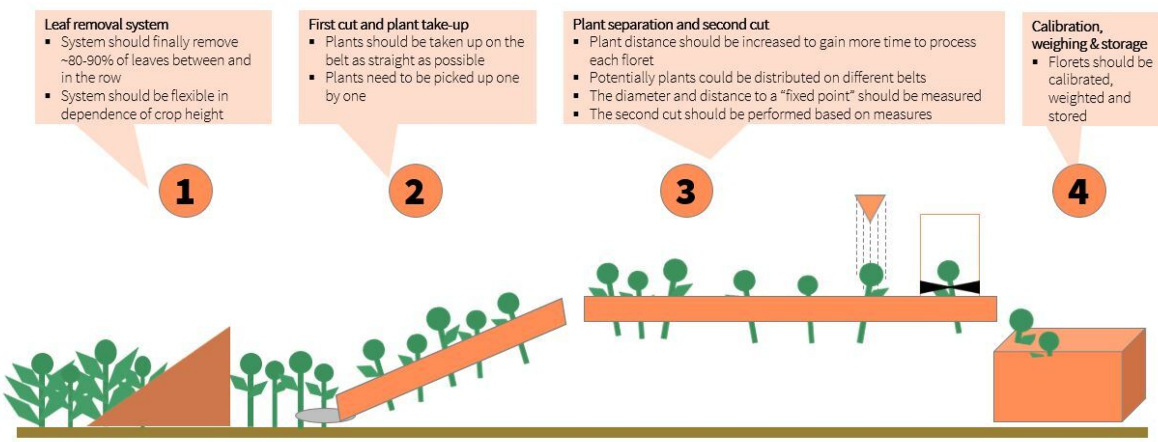


Figure 1: Schematic drawing of the stages of process of the new variety broccoli, from field to a product

1.5 Problem

The current methods of mechanical leaf removal for broccoli are not efficient enough, not precise enough and not gentle enough on the broccoli heads. Leading to low productivity and high amounts of damaged produce. There is a need for a new mechanical leaf removal machine, but the lack of uniformity makes it difficult. Breeding and genetic modification, using the most advanced techniques, will not give the assurance that product A will be the same as product B of a certain crop. Under controlled environments existing technologies are not so extensive that uniformity has been reached. Even Rijk Zwaan, which is specialised in this field, could only ensure uniformity until a certain level. It is still a plant growing from a seed, so essentially aspects like environmental influences also change characteristics. Therefore, mechanical leaf removal faces many challenges and has to find a way to overcome or even use these to make the agricultural sector a less labor-intensive sector. For this specific case, it is needed to make this new product economically viable.

1.6 Goal

The objective of this project is to gather information and develop an efficient leaf removal design for this variety of broccoli. This has two main aspects, the efficiency of (the amount of) leaves removed and the damage to the stem and/or product. Most desirable is a design that is capable of removing all the leaves of the plant without damaging the broccoli in any way. To verify the performance and destructiveness of the design, a way to evaluate will also be created.
The goal of this broccoli leaf removal design is to remove 80 to 90% of the leaves of broccoli while moving at a speed of at least 1 km/h, without damaging more than 10% of the broccoli heads. The machine should be designed to adhere to food safety rules, be simple to clean and maintain, have the fewest possible sensors and parts. This will minimize maintenance requirements. The machine should be made to only pass each broccoli once when removing leaves and should be capable of handling numerous rows with a minimum of one bed. The machine should not harm the florets, be able to withstand weather conditions like wind and rain, have a flexible and changeable design based on crop height and bed variances. The machine must be transportable, able to function continuously without pausing for maintenance or cleaning, simple to set up and operate, requiring little supervision while in use. Efficiency in removing leaves, accuracy in removing leaves, speed of operation, food safety, upkeep and cleaning, adaptability and flexibility, robustness and durability, simplicity, transportability and continuous operation will all be considered when evaluating the machine's performance.

2 Method

2.1 Plant and Bed Specifications

The new variety of broccoli will be grown in multiple countries: The United States, United Kingdom, Mexico, Germany, Spain and of course the Netherlands. The broccoli will grow in an open field. The characteristics of these broccoli's will differ in each country because of the different climates. The plants will also grow at different times. For example let's compare the Netherlands and Spain. In the Netherlands, where the climate is cooler, broccoli may grow more slowly but with a higher quality and longer shelf life. In Spain, the warmer and sunnier conditions may lead to faster growth, but the heat and humidity can also cause the broccoli to bolt (produce seeds) quickly, reducing the size and quality of the harvest. The ultimate size of the broccoli will depend on how well the crop is managed and the specific growing conditions in each location. Differences within one variety, grown in one country, even within the same bed could be significant. The specifications should be demarcated to quantify it.
There are two different specifications, the bed and the plant specifications. The bed specifications will be determined beforehand. While different configurations might result in better outcomes, there will be a focus on one. The specifications for the bed, can be found in Appendix D.
The plant specifications are less predictable than the bed specifications. Environmental factors will have a large influence on the growth of the crop. In addition, multiple different varieties are used in this research. The varieties will be named X, Y or Z and in the Appendix the corresponding variety could be found. The plant specifications are shown in Appendix D, these are based on the results found in the Netherlands.

2.2 Functional Requirements

2.2.1 Machine Requirements

For the whole process, multiple aspects need to be covered. Rijk Zwaan divided this into four parts, which contain: Leaf removal, harvesting, cutting at the right height and boxing per size. This has already been shown in Figure 1. Therefore the emphasis for leaf removal will lie in the pre-harvest moment, however solutions outside this scope will also be taken into account to cover all bases. Requirements, constraints and criteria will be discussed below to indicate all the checkboxes or ranges that the machine should be able to comply with.
The specifications along with the wishes of the company have been setup into a set of functional requirements, performance criteria and constraints. The functional requirements consist of the tasks that the machine must complete in order to be deemed functional.

- The machine should be able to remove 80 to 90% of the leaves from broccoli.
- The machine should be able to operate at a speed of 1 km/h or more.
- The machine should be able to remove leaves without causing more than 10% of the broccoli heads to be destroyed.
- The machine should be built to meet food safety regulations.
- The machine should be easy to clean and maintain.
- The machine should have minimal sensors and parts to reduce potential problems and maintenance.
- The machine should be designed for single pass leaf removal, moving past every broccoli only once.
- The machine should be able to handle multiple rows, with a minimum of one bed.
- The machine should have a flexible and adjustable design depending on crop height and bed differences.
- The machine should not damage the floret.

- The machine should be able to endure environmental factors, such as wind and rain.
- The machine should be able to remove leaves before harvest.
- The machine should be easy to set up and operate.
- The machine should require minimal supervision and adjustments during operation.
- The machine should be transportable, able to be moved from a shed to the field.
- The machine should be able to perform continuous operation without stopping for maintenance or cleaning.

2.2.2 Constraints

The constraints are the either defined or undefined criteria that limit what the machine could do.

- The machine should have minimal sensors and parts to reduce potential problems and maintenance.
- The machine should be designed for single pass leaf removal, moving past every broccoli only once.
- The machine should be able to handle multiple rows, with a minimum of one bed.
- The machine should not damage the floret.
- The machine should be able to operate at a speed of 1 km/h or more.
- The machine should be built to meet food safety regulations.
- The machine should be easy to clean and maintain

2.3 Criteria

The performance criteria consist of the requirements that the machine should take into account. Their solutions are used to distinguish between the concepts during the final selection. For both the functional requirements and the performance criteria, there is no set solution on how to achieve them. The specifications, on the other hand, are the already-defined criteria that the machine should account for. The machine is evaluated on...

- Efficiency of leaf removal (removing the leaves without causing damage to the broccoli heads)
- Precision of leaf removal (removing the desired amount of leaves)
- Speed of operation (ability to remove leaves at a speed of 1 km/h or more)
- Safety (meeting safety regulations)
- Maintenance and cleaning (ease of cleaning and maintenance)
- Flexibility and adaptability (able to adjust to different crop heights and bed differences)
- Durability and robustness (able to endure environmental factors)
- Simplicity and minimalism (minimal sensors and parts, easy to set up and operate)
- Transportability (able to be moved from a shed to the field)
- Continuous operation (able to perform continuous operation without stopping for maintenance or cleaning)

These criteria will be made into a table. Which will be used to select the ideas that will be made into designs. In Appendix B all the ideas discussed in the morphological overview will be given a weighed score. The best three concepts will be made into a prototype.

Criteria	Weightage (1-10)	Ranking		Score	Weighted Score
		1	5		
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good		0
- Beds	7	Poor	Good		0
Reliability	10	Low	High		0
Speed	8	Slow	Fast		0
Continuousness	6	Erratic	Ongoing		0
Destructiveness	7	Destructive	Delicate		0
					0
Design	50	-	-		
Robustness	7	Fragile	Robust		0
Simplicity	7	Complicated	Simple		0
Safety	6	Unsafe	Very safe		0
Transportability	7	Hard	Easy		0
Operating-sufficiency	6	Poor	Very		0
Cost-Performance Ratio	8	Bad	Good		0
Maintenance	5	Much	Little		0
Manufacturability	4	Hard	Easy		0
					0
				Total	0

Figure 2: Weighted criteria table used to rank the expected effectiveness of the ideas

The criteria are divided into performance and design. A weighted factor indicates how important an aspect is. When the weighted factor is 10, this means it is an extremely important aspect; when the weightage is 1 it means this aspect is not important at all. The ranking goes from 1 to 5 and underneath it is shown what is meant by a high or low score. In general a low score is bad and a high score is good.
The performance is subdivided into parts, which all tackle some part of this criteria. It is crucial to make sure the machine is operating properly. Any variation from the necessary performance standards could prevent the machine from properly removing leaves, leaving a product that is not ready to be collected in the field. To clarify the elements in Figure 2 and how the weightage is established, the criteria will be explained one by one below.

Adjustability This is how the design is being able to be adjusted to different plant configurations. This is important due to the variability within the broccoli plants. The plant height will always differ as it is a natural product that is affected by environmental factors. At the same place, in a very similar season with approximately the same (environmental) conditions, the plants will probably look fairly similar. In different countries, the environmental conditions will vary and as mentioned therefore quite some changes of plant characteristics. Not only in different countries, but even at the same location with a few days difference the plants could look different. Therefore it is very important that the

design could adjust to the current plant configurations, as this largely influences the performance. This makes this criteria have a weightage of 9.
The machine needs to be able to adjust to the beds, as these could vary per country or even per grower. The plant density per square meter will be different and therefore the design should change to keep up with the performance. This also includes how much space the mechanism between the rows has. As in most cases similar bed configurations will be used or only need to be able to do a few different configurations, a weightage of 7 is given to this criteria.

Reliability This is how well the machine actually completes the task of removing the leaves. So if all the leaves of a broccoli plant are removed, this means a maximum score for the reliability. An important aspect for the leaf removal is that the leaves on the top are more important than those on the bottom. So when 60% of the leaves are removed which are all the leaves on the top, but the leaves on the bottom (40%) are still on. This will lead to a better performance than 80% removed, with the remaining 20% being on the top. The next step will be harvesting, during which the bottom leaves will most likely be separated by the harvesting process. This also accounts for the differences in harvest; if one harvest is very good and the next is bad, then it is not consistent and therefore not reliable. This is the most important aspect regarding the performance, so a weightage of 10 is given.

Speed This is regarding how fast the machine is able to move through the field. At what speed can the machine clear a field while maintaining its approximate performance. Speed is crucial as it directly impacts the commercial viability of the product, therefore, faster speeds equate to higher productivity. A weightage of 8 is given to this category.

Continuousness Included in this category is the continuous movement of the machine. If the machine is very erratic, so has to stop a lot of times, the score will decrease. For a single pass harvest machine it is important that the machine is continuous, however if it is a bit erratic and still fast it is not that much of an issue. Therefore it scores lower than speed, with a weightage of 6.

Destructiveness How destructive is the machine? The machine should remove the leaves, but it should not damage the floret or the upper part of the stem as this is the product that will be sold. A high performance machine that also highly damages the product is therefore not an optimal machine. Here a score of 7 is given as weightage.

The design is also an important aspect, as it should be able to bring this machine to the market. When there is a working concept but a major design flaw that makes it not usable. Then the machine will not be able to fulfill its function.

Robustness When working in the field a lot of (environmental) conditions will be in play. A machine should be able to withstand all these conditions and be able to keep operating. Parts should not break or have too much degradation. This has a weightage score of 7.

Simplicity When the machine is simple, this has a lot of benefits. This will not only lead to less maintenance, but also the maintenance will most likely be easier than in complex systems. Also the operator of the machine will probably use the machine as it is supposed to, in comparison to a very complicated system that could lead to mistakes. Not only for maintenance but also for overall cost a simple system will most likely have the advantage. For these reasons the weightage is 7.

Safety While safety is often a crucial factor, it is important to keep it in perspective. Fast rotating parts without any protective part or sharp edges are normally a no-go. This is in the agricultural sector a more common reappearance in machines. As long as there are no parts flying around or very unpredictable movements, it should be OK. For this reason, the safety only has a weightage score of 6.

Transportability The machine most likely has to go from storage to the field and back. Therefore the machine should be easily transportable on and off the field. If this is very hard, then there most likely needs to be additional adjustments or solutions to cover this aspect. Also if it is easily transportable, then the machine will be protected from the environment when not operating. Therefore it also includes how compact the machine could be made. This has been given a weightage of 7.

Operating-sufficiency How much human input is needed to operate the machine. This not only accounts for how many people there are, but also for how skilled or trained the operator must be. This has been given a weightage of 6.

Cost-Performance Ratio While the cost of the machine plays a role, it is less important if it has very high performance. A better performance makes the machine more valuable. How lower the cost in combination with higher performance results in the ultimate outcome. However, this ratio also means that if the machine is quite expensive, but its performance is outstanding then the overall will still be high. This therefore has a weightage of 8.

Maintenance This includes the amount of maintenance that is needed to keep the machine in proper working order. If a machine is very low maintenance, with parts that only need to be replaced a minimum amount of times and also being able to keep going without too many adjustments (like cleaning or sharpening). This could reduce costs, but it is not that significant. Therefore the weightage for this criteria will be 5.

Manufacturability Having a concept that could barely be brought to life, makes the concept much less valuable. If manufacturing requires very special machines or complicated methods that extremely slow down production, then it is also very hard to sell these to growers. If it is simple to manufacture, it will not only be easy to find a supplier. You are also more confident in being able to provide every grower with this machine or replacement (parts) if needed. However the current technology is on a high level and it is very unlikely that something could not be produced. Therefore this only has a score of 4 regarding the weightage.

2.4 Morphological Overview & Concept Selection

The morphological overview is visualised in Appendix A. Where a table has been made using different categories. Ideas for solutions for a moment in time in relation to harvest (pre/peri/post) are placed against different mechanisms that could be used. If the idea is in the box of a pre-moment, this means that the leaf removal is before the harvest and so on. These concepts will be assigned descriptive labels that serve to clearly identify and distinguish each idea. All of the concepts have a simplified visualisation, which in combination with the description should clarify the working principle.
Using the ideas stated in the morphological overview the three most promising will be selected. The criteria table, found in 2.3. Criteria, decide which concepts are made into tangible models. Where the functionality will be demonstrated in terms of testing.
A mechanical engineer is able to utilize a weighted criteria table to select the best concepts from a morphological overview since it enables a systematic and balanced evaluation of the numerous design possibilities. The criteria table shows the many design parameters, the relevant considerations that must be taken into account for each and their associated weights in the final assessment. Then, depending on the values for each factor, the weighted scores for each design option are generated. This enables a thorough comparison of the many options and aids in determining which is the best choice given the predetermined criteria. This strategy guarantees that decision-making is impartial and provides a justification for selecting the best design.
Although it is a thought experiment, using a criteria table with weighted scores to choose the best concepts from a morphological overview, it is nonetheless a controlled and systematic method that aims to unbiasedly evaluate design possibilities. It could still be subjective in the sense that one person made the decisions based on the criteria and their weightings. However, the review process becomes more objective and less subjective by predefining these criteria and weightings and then systematically applying them to all design possibilities.
Consequently, the results of these criteria are stated in Appendix B. When we evaluate these results, the following are most promising: Fin Design (343), Machine Company Idea (332), Vertical Helical Screw (330), Helical Screw (325), Metal Wire (322), Car Wash (315), Triangle Block (303) and Air blast (303).
The Machine Company Idea has already been made into a prototype and tested by the company. The Fin Design and Helical Screw are different implementations of the same principle. Therefore if one is tested it gives an indication for the other and in later optimisation studies these alterations could be examined. A similar situation displays for Metal Wire versus the Car Wash idea, the main difference is the characteristics of the extending parts (stiffness, material, etc.). Accordingly, the three designs which will be made into prototypes are: Fin Design, Vertical Helical Screw and Metal Wire.
An engineer can verify an idea's viability through prototyping, try out various designs and features and make any necessary adjustments before mass production. Depending on the requirements of the project, the prototype can range from a straightforward, hand-made model to a more sophisticated, functional model. As will follow in the next sections for the prototypes, a more general approach is used. At first, a steady base will be created at which the working principle can be tested. Afterwards, there are three design ideas that will be made into a prototype. Each prototype will be enlightened, also all features and design choices will be elucidated.

2.5 Concept Development: Main Frame

All the designs need a steady frame surrounding the broccoli plants to secure the working principles without obstructing testing. Maintaining all elements in the right position without too much noise. Meaning that without the frame, undesired movements and vibrations could hinder testing. This main frame is for one separate row of broccoli.
The frame was designed so adjustments are easily made and any additions could be implemented. This was mainly established by using aluminum ISB-profiles of 40x40 mm and fixed lengths. Relatively large measurements are needed to ensure the flexibility of the designs. These profiles have slits on the four sides in a longitudinal direction, in which connecting items or customized parts can be placed. Four ISB-profiles with a length of 1.0 meter and six ISB-profiles with a length of 0.5 meter. When putting this together in a 3D-modeled version, it will look like Figure 3.

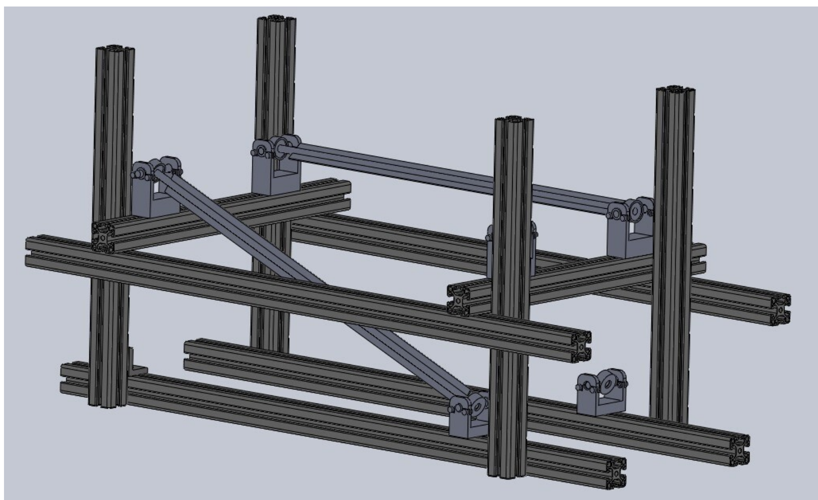
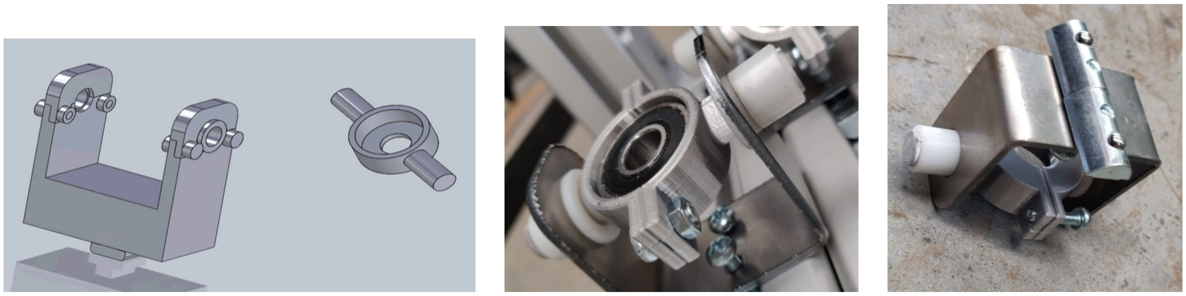


Figure 3: Solidworks model of the main frame with two configuration capabilities

These will be kept in place by connecting parts and fixing the ISB-profiles together in the desired configuration. Within the slits of these ISB-profiles, receivers can be added. These receivers hold a shaft with welded rectangular plates in which holes are strategically placed. Due to the design of that shaft with rectangular plates, it is flexible enough to have multiple elements attached to the system.
The receivers have one main function, which is to hold the ends of the shaft into place within the frame. A slope could be created when desired. Two different configurations, horizontal or with a slope, are shown in Figure 3. In early designs, the receivers were made out of 3D-printed material. Existing of a connection to the ISB-profiles and a bearing holder which make a rotation around its longitudinal direction possible, due to the ball bearing. As the plastic has too fragile characteristics, this is updated to a steel version. The 3D-parts and the updated version with ball bearing included is shown in Figure 4. Through this ball bearing, the shaft with rectangular plates will be placed, with the ends of the shaft protruding. This extended part of the shaft can be attached to a hand drill, which will be the drive for this system. This steel shaft of 10 mm diameter and a length of 55 cm had the rectangular steel plates with holes welded to the shaft. These will look like the shafts shown in Figure 5.



