University of Strathclyde

Mechanical and Aerospace Engineering

ME519 Group Project

Enhancement of Forestry Tree Planting Machine

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Report Submitted: 21st March 2016

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Abstract

A team of 5th year Mechanical Engineering students were tasked with designing a new best in class mechanical tree planter. Working alongside a simulation company called Simultech, the group must produce a full Computer Aided Design (CAD) model of their chosen design. Simultech intend to use the CAD model to create a simulation programme for training purposes.

Roles were allocated to each member of the team, based on strengths working in a group environment. A detailed project plan was created leading to a contract being agreed between the team, Simultech and the academic advisor. A critical analysis was conducted on current planting methods used in Scotland, as well as other forestry equipment and related areas of interest. The critical analysis allowed a product design specification to be produced and this was presented and accepted by Simultech and the academic advisor.

As part of the critical analysis, and in order to gain a better understanding of the industry, the team completed several site visits. The visits consisted of meetings with people working in the forestry industry and viewing forestry equipment. Some of the site visits have been to other heavy engineering industries in order to gain a better understanding of things such as hydraulic systems. The critical analysis enabled the team to gain a solid understanding of the forestry industry and currently available planting machinery.

As a result of the critical analysis, the decision was made to base the design on improving the current Bracke P11a planter. The mound quality and the reduction of manual sapling loading time were identified as the areas where significant improvement was needed. Conceptual designs were produced to solve each problem with many different options considered. The group designed a new scarification blade for the Bracke. The blade incorporates a serrated leading edge and trapezoidal blade shape that provides better soil containment and compaction. A fast loading system has been designed to allow all the tree saplings to be loaded simultaneously. These new designs reduced machine downtime for loading as well as increasing mound quality which leads to greater survival rates. A 3D CAD model of the original Bracke P11.a and the new planting machine were produced for comparison.

Acknowledgements

The group wish to extend great appreciation to Professor David Nash for advising the project and Mr William McArthur from Simultech Scotland for providing endless support over the project duration. Further, the group wish to acknowledge the following persons and companies for accommodating visits and providing assistance in their respective areas of expertise:

- Andrew Campbell – ScotJCB
- Mick Bottomley – BSW Timber Group
- Jock McKie – John Deere Forestry
- Bill Jones and James Hand – Forestry Commission Scotland
- Aileen Gray and Neil Watson– Simultech Scotland
- Rafael Martínez – Universidad de Valencia
- Malcolm Harris – Hytec Hydraulics
- Brian McCamon and staff – Christie Elite Nurseries
- Jas P Wilson
- Edinburgh Trams
- Bracke Forest
- ECM Vehicle Movers
- Helac Inc.
- Enterprise Rent-A-Car
- William Clark – Clark Engineering
- Jose González Pérez – Universidad de Oviedo (EPI Gijón)
- Jill Hodge – Trees for Life
- Jake Williams – Bogancloch
- Peter Livingstone – Eadha Enterprises

- Chris Cameron – University of Strathclyde MAE Department
- MAE Administration Staff – University of Strathclyde
- MAE Stores – University of Strathclyde