(a) (b) (c)

Figure 4: Solidworks model and updated metal versions of the receivers, included with ball bearings for guiding shaft and making rotation possible
(a) 3D-model (b) Updated metal version (c) Connection to ISB-profile

Figure 5: Steel shaft with a diameter of 10 mm with rectangular plates welded to the sides, containing holes every 20 mm

When every element is included in one assembly, this converges to the system in Figure 6. In this frame, one of the prototypes (Metal Wire) has been attached to the rotating shaft.

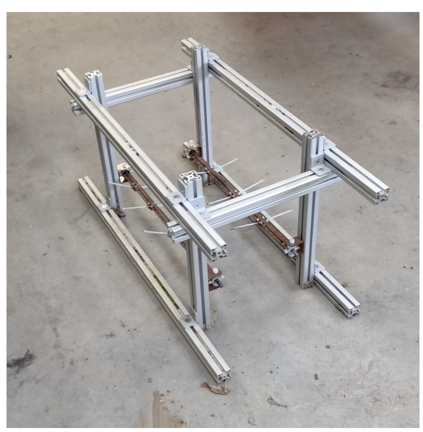


Figure 6: Example of the frame with a configuration of the Metal Wire design attached

2.6 Prototype: Vertical Helical Screw

This design, as the name might give away, is based on vertical helical screws. During a patent literature review conducted before this project, a lot of patents use a helical screw. With multiple applications of this working principle, none of those were in a vertical position. The main mechanism was to pull leaves off, in some cases with sharp edges to cut through the petiole of the leaves.

For application in this project, the helical screw is placed vertically. For testing only one is used, however if the principle indicates to work the machine would be upgraded. Then multiple helical screws will be put behind each other on both sides of the row. When leaves get caught in between the blades of the helical screw, the rotating movement will push the leaf slowly down. As the machine will be moving forward, it could therefore help to have more helical screws. When the leaf has not been pushed far enough to break off. The additional helical screws could take over the leaf at that position and push it further until it breaks off. The width of the blades of the vertical helical screw and the vertical distance between each blade is important for this design. When the width is too small, the leaves will escape from underneath the blades. If the width is too wide, the blades will interfere with surroundings.

To manufacture these vertical helical screws, multiple methods are possible. One option would be to have the helical screws custom made. This would be expensive and preliminary testing might prove that other principles are more efficient. In addition, a small volume increases the challenge of finding a company willing to realize this request. The time needed for manufacturing and shipping will most likely also be relatively high. Another option is to manufacture a helical screw yourself. Using a metal sheet that could be cut precisely by a laser and weld that to a shaft. However, the task of constructing and welding it precisely will pose a significant challenge. Besides the thickness is important for the strength, but also for the extent to which it can be bent. This will be a lot of work, with a high chance of not resulting in the desired product. The third option is to buy a ground drill part, which already exists to make holes in the ground. This will be the best option, as these exist in multiple shapes and sizes. These are not too expensive and should give a good indication of what the results of this working principle could be.

Additional parts are needed to keep the helical screw vertical, with the option to have the drill operate the rotation. A ball bearing will be incorporated near the ground to enable the screw to rotate smoothly, an additional component will be placed higher up to maintain stability and ensure vertical alignment. The whole design could be observed in Figure 7.

(a) (b) (c)

Figure 7: Photo's of the Vertical Helical Screw prototype, with zoomed in pictures for the alignment (a) Zoomed into lower part with bearing for rotation (b) The whole system (c) Zoomed in to stabilizing part

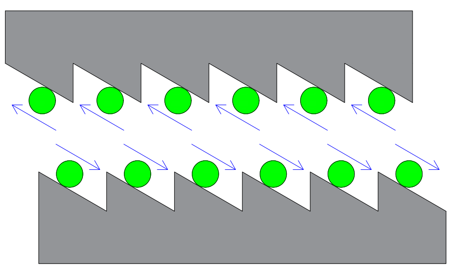
During preliminary testing, the results for the Vertical Helical Screw were not as promising as hoped. The frame was obstructing proper testing. This was because of the connection that holds the lower bearing, in which the screw turns. It would be possible to move the aligning parts to a position next to the frame. However, due to the limited time for testing, this concept was also tested without the frame. Placing the Vertical Helical Screw optimally next to the broccoli did not largely improve the results. In addition, the results that were included were taken from average/ slightly above average plants. Furthermore most of the leaves were not removed, but broken and still hanging by a thread.
Although the results of this concept were not that great, the conditions could have been approved a bit. Only one helical screw was used and therefore the broccoli was pushed to one side. As mentioned, it could be argued that multiple helical screws on both sides, would have improved the results. Firstly, by countering the broccoli being pushed to one side. Secondly, due to giving the system a better opportunity to defoliate the broccoli.
Very little (n = 10) broccoli's were used for quantifying the results. About 20% of the leaves were removed during this testing. The low performance however, also resulted in broccoli's which were barely damaged. Some figures illustrating the results of this design are given in Appendix E.

2.7 Prototype: Fin Design

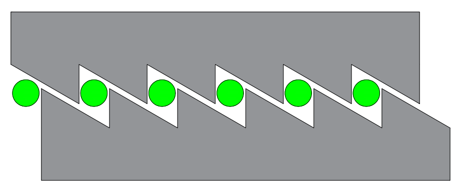
2.7.1 Working Principle & Features

The main purpose behind this mechanism is that a resilient material, like a hard rubber, pushes down the leaves. The fins will be integrated on both sides of the row of broccoli. Both rotating inward, meaning two fins start in an upward position, rotate toward each other, and then rotate outward to a downward position. The leaves will be removed with the least amount of force and complications, by pulling them downward. The stem is minimally affected because the cutting element is avoided, because of the resilient material.

First, all the features of this design will be clarified and afterwards the whole system will be shown. The design is constructed so leaves within the row of the broccoli also get defoliated, but the stem will take minimal damage. This is a design feature where the fins have an opposite direction, which creates rectangular holes. These designated holes contain room for the stem of the broccoli. This is better visualized in the figures below. In Figure 8a the green circles are the stems and the blue arrow indicates the direction in which the stems are pushed due to the shape of the fin. In Figure 8b this has been put together and as could be observed the designated holes for the stems are created.



(a)



(b)

Figure 8: Schematic drawing of the design of the fins explained, where the grey parts are the fins. The green circles are the stems and the blue arrows are the direction in which the stems are pushed.
(a) Direction the stems are being pushed (b) Sides of (a) put together

To improve the working principle around this design, the relative speed of the rotation of the fins and the ground speed will be applied. While the shape helps when the stems are not perfectly aligned, the relative speed makes sure the designated holes are where the stem should be. To give an example:

When considering a ground speed of 1 km/h, or in other words 27.78 cm/s. For the distance between each planted seed, we will take 4.4 cm. This means the machine passes slightly more than six broccoli plants per second or every 0,16 seconds a broccoli will be passed. Now depending on how many fins are used, every 180 degrees means two fins and every 90 degrees means four fins. If every 90 degrees a fin is attached, the fin should rotate $\pi/2$ when the machine moves 4.4 cm forward. When considering a diameter of the fins of approximately 10 cm this equals a circumference of $\frac{1}{10} \cdot \pi$ m or $\frac{1}{40} \cdot \pi$ m between every fin.

Therefore 4,4 $[cm]$ / 27,78 $[cm/s] = 0.158$ s to make a 90 degree turn of the fin. So the rotational speed $= \frac{1}{40} \cdot \pi$ / 0.158 s which is almost 0.5 m/s or 9.9 rad/s or almost 95 rpm. However, this is a specific case for the given variables and if a quarter rotation is needed before the system arrives at the next plant.

Another feature of this mechanism is the adjustable height. This is done using the mechanism, which is shown in Figure 9. Angle α can be adjusted by moving the left part up, resulting in the right part moving to the left and vice versa. The green part in between these points represents the shaft of the Fin Design.

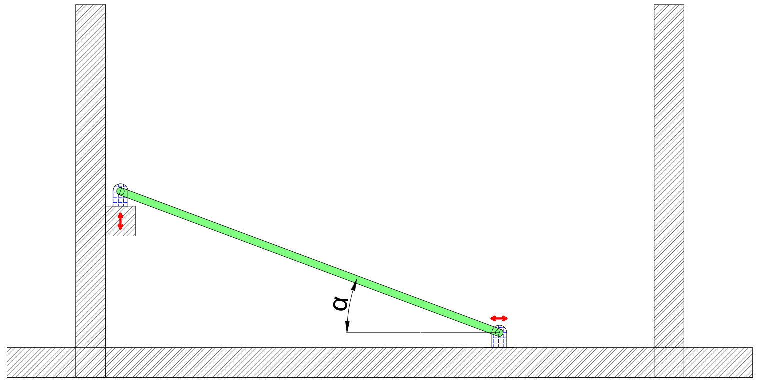


Figure 9: Schematic drawing of the frame with shaft and receivers, which show how an adjustable height is created

Previously, the designs were shown for one row of broccoli. To save some space, an alternation of 45 degrees could be used. This allows the fins to have a larger shape and due to the same rotation speeds this should not cause too many issues. This is shown in Figure 10, where the green rectangles represent the broccoli stems.

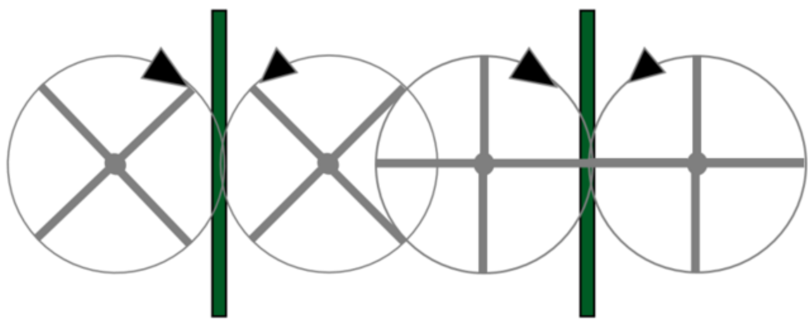


Figure 10: Schematic drawing of two rows of broccoli with the Fin Desing having alternating fins

As mentioned at the beginning of this design, the material used will be a resilient rubber. For this material, multiple strengths of rubber could be used. For rubber the hardness is given by Shore. Using Figure 11 it was decided to get two different rubbers, one with 65 Shore A and one with 70 Shore A. Both will have a thickness of 5 mm to allow some strength and stiffness while still maintaining a bit of flexibility. In addition, a thicker sheet would cause problems with the fixation to the shaft.

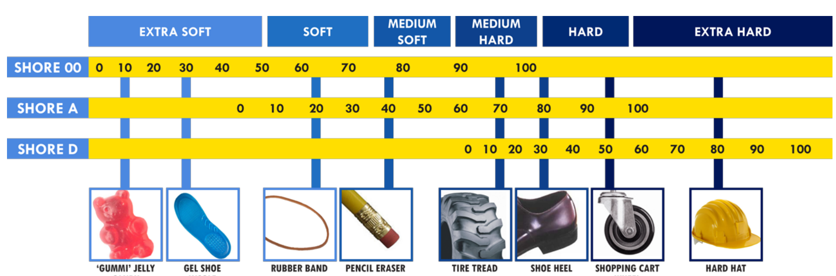


Figure 11: Hardness scale of rubber [24]

For the design of the fins, multiple options were explored using a 2D drawing. To explore the possibilities, afterwards this will be adjusted for the slope of the fins. This gave the three designs given in Figure 12.

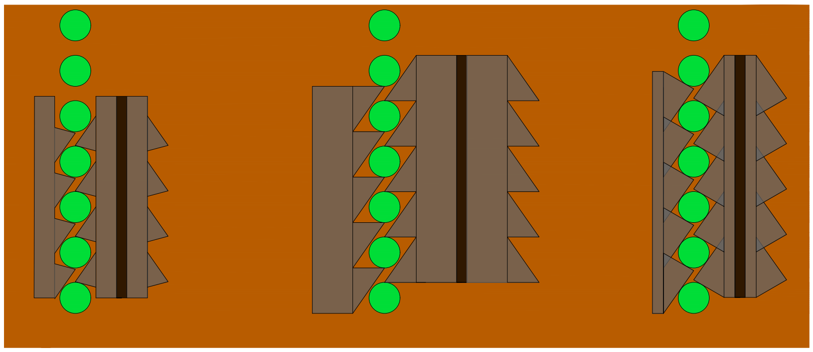


Figure 12: Schematic drawing of the top view of a broccoli field with three design options

In Figure 13 the dimensions of this design are given in a 2D profile, so when the fin would be parallel with the ground. The right figure (b) has the adaptation of the same design but for a slope of 20 degrees.

(a) (b)

Figure 13: Schematic drawing of the design for prototype of Fin Design with measurements
(a) 2D-design (b) Design for a slope of 20 degrees

To establish the appropriate dimensions of the design, an approximation of a typical, larger-sized broccoli plant has been developed. This approach was taken as only a limited number of the plants reach the maximum size. By focusing on the larger specimens, which are more commonly used for commercial purposes, outliers are avoided while creating a more representative example. The example broccoli is given below, in Figure 14.

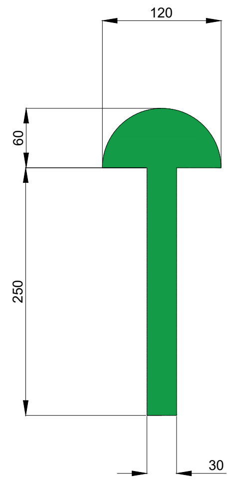


Figure 14: Schematic drawing of an example broccoli with measurements

The side view of the Fin Design is visualised in Figure 15. As the sowing distance taken is 4.4 centimeters apart. In the figure, a red line indicates the shaft. The fins also have a length and a width, so an angle of approximately 20 degrees will be enough. If the shaft is getting too high, it will start to hit the florets or if it is too low, will be obstructed by the soil. Therefore not the whole length has to be used during testing and 20 degrees will be sufficient to test multiple configurations.

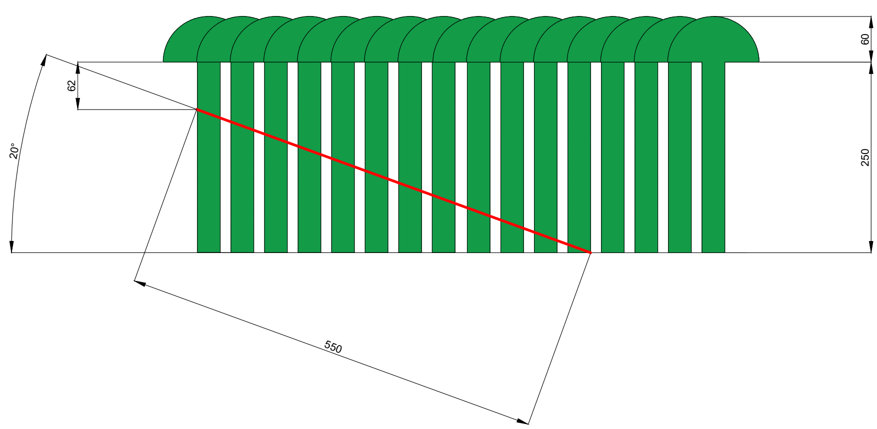


Figure 15: Schematic drawing of the sideview of the 20 degree slope shaft with example size broccoli on the background

Putting all elements together in a prototype, results in the system shown in Figure 16.

(a) (b) (c)

Figure 16: Pictures of the main frame with the Fin Design mechanism attached to the shafts (a) Close together showing designated holes (b) Slope of 20 degrees shown (c) Whole system

During preliminary testing, the machine was put together as shown. The first problem was that the prototype was operated by two hand drills. Using drills a constant rpm is only achievable at its maximum, therefore not controllable. Besides this drawback, the rubber was not stiff enough and folded around the shaft. The rubber should deform by a small degree, approximately 5 to 10 degrees should be more than enough. When the rubber folds it loses its function. Therefore a quick fix was developed by adding thin ($\approx 2\,\text{mm}$ thick) aluminium plates behind the rubber. The rubber will be larger than the plates to prevent contact between the leaves and the metal plates. The aluminium plates that were behind 80% of the rubber perpendicular to the shaft. Those updates and placing the system closer together made improvements, which were tested afterwards.
Where the metal additions worked well, however the rubber parts should still be stiffer. The function of removing the leaves in between the broccoli in a row is lost due to the flexibility of the rubber. The combination improved the destructiveness, as the rubber protected the stem while the metal plates took care of most of the removal.
A problem that was noticed very early was that there were a lot of differences within one row. If one broccoli is growing to the left and another to the right, the ramifications are relatively large differences. When observing the system in slow motion, the system coped with these sideways differences. As mentioned before, the rpm of the drills had to be relatively high giving almost a cutting mechanism instead of a pushing mechanism. Resulting in not only a switch of mechanism, but also the designated holes which were designed would not be used anymore.
An even bigger problem was the whole frame, which was blocking the process. The legs and sides of the frame pushed the broccoli in the direction in which the system was being pulled. Resulting in the row of broccoli being bent forward. Also when a broccoli was misplaced, these could get underneath the shaft and then the plant would be destroyed. Better uniformity might solve this, however this is only possible to a certain level. Therefore additions to better cope with not uniform products could

give the solution; for example, a funnel will most likely improve the performance.
In conclusion, the preliminary results were promising, but the frame needs to be adjusted to have minimal interference with the testing. This will be accomplished by moving the ISB-profiles as far as possible to the side, away from the row. Damage was acceptable if the broccoli was not too far to one side, which enabled it to get caught underneath the shaft. Small differences were corrected by the system, placing the broccoli's in the middle of the frame. The speed of the rotation should be the same on both sides, this could be done by using a transmission. At last, the material is not ideal and an upgrade would be preferable.
Some figures illustrating the results of this design are given in Appendix E, including the bending of the plants. Very few (n = 15) broccoli's were used for quantifying the results. From the results that were taken, around 50% of the leaves were removed.

2.7.2 Calculations

Deflection As explained, a metal plate was needed behind the rubber. This was because the rubber was not stiff enough. Due to the time-sensitive nature of the project, this was assumed and not calculated. Therefore the explanation for folding will be given below. In Figure 17a the realistic view has been drawn when looking directly at the cross-section of the shaft. The other subfigures are used as a visualisation of the Fin Design used for certain calculations. The z-axis is pointed out of the paper towards the reader, according to the right-hand rule.

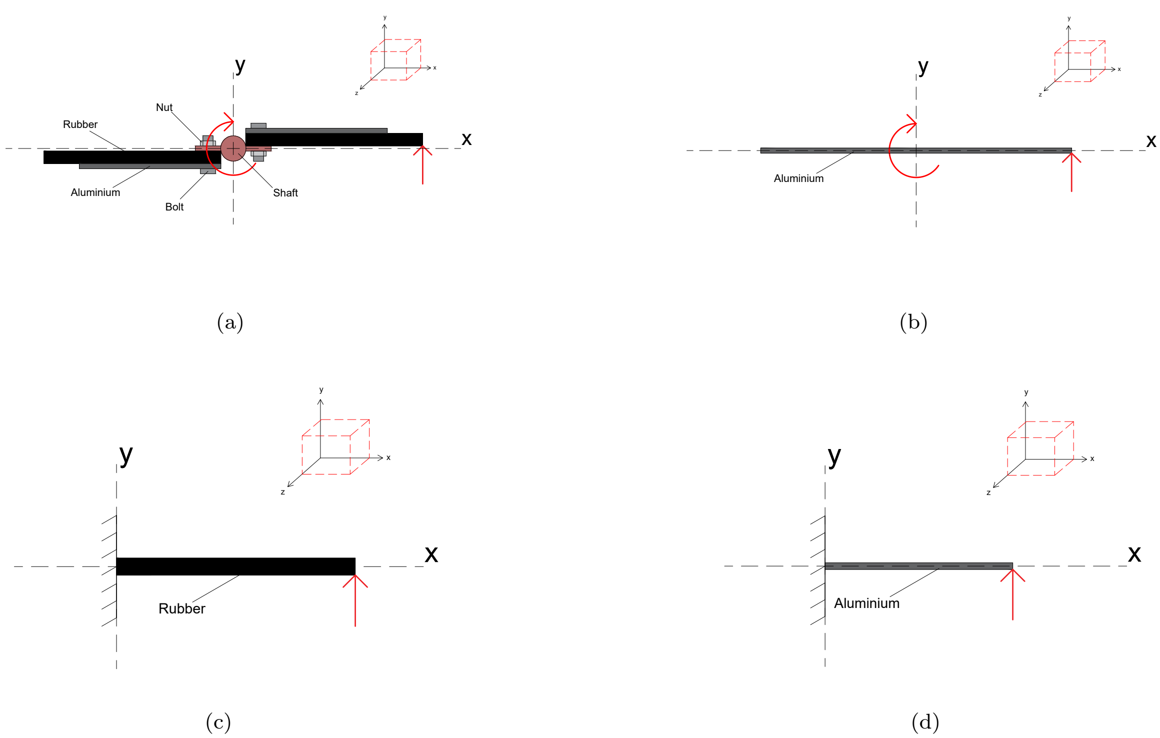
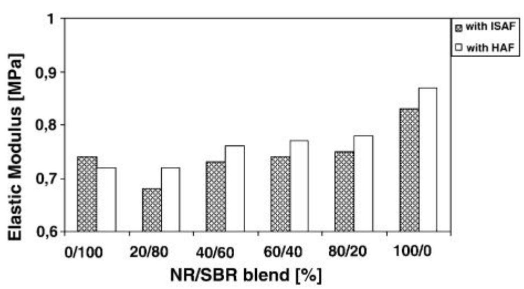
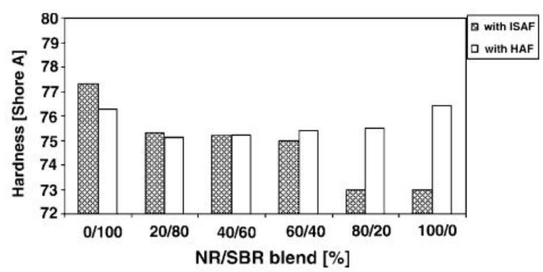


Figure 17: Schematic drawing of the Fin Design, view in longitudinal direction of the shaft
(a) Realistic representation (b) Modeled for forces (c) Modeled for deflection of the rubber (d) Modeled for deflection of the metal

For the deflection of the rubber Figure 17c is used and for the deflection of the metal Figure 17d is used. The connection to the shaft has been assumed to be infinitely stiff, so fixed. According to a study conducted by Lee-Wen during an internship at Rijk Zwaan the force needed to remove the leaves from the 'X' variety was ±35 N [25]. Therefore a force of 35 N will be used for the calculations. The force will be assumed to act on the ends of the fins, as also shown by the red vertical arrow in the figures.
The moment of inertia for a rectangular object will be given by $I_z = \frac{1}{12} \cdot b \cdot h^3$ [26]. The rubber will be modeled as a rectangular block, ignoring the fins. The thickness is 5 mm, which is h in the formula. The width (b) is the length of the shaft in longitudinal direction, which will be 20 cm. The length (l) is the perpendicular direction to the shaft, which is 7 cm. Therefore the moment of inertia is given by $I_z = 2.08 \cdot 10^{-9}\text{m}^4$.
The elastic modulus of the rubber used in this prototype is NR/SBR rubber. In a study done by F. Findik et al. [27] the elastic modulus of this material was given for different configurations, corresponding with an even slightly higher Shore A. For this calculation, a relatively large value of E = 0.85 MPa be used.



(a)



(b)

Figure 18: The variation of elastic modulus / Shore of NR/SBR blends with the proportion of rubber and filler materials [27]
(a) Elastic modulus vs NR/SBR blend (b) Shore A vs NR/SBR blend

For a deflection on a beam with a force applied by the end, the angle is given by:

$$\phi = \frac{F \cdot l^2}{2 \cdot E \cdot I_z} [26] \tag{1}$$

$$\phi = \frac{35 \cdot 0.07^2}{2 \cdot 0.85 \cdot 10^6 \cdot 2.08 \cdot 10^{-9}} \tag{2}$$

$$\phi = 48.4\,\text{rad} = 2775° \tag{3}$$

Which explains the rubber material folding around the shaft. A swift fix was applied using aluminum plates behind these rubber parts. These will only partly be behind the rubber, with the following values:
$h = 2\,\text{mm} = 2 \cdot 10^{-3}\text{m}$ & $b = 15\,\text{cm} = 0.15\,\text{m}$ & $l = 5.6\,\text{cm} = 0.056\,\text{m}$ & $E = 70\,\text{GPa}$

$$I_z = \frac{1}{12} \cdot b \cdot h^3 = 1 \cdot 10^{-10}\text{m}^4 \tag{4}$$

$$\phi = \frac{F \cdot l^2}{2 \cdot E \cdot I_z} = \frac{35 \cdot 0.056^2}{2 \cdot 70 \cdot 10^9 \cdot 1 \cdot 10^{-10}} \tag{5}$$

$$\phi = 7.84 \cdot 10^{-3}\text{rad} = 0.45° \tag{6}$$

So this will help against the folding of the rubber material. The relatively soft and flexible rubber will guard the plants a bit from being damaged by the aluminium. However, as indicated before the material used should give in a bit. This will be more flexible in terms of defoliation and less destructive. So if an other material will be selected and the same dimensions are used as for the rubber. With an angle that is assumed at 5°, then the material will need to have an elastic modulus of:

$$\phi = \frac{F \cdot l^2}{2 \cdot E \cdot I_z} \tag{7}$$

$$E = \frac{F \cdot l^2}{2 \cdot \phi \cdot I_z} = \frac{35 \cdot 0.07^2}{2 \cdot 0.087 \cdot 2.08 \cdot 10^{-9}} \tag{8}$$

$$E = 472\,\text{MPa} \tag{9}$$

So the ideal material will have an elastic modulus of around 470 MPa, if a bit more flexibility is required a lower elastic modulus (E = 236 MPa for 10°) is needed and vice versa.

Force exerted As the rubber doesn't influence the strength of the system, the force generated by the Fin Design will be calculated only considering the metal parts, this is visualised in Figure 17d. As mentioned, a force of approximately 35 N is needed to remove the leaves of the broccoli. To simplify the design the shaft will be neglected, due to the assumption that the connection of the metal plate to the shaft is infinitely stiff. The system will be observed as a plate rotating around the x-axis, as shown in Figure 19. Other assumptions taken for these calculations are that the frame is infinitely stiff, resulting in a rigid body. The center of mass is in the middle of the surface of the metal plate and there will be no friction forces between the fin and the leaves during impact.

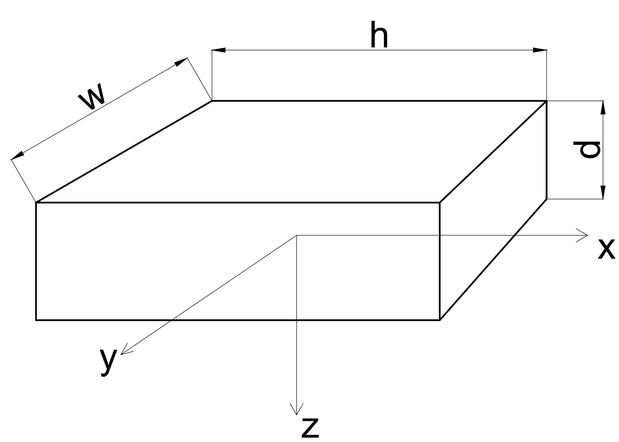


Figure 19: Schematic drawing of the configuration used to determine the mass moment of inertia of a cuboid solid (Enhanced version of [28])

A mass moment of inertia for this configuration will be given by $I_{xx} = \frac{1}{12} \cdot m \cdot (w^2 + d^2)$. Where $w = 2 \cdot 5,6 + 1 = 12.2\,\text{cm} = 0.122\,\text{m}$ which is the length of the metal plates plus the shaft diameter. Furthermore, the dimensions are $h = 15\,\text{cm} = 0.15\,\text{m}$ & $d = 2\,\text{mm} = 2 \cdot 10^{-3}\text{m}$ when using Figure 19 and a rotation speed of 1800 rpm which is the speed of the drill. Using the density for aluminum of $2.7\,\text{g/cm}^3$, the mass will be 98.82 gram ($98.82 \cdot 10^{-3}$ kg).

$$\Delta T = \frac{1}{2} \cdot m \cdot v^2 + \frac{1}{2} \cdot \omega^T \cdot I_o \cdot \omega[28] \tag{10}$$

With:

$$I_o = \begin{pmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{pmatrix} \tag{11}$$

$$I_o = \begin{pmatrix} \frac{1}{12} \cdot m \cdot (w^2 + d^2) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \tag{12}$$

$$\omega = \begin{pmatrix} 1800 \\ 0 \\ 0 \end{pmatrix} \text{rpm} = \begin{pmatrix} 188.5 \\ 0 \\ 0 \end{pmatrix} \text{rad/s} \tag{13}$$

As the mass moment of inertia and the rotation speed are only in relation to the X-axis, these will be used as I_{xx} and ω_x. Therefore the kinetic energy will be rewritten as:

$$\Delta T = \frac{1}{2} \cdot m \cdot v^2 + \frac{1}{2} \cdot \omega_x \cdot I_{xx} \cdot \omega_x \tag{14}$$

$$v = \omega_x \cdot r \tag{15}$$

$$v = 188.5 \cdot 6.1 \cdot 10^{-2}\text{m/s} \tag{16}$$

$$\Delta T = \frac{1}{2} \cdot (98.82 \cdot 10^{-3}) \cdot 132.2 + \frac{1}{2} \cdot 188.5 \cdot 1.23 \cdot 10^{-4} \cdot 188.5 \tag{17}$$

$$\Delta T = 6.53 + 2.18 \text{ kg} \cdot \text{m}^2/\text{s}^2 \tag{18}$$

$$\Delta T = W = F \cdot d \tag{19}$$

$$F = \frac{(6.53 + 2.18)}{d} \tag{20}$$

Which is the force over a displacement in the direction of the force. As the fins have a radial direction of movement, the force would work over a part of the circumference. Approximately over a region of 60 degrees, as is visualised in Figure 20. The circumference of a circle is given by $C = 2 \cdot \pi \cdot r$, so 60 degrees will be 1/6th of this.

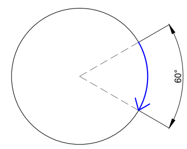


Figure 20: Schematic drawing of a circle representing the distance of work

$$d = \frac{2 \cdot \pi \cdot r}{6} = 0.064\,\mathrm{m} \tag{21}$$

$$F = 136\,\mathrm{N} \tag{22}$$

This concludes that the prototype is able to provide enough force to remove the leaves of the broccoli, as $136\,\mathrm{N} > 35\,\mathrm{N}$.

2.8 Prototype: Metal Wire

2.8.1 Working Principle & Features

The design incorporates metal wires that rotate inwardly to efficiently remove the leaves from the broccoli plant, offering a precise and rapid solution to the leaf removal process. This idea has a resemblance to current grass trimmers. For those grass trimmers, a hardened, monofilament nylon wire is used to cut grass at the desired height [29]. For the application in the broccoli field, the wires will rotate inwardly from both sides. Due to the stem having stronger characteristics than the leaves, it will survive while the leaves are being removed. Between the rows of broccoli plants, leaves often accumulate that are more difficult to remove. This working principle will get those leaves as well, due to the wires reaching in between or grabbing onto a part of the leaf. The design feature of the wires touching the stem may result in some damage, but this is acceptable as long as it occurs lower down the stem and does not compromise the stability of the rest of the plant.
Broccoli plants have stronger characteristics than grass, therefore thicker wires are needed. In addition considering food safety reasons, plastic wire will have plastic residue when the wires are breaking down. Other advantages are the durability, fatigue resistance and relative flexibility while maintaining high strength.
In very early preliminary testing a wire was attached to a drill and results indicated that a minimum of 4 mm diameter is needed to produce results. The wires used are steel cables, which consist of woven smaller steel cables. These cables unravel when they rotate quickly and hit objects. The fast rotating shaft and the impact on the leaves caused this to happen. Due to the unravelling of the entire wire, the loose strings would detach from the rotating shafts, as these are connected by applying a pressure force to keep those in place. Therefore a solution had to be constructed to prevent the wires from fully unravelling; however, partly unravelling on purpose to create a more delicate approach with a larger area of attack could be beneficial.
Solutions for the unravelling were explored by using duct tape, soldering, welding, shrink tube and clamping a nut. The duct tape did not adhere properly to be strong enough and soldering wasn't possible as it did not fuse to the wire. The other options are explored in 3.2, but the wire did stay together in each of these solutions.
For the positioning of the shafts, preliminary testing showed that when you place them too far apart, the leaves will still be attached to the plant. When placing them closer together, creating an overlapping hitting area, those have a more destructive effect. It results in plants getting stuck underneath the shafts and being demolished. It seems to be best to place them in a configuration that the hitting area is very close, where the ends almost touch. For the next test, the wires will be placed at the same spots on the shafts. These wires, which are placed perpendicularly on the shaft, will be in the same position on the shaft and therefore be in each other longitudinal lengths.
As there will be a forward motion, multiple wires are used on both sides. Tests will be done with four wires on each side. By doing so, sufficient space is created between each wire and sufficient opportunities for defoliation are provided. The fast rotating wires possess a beating mechanism, destroying or beating the leaf down. This might have the effect of pulling the whole plant to one side, which is countered by the wire positioning.
The example broccoli used in 2.7. Fin Design, is also used to make the prototype for the Metal Wire. This gives an indication of how long the wires can be before they touch the frame, ground or broccoli. When the maximum length has been acquired, the height is also given. This maximum length is necessary due to the shafts being destructive if a plant gets too close to them.

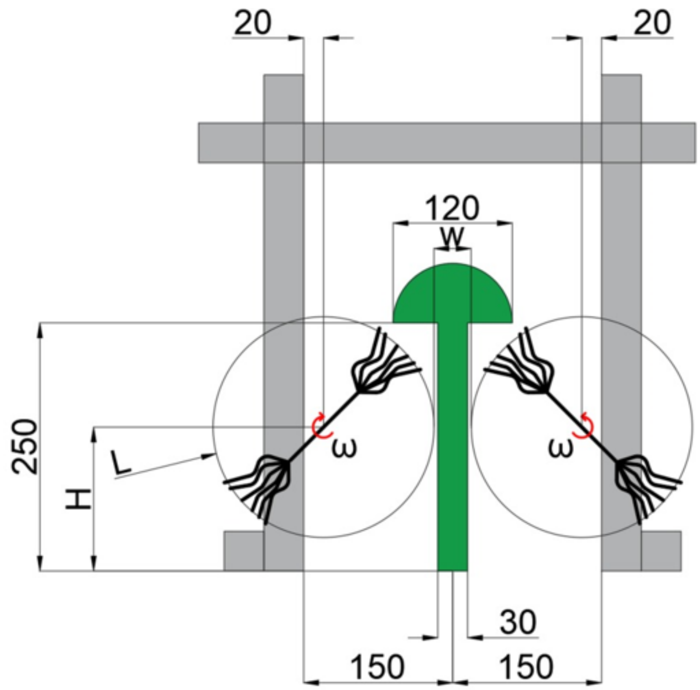


Figure 21: Schematic drawing of the front view of the Metal Wire mechanism with example broccoli

The wires will be attached to the shafts by having two rectangular plates with holes between the shaft and the wire. These plates will be clamped onto the shaft by nuts and bolts. So the wires will be force-locked, which makes it easy to remove them.
In Figure 22 an example of one of the configurations of the Metal Wire mechanism is given. This mechanism will be operated by connecting hand drills to the ends of the shafts.

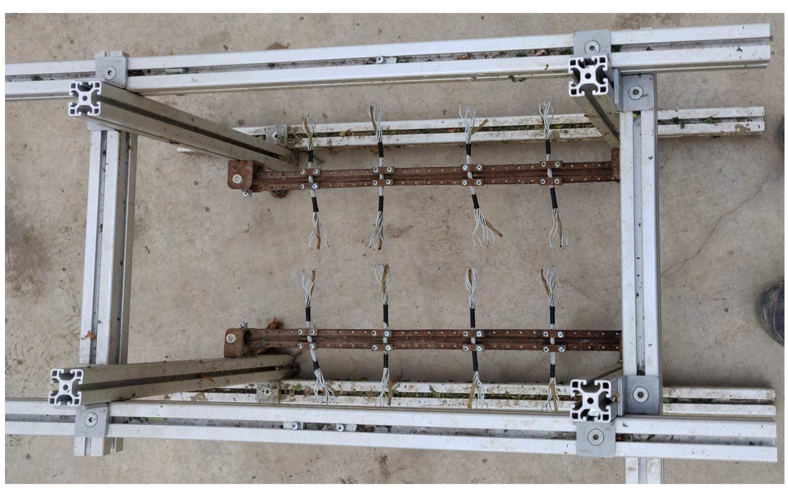


Figure 22: Example of the Metal Wire, with a 6 mm wire with unravelled ends

During preliminary testing problems with unravelling are found and potential solutions are provided. These will be examined in the results (3.2). The added mass at the end of a wire might result in too much kinetic energy, so it acts like a hammer. In addition, the thickness will also have an effect on the destructiveness. Configurations are combined to gain information with minimal testing. The first two tests will be reviewed and used for the configuration on the third test. Observation with the help of a slow-motion camera will give more insight on the tests. During the preliminary testing, no results were examined as the right configuration was yet to be found. Pictures of the results of the preliminary testing can be found in Appendix E.

2.8.2 Calculations

Forces exerted In Figure 23a the realistic view has been drawn when looking directly at the cross-section of the shaft. The wire is locked onto the shaft by a small steel plate which is pushed towards the shaft by nuts and bolts. This is shown in Figure 23b with red arrows as forces. To simplify the design for calculating the forces, the shaft will be neglected. As well as the wire being modeled as one wire with a diameter of 5 mm and no unravelled ends, this is drawn in Figure 23c. The z-axis is pointed out of the paper towards the reader, according to the right-hand rule. Other assumptions taken for these calculations are that the frame is infinitely stiff, resulting in a rigid body. The center of mass is in the middle of the surface of the metal wire and there will be no friction forces between the wire and the leaves during impact.

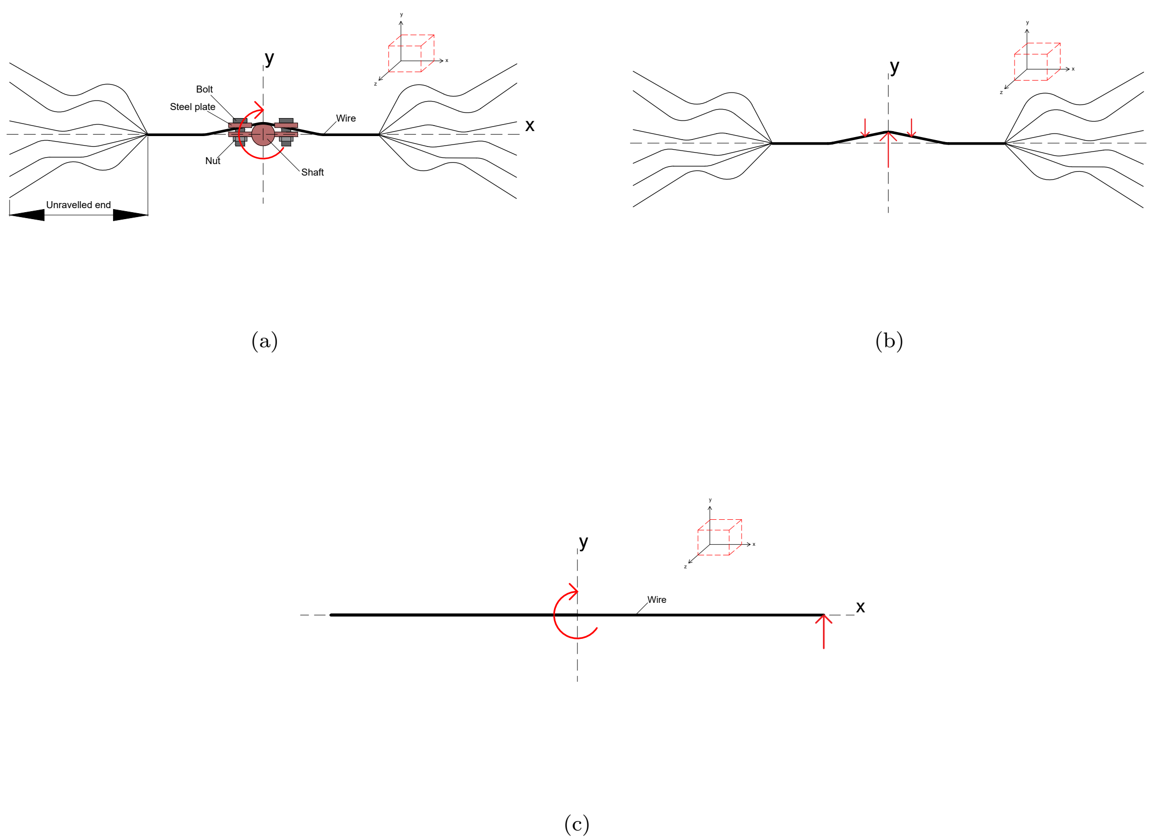


Figure 23: Schematic drawing of the Metal Wire, view in longitudinal direction of the shaft
(a) Realistic representation (b) Force-locked shown with forces (c) Modeled for forces

Known is that ±35 N is needed to remove the leaves of the broccoli plants. The kinetic energy of the system will be given by:

$$\Delta T = \frac{1}{2} \cdot m \cdot v^2 + \frac{1}{2} \cdot \omega^T \cdot I_o \cdot \omega \tag{23}$$

With:

$$I_o = \begin{pmatrix} I_{xx} & I_{xy} & I_{xz} \\ I_{yx} & I_{yy} & I_{yz} \\ I_{zx} & I_{zy} & I_{zz} \end{pmatrix} \tag{24}$$

For a solid cylinder, the mass moment of inertia is given below using Figure 24:

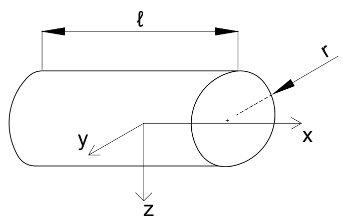


Figure 24: Schematic drawing of the configuration used to determine the mass moment of inertia of a solid cylinder (Enhanced version of [28])

$l = 22\,\text{cm} = 0.22\,\text{m}$ & $m = 18.5\,\text{g} = 18.5 \cdot 10^{-3}\text{kg}$ & $t = 5\,\text{mm} = 5 \cdot 10^{-3}\text{m}$ & $\omega = 1800\,\text{rpm}$

$$I_o = \begin{pmatrix} \frac{1}{2} \cdot m \cdot r^2 & 0 & 0 \\ 0 & \frac{1}{12} \cdot m \cdot (3 \cdot r^2 + l^2) & 0 \\ 0 & 0 & \frac{1}{12} \cdot m \cdot (3 \cdot r^2 + l^2) \end{pmatrix} \tag{25}$$

$$\omega = \begin{pmatrix} 0 \\ 1800 \\ 0 \end{pmatrix} \text{rpm} = \begin{pmatrix} 0 \\ 188.5 \\ 0 \end{pmatrix} \text{rad/s} \tag{26}$$

As the rotation speed is only in relation to the y-axis, only I_{yy} and ω_y will be used. Therefore the kinetic energy will be rewritten as:

$$\Delta T = \frac{1}{2} \cdot m \cdot v^2 + \frac{1}{2} \cdot \omega_y \cdot I_{yy} \cdot \omega_y \tag{27}$$

$$v = \omega_y \cdot r \tag{28}$$

$$v = 188.5 \cdot 11 \cdot 10^{-2}\text{m/s} \tag{29}$$

$$\Delta T = \frac{1}{2} \cdot (18.5 \cdot 10^{-3}) \cdot 429.9 + \frac{1}{2} \cdot 188.5 \cdot 7.46 \cdot 10^{-5} \cdot 188.5 \tag{30}$$

$$\Delta T = 3.98 + 1.33 \ \ \text{kg} \cdot \text{m}^2/\text{s}^2 \tag{31}$$

$$\Delta T = W = F \cdot d \tag{32}$$

$$F = \frac{(3.98 + 1.33)}{d} \tag{33}$$

Which is the force over a displacement in the direction of the force. As the wires have a radial direction of movement, the force would work over a part of the circumference. Approximately over a region of 60 degrees, as is visualised in Figure 20. The circumference of a circle is given by $C = 2 \cdot \pi \cdot r$, so 60 degrees will be 1/6th of this.

$$d = \frac{2 \cdot \pi \cdot r}{6} = 0.115\,\text{m} \tag{34}$$

$$F = 46\,\text{N} \tag{35}$$

This concludes that the prototype is able to provide enough force to remove the leaves of the broccoli, as $46\,\text{N} > 35\,\text{N}$. Furthermore if this force was less than the given 35 N, the leaves could still be removed as the system has multiple wires. One leaf will be hit more than ones, which also could have removed the leaf bit by bit.
The mass moment of inertia which is given in this calculation is for a cylinder solid. When the wires are unravelled this will cause the mass moment of inertia to increase, which eventually causes the force to increase as well. A simplified wire is used as the asymmetrical shape which differs for each wire would be too complicated to calculate how much it influences the results.