Contents

Nomenclature

L_{c1}	Blade cylinder buckling length (m)
A_{c1}	Blade cylinder piston area (m^2)
d_{c1}	Blade cylinder piston rod diameter (m)
P_{c1}	Blade cylinder pressure (bar)
A_{bolt}	Bolt area (mm^2)
F_B	Breakout force (N)
F_L	Buckling force (N)
K	Buckling load (N)
F_c	Compaction test applied load (N)
W_c	Compaction test soil mass (kg)
L_{c2}	Dibble cylinder buckling length (m)
A_{c2}	Dibble cylinder piston area (m^2)
d_{c2}	Dibble cylinder piston diameter (m)
P_{c2}	Dibble cylinder pressure (bar)
D_B	Dipper cylinder diameter (m)
η_{total}	Efficiency of hydraulic pump
p, W_{max}	Excavator power (kW)
P	Excavator pump pressure (bar)
S	Factor of safety
Q	Flowrate (L/min)
F_{bolt}	Force on bolt (N)
g	Gravitational acceleration (m/s^2)
P_g	Ground Pressure (bar)
d_{handle}	Handle length (m)
$M_{sapling}$	Individual sapling mass (kg)
J	Inertia of rod cross-section (m^4)
M_s	Mass of soil (kg)
D_{max}, D_{min}	Maximum and minimum bolt diameter (mm)
n	Number of saplings
F_{pawl}	Pawl Force (N)
F_f	Plate friction force (N)
d	Plate pitch circle diameter (m)
T	Plate torque (Nm)
A, B, C, D_D	Respective excavator dimensions (m)
τ	Shear force at bolt (MPa)
μ_s	Soil resistance factor
P	Thread pitch (mm)
$m_{saplingtotal}$	Total mass of saplings (kg)
L_{track}	Track level (m)
R_{track}	Track shoe width (m)
$F_{applied}$	Turning force (N)
V_s	Volume of soil (m^3)
W_s	Weight of soil (N)
W_L	Wheel load (kg)
E	Young’s Modulus (GPa)

1.0 Project Definition

1.1 Task Outline

As part of technological development in forestry machinery, this 5th year group project aimed to improve existing mechanical tree planting machines in use in Scottish forests. In 2013, approximately 7.1 million tonnes of round wood was harvested in Scotland [1]. Studies have shown that this harvesting rate far exceeds the rate of tree planting [2]. The differences in these rates leads to a defecit in the forestry stock required for future harvesting. Despite the majority of forestry operations experiencing a mechanical overhaul many decades ago, planting continues to be tackled in a predominantly manual fashion. With only three active mechanical planting machines operating in Scotland manual planting still dominates. Mechanical planting does boast a rich history, but designs are not considered fit for purpose or, in most cases, not cost effective enough to challenge manual planting. The challenges facing mechanical are greater than simply cost. In Scotland, the planting environment is a particular challenge, with steep inclines and soft marshlands a common occurance.

Craobh planting, derived from Scottish Gaelic to mean “tree”, consists of five Mechanical Engineering students working as consultants to deliver a series of objectives as part of a Master’s degree project. The main basis includes understanding current designs, particularly their issues, and identifying improvements, before developing these ideas in a series of CAD analyses and finally implementing a 3D CAD model capable of being taken forward into simulation.

As part of the project the group has been partnered with a simulation company. The industry representative from Simultech Scotland is Mr William McArthur. Simultech Scotland is a small enterprising company that provides simulation solutions and training predominantly in the engineering sector. Beyond the final outcome of developing a planting machine that betters existing designs, Simultech Scotland aim to create a simulation from the CAD model. The simulation will be used to train new operators in the safe workings of the machine, before using the real machine. The academic representative for the group project is Professor David Nash.

1.2 Contract

Before the project began an initial contract was drawn up outlining the project objectives and stipulating the obligations of the consultants and the clients. From the consultants, these included ensuring that all objectives and project requirements were met within the specified time. The following objectives were discussed and finalised with Professor Nash and William McArthur.

- Present a critical analysis of current machinery, the industry in which they operate and the planting environment.
- Define the requirements of a new design.
- Generate concepts that adhere to agreed design requirements and produce a detailed design of the chosen concept.
- Produce a CAD model showing the components of the final design and conduct Finite Element Analyses (FEA) on selected features of the final design to highlight its operational compatibility and identify possible areas of weakness.
- Compile an overall design package for handover to Simultech to continue the project into a simulation phase.

- Create a website to document and display the project.
- Over the course of the project, meet deadlines for various technical papers, overall project report and attend assessments.

Alongside this agreement, one critical obligation requested of the clients was ensuring adequate resources were available over the project course. This would include facilitating meetings, ensuring the budget was suitable to the project objectives and facilitating outside industry visits amongst others. Further to this, the contract also outlined potential resources that would be used to enhance the project and the roles that group members would adopt throughout the project duration.

The contract was also used by the group to identify the projects major phases and the resources that would be required to complete each task. Flexibility of phase completion was outlined in the document to allow the group to react proactively to any unforeseen situations that may arise throughout the project but still ensure that deadlines were met.