Deflection The wire itself will not deflect too much, however the unravelled ends might. Therefore this is checked with a standard wire of a total length of 22 cm with 6 cm unravelled at each end. The wire is 5 mm thick and an unravelled wire will be estimated at 1/3th of that thickness. For both connections, it is assumed that they are infinitely stiff, this is visualised in Figure 25. Furthermore these will be handled as solid cylinders.

(a) (b)

Figure 25: Schematic drawing of the deflection of the Metal Wire shown in side view fixed to one end (a) Modeled for deflection of the thick inner part (b) Modeled for deflection of the thin ends

First the wire until the unravelled ends will be examined. The z-axis is pointed out of the paper towards the reader, as mentioned before.
$l = 5\,\text{cm} = 0.05\,\text{m}$ & $d = 5\,\text{mm} = 5 \cdot 10^{-3}\text{m}$

$$I_z = \frac{\pi}{64} \cdot d^4 = 3,07 \cdot 10^{-11}\text{m}^4 \tag{36}$$

For a deflection on a beam with a force applied by the end the angle is given by:

$$\phi = \frac{F \cdot l^2}{2 \cdot E \cdot I_z} \tag{37}$$

With a force of 35 N and the E for stainless steel of $E = 210\,\text{GPa}$.

$$\phi = \frac{35 \cdot 0.05^2}{2 \cdot 210 \cdot 10^9 \cdot 3,07 \cdot 10^{-11}} \tag{38}$$

$$\phi = 6,79 \cdot 10^{-3}\text{rad} = 0,39° \tag{39}$$

For the unravelled ends, it will be assumed that they are connected to a fixed position, which is possible as the deflection of the wire before unravelling is very minimal. The deflection for these unravelled end's will be:
$l = 6\,\text{cm} = 0.06\,\text{m}$ & $d = 5/3\,\text{mm} = 1,67 \cdot 10^{-3}\text{m}$

$$I_z = \frac{\pi}{64} \cdot d^4 = 3.82 \cdot 10^{-13}\text{m}^4 \tag{40}$$

$$\phi = 0.786\,\text{rad} = 45° \tag{41}$$

As could be observed, the ends are far more flexible than the solid wire by itself. Resulting in a less destructive element with a larger area to get in contact with leaves.

2.9 Evaluating and Result Quantification

2.9.1 Evaluating Preliminary Testing & Setting Testing Conditions

After seeing the results from the preliminary testing session, it was decided to continue with two of the concepts and leave one as is. The reason for this decision is that there is a limited time that the broccoli's grow and therefore can be tested. Adjustments to a prototype take time, to develop or order parts, so for the best outcome there should be prioritized.

All the prototypes showed some setbacks during preliminary testing. Two designs showed promising results with enough room for improvement. One design did not show enough results to continue with a second testing session. This is the Vertical Helical Screw design. The results, even when optimising the conditions, were minimal. Optimisation would be possible, as mentioned before, but would not significantly improve the working principle behind this concept. Even when the prototype showed results, these were with broken leaves, not removed.

During this preliminary session not many results were quantified, so the figures shown in Appendix E will give the best impression of the results. During the second testing session the test will be better coordinated.

For the Fin Design the frame will be adjusted so the ISB-profiles will not bend the broccoli's. Preferably a new material and controllable rpm was included during testing. This controllable rotational speed would be achieved by combining an electric motor with a frequency converter and, ideally, a transmission so that the counter rotation is simultaneous. Due to limited time, not all adjustments could be made for the initial testing session. Two tests will be done, one with the shafts 'far apart' ($\approx$ 2 cm gap) and one with the shafts 'closer together' (almost touching). Normal frame with the shafts at an angle of 20 degrees. Starting at 7 cm from the ground, ending 18.8 centimeters higher. Making sure the fins at their highest point come to 22 cm height.

For the Metal Wire it is not yet clear what the best solution is regarding the unravelling. So three tests will be done regarding the best solution to the unravelling. What is the best way to keep the wire together and do the unravelled ends have a positive effect on the defoliation? Therefore the first test will be done with four wires on each shaft, eight in total. These wires are at the same position on the shaft, the four in the front will be 4 mm diameter wires with welded tips. The four wires behind these, so two on each shaft, will be normal 4 mm diameter wires. This test will show the effectiveness of the welded tips and whether the normal 4 mm would unravel again.

Afterwards, two other methods will be tested. The four wires in the front will be 4 mm diameter, with shrink tube holding the ends together. This test shows the effectiveness of shrink tube in holding the wires together. Behind those wires there will be four wires of 5 mm diameter with a nut at 5 cm from the ends clamped on the wire. These ends will be unravelled before testing. In this test, the method of clamping the wires together with a nut will be tested. In addition, the effect of purposely unravelling the wire will be tested.

The third test in this series is to use the results of the previous two tests for the design of the third and last test of this initial testing phase. So the method of keeping the wire together will be determined and whether an unravelled end will be effective. There will be a focus on the variety of broccoli and when possible use similar rows in one bed to keep changes to a minimum.

Testing will be done in one row of broccoli's, which will be freed from any surrounding elements. Meaning mainly that the rows next to this row will be removed. There the design will be adjusted to the bed and plant configurations. Hand drills are utilised when possible, with a rpm of 1800. Testing will be done with a forward motion, applied by being pulled forward. One person will pull the system at a 'constant' pace ($\approx$ 1 km/h) while another person will operate the hand drills. This constant pace is a relative term, due to the system being dragged along instead of using a driving mechanism. Afterwards, when the defoliating process is over, the broccoli's will be examined. This testing phase will determine which mechanism will be optimised.

2.9.2 Quantifying Results

Results will be quantified, this will be done three ways, which will be enlightened. The first quantification of the results has been done by dividing the stem without floret head into three equal parts. When the three sections are determined, the leaves will be counted per section. So this will be divided as shown in Figure 26a. First, will be counted how many leaves there were per section before the machine removed them. Then the amount of leaves that are removed will be counted. This will be done multiple times so that an estimation can be made with percentages about the performance. To summarize, it is the amount of leaves removed divided by the amount of leaves that the broccoli had. To give an example, if a section of the broccoli had 10 leaves and 6 of those leaves were removed, the performance would be 60%. Looking at the figure where 1 is more important than 2 and 2 is more important than 3, so $1 > 2 > 3$. The third section is less important due to its position on the stem, but in addition only a very small amount of leaves are in that section. After leaf removal, the top part of the stem with the floret will be harvested and cut at the desired height. Therefore this third section is less important.
During testing, while not desired, some broccoli's will be damaged or even destroyed. This needs to be quantified as well. Therefore the amount of completely destroyed leaves will also be quantified during a testing session. Represented using Figure 26b, where the X's will be replaced with a number. To give an example, if the sample size is given by n = 100, then 100 broccoli's have been tested, and 20 of those are destroyed. Then the percentage destroyed will be 20% and the X's in that figure will be replaced by the number 20. Only full percentages will be used for this representation. A broccoli will only be added to this percentage if and only if the head has been severed off.

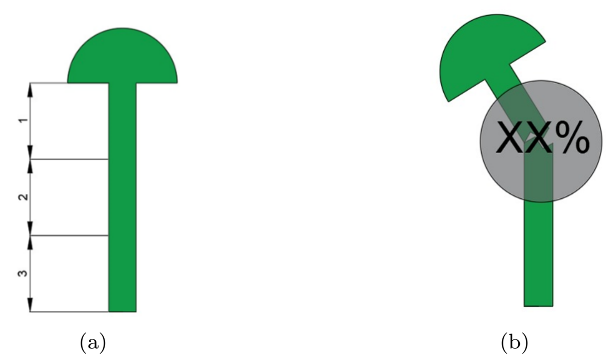


Figure 26: Schematic drawing of result representations
(a) Equal divided stem (1=2=3) (b) Representation of amount of leaves removed

The last quantification of results will be established by assiging a number to the destruction done to the broccoli. When the machine with a certain prototype is removing the leaves of the broccoli, most certainly the plants will receive some kind of damage. This has to be considered when reviewing the performance of the machine. When the leaves are removed, but the floret is highly damaged as well. This will not be a sufficient machine. However, this is a more subjective method than previous results. Therefore it is important that guidelines for these results are constructed. Every broccoli will be rated between 1-10, using the list on the next page. As damage to the floret is more problematic than damage to the lower stem, this will be weighted heavier.

1. Fully good / very little damage
2. Barely any damage
3. Stem somewhat damaged, rest is fine
4. Some damage close to the higher part of the stem, but floret is OK
5. Some damage and very little damage to floret
6. Some damage to floret
7. Damages to floret
8. Significant damage to floret
9. Very damaged floret
10. Floret (almost) completely destroyed

This will still produce a subjective result, but because only one person rates each broccoli, the reliability is increased. Still might give a slightly biased result, but the average over a lot of broccoli do give an indication of how much the average broccoli has been destroyed. This factor will be named the Destroy Factor and often given by DF = XX,X. Where the X's will again be replaced by a number.
After these tests, the results give an indication of the performance and potential of every prototype. Based observation and results a decision will be made to continue with a certain concept.
The third testing session could be best explained by the optimisation phase. The best concept with its working principle will be chosen and the recommendations for the machine will be developed. This will be done by creating a base configuration for the machine. After this configuration with the settings have been accomplished, the variables will be determined. Some of the variables will just give an indication of how the machine will be affected. These are the parameters that can not be changed, which will mostly be the environmental aspects. Other variables that could be described as machine settings will be elucidated. These are the variables which will be tested. To give an example, the height differences of broccoli's within one row can not be adjusted, but the speed at which the shafts rotate can be adjusted. Therefore, the speed will be tested by using different speeds to see at which speed or range the machine operates most optimal.

3 Results: Initial Testing

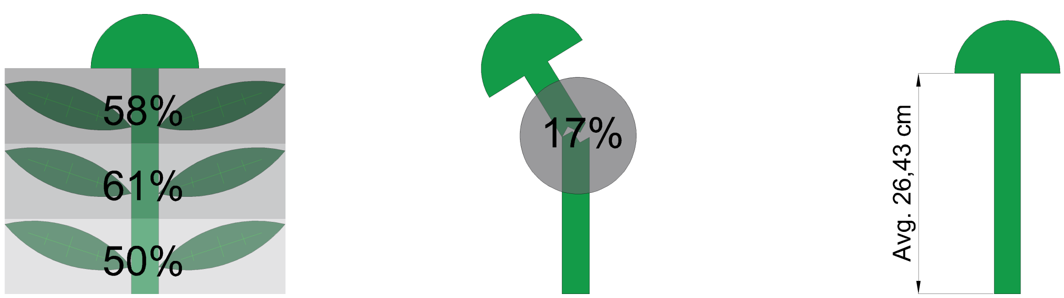
3.1 Results Initial Testing: Fin Design

3.1.1 Fin Design Testing with 'Far Apart' Configuration

The configuration of the system will be shown in Figure 27. This test has been done on the 'X' variety with a sample size of n = 48. A relatively smaller sample size as the results were taken until a rubber got loose. During this testing most results were produced by one shaft at a time. Therefore one side has almost all the leaves attached and the other side has a large portion removed. The average height, performance and the percentage destroyed are shown in Figure 28. Furthermore, there was an average Destroy Factor of 3.98.
Visual results of this testing session will be placed in Appendix E.

(a) (b)

Figure 27: Initial testing configuration where shafts are 'far apart'
(a) Top view (b) View of the slope



(a) (b) (c)

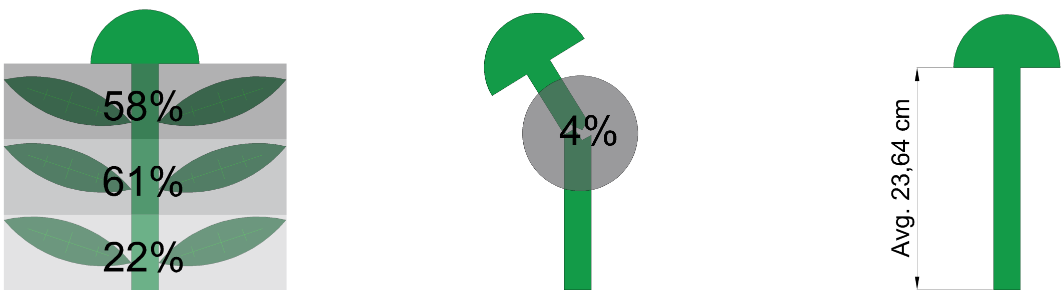
Figure 28: Results inital testing, first session Fin Design: 'far apart'
(a) Performance (b) Destruction (c) Average height

3.1.2 Fin Design Testing with 'Close Together' Configuration

The configuration of the system will be shown in Figure 29. With an n = 84 sample size, this test was performed on the 'Y' variety. The average height, performance and the percentage destroyed are shown in Figure 30. Furthermore, there was an average Destroy Factor of 5.25.
Visual results of this testing session will be placed in Appendix E.

(a) (b)

Figure 29: Initial testing configuration where shafts are 'close together'
(a) Top view (b) View of the slope



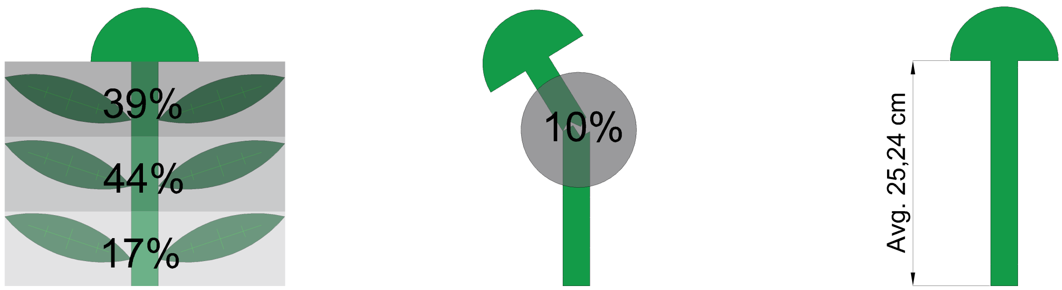
(a) (b) (c)

Figure 30: Results initial testing, second session Fin Design: 'close together'
(a) Performance (b) Destruction (c) Average height

3.2 Results Initial Testing: Metal Wire

3.2.1 Metal Wire Testing with 4mm Welded + 4mm Normal Configuration

This test was carried out on the 'X' variety with a sample size of n = 88. The average height, performance and the percentage destroyed are shown in Figure 31. Furthermore, there was an average Destroy Factor of 4.29.
Only one figure of this testing session was taken and will be placed in Appendix E.



(a) (b) (c)

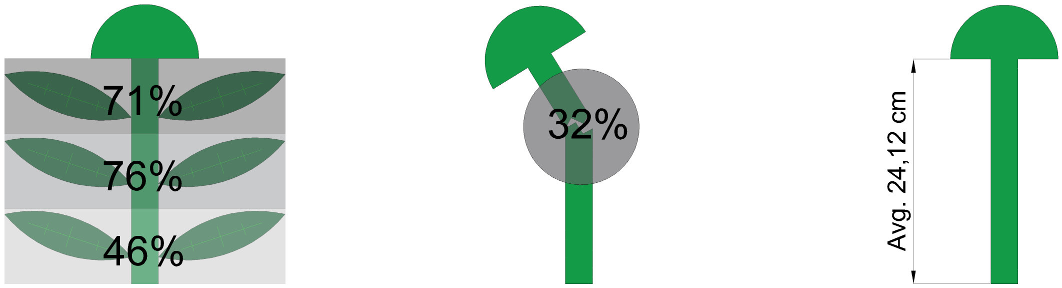
Figure 31: Results initial testing, first session Metal Wire: 4 mm welded + 4 mm normal
(a) Performance (b) Destruction (c) Average height

3.2.2 Metal Wire Testing with 4mm Shrink + 5mm Nut Unravelled Configuration

The configuration of the system will be shown in Figure 32. This test was carried out on the 'Y' variety with a sample size of n = 85. The average height, performance and the percentage destroyed are shown in Figure 33. Furthermore, there was an average Destroy Factor of 6.48.
Visual results of this testing session will be placed in Appendix E.

(a) (b) (c)

Figure 32: Metal Wire 4 mm shrink + 5 mm nut unravelled
(a) Full configuration (b) 5 mm nut wires (c) 4 mm shrinktube wires



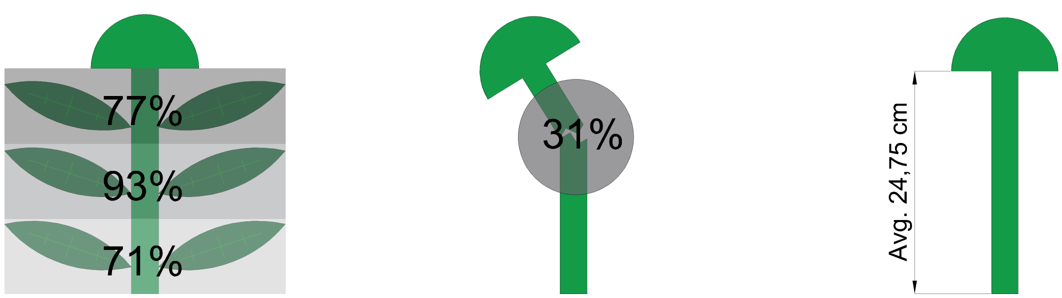
(a) (b) (c)

Figure 33: Results initial testing, second session Metal Wire: 4 mm shrinktube + 5 mm nut unravelled (a) Performance (b) Destruction (c) Average height

3.2.3 Metal Wire Testing with 5mm Shrink Unravelled Configuration

The configuration of the system will be shown in Figure 34. This test has been done on the 'X' variety with a sample size of n = 131. The average height, performance and the percentage destroyed are shown in Figure 35. Furthermore, there was an average Destroy Factor of 4.88.
Visual results of this testing session will be placed in Appendix E.

Figure 34: Metal Wire 5 mm shrinktubes unravelled



(a) (b) (c)

Figure 35: Results initial testing, third session Metal Wire: 5 mm shrinktube
(a) Performance (b) Destruction (c) Average height

4 Method: Optimisation

4.1 Design Selection

Two concepts are left and one needs to be discarded so the other can be optimised. Both have promising aspects and results. The best results from both concepts are shown again below.
The results of placing the shafts closer together are used for the Fin Design. This test was done for the 'Y' variety, with a sample size of n = 84 and a Destroy Factor of DF = 5.25. The other results are shown in Figure 36 and Appendix E.
For the Metal Wire the results were best when the 5 mm wires with unravelled ends were used. This test was conducted with the 'X' variety, with a sample size of n = 131 and a Destroy Factor of DF = 4.88. The other results are shown in Figure 37 and Appendix E.

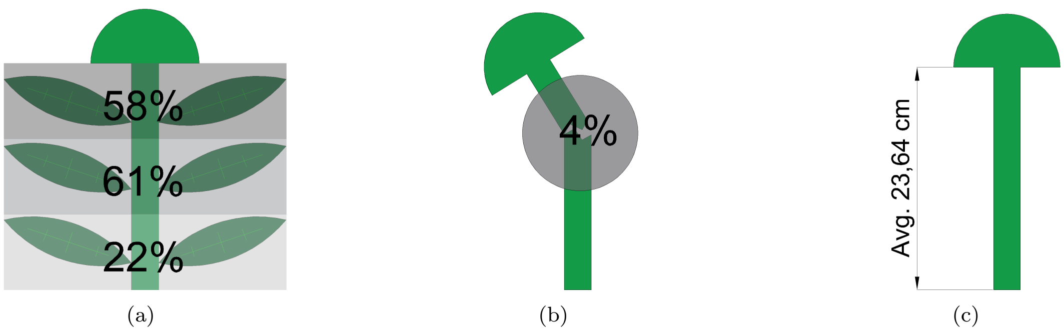


Figure 36: Best results Fin Design (DF = 5.25)
(a) Performance (b) Destruction (c) Average height

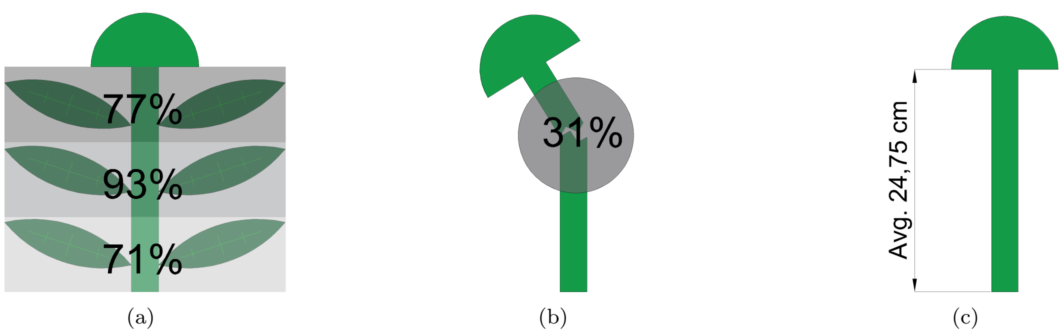


Figure 37: Best results Metal Wire (DF = 4.88)
(a) Performance (b) Destruction (c) Average height

If we summarize this from the Metal Wire's point of view:

Performance top section:	+19%
Performance middle section:	+32%
Percentage completely destroyed:	+27%
Destroy factor:	-0.37%

The performance of the lowest section has not been taken into account. As mentioned before, the lowest section is far less important due to the whole process and the significantly less leaves in this section.
The performance seems to be linked to the destruction. Meaning that a higher performance will most likely lead to a higher Destroy Factor or complete destruction. In most cases, it would be easier to reduce destruction without losing performance than to gain performance (without increasing destructiveness). Making the products more uniform will already increase performance while decreasing destructiveness. This could be established by improving the product or adding features to the machine. Such a feature could be a funnel.
Another important factor that should be taken into account is that results might be slightly affected by the leaf removal process. The performance might be better than it is due to the broccoli being removed and moved to an other location. The broccoli could lose additional leaves as a result of pulling them out of the soil. In the next step, while putting those into crates, moving them to an other space and getting them out of this case to take results. All could influence the performance by causing leaves to fall off or accidentally getting removed by hand. Additionally, when leaves are very small these will not be taken into account for the performance. However when very small leaves have been destroyed, this is hard to see after removal and these will be taken into account. This will again improve the performance.
On the other hand, this whole process also influences the Destroy Factor and the amount completely destroyed. The Destroy Factor will increase during this process as the plants could get damaged. The same applies for the amount destroyed, however, this will be less as more force is needed to go from a plant with the floret attached to a situation where the broccoli is completely destroyed. Furthermore, the amount of broccoli's completely destroyed will be lower in most cases, due to plants that are taken into account that shouldn't have been. This is when a broccoli is not mature enough to be taken into the results. However it is hard to tell whether a broccoli was mature enough when only the lower half is left. Therefore this not mature broccoli, which normally wouldn't have counted, will be added to the amount completely destroyed.
So in short, there is a possibility that the performance is slightly worse than shown and that the Destroy Factor and amount completely destroyed is slightly less than shown.
Taking everything into account, the performance of the Metal Wire is significantly better than that of the Fin Design. The Destroy Factor also indicates that the destructiveness of this design could become a problem. Even when the amount destroyed is much less, this could lead to a lot of damaged products which could not be used. This is also a very simple prototype, so little changes could have a large impact. When the frame, while being pulled, makes an angle or is shifted to one side, this could lead to more destructive results. Therefore, it could be expected that the destructiveness of a concept goes down when a more precise machine is developed. So with that in mind and the goal being leaf removal, lead to the Metal Wire as the concept which will be optimised.

4.2 Test Setup/ Protocol

A detailed investigation of numerous parameters and variables is required to optimise the selected design. A carefully thought-out base configuration is crucial to guaranteeing the reliability and accuracy of the results. In this arrangement, while retaining consistent control over those factors that cannot be changed, the variables will be tweaked which might have an impact on the design's performance. By doing this, the hope is to find the design's ideal configuration, which will increase performance and efficiency. Parameters which are a given that influence the characteristics of a broccoli:

- Height of the broccoli plants
- Width of the broccoli plants (as well leaves as the floret head/ stem)
- Floret size
- Growing angle
- Weather (soil & plant characteristics)

- Day of testing (maturity)
- Variety (changes in leaves)
- Germination
- etc..

The machine variables that could be adjusted during testing are:

- Ground speed
- Rotation speed (of shafts)
- The length of the wires
- The unravelled lengths of the ends
- The thickness of the wire
- The material of the wire
- The gap between the ends of both wires (distance between shafts)
- The amount of wires
- The distance between each wire
- Height of the shafts
- With/ without funnel
- The design

All the items mentioned above will be used for the optimisation phase. With the exception of the ground speed, material of the wire, the distance between the wires and the amount of wires.
The ground speed will not be tested, as the prototype is not yet advanced enough to be driven by a motor. This could be added in a later stage where wheels are attached and a variable speed could be obtained. It is very likely that when a machine would be made from this design, it will be powered by a tractor. That way a variable speed of the shafts can be accomplished and the ground speed will be determined by the tractor. However if this is not the case, the machine would also be capable to drive on its own with variable speed options, when some modifications have been made. For now due to the complexity of adding those features and the stage that the prototype is in. It is best to keep it as is, which is a relative constant speed of $\approx$1 km/h while being pulled. This is based on tests. Distance and time of these tests were used to approximate the pulling speed.
The wire material will not be adjusted, as this material is working well enough at this point. The material characteristics at this point are not far from perfect for this phase. The strength properties of the wire and the unravelled lengths are good enough to test with and are easily adjustable by changing the thickness. The unravelling wires are useful for the design and therefore these wires with those capabilities are great.
The amount of wires is not adjusted as there was a fixed length for the shafts. To give the prototype enough chance to defoliate the broccoli there has been chosen to use the maximum amount of wires which could be added to the shaft. With the side note that each wire should have enough space around the wire so it acts on its own. Therefore the distance between the wires will also not be adjusted. When the wires are positioned too close, they could get entangled and the effect will thereby be changed.
The other variables will be tested for the following reason, with a hypothesis of the results:

Rotation speed (of shafts) Currently due to the resources available, a hand drill is used for both axes. This is a non-controllable rpm and has a low and a high configuration. To get a better overview of what might be the influence of the speed of the rotation, a constant and adjustable rpm is needed. The current drill rpm will be taken as a reference and a slower and faster rpm will be tested. Expected will be that current rpm or slightly higher would be ideal for this system.

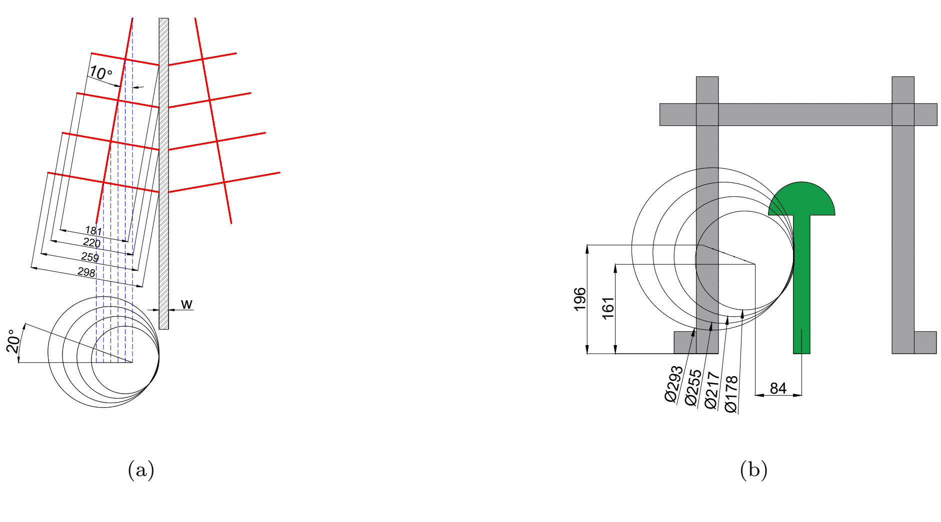
The length of the wires The length of the wire is now close to maximum i.r.t. the height of the ground. The height of the ground is taken by looking at an average plant and using the maximum length of a cable for this height. If the wire becomes longer, it will interfere with the frame or surrounding. The wire could get stuck or damage the frame and the wire will be affected by it as well. It is expected that the 'maximum' length will be best, however, it is worth trying smaller lengths.

The unravelled lengths of the ends The area of effect and the grabbing aspect was improved by having unravelled wires. Stopping the unraveling effect too early (so close to the ends) might still leave you with a very destructive wire, however most likely also with a good performance. Stopping the unraveling too late, might make the wires too weak to do the defoliating properly. Expected is a distance of around 5 cm from the end, as it could be ideally between both aspects mentioned above.

The gap between the ends of both wires (distance between shafts) The closer the wires are, the better leaf removal should be. This is due to the impact being close to the stem and the more sturdy parts of the leaves, which could help with overall breaking. However too close together and the damage to the stem could be very significant or even completely destructive. That is why this is being researched, to find a good optimized position for the distance between the wires. This would be the configuration with the best performance-destruction ratio. Given that the diameter of the stem is approximately 1.6-3.2 cm, expected could be that a distance between the wires of 2.5 cm would be ideal. Then a high amount of the stems are only slightly damaged in the position where these wires are in each others longitudinal direction.

With/ without funnel As mentioned before, a funnel could add value without causing problems. The funnel will make the broccoli's in the row more uniform. A more uniform product is easier to be handled by the machine and therefore better.

The design It might be useful to have smaller wires close the stem at lower points, in that case the smaller plants are more safe. And the longer wires at the top for the bigger plants and leaves. In Figure 38 an approximation is made for the lengths of the wires. A slope and a funnel design are implemented. A 10 degree funnel and a slope with a 20 degree angle are used.



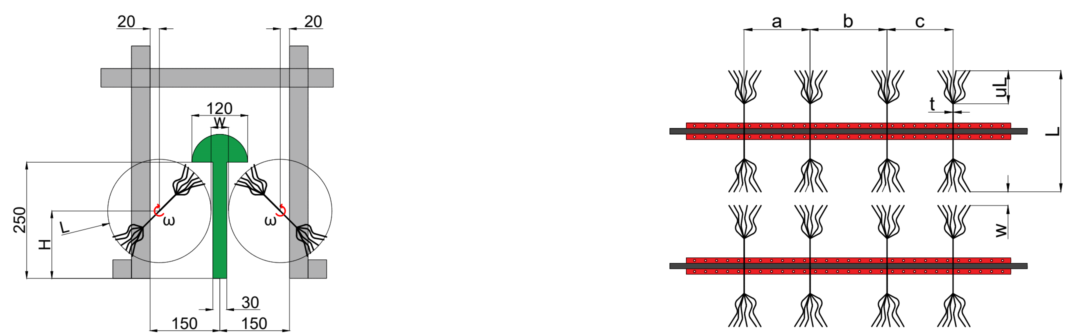
(a) (b)

Figure 38: Schematic drawings for determining the lengths of the wires for the new design of Metal Wire
(a) Top view (b) Side view

A similar testing method will be used during the selection tests of the concepts. The frame will be adjusted according to what needs to be tested. Afterwards, one row in a bed will be freed from any surrounding elements. Then one person will pull the system at a 'constant' pace, while another person will operate the hand drills. Each testing session one of the variables will be tested while the others stay constant. When not mentioned otherwise, the variables will be:

H = 14.5 cm (Height)
L = 22 cm (Length)
uL = 6 cm (unravelled Length)
t = 5 mm (thickness)
w = 2.5 cm (gapwidth between wires)
ω = 1800 rpm (rotational speed)
a = c = 12 cm (distance between outer wires)
b = 14 cm (distance between middle wires)

These values correspond to the values in the Figure 39a/b. Here the same example broccoli as before is used as representation of the system. Figure (39b) represents a top view of the shafts with the wires.



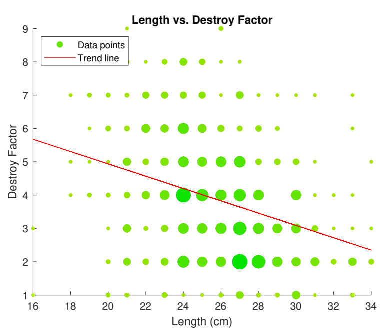
(a) (b)

Figure 39: Schematic drawing of the Metal Wire design with letters given for the variables
(a) Front view prototype (b) Top view shafts

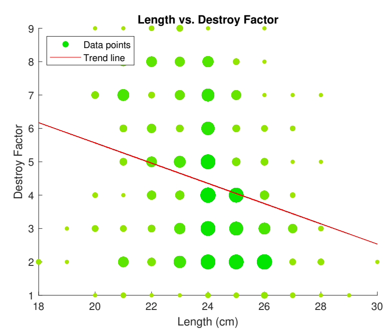
5 Results: Optimisation

5.1 Information on the Varieties During Testing

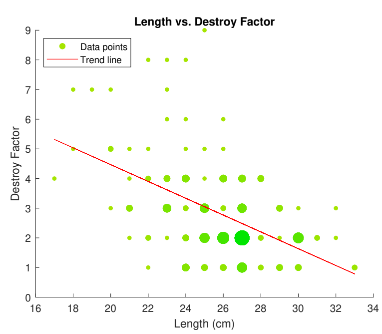
In total during the preliminary testing, initial testing and optimisation 1575 broccoli's have been examined. Only 25 of those have been in the preliminary tests, where the variety was not written down. During the initial tests, 304 samples were taken and for the optimisation 1114. These numbers are including the ones that are completely destroyed.
Three varieties have been used during testing of which variety 'X' the most. In total 610 broccoli's of 'X' survived testing without getting destroyed and used for results, 399 of 'Y' and 155 of 'Z'. There are large differences in the number of leaves per section. There were a total of 1958 leaves for 'X' in the top section, 3518 in the middle section, and 39 in the bottom section. This gives an average of 3.2 leaves per broccoli in the top section, 5.8 leaves in the middle section and 0.1 leaf in the bottom section. For 'Y' this was on average 4.2 leaves in the top, 5.9 in the middle and 0.1 leaf in the bottom. For 'Z' this was on average 3.6 on top, 5.3 in the middle and 0 on the bottom.
Within these varieties, there were a lot of different lengths of the stem. As this might influence the Destroy Factor these two have been put in a graph. In this graph the data points are given by dots. If multiple data points were in the same location, the dot was enlarged.To better distinguish between differences, not only is size used, but color is also used, which changes depending on the number of data points for a specific dot. In addition, a trend line is added to visualise the approximate Destroy Factor with increasing length of the stem. The graphs are shown in Figure 40. Furthermore, during study at Rijk Zwaan it is noted how much of the broccoli at time of harvest were not mature enough. This ranged from 4 to 24% and was on average 15% for the three varieties.



(a)



(b)



(c)

Figure 40: Graphs of the Destroy Factor given per length for all the data obtained during the tests (a) 'X' Variety (b) 'Y' Variety (c) 'Z' Variety

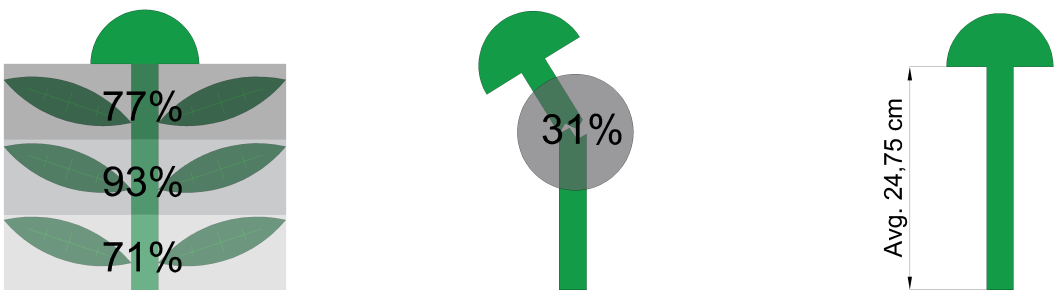
5.2 Width of the Gap Between the Wires

In Figure 41 the three configurations that were tested are displayed. Going from touching tips to a gap of 5 cm to determine the ideal distance or range of distance. Below in Figure 42/43/44 the results per configuration are shown. Visual results of this testing session will be placed in Appendix E.

(a) (b) (c)

Figure 41: Metal Wire configurations shown for different widths that are tested
(a) 0 cm (b) 2.5 cm (c) 5 cm

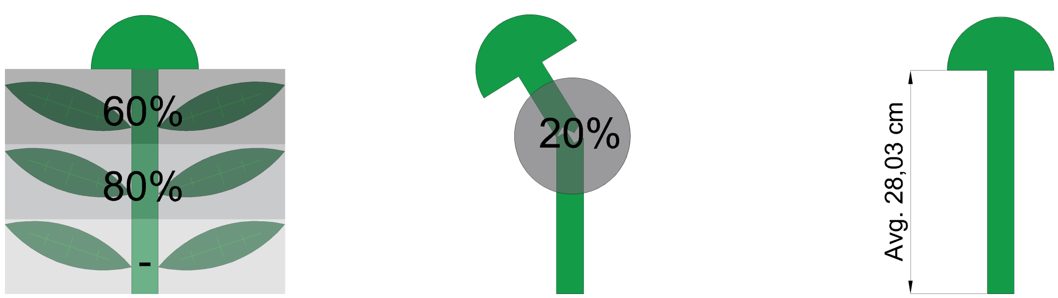
Width = 0 cm This testing session has been done using the 'X' variety. It had a Destroy Factor of DF = 4.88 and a sample size of n = 131. Results are shown in Figure 42.



(a) (b) (c)

Figure 42: Metal Wire optimisation results for Width = 0 cm
(a) Performance (b) Destruction (c) Average height

Width = 2,5 cm This testing session has been done using the 'X' variety. It had a Destroy Factor of DF = 3.22 and a sample size of n = 90. Results are shown in Figure 43.



(a) (b) (c)

Figure 43: Metal Wire optimisation results for Width = 2.5 cm
(a) Performance (b) Destruction (c) Average height

Width = 5 cm This testing session has been done using the 'X' variety. It had a Destroy Factor of DF = 2.92 and a sample size of n = 58. Results are shown in Figure 44.

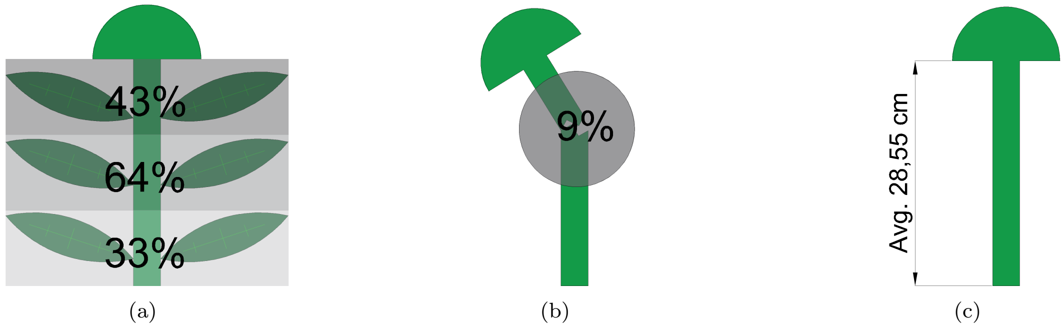


Figure 44: Metal Wire optimisation results for Width = 5 cm
(a) Performance (b) Destruction (c) Average height

5.3 Thickness of Wires

In Figure 45 the three configurations that were tested are displayed. Going from the thinnest (4 mm) to a more destructive wire of 6 mm to determine the ideal thickness or range of thickness. Below in Figure 46/47/48 the results per configuration are shown. Visual results of this testing session will be placed in Appendix E.

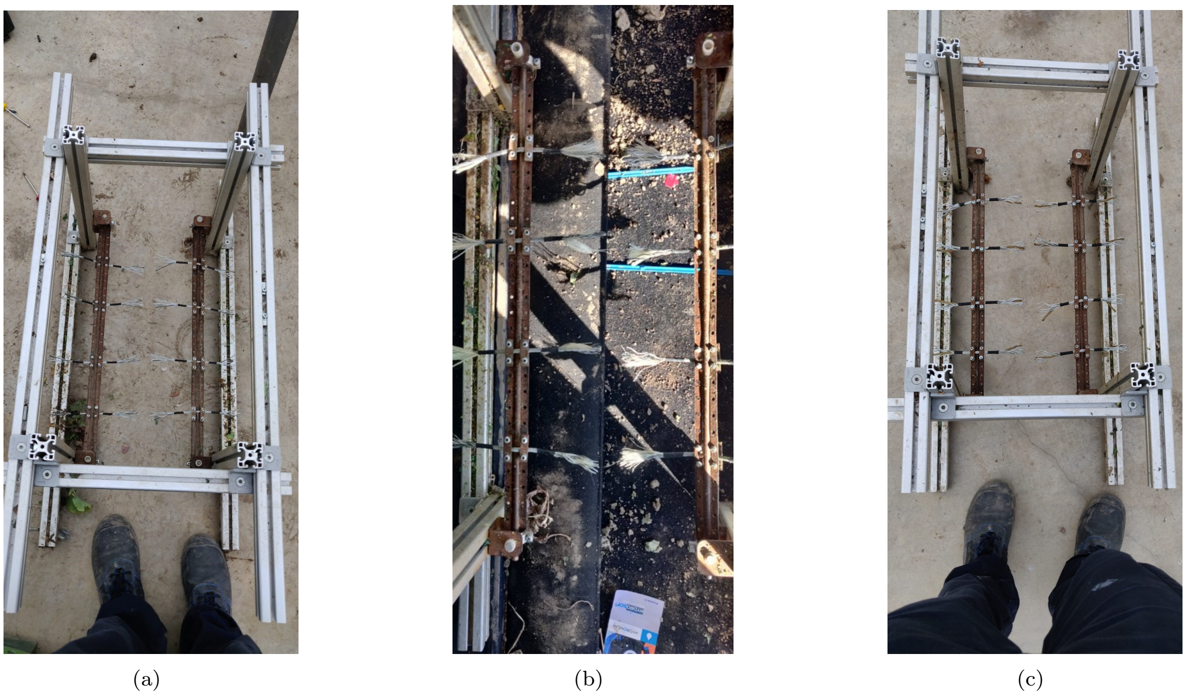


Figure 45: Metal Wire with the different thicknesses that are tested
(a) 4 mm (b) 5 mm (c) 6 mm

Thickness = 4 mm This testing session has been done using the 'Y' variety. It had a Destroy Factor of DF = 2.60 and a sample size of n = 36. Results are shown in Figure 46.