2.0 Project Business

2.1 Team Management and Structure

To successfully complete any project it is essential to outline objectives and set in place a clear plan of how to meet these objectives. It was decided that the most efficient way to ensure objectives would be met was to assign each team member a specific role. A successful and efficient team will be made up of a number of different roles, most people will have certain roles that they are suited to and other roles they are not comfortable with or capable of. Identifying the most effective roles for everyone was crucial to the success of the project. To help define roles each group member filled out a Belbin Self Perception Inventory [3]. The Belbin test was designed to highlight which team role best suits each member. The test was made up of eight sections; each section illustrated a different situation you might encounter in a team project, followed by a number of different reactions that may be typical of the correspondent. With a maximum score of ten for each section, the correspondent distributed this score across the options they felt were most applicable to them. The score for each section was then tabulated and these scores for each section identified the most suitable role for the each individual. To ensure the most effective group, it was important to understand the strengths and weaknesses of each individual. Using the Belbin inventory allows roles to be selected based upon competence with a view to ensuring the group has a broad range of skill sets. The roles given in the Belbin test were; chairman, shaper, company worker, completer finisher, team worker, plant, resource investigator and monitor evaluator. The results of each team member are shown in Table 1.

Table 1: Belbin result and team roles

Group Member	Belbin Test Result	Team Role
Kirk	Chairman/Shaper	Head of Communications
Graeme	Completer Finisher/ Shaper	Head of Product Design
Isabel	Company Worker/ Completer Finisher	Head of CAD
Fraser	Company Worker/ Completer Finisher	Head of Reporting
Kazuki	Team Worker/ Completer finisher	Head of Critical Analysis and Initial Research

Table 1 shows the primary and secondary roles each member obtained. Using these results as a guideline, specific roles were allocated. As a team it was decided that the most efficient way to assign roles was to base them on the needs of the project and certain mile stones that needed to be met. A head of communications was needed in order to simplify communications with our supervisor and industrial contact. The main roles of the Head of Communications include; arranging meetings with supervisor and industrial contact, relaying progress reports to supervisor and industrial contact, contacting companies in industry to arrange site visits, contact professionals in industry to gain information. A Head of Reporting was seen as a vital role to ensure the reports were written in a consistent fashion and to ensure on time delivery. The project itself was divided into three main sections based on the agreed objectives. In order to ensure that each section was completed fully and on time the group decided to have a team member in charge of each section. The main roles of the Head of Critical analysis were; to divide up the research sections, and ensure that each team member completed their section in appropriate detail. The Head of CAD was in charge of most of the 3D modelling and ensuring all parts made by other members were done so on time and assembled correctly. The final role was the Head of Design, this person laid out a clear design process and ensured it is carried out by the team members. The group identified that when the Belbin test was repeated the results could be very different to previous attempts. It was decided that roles also be allocated based upon competence in different fields and previous experience. Below are the roles that were assigned to each group member:

Kirk: Allocated the role of Head of Communications because results revealed him to be a chairman and shaper, he also has previous leadership experience from sport and summer jobs. Belbin defines a shaper as someone that can provide the drive to keep the team moving [3].

Graeme: Given the role of Head of Design based on his Belbin result as a completer finisher and a shaper. Graeme's previous experience as an architecture student was also a deciding factor. As a completer finisher, Graeme was very effective at the end of tasks to polish and scrutinise errors, ensuring that the highest standards were maintained [3].

Isabel: Isabel displayed the attributes of a good company worker and completer finisher. She has previous expertise in CAD, this is the reason she was assigned the Head of CAD. Her strengths as a completer finisher was vital when producing a detailed 3D model.

Fraser: Given Fraser's results as a company worker and completer finisher, it was decided that the role of Head of Reporting would be a perfect fit. Fraser showed a keen eye for detail, and strived to ensure that all tasks were completed on time.

Kazuki: As a good team worker who likes to make sure everything gets completed, it was decided that managing the initial research and critical analysis phase of the project was the most suitable role. Another major factor in designating this role for Kazuki was the fact that he was only a member of the group for the first semester.