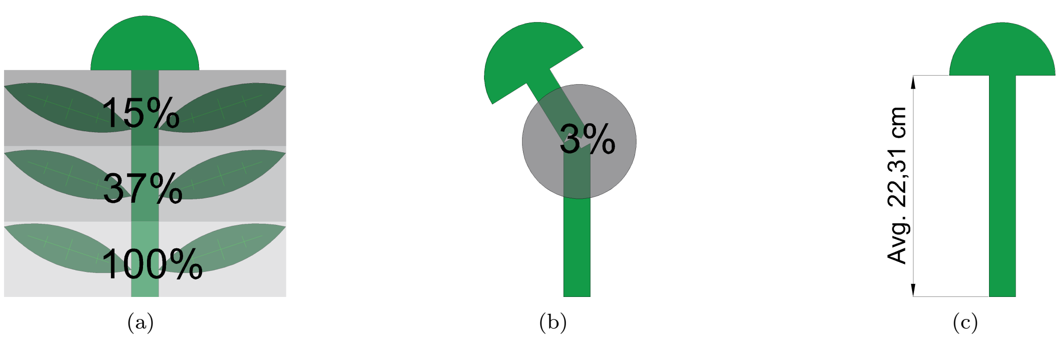


Figure 46: Metal Wire optimisation results for Thickness = 4 mm
(a) Performance (b) Destruction (c) Average height

Thickness = 5 mm This testing session has been done using the 'X' variety. It had a Destroy Factor of DF = 3.22 and a sample size of n = 90. Results are shown in Figure 47.

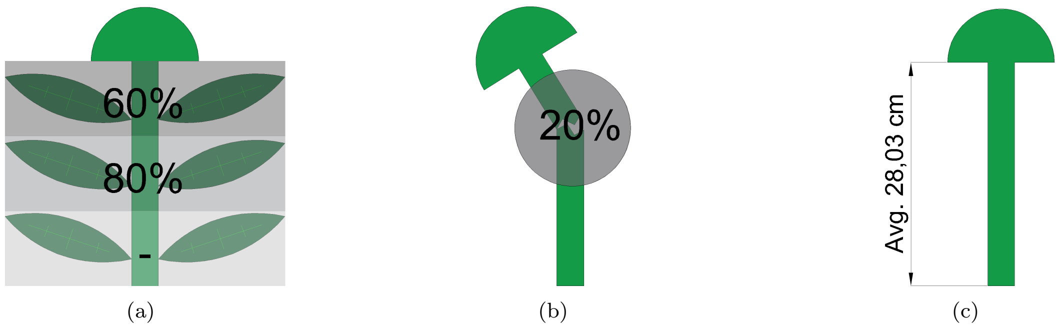


Figure 47: Metal Wire optimisation results for Thickness = 5 mm
(a) Performance (b) Destruction (c) Average height

Thickness = 6 mm This testing session has been done using the 'Y' variety. It had a Destroy Factor of DF = 4.20 and a sample size of n = 102. Results are shown in Figure 48.

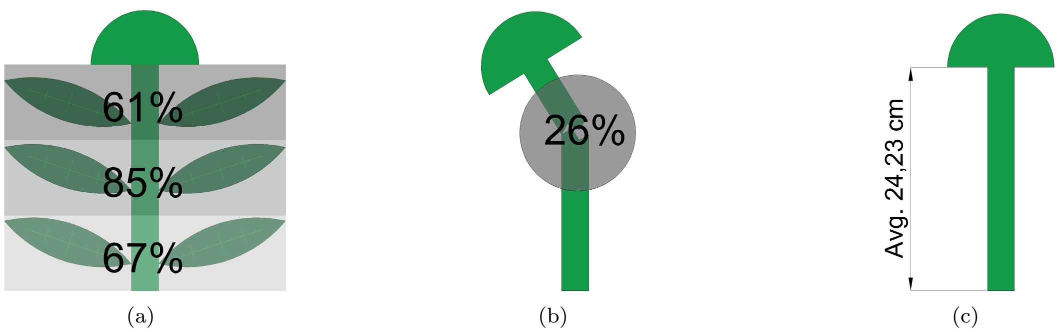


Figure 48: Metal Wire optimisation results for Thickness = 6 mm
(a) Performance (b) Destruction (c) Average height

5.4 Unravelled Length

The three configurations that were tested have to do with the lengths of the ends which are unravelled, kept into place by a shrink tube. Going from shortest (4 cm) to a more frayed wire of 8 cm to determine the ideal unravelled length or range of lengths. Below in Figure 49/50/51 the results per configuration are shown. Visual results of this testing session will be placed in Appendix E.

Unravelled Length = 4 cm This testing session has been done using the 'Y' variety. It had a Destroy Factor of DF = 3.47 and a sample size of n = 99. Results are shown in Figure 49.

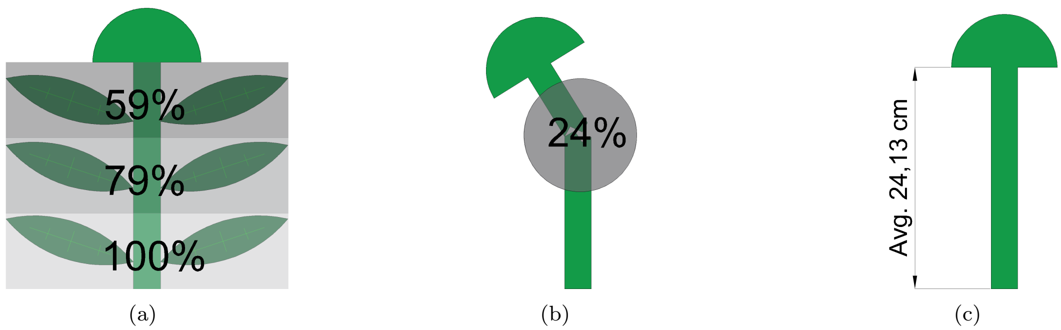


Figure 49: Metal Wire optimisation results for Unravelled length = 4 cm
(a) Performance (b) Destruction (c) Average height

Unravelled Length = 6 cm This testing session has been done using the 'X' variety. It had a Destroy Factor of DF = 3.22 and a sample size of n = 90. Results are shown in Figure 50.

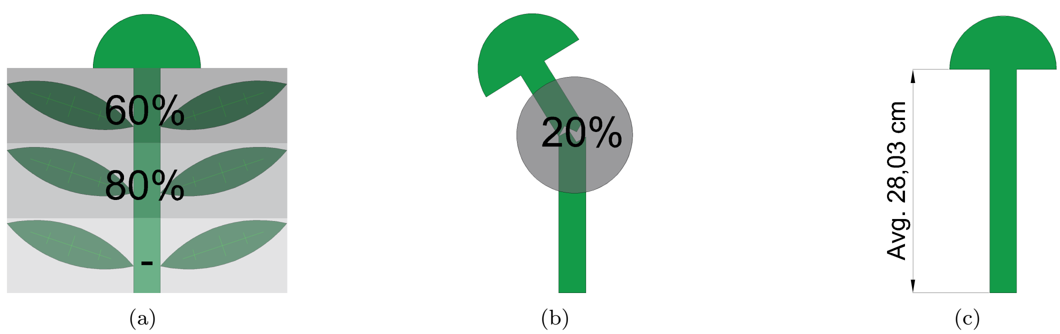


Figure 50: Metal Wire optimisation results for Unravelled length = 6 cm
(a) Performance (b) Destruction (c) Average height

Unravelled Length = 8 cm This testing session has been done using the 'Y' variety. It had a Destroy Factor of DF = 3.93 and a sample size of n = 94. Results are shown in Figure 51.

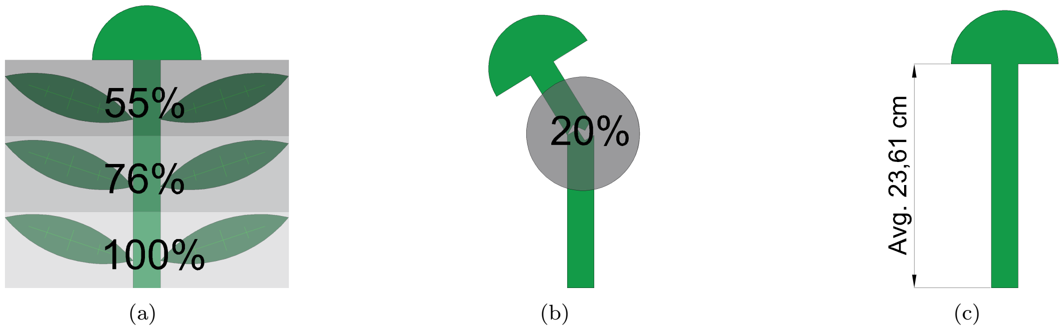


Figure 51: Metal Wire optimisation results for Unravelled length = 8 cm
(a) Performance (b) Destruction (c) Average height

5.5 Length of Wires

The two configurations that were tested are regarding the lengths of the wires. Going from shortest 18 cm to a longer wire of 22 cm to determine the ideal length or an indication of what lengths could be ideal. Below in Figure 52/53 the results per configuration are shown. Visual results of this testing session will be placed in Appendix E.

Length wire = 18 cm This testing session has been done using the 'Z' variety. It had a Destroy Factor of DF = 3.15 and a sample size of n = 112. Results are shown in Figure 52.

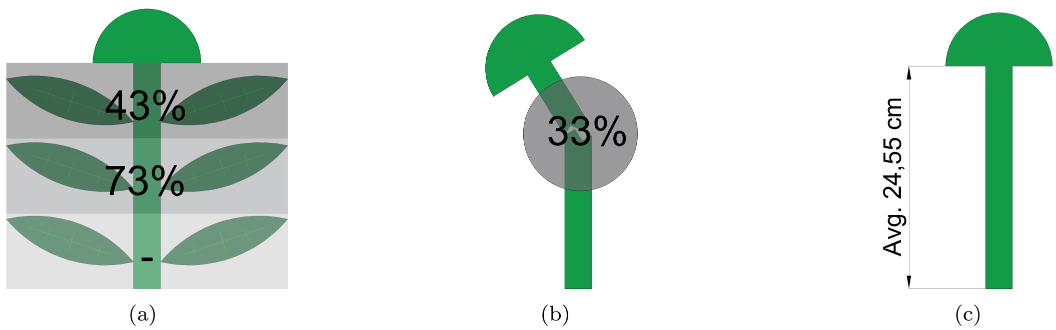


Figure 52: Metal Wire optimisation results for Length wire = 18 cm
(a) Performance (b) Destruction (c) Average height

Length wire = 22 cm This testing session has been done using the 'X' variety. It had a Destroy Factor of DF = 3.22 and a sample size of n = 90. Results are shown in Figure 53.

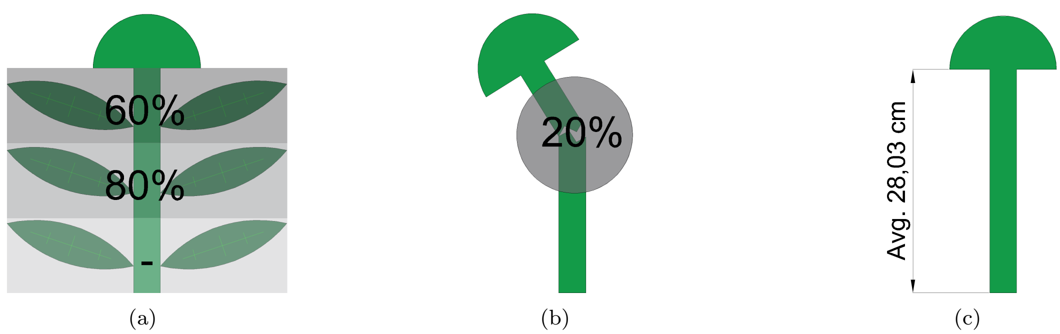


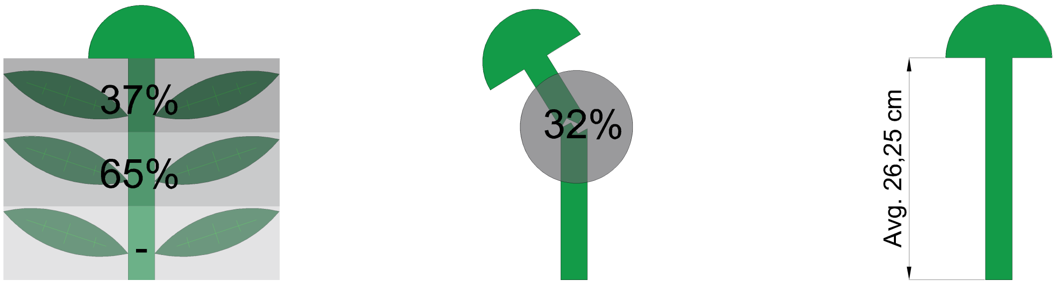
Figure 53: Metal Wire optimisation results for Length wire = 22 cm
(a) Performance (b) Destruction (c) Average height

5.6 Funnel

In Figure 54 the funnel that was tested is displayed. This will determine whether this funnel has a positive influence on the results. Below in Figure 55/56 the results per configuration are shown. Visual results of this testing session will be placed in Appendix E.

Figure 54: Metal Wire configuration with the funnel used during testing

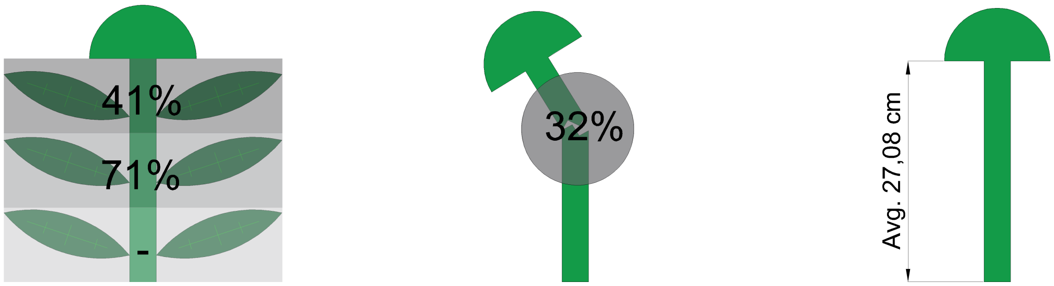
With funnel This testing session has been done using the 'Z' variety. It had a Destroy Factor of DF = 2.18 and a sample size of n = 59. Results are shown in Figure 53.



(a) (b) (c)

Figure 55: Metal Wire optimisation results for: With a funnel
(a) Performance (b) Destruction (c) Average height

Without funnel This testing session has been done using the 'Z' variety. It had a Destroy Factor of DF = 3.05 and a sample size of n = 59. Results are shown in Figure 53.

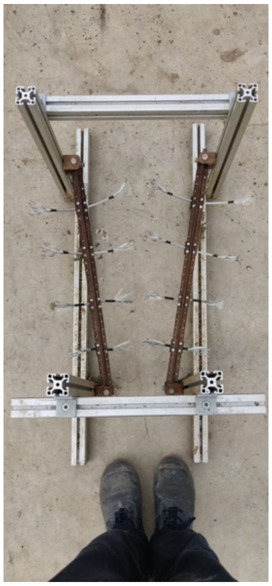


(a) (b) (c)

Figure 56: Metal Wire optimisation results for: Without a funnel
(a) Performance (b) Destruction (c) Average height

5.7 Different Design

In Figure 38 the approximation for the design is shown. A slope and a funnel design are implemented. A funnel of 10 degrees and a slope with a 20 degree angle are used. In Figure 57 this configuration is shown in the prototype. This will determine whether another design has a positive influence on the results. Below in Figure 58/59 the results per configuration are shown. Visual results of this testing session will be placed in Appendix E.

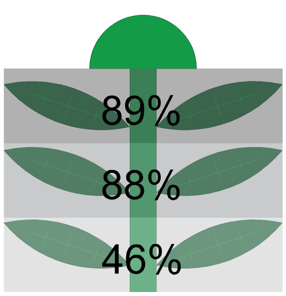


(a)

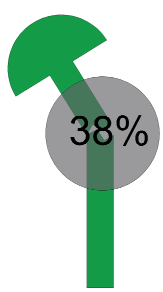
(b)

Figure 57: Photo's of the adjusted Metal Wire Slope design
(a) Top view (b) Side view

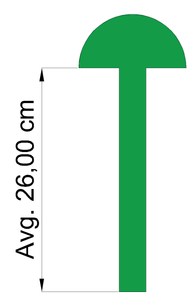
Slope design This testing session has been done using the 'X' variety. It had a Destroy Factor of DF = 5.26 and a sample size of n = 112. Results are shown in Figure 58.



(a)



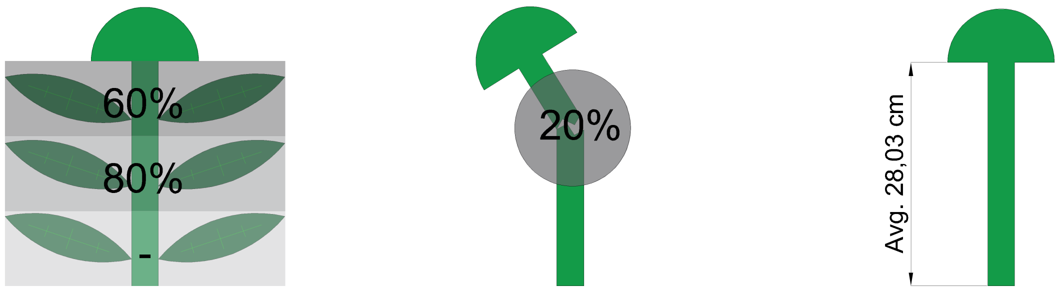
(b)



(c)

Figure 58: Metal Wire optimisation results for Design: Slope
(a) Performance (b) Destruction (c) Average height

Normal design This testing session has been done using the 'X' variety. It had a Destroy Factor of DF = 3.22 and a sample size of n = 90. Results are shown in Figure 59.



(a) (b) (c)

Figure 59: Metal Wire optimisation results for Design: Normal
(a) Performance (b) Destruction (c) Average height

5.8 Rotational Speed

The three configurations that were tested have to do with the rotation speed of the shaft holding the wires. Going from slowest 1300-1400 rpm up to a faster rotating shaft of 2000-2100 rpm to determine the ideal speed or an indication of what speed could be ideal. Below in Figure 60/61/62 the results per configuration are shown. Visual results of this testing session will be placed in Appendix E.

Slow speed This testing session has been done using the 'X' variety. It had a Destroy Factor of DF = 3.25 and a sample size of n = 99. Results are shown in Figure 60.

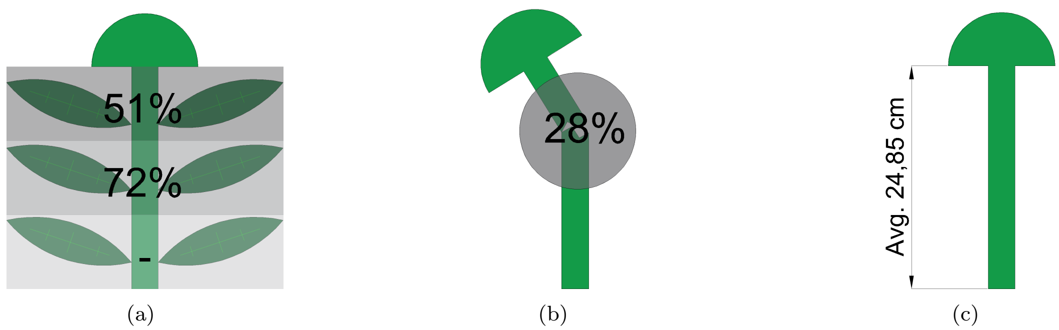


Figure 60: Metal Wire optimisation results for Rotational speed = 1300-1400 rpm
(a) Performance (b) Destruction (c) Average height

Medium speed This testing session has been done using the 'X' variety. It had a Destroy Factor of DF = 3.19 and a sample size of n = 105. Results are shown in Figure 61.

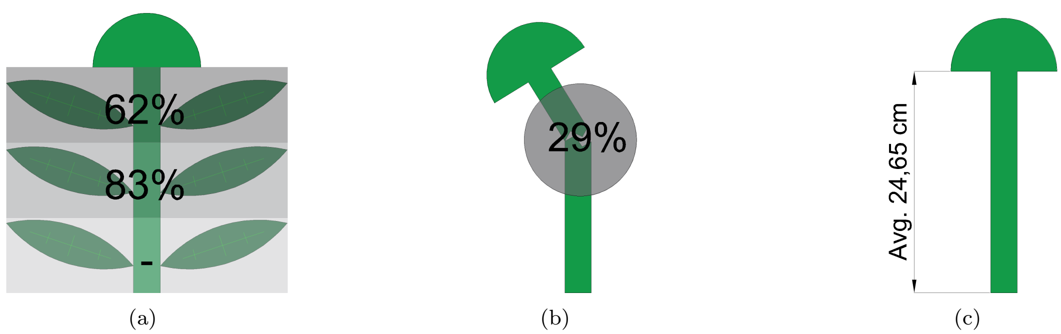


Figure 61: Metal Wire optimisation results for Rotational speed = 1800-1800 rpm
(a) Performance (b) Destruction (c) Average height

High speed This testing session has been done using the 'X' variety. It had a Destroy Factor of DF = 3.37 and a sample size of n = 89. Results are shown in Figure 62.

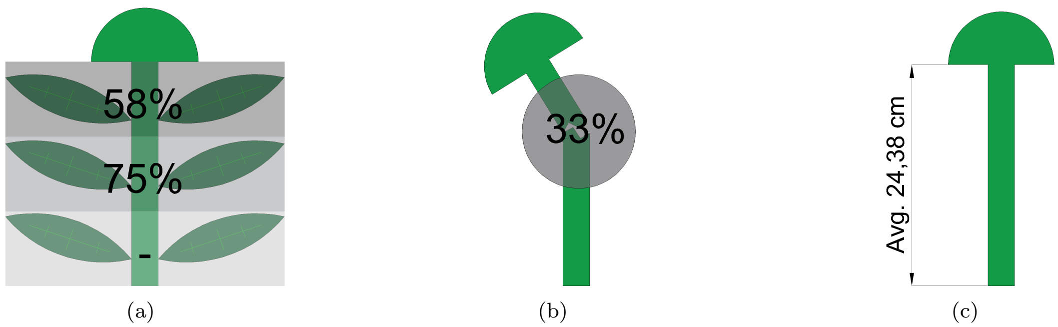


Figure 62: Metal Wire optimisation results for Rotational speed = 2000-2100 rpm
(a) Performance (b) Destruction (c) Average height

6 Discussion

6.1 Testing Conditions

As discussed the performance, amount destroyed and Destroy Factor are influenced by the process after the prototype has done its job. Another important factor is the different varieties used. The 'Y' variety has leaves pointing upward in comparison to the 'X' variety. Meaning that the leaves are harder to remove, but also that the floret is better protected. In conjunction with the fact that, on average, 15% of the broccoli is not mature enough when harvested. According to Figure 40, the percentage of destruction likely affects the smaller broccoli more, meaning that relatively speaking, the actual percentage of destruction would be lower.
The results are affected by the prototype being pulled manually. Despite attempts to maintain a consistent pulling speed, there will still be variations in speed between each test. In addition, every slight angle to the right or left would influence the results. The overall placement, so also when the prototype is positioned a bit more to the right or left, also influences everything.
The frame poses an obstacle to conducting proper testing. Best would be to get rid of the frame that touches the soil/ is on plant height and the shafts. Tackling the problem where all elements come from above the plants. The shafts cause a lot of broccoli's to be destroyed when the plants get caught underneath. Elements are also force-locked, which is prone to error if not done correctly. This is also the case for the frame, where it could influence the results if bolts are not tightened enough. The machine is now driven by hand drills. This has been done due to its convenience. However in an ideal situation this would be replaced by a controllable electric motor. To control this a frequency converter is needed.
In retrospect, it would have been preferable to try to schedule the test with fewer days in between. This results in relatively large differences (height and variety), which make it harder to compare. Remember that the results of the lowest section are far less important, even neglectable. The plots that were used are the ones that had been planted for this research. There was a slight time frame in between (≈ one week) the sowing moments. This made sure that there were multiple weeks for testing and not just one time frame of a few days in which everything would be mature enough for testing. The ideal variety was the 'X' variety, as that was the one for which the prototype was designed. When there were no mature broccoli's available of the 'X' variety, an other variety was used.
In addition, the broccoli's do not grow all year round, so at some point there were no broccoli's left to test with. Therefore, a tight schedule was used to test as many variables as possible. This also had as result that when a test did not go ideal this could not be corrected due to the limited time.

6.2 Variables

6.2.1 Width of the Gap Between the Wires

Per variable is discussed which configuration will most likely give the best output. While still working with a simplified prototype, this could slightly change due to the advantages of a sturdy, detailed machine specially designed for this task.
The same variety from the same plot has been used during the tests for the width of the gap. A difference is that the 0 cm gap has been tested 7 days before the 2.5 cm and the 5 cm has been done 3 days later. This leads to a difference in maturity. Doing tests a few days later has the result that these will be more developed and therefore larger. This could be observed when looking at the differences in average height.
There is a relatively large amount of the sample size completely destroyed by the prototype. This will most likely been less when the broccoli's were a week more mature. Also the DF would be lower because the florets would be higher up, so fewer of them would be damaged. Compare that with the results from Figure 40a the approximate destruction would be less.
Looking at the results, the 5 cm gave the least losses, however also a relatively low performance. The 2.5 cm seems to have a better equilibrium between performance and amount destroyed. The 0 cm has

the best performance, however also the most destructive results.
Considering the 0 cm results obtained when the plants were not as mature. The best results will most likely be between 0 cm - 2.5 cm. The closer to 0 cm the higher the performance and the more destructive. Therefore, closer to 2.5 cm, such as 2.0 cm, will give better balance.

6.2.2 Thickness of Wires

Two different varieties have been used during these tests. The 5 mm thickness will be used, as that was already tested for the width. That study used the variety 'X'. The 4 and 6 mm studies have been tested on variety 'Y' of the same plot. This variety, also during these tests, was smaller and had different leaves. The leaves of these broccoli are not as sideways, but more upward. Especially in the top section this shows. This has the effect that these leaves are harder to remove, however, the florets are also better protected and therefore the damage should be less. There is a three-day difference between the 'Y' studies, where the 4 mm has been done before the 6 mm.
Both of these elements present themselves in the average height. The 'Y' values are significantly smaller than the 'X' test. In addition, the 4 mm which has been done before the 6 mm tests is also $\approx$2 cm shorter on average.
These shorter broccoli's should result in a higher amount being destroyed as they are less mature. However as the results show, the 4 mm is too weak to do that much damage. Therefore, having a very low DF and percentage destroyed, but also a low performance.
Results of the 5 mm are in more advantageous conditions than the 6 mm. The performance is very similar, but the percentage destroyed, and especially the DF is much higher.
The best results will be for a 5 mm or 6 mm wire as 4 mm was too weak and 7 mm would get too destructive. While considering the advantageous conditions, the best solution will most likely still be the 5 mm wire. As this is capable of the same performance, so strong enough, but a little bit less destructive than the 6 mm.

6.2.3 Unravelled Lengths

Two different varieties have been used during these tests. The 6 cm unravelled length will be used, as it was already tested for the width. That study used the variety 'X'. The 4 and 8 cm studies have been tested on the variety 'Y' of the same plot. There is only a day difference between the 4 and 8 cm tests and therefore not have a large influence on the results. The 8 cm unravelled length has been done one day before the 4 cm.
For the 8 cm the test did not go perfectly. The frame was often a bit sideways during testing. In addition, at some point one of the wires got loose. This was noticed right away and results were taking up until that point. The results showed leaves that were better removed on one side than on the other.
Considering all these elements, it is not unexpected that the DF of the 8 cm is a bit higher. The percentage destroyed would have been lower as well. As a result of the conditions during testing, these are likely higher than they normally would be.
The 4 and 8 cm are significantly smaller than the 6 cm unravelled length. The performance however is very similar. The 4 cm would probably have been less destructive if tested using a more mature 'X' variety.
Because of the very similar results in every aspect, the lengths of the unravelled ends do not seem to have a large impact. Especially due to the test of the 8 cm not going great, it would be recommended to look at this more in-depth. This might be an important key to reduce destructiveness while maintaining performance. Even a brush-like mechanism with all small wires like unravelled ends might be an upgrade.

6.2.4 Length of Wires

Two different varieties have been used during these tests. The 22 cm length will be used, as that was already tested for the width. That study used the variety 'X'. The 18 cm study has been tested on the

variety 'Z' from the same plot.
Again there is a significant difference in height between the two tests, in addition to a different variety. This variety is also quite small and noticeable was that there were a lot of differences within the same plot. During these tests many broccoli's were out of line, meaning that they had an angle that made them lean to left or right.
The 18 cm causes the shafts to be closer together, which resulted in a very destructive prototype. The broccoli got caught underneath the shaft and that was what destroyed most of the broccoli's.
The 22 cm gave better results, but more tests are needed for a better understanding. Removal of the destructive shafts and then testing different lengths would give a better impression. Even better would be to also get rid of the frame as it obstructs the testing with wires larger than 22 cm as well.

6.2.5 Funnel

The same variety from the same plot on the same day has been used during this testing. The variety that was used was the 'Z' variety. Even the exact same sample size has been used for the tests and the same amount has been completely destroyed. The funnel used is shown in Figure 54. This approach was a bit too simplistic, with a bent steel plate attached to the sides. The idea was that the steel plates would have an angle of 40 degrees i.r.t. the alignment with the frame. Leaving a gap of 5 cm in between the ends of the steel plates.
During testing, the funnel did indeed push the stems to the middle when they were out of line. Making the broccoli more uniform is what should improve the performance and decrease the amount destroyed. However, after the misaligned broccoli's were pushed into the right position and past the funnel, they bent back to their original position. Making this funnel basically a useless addition to the system. This also shows in the results, which are very similar, even better for the test without a funnel. The DF seem to be a bit lower; this could mean that it did slightly help. However, it could also be that the alignment with the row was better during this session.
Considering everything discussed, the only real conclusion would be that this particular funnel does not change much. An other funnel could be a great addition and has the potential to improve the results. The idea to place the funnel just above the soil works great due to the low amount of leaves in this section. If there are leaves, these are very small and easily deformable. An easy fix for this funnel would be to use the same start, but add a trench afterwards. Then after they are pushed into place they will be kept in place, when leaving the first part of the funnel. With the condition that this is stiff enough, so it does not get pushed to the side.

6.2.6 Different Design

The same variety has been used during this testing session. The variety used was the 'X' variety. This was done from a different plot. The 22 cm length will be used, as that was already tested for the width. There is a height difference of ≈2 cm. This is not as significant as we have seen before. The new design is far more destructive, both in terms of DF and amount destroyed. The reason for this could be the shafts which are closer together at the start, however more likely is that the longer wires are causing this increase in destructiveness. A longer wire means a longer arm so a larger force and impact at the ends for the same rotation speed.
In addition the design used, as shown in Figure 57 has a higher chance of destroying wider florets. The circles in this picture represents the area of attack. These operate in a larger area, which makes the wider florets that are not as tall more vulnerable to the wires. The recommended solution would be to optimise the normal design before exploring other design options with a funnel/ slope design.

6.2.7 Rotational Speed

The same variety from the same plot has been used during these tests. The variety used for these sessions was the 'X' variety. There is also just one day difference between the test with medium speed in comparison to the tests with slow and high speed.

As mentioned before, hand drills are used as the motor for the rotating shafts. A controllable motor would have been far more ideal. However due to lacking time and these resources being relatively expensive for testing one aspect, it was chosen to continue with hand drills. Therefore, available resources were used, with the approximation of having a difference of 500 rpm between each session. So different drills are used, which only made it possible to have the following rpm's: 1300/1400/1800/1800/2000/2100. Therefore slow would be 1300 and 1400, medium would be 1800 and 1800, fast would be 2000/2100. Which is not the ideal test, but it does give an indication of the differences in speed.
One of the drills for the fast speed started slipping after using it for a short time. The result of this problem was that this testing session was done in multiple short intervals.
What could be expected, as most conditions were very similar, is that the performance and destructiveness would increase with increasing speed. The DF is very similar in each session and the amount destroyed is slightly increasing. Between the slow and the medium speed an increase of 11% in performance is shown. The high speed does not increase performance, but this could be explained by the slipping drill.
Recommended would be to have a controllable motor. This would be easiest with an electric motor with a frequency converter. Then different speeds are easily tested. For now a speed of around 1800-2000 rpm show best results.

6.2.8 Trade-off

As seen in the results, a trade-off is taking place between performance and destruction. An adjustment that improves performance is likely to increase the destructive aspect as well. This works both ways, however there are exceptions. Improving the frame in terms of precision and stiffness will be beneficial for both. Same goes for features improving the uniformity, such as a funnel.
The variables however, such as speed or dimensions of the wire, will have an effect on both. Which is most likely to advantage one and disadvantage the other aspect. Increasing the thickness of the wire will improve the performance, but also increase the amount destroyed and Destroy Factor. Therefore an optimal balance, taking in account the preferred results, will be looked for when considering the trade-off.

6.3 Scaling up

One row is not the same as a whole bed. For scaling up, Figure 63 is used to show how that could be implemented, shown from a top view perspective. The green circles are stems, not floret heads. When you copy the shafts with wires of the current prototype and make one machine, it will look like this. If we zoom in we can see that even a floret head of 12 cm diameter will not get touched. In addition, the shafts are rotating inwardly. Therefore if the rows next to the row that gets defoliated gets hit, this will only push leaves up or slightly damage the leaves. The leaves will therefore protect the floret from wires designated for the row next to this row.
An improved machine could get rid of a shaft, with an example shown in Figure 63c/d. An important upgrade is that there is no shaft and minimal elements at the height of the plant. So there are enough opportunities to scale up the prototype and this will not lead to too many problems. Scaling to multiple beds will not be a problem, just a space issue.

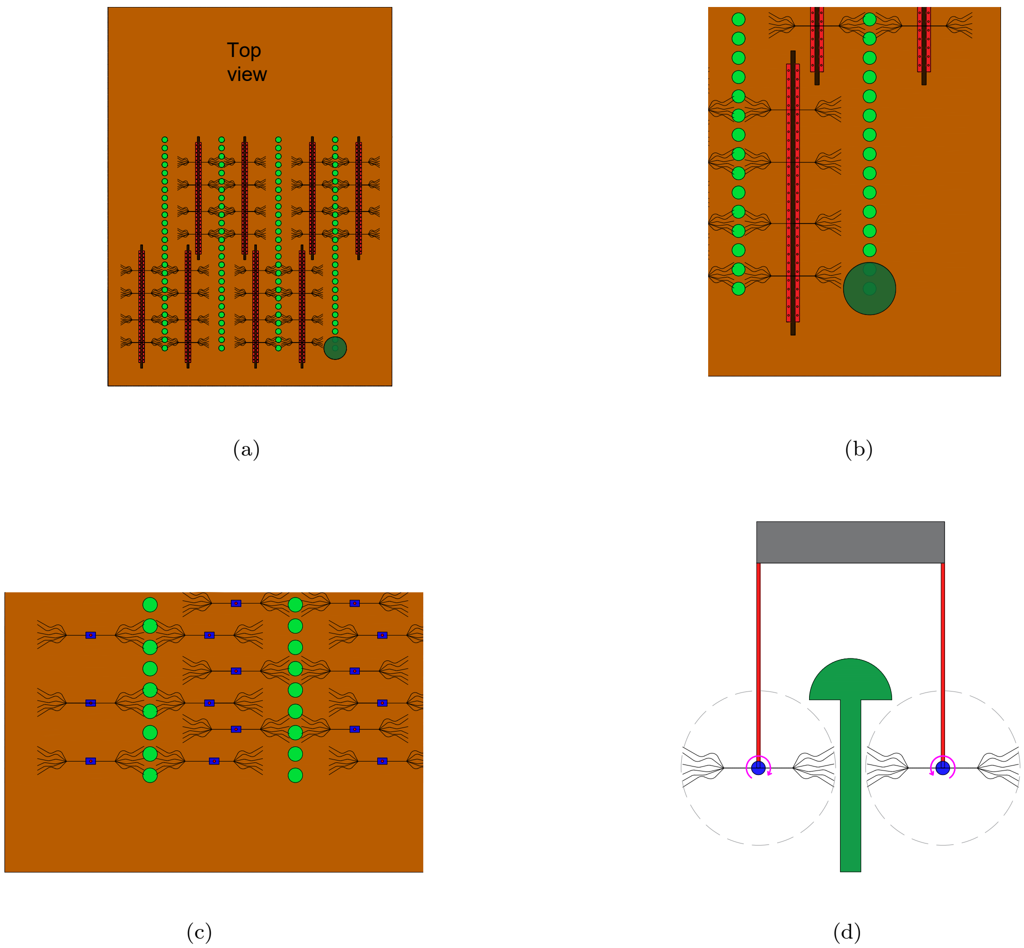


Figure 63: Schematic drawing of an overview for scaling up, using a top view of an example bed where the light green circles are broccoli stems
(a) Whole (b) Zoomed-in (c) If shafts were removed top view (d) If shafts were removed front view

6.4 Comparison With Existing Solutions

In 1.2 and 1.3 the current solutions are provided for removing the leaves of broccoli. Mainly selective harvesting solutions are provided for removing the leaves. Using sensors for crop detection or even to check size/ maturity. These ideas will be a more precise approach, where there will be less broccoli's destroyed. On the other hand, the machine will be much slower than a continuous solution. Again a trade-off is seen, now instead of a performance-destruction a speed-performance/destruction trade-off is shown. As for this machine, were speed is a vital part of the requirements, the selective harvesting will not be a sufficient solution.

Other existing solutions involve removing broccoli from the soil. This method makes the leaf removal part easier, however the retrieval from the soil harder. When the leaves are removed, there will be fewer obstructions that could hinder or even jam the harvest machine. In addition, extra steps are needed which will increase the cost and time of the whole process, decreasing the overall speed. These solutions are less efficient and would not be preferred over the current design.

The closest comparison that could be made is between the prototype that was built during this research and the beating mechanism shown in the patents. This is a continuous machine which uses "finger-

like" leaf strippers. Important differences are the dimensions and stiffness of the fingers. The smaller wires with flexible unravelled ends provide a more delicate solution in comparison to this other beating mechanism. These fingers will be too destructive for this application, with too little performance improvement over the current design.
There are a lot of patents that could be found regarding leaf removal of other crops, for example a tobacco stalk. These contain solutions that might work for broccoli as well, however it is important to cope with the certain characteristics of the crop. Furthermore, if leaves are the product instead of excess material, a different approach is often needed.
As these broccoli's have different characteristics, the existing solutions have a disadvantage as these are created for other characteristics.

6.5 Future Research

Recommendations for optimal use of the prototype have been given. In the ideal situation, a machine would be built which could be adjusted for these aspects. The possibility of adding different funnels, which are expected to be a very easy solution to positively improve the system. The frame and shafts negatively influence the results and should be replaced by less intrusive elements. Therefore, the best solution would be to have most of the items for stability above the broccoli's. Elements that are needed for the defoliation could be lowered within the rows.
The best would be to use the given recommendations as a guideline and carry out tests on the same day, in the same plot with the same variety. This could verify the given results with less noise/ variables. Something else that is also an important aspect that was not tested is the ground speed. This also affects the other variables, such as the rotation speed needed for a certain performance. An other addition could be looking into methods to preserve the florets. Other materials could be tested or even the more brush-like design as mentioned before.

7 Conclusion

The objective was to create a design that was capable of removing a large majority of the leaves of a certain new variety of broccoli. This variety is specified in Appendix D. A quantification of the results has been established by taking a percentage of leaves removed per section. The broccoli is divided into three equal parts with a top, middle and bottom section. Also, the amount of broccoli destroyed and the damage to the stem and floret have been taken into account. The design should have been able to remove 80 to 90% of the leaves, while moving with at least 1 km/h and destroyed no more than 10% of the broccoli's. A prototype has been created and optimised, which was able to defoliate the majority of this variety. The speed of 1 km/h was obtained, however other requirements have not been met.The best results were 77% for the top and 93% for the middle section, but it destroyed 31% of the product. An average result could be ensured for this machine at 60 % top and 80% for the middle section, with 20% of the broccoli's destroyed. This is not up to the standards constructed at the beginning of this development. Criteria such as minimalistic/flexible/robust design, continuousness and transportability have been met to a certain degree. The performance and destruction have not been acquired. The efficiency of removing leaves is insufficient, while the destructive aspect is excessive.

Despite taking into account an average of 15% that would not be mature enough for utilisation, the combined amount of destroyed products and those that are too damaged to be used is still too high, especially because these two categories have some overlapping products. A clear trade-off comes forward in the results between performance and destruction. There are exceptions; however, in most cases an increase in performance leads to an increase of destruction as well. Therefore, at the moment, the optimal balance is not yet available within the required destruction-performance region.

The prototype that was created has a simple design, which also makes it vulnerable to human errors. Slight changes during the tests, such as uneven pulling of the frame, could have a large influence. Elements are force-locked, including frame connections, which have the probability of parts moving when something vibrates loose. This is also a reminder of the design which was used for testing being a prototype. Aspects could be improved, where an actual machine would solve a lot of the problems. Alignment, adjustable speeds, funnels, getting rid of the frame and having minimal items at the height of the broccoli's would not only reduce the destruction, but also boost the performance.

Although not yet at the desired level, the current design has been optimized using the results of the tests. This differentiates when the system is being upgraded to a machine. At this stage, according to this research, the best way to defoliate this particular type of broccoli is by using metal wires. These metal wires are made of stainless steel and are woven by smaller wires. These operate best when the ends of these wires are unravelled. Using multiple (four) wires on each side of the broccoli, rotating inward and beating the leaves down from both sides. A wire of a thickness from 5-6 mm with a length of around 22 cm with unravelled ends works best. The space between these wires will be most optimal between 0-2.5 cm and work best with a rotation speed of around 1800-2000 rpm. These are optimised for a ground speed of 1 km/h and therefore a higher speed will alter the optimisations.