A number of the group members showed the same strength of being a completer finisher, Belbin warns that completer finishers can worry about things unnecessarily, and be reluctant to delegate [3]. This was something that the group had been aware of and attempted to prevent becoming a problem. Although everyone was given specific roles to focus on, it was agreed that each group member had an active role throughout every phase of the project. In order to organise group meetings a Facebook page was created, as well as a group chat. Facebook was deemed the easiest way to communicate as all members had access to it from their phones, allowing messages to be relayed quickly and easily. The final team structure is illustrated in Figure 1.

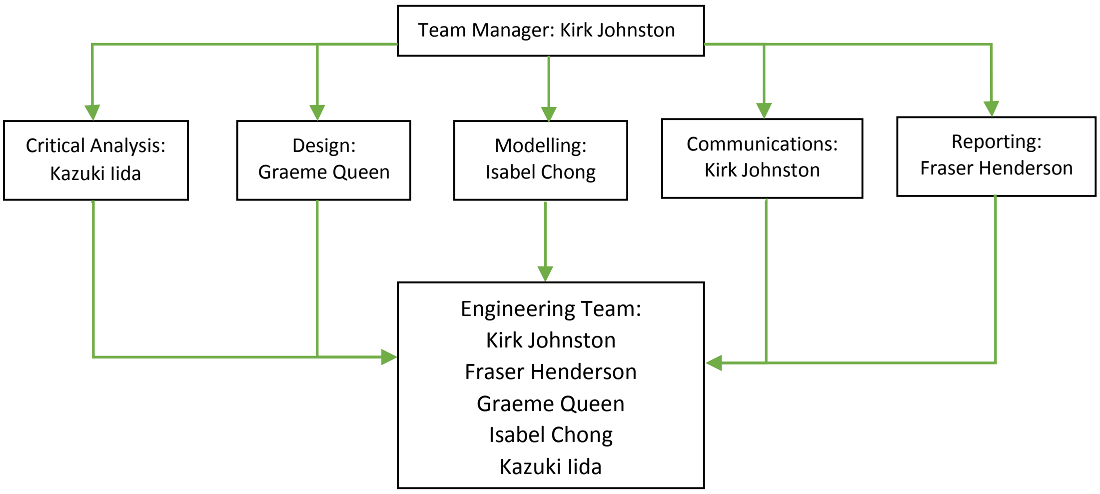


Figure 1: Team structure.

2.2 Stage Gate Process

To ensure that the project progressed as required, the group decided to employ the stage gate process. The stage gate process was made up of a combination of stages and gates. Each stage had a set of specific activities and the gates acted as checkpoints to decide whether the stage had been completed to specification or not. The stage gate process is shown in Figure 2 and Figure 3.

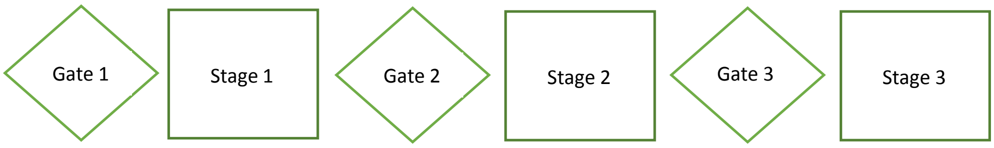


Figure 2: General Stage Gate Process.

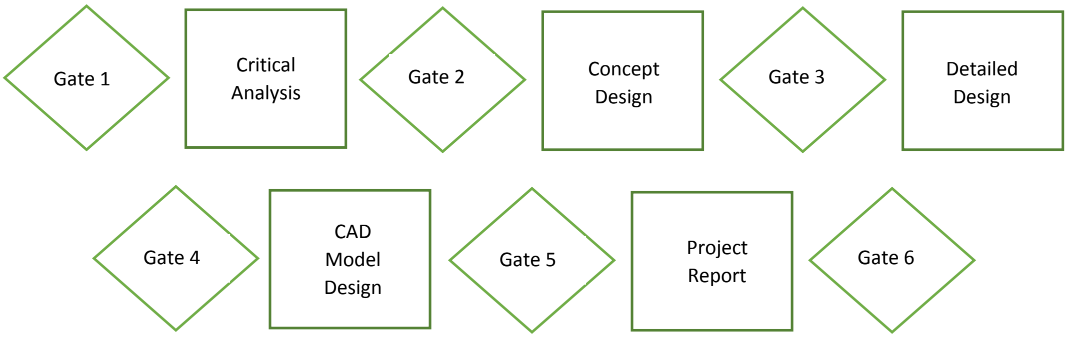


Figure 3: Specific Stage Gate Process.

At each gate an assessment was made to determine if a stage had been satisfactorily finished or not. This assessment was made either by the gate keeper/manager of each stage or in agreement with the key project stakeholders. The gate was also used as an opportunity to outline the requirements of the next stage and tasks to be completed. The group agreed to use a coding system to represent the decisions made at each gate. These are outlined below:

Code 1: All tasks have been completed to specification and assessor's satisfaction, and thus project can progress to next stage as planned.

Code 2: Some tasks have not been completed to specification or assessor's satisfaction, but agreement has been reached on amendments. Project can progress to next planned stage with amendments incorporated.

Code 3: Some tasks have not been completed to specification or assessor's satisfaction, thus previous stage must be revisited and revised.

The group decided on four stages for the project and assigned a gate keeper for each stage. The first three stages were based on the major project sections. These were decided when assigning team roles. Stage One was the critical analysis and initial research. As head of this section Kazuki was also selected as the gatekeeper. Stage Two was defined as the design process/development of a final design, Graeme was chosen as the gate keeper as he was the Head of Design. In Stage Three the 3D model of the final design was produced, and as Head of CAD, Isabel was the gate keeper for Stage Three. The fourth and final stage was the final report production. This section was an ongoing development throughout the project but was not completed until stages one to three were passed. As Head of Reporting, Fraser was the gatekeeper and ensured the report was finished to an appropriate standard.

The group also used the gates as an opportunity to get feedback from Prof Nash and Mr McArthur. Meetings were arranged to coincide with each gate. Gate One was on the 6th of November to determine whether the critical analysis stage was complete or not. Gate Two was on the 5th of February; this was led by Graeme as the Head of the Design process. Gate

Three was on the 5th of March; this review was led by Isabel. The final gate was conducted on the 19th of March, a few days before the project deadline, allowing time for any final changes to the report.

2.3 Communication

To ensure smooth project operation and efficient time management, communication was vital, both internally amongst group members and externally with Prof Nash, Mr McArthur and other parties.

2.3.1 Internal Communication

To maintain constant communication throughout the group, a Facebook page was created for uploading documents and progress updates. This was a vital link for communication where documents could be quickly distributed amongst everyone and a response obtained without meeting in person. A group chat was also created for organising meetings and delegating tasks where time is short. These communication methods ensured the group communicated efficiently and effectively.

2.3.2 External Communication

Beyond communicating internally as a group, working with Mr McArthur meant ensuring the group had a clear and constant communication link with him. This was achieved by having a Head of Communications focussing on communicating with external parties. Externally, the primary communication method was email. Sending and receiving emails from one address over the entire project duration was utilised by the group as a good method of ensuring no vital information or documentation was lost. Communicating with the project supervisor, Prof Nash, was also accomplished via email, providing updates on project progress and to arrange meetings between all parties as and when required.

2.4 Media Presence

As an academic requirement, a website was created to explain the group projects aims, scope and outcomes to outside parties. Website development was set aside as a task for semester two when all the critical analysis was accomplished and a final design for the model was developed. After researching different web editors www.wix.com was chosen due to its simplicity. This web editor offered the possibility of creating a website using HTML5 and mobile phone version. A screenshot of the website can be seen in Figure 4.

The website contains a visual representation of the whole project. It was divided into four main sections, namely Project Management, Project Design, Visits and Acknowledgement.