Further research is needed to improve the optimal balance between performance and destruction, but proof of concept has been acquired and a first step towards a broccoli leaf removal machine was made.

A Appendix A

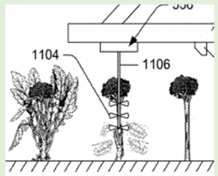
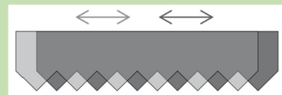
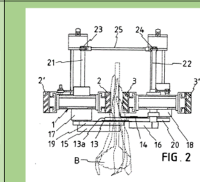
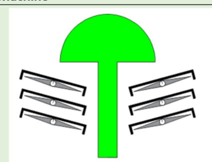
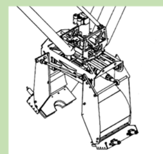
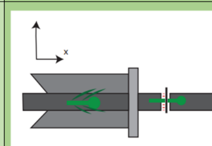
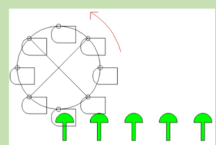
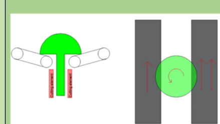
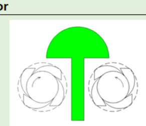
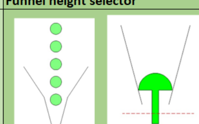
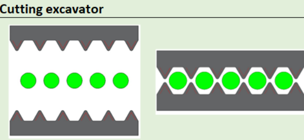
		Pre	Peri	Post
Cutting	Name	Patent: Selective Surrounding Knive *1	Reciprocating Adjustable Height	Patent: Upside Down Rotary *2
	Visualisation			
	Description	Shafts surrounding downward motion with knives	Reciprocating knive at adjustable heights	Hung upside down and cut on sides by rotary cutter
	Name	Shred Machine	Patent: Claw machine *3	Lee-Wen Solution *4
	Visualisation			
	Description	Rotating knife elements, protected by a guarding cover	A claw grabbing the broccoli from above, removing the floret from the stem. (with or without sensors)	On side on conveyor, gets measured by head and moves forward and cut at right position
	Name	Machine Company Idea	Floret Wheel	Conveyor Scythe
	Visualisation			
	Description	Classified	Ferris wheel with designated boxes for florets	On conveyor rotating and cutting elements (scythe-like) on both sides.
	Name	Smooth razor		Funnel height selector
	Visualisation			
	Description	Outside is smooth, inside has cutting edge. Leaves get stuck by sharp inner edge and outside only pushes stem a bit		Harvested broccoli's will come in by a funnel like conveyor which uses its design to hold a floret at different heights. A cutting element removes the stem with leaves
	Name	Cutting excavator		
	Visualisation			
	Description	Teeth closing with round edges to push in right holes. Move downward with potentially knive elements underneath. Then move up and uitward to drive forward to new crops		

Figure 64: Morphological overview with the ideas for a cutting mechanism given per moment in time of leaf removal (*1:[15] *2:[19] *3:[17] *4:[25])

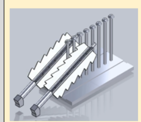
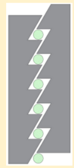
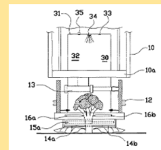
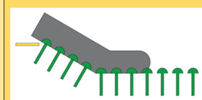
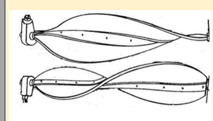
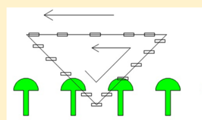
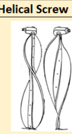
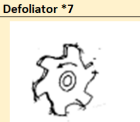
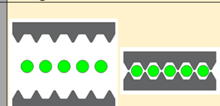
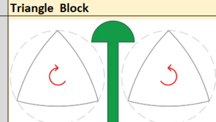
		Pre	Peri	Post
Pulling	Name	Fin Design	Push & Cut *5	Check Valve Conveyor
	Visualisation	 		
	Description	Rotating fins (Scalloped) pushing leaves down	Surrounding circumference and pulling down leaves while head is getting cut	Conveyor with designated check valves which takes in florets and pull them from the ground
	Name	Helical Screw *6		
	Visualisation			
	Description	Helical screw rotating to push down leaves		
	Name	Upside Down Triangle		
	Visualisation			
	Description	An upside down triangle design with equally spaced blocks which push down leaves. Relative speed is used		
	Name	Vertical Helical Screw *6		
	Visualisation			
	Description	Vertical spirals pushing down leaves. Stems are getting pushed aside a bit. So no sharp edges. The lead will be shorter then the figure		
	Name	Gear Defoliator *7		
	Visualisation			
	Description	Gear-like defoliator, with large tooth grabbing and removing leaves		
	Name	Pulling Excavator		
	Visualisation			
	Description	Teeth closing with round edges to push in right holes. Move downward, then move up and uitward to drive forward to new crops		
	Name	Triangle Block		
	Visualisation			
	Description	Continuously slowly rotating against stem and removing leaves in the process		

Figure 65: Morphological overview with the ideas for a pulling mechanism given per moment in time of leaf removal (*5:[16] *6:[30] *7:[31])

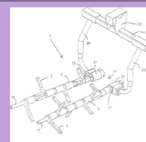
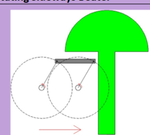
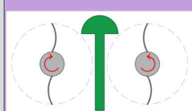
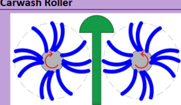
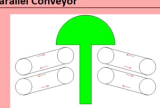
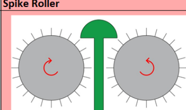
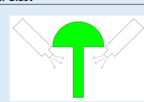
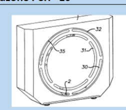
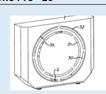
		Pre	Peri	Post
Beating	Name	**Patent: Arm Beater *8**		**Patent: Conveyor Side Beater *9**
	Visualisation			
	Description	Longitudional shaft with rotating arms		On conveyor belt rotating and beating elements next to stem
	Name	**Rotating Sideways Beater**		
	Visualisation			
	Description	Rotating downward pushing shafts, rotates backwards as machine moving forward. Relative speed used		
	Name	**Metal Wire**		
	Visualisation			
	Description	Grass trimmer that destroys leaves, but only damages stem of broccoli		
	Name	**Carwash Roller**		
	Visualisation			
	Description	Carwash rollers to beat off leaves		
Rolling	Name	**Parallel Conveyor**		
	Visualisation			
	Description	Parallel placed conveyors with a little bit room to get leaves and pull them off		
	Name	**Spike Roller**		
	Visualisation			
	Description	Roller with spikes, where spikes grab onto leaves		
Air	Name	**Air Blast**	**Deadzone Peri *10**	
	Visualisation			
	Description	Air valves shooting blasts of air onto leaves	Rotating nozzles creating deadzone in the middle	
	Name	**Deadzone Pre *10**		
	Visualisation			
	Description	Rotating nozzles creating deadzone in the middle		

Figure 66: Morphological overview with the ideas for beating, rolling and air mechanisms given per moment in time of leaf removal(*8:[14] *9:[18] *10:[32])

B Appendix B

Patent: Selective Surrounding Knive					
Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	5	45
- Beds	7	Poor	Good	4	28
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	1	8
Continuousness	6	Erratic	Ongoing	1	6
Destructiveness	7	Destructive	Delicate	3	21
					148
Design	50	-	-		
Robustness	7	Fragile	Robust	2	14
Simplicity	7	Complicated	Simple	1	7
Safety	6	Unsafe	Very safe	4	24
Transportability	7	Hard	Easy	4	28
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	2	8
					127
				Total	275

(a)

Shred Machine					
Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	3	27
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	4	32
Continuousness	6	Erratic	Ongoing	4	24
Destructiveness	7	Destructive	Delicate	2	14
					158
Design	50	-	-		
Robustness	7	Fragile	Robust	2	14
Simplicity	7	Complicated	Simple	2	14
Safety	6	Unsafe	Very safe	1	6
Transportability	7	Hard	Easy	2	14
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	2	8
					102
				Total	260

(b)

Machine Company Idea					
Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	2	18
- Beds	7	Poor	Good	4	28
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	4	32
Continuousness	6	Erratic	Ongoing	4	24
Destructiveness	7	Destructive	Delicate	1	7
					149
Design	50	-	-		
Robustness	7	Fragile	Robust	4	28
Simplicity	7	Complicated	Simple	4	28
Safety	6	Unsafe	Very safe	2	12
Transportability	7	Hard	Easy	4	28
Operating-sufficiency	6	Poor	Very	4	24
Cost-Performance Ratio	8	Bad	Good	4	32
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	4	16
					183
				Total	332

(c)

Smooth Razor					
Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	3	27
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	2	20
Speed	8	Slow	Fast	3	24
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	3	21
					131
Design	50	-	-		
Robustness	7	Fragile	Robust	4	28
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	3	21
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	2	8
					153
				Total	284

(d)

Figure 67: Grading of ideas from Morphological Overview, in cutting mechanism for pre moment of leaf removal
(a) Patent: Selective Surrounding Knive (b) Shred Machine (c) Machine Company Idea (d) Smooth Razor

Cutting Excavator					
Criteria	Weightage (1-10)	Ranking 1	5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	2	18
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	3	30
Speed	8	Slow	Fast	2	16
Continuousness	6	Erratic	Ongoing	2	12
Destructiveness	7	Destructive	Delicate	3	21
					118
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	2	12
Transportability	7	Hard	Easy	2	14
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	3	12
					131
				Total	249

(a)

Reciprocating Adjustable Height					
Criteria	Weightage (1-10)	Ranking 1	5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	2	18
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	4	32
Continuousness	6	Erratic	Ongoing	4	24
Destructiveness	7	Destructive	Delicate	2	14
					149
Design	50	-	-		
Robustness	7	Fragile	Robust	2	14
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	1	6
Transportability	7	Hard	Easy	3	21
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	3	12
					126
				Total	275

(b)

Claw machine					
Criteria	Weightage (1-10)	Ranking 1	5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	4	36
- Beds	7	Poor	Good	4	28
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	1	8
Continuousness	6	Erratic	Ongoing	1	6
Destructiveness	7	Destructive	Delicate	3	21
					139
Design	50	-	-		
Robustness	7	Fragile	Robust	2	14
Simplicity	7	Complicated	Simple	2	14
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	3	21
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	2	16
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	2	8
					113
				Total	252

(c)

Floret Wheel					
Criteria	Weightage (1-10)	Ranking 1	5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	2	18
- Beds	7	Poor	Good	2	14
Reliability	10	Low	High	2	20
Speed	8	Slow	Fast	3	24
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	3	21
					115
Design	50	-	-		
Robustness	7	Fragile	Robust	2	14
Simplicity	7	Complicated	Simple	2	14
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	2	14
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	2	16
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	2	8
					106
				Total	221

(d)

Figure 68: Grading of ideas from Morphological Overview, in cutting mechanism for pre/peri moment of leaf removal
(a) Cutting Excavator (b) Reciprocating Adjustable Height (c) Claw Machine (d) Floret Wheel

Patent: Upside Down Rotary					
Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	5	45
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	1	8
Continuousness	6	Erratic	Ongoing	1	6
Destructiveness	7	Destructive	Delicate	3	21
					141
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	1	7
Safety	6	Unsafe	Very safe	4	24
Transportability	7	Hard	Easy	2	14
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	2	8
					120
				Total	261

(a)

Lee-Wen Solution					
Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	4	36
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	1	8
Continuousness	6	Erratic	Ongoing	1	6
Destructiveness	7	Destructive	Delicate	4	28
					139
Design	50	-	-		
Robustness	7	Fragile	Robust	4	28
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	2	14
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	2	16
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	3	12
					142
				Total	281

(b)

Conveyor Scythe					
Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	3	27
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	2	16
Continuousness	6	Erratic	Ongoing	2	12
Destructiveness	7	Destructive	Delicate	3	21
					137
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	4	24
Transportability	7	Hard	Easy	2	14
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	2	16
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	3	12
					135
				Total	272

(c)

Funnel Height Selector					
Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	4	36
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	3	30
Speed	8	Slow	Fast	2	16
Continuousness	6	Erratic	Ongoing	1	6
Destructiveness	7	Destructive	Delicate	3	21
					130
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	2	14
Safety	6	Unsafe	Very safe	4	24
Transportability	7	Hard	Easy	2	14
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	3	12
					136
				Total	266

(d)

Figure 69: Grading of ideas from Morphological Overview, in cutting mechanism for post moment of leaf removal
(a) Patent: Upside Down Rotary (b) Lee-Wen Solution (c) Conveyor Scythe (d) Funnel Height Selector

Fin Design					
Criteria	Weightage (1-10)	Ranking 1	5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	4	36
- Beds	7	Poor	Good	4	28
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	3	24
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	4	28
					174
Design	50	-	-		
Robustness	7	Fragile	Robust	4	28
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	3	21
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	4	32
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	4	16
					169
				Total	343

(a)

Helical Screw					
Criteria	Weightage (1-10)	Ranking 1	5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	4	36
- Beds	7	Poor	Good	4	28
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	3	24
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	3	21
					167
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	3	21
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	4	32
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	3	12
					158
				Total	325

(b)

Upside Down Triangle					
Criteria	Weightage (1-10)	Ranking 1	5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	3	27
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	3	30
Speed	8	Slow	Fast	2	16
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	2	14
					126
Design	50	-	-		
Robustness	7	Fragile	Robust	2	14
Simplicity	7	Complicated	Simple	2	14
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	2	14
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	2	8
					114
				Total	240

(c)

Vertical Helical Screw					
Criteria	Weightage (1-10)	Ranking 1	5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	3	27
- Beds	7	Poor	Good	4	28
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	3	24
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	3	21
					158
Design	50	-	-		
Robustness	7	Fragile	Robust	4	28
Simplicity	7	Complicated	Simple	4	28
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	3	21
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	4	32
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	3	12
					172
				Total	330

(d)

Figure 70: Grading of ideas from Morphological Overview, in pulling mechanism for pre moment of leaf removal
(a) Fin Design (b) Helical Screw (c) Upside Down Triangle (d) Vertical Helical Screw

Gear Defoliator					
Criteria	Weightage	Ranking		Score	Weighted
	(1-10)	1	5		Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	3	27
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	2	20
Speed	8	Slow	Fast	3	24
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	2	14
					124
Design	50	-	-		
Robustness	7	Fragile	Robust	4	28
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	3	21
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	3	12
					157
				Total	281

(a)

Pulling Excavator					
Criteria	Weightage	Ranking		Score	Weighted
	(1-10)	1	5		Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	2	18
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	3	30
Speed	8	Slow	Fast	2	16
Continuousness	6	Erratic	Ongoing	2	12
Destructiveness	7	Destructive	Delicate	3	21
					118
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	3	21
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	3	12
					144
				Total	262

(b)

Triangle Block					
Criteria	Weightage	Ranking		Score	Weighted
	(1-10)	1	5		Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	3	27
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	2	20
Speed	8	Slow	Fast	3	24
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	3	21
					131
Design	50	-	-		
Robustness	7	Fragile	Robust	5	35
Simplicity	7	Complicated	Simple	4	28
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	3	21
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	2	16
Maintenance	5	Much	Little	4	20
Manufacturability	4	Hard	Easy	4	16
					172
				Total	303

(c)

Push & Cut					
Criteria	Weightage	Ranking		Score	Weighted
	(1-10)	1	5		Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	5	45
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	5	50
Speed	8	Slow	Fast	1	8
Continuousness	6	Erratic	Ongoing	1	6
Destructiveness	7	Destructive	Delicate	4	28
					158
Design	50	-	-		
Robustness	7	Fragile	Robust	2	14
Simplicity	7	Complicated	Simple	2	14
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	2	14
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	2	8
					114
				Total	272

(d)

Check Valve Conveyor					
Criteria	Weightage	Ranking		Score	Weighted
	(1-10)	1	5		Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	2	18
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	2	20
Speed	8	Slow	Fast	2	16
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	3	21
					114
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	3	21
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	2	16
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	3	12
					136
				Total	250

(e)

Figure 71: Grading of ideas from Morphological Overview, in pulling mechanism for pre/peri/post moment of leaf removal
(a) Gear Defoliator (b) Pulling Excavator (c) Triangle Block (d) Push & Cut (e) Check Valve Conveyor

Patent: Arm Beater

Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	3	27
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	3	24
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	2	14
					144
Design	50	-	-		
Robustness	7	Fragile	Robust	2	14
Simplicity	7	Complicated	Simple	4	28
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	2	14
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	4	32
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	2	8
					147
				Total	291

(a)

Rotating Sideways Beater

Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	2	18
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	3	30
Speed	8	Slow	Fast	2	16
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	3	21
					124
Design	50	-	-		
Robustness	7	Fragile	Robust	2	14
Simplicity	7	Complicated	Simple	4	28
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	3	21
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	4	16
					149
				Total	273

(b)

Metal Wire

Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	3	27
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	4	32
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	2	14
					152
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	4	28
Safety	6	Unsafe	Very safe	2	12
Transportability	7	Hard	Easy	4	28
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	4	32
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	4	16
					170
				Total	322

(c)

Carwash Roller

Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	3	27
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	3	30
Speed	8	Slow	Fast	3	24
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	4	28
					148
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	4	28
Safety	6	Unsafe	Very safe	4	24
Transportability	7	Hard	Easy	3	21
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	4	16
					167
				Total	315

(d)

Patent: Conveyor Side Beater

Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	4	36
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	4	40
Speed	8	Slow	Fast	2	16
Continuousness	6	Erratic	Ongoing	2	12
Destructiveness	7	Destructive	Delicate	3	21
					146
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	2	14
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	3	15
Manufacturability	4	Hard	Easy	3	12
					137
				Total	283

(e)

Figure 72: Grading of ideas from Morphological Overview, in beating mechanism for pre/post moment of leaf removal
(a) Patent: Arm Beater (b) Rotating Sideways Beater (c) Metal Wire (d) Carwash Roller (e) Patent: Conveyor Side Beater

Parallel Conveyor

Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	2	18
- Beds	7	Poor	Good	2	14
Reliability	10	Low	High	2	20
Speed	8	Slow	Fast	2	16
Continuousness	6	Erratic	Ongoing	2	12
Destructiveness	7	Destructive	Delicate	2	14
					94
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	2	14
Safety	6	Unsafe	Very safe	3	18
Transportability	7	Hard	Easy	2	14
Operating-sufficiency	6	Poor	Very	2	12
Cost-Performance Ratio	8	Bad	Good	2	16
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	2	8
					113
				Total	207

(a)

Spike Roller

Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	3	27
- Beds	7	Poor	Good	3	21
Reliability	10	Low	High	3	30
Speed	8	Slow	Fast	3	24
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	2	14
					134
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	2	12
Transportability	7	Hard	Easy	3	21
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	3	12
					139
				Total	273

(b)

Air Blast

Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	4	36
- Beds	7	Poor	Good	4	28
Reliability	10	Low	High	3	30
Speed	8	Slow	Fast	2	16
Continuousness	6	Erratic	Ongoing	3	18
Destructiveness	7	Destructive	Delicate	3	21
					149
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	4	24
Transportability	7	Hard	Easy	4	28
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	2	8
					154
				Total	303

(c)

Deadzone Pre

Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	4	36
- Beds	7	Poor	Good	4	28
Reliability	10	Low	High	3	30
Speed	8	Slow	Fast	2	16
Continuousness	6	Erratic	Ongoing	2	12
Destructiveness	7	Destructive	Delicate	3	21
					143
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	4	24
Transportability	7	Hard	Easy	4	28
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	2	8
					154
				Total	297

(d)

Deadzone Peri

Criteria	Weightage (1-10)	Ranking 1	Ranking 5	Score	Weighted Score
Performance	47	-	-		
Ajustability		-	-		
- Plant height	9	Poor	Good	4	36
- Beds	7	Poor	Good	4	28
Reliability	10	Low	High	3	30
Speed	8	Slow	Fast	2	16
Continuousness	6	Erratic	Ongoing	2	12
Destructiveness	7	Destructive	Delicate	3	21
					143
Design	50	-	-		
Robustness	7	Fragile	Robust	3	21
Simplicity	7	Complicated	Simple	3	21
Safety	6	Unsafe	Very safe	4	24
Transportability	7	Hard	Easy	4	28
Operating-sufficiency	6	Poor	Very	3	18
Cost-Performance Ratio	8	Bad	Good	3	24
Maintenance	5	Much	Little	2	10
Manufacturability	4	Hard	Easy	2	8
					154
				Total	297

(e)

Figure 73: Grading of ideas from Morphological Overview, in rolling/air mechanism for pre/peri moment of leaf removal
(a) Parallel Conveyor (b) Spike Roller (c) Air Blast (d) Deadzone Pre (e) Deadzone Peri

C Appendix C

The Destroy Factor is the number that will be given to each broccoli which is not completely destroyed. Figure 74 is the representation of the list given below. On the left, a completely destroyed broccoli is given, which is named 0 in the list below. These broccoli's will NOT be included in the Destroy Factor, but they will be added to the percentage destroyed.

0. Completely destroyed
1. Fully good / very little damage
2. Barely any damage
3. Stem somewhat damaged, rest is fine
4. Some damage close to the higher part of the stem, but floret is OK
5. Some damage and very little damage to floret
6. Some damage to floret
7. Damages to floret
8. Significant damage to floret
9. Very damaged floret
10. Floret (almost) completely destroyed

Figure 74: Representation of the Destroy Factor, going from 0 to 10

D Appendix D

This appendix is confidential and is not public.

E Appendix E

This appendix is confidential and is not public.

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