Since the second part of this project consisted of designing a fully functional CAD model of the planting machine, the website allows a video of the model to be displayed. It provides a place to share the group's final work with all industrial and academic contacts and to thank them for their time and contribution. The development of the website was split between all group members. Every member had a different role within its creation.

Isabel was in charge of modifying the chosen template and putting all the parts together, further to editing the project design section along with Graeme. Fraser and Kirk compiled the visits and acknowledgement sections and provided help with the project design section.

To visit the craobh planting website use the following link: www.craobhplanting.wix.com/craobhplanting

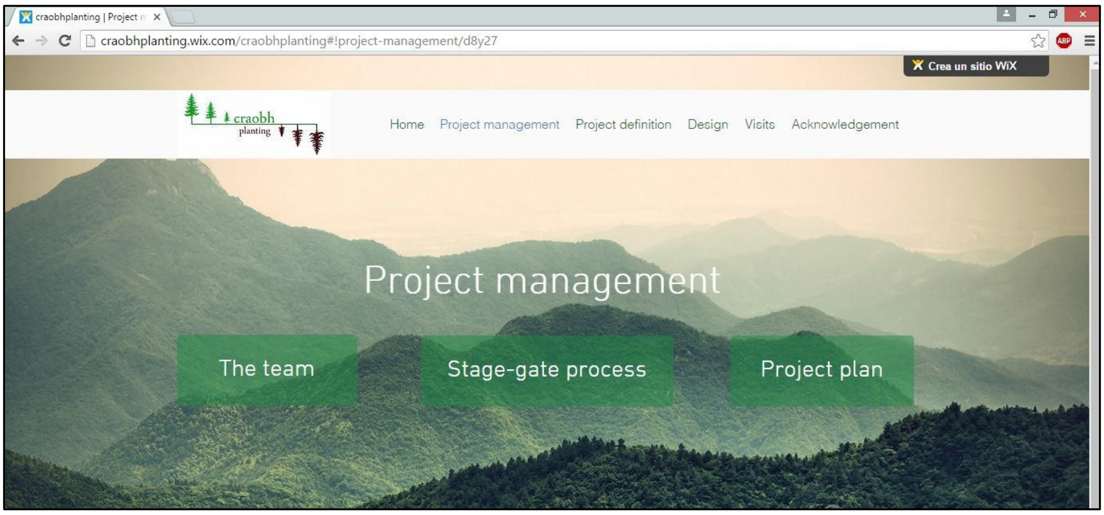


Figure 4: Screenshot of website.

A Facebook page and Twitter account were also created. These social media sites provide a communication means to outside parties. Figure 5 shows screenshots of the social media pages developed.

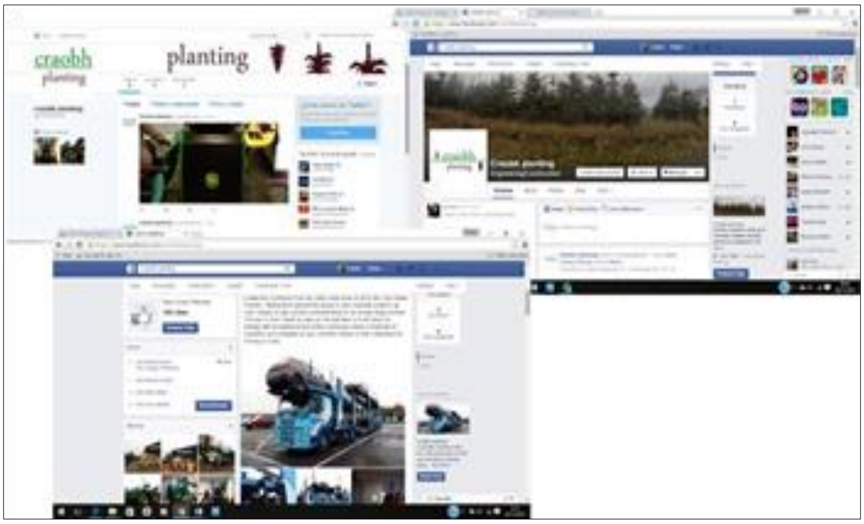


Figure 5: Screenshots of Facebook and Twitter pages.

2.5 Finance

At the beginning of the project, a budget of £100 per group member was allocated, providing an overall total of £500 to be distributed and used accordingly on resources. From initial meetings, it was decided that the nature of the project meant procurement of resources initially would not be required. As a design exercise there was no need for a finance director. In the end, an Excel spreadsheet was created and made available to all group members to make amendments to where appropriate.

The greatest expenses were found to occur in the earlier stages of the project. The group conducted a thorough critical analysis to develop a greater understanding of the forestry industry and existing equipment used in the harvesting and replanting of trees. It was also a time for the group to focus on the fundamentals of how these machines work using knowledge from previous class experience and the knowledge of industry experts. With the help of Mr McArthur, the group organised a wide range of meetings and industry visits. These all required travel and as such, expenses were claimed back from the university through the group budget. An outline of all travel expenditure for the project can be seen in Table 2.

A considerable portion of the budget was spent on travel. However, this proved very rewarding and beneficial to be active in the field meeting with experts and widening the contact base for the project. It was also seen as a method of engaging directly with the problems faced in the industry.

Table 2: Project travel expenses

Craobh Planting Travel Expenses 2015/16					
Expense	**Date of Travel**	**Quantity**	**Responsibility**	**Net Cost (£)**	**Amount (£)**
Vehicle Hire	N/A	4	FH & KJ	50.00	200.00
Fuel (Vehicle Hire 1)	23.10.2015	1	FH	22.00	22.00
Fuel (Vehicle Hire 2)	4.11.2015	1	KJ	27.00	27.00
Fuel (Vehicle Hire 3)	25.11.2015	1	KJ	35.00	35.00
Fuel (Vehicle Hire 4)	8.2.16	1	FH	37.50	37.50
Fuel (Own vehicle used)	25.1.2016	1	GQ	24.50	24.50
Train Travel	12.11.2015	4	FH, GQ, KJ, KI	12.60	50.40
				Total Cost (£)	396.40
				Project Budget (£)	500.00
				Resulting Budget (£)	103.60

As the group completed the design phase, 3D printing was required for the scarifying blade so testing of the compaction quality of different designs could be conducted. Initially when drafting the contract, a discussion was had with laboratory superintendent Mr Chris Cameron who outlined that the cost of printing would be approximately 15 p/cm^3 of plastic used. The final volume of the components that were printed was approximately 1470 cm^3 and so the cost of printing totalled £2.25.

Considering the budget available throughout the project, Figure 6 outlines the distribution of expenses over the active months.

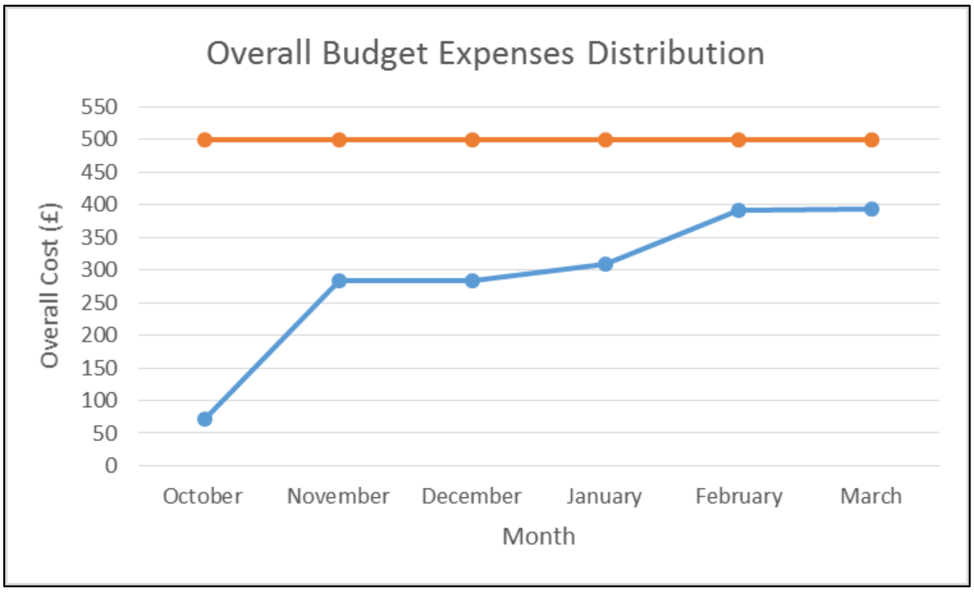


Figure 6: Overall budget expenses distribution.

It can be seen that the greatest expenses occurred in the initial phases of the project when the group focussed on creating a knowledge base for the critical analysis. At the end of each month a check was made to identify the financial situation to ensure enough of the budget was left for following months and if not then there was enough time to take action to resolve any monetary issues with the clients. Where possible, savings were identified however this was difficult due to the fact that hiring vehicles was beyond the control of the group and the hire company was chosen based on university accounts. Similarly fuel costs were paid as required and the overall cost dependent upon the distance of travel on each trip. Where the group did make a saving was selecting train travel for one trip as this was more efficient both in terms of time available and in cost.

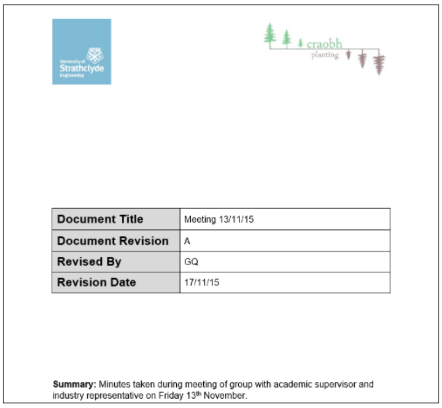
From the beginning, it was difficult for the group to project overall costs due to the unknown nature of what visits were going to take place and which were not feasible. On some occasions, trips were decided at the last minute based on the availability of companies, however with effective time management, the group were flexible in being able to uptake the offers.

Overall, Figure 6 shows that the project finished under budget even with the later short notice trips made and 3D printing of components. It can be noted that little hardware costs were incurred throughout the project and instead, finance was directed towards meeting with industry representatives. Financial management of the project was successful and only 79% of expenses were spent to complete the project.

2.6 Document Control

One of the largest challenges involved in a group project was document control. Group productivity would have been significantly diminished if information could not be shared easily. It was decided from the outset to create a group Google Drive folder in order to have a central location for information sharing, to be used in conjunction with the group Facebook page.

The group decided to employ a document revision process such that all changes would be recorded and obvious to the reader. Firstly a standard document front cover was designed to control information to be shared on each document as shown in Figure 7. This format required the creator/reviewer of the document to list a document name, which revision level the document currently holds, when this revision was made and who made it. The standard document front cover also gave the original creator the opportunity to summarise the document contents.

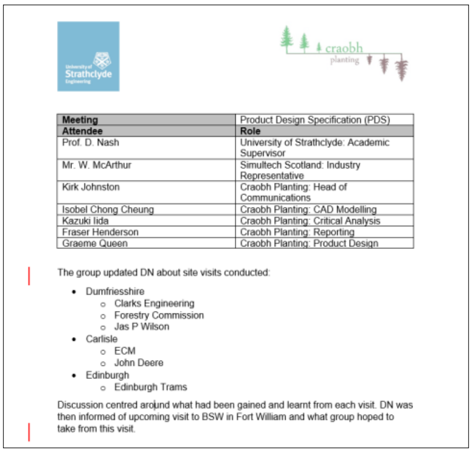


Document Title	Meeting 13/11/15
Document Revision	A
Revised By	GQ
Revision Date	17/11/15

Summary: Minutes taken during meeting of group with academic supervisor and industry representative on Friday 13th November.

Figure 7: Document standard front cover format.

Within the documents themselves, any changes made from the previous revision were marked using Microsoft Word revision features. This gave the reader an instant appreciation as to where changes had been made. The use of revision lines is illustrated in Figure 8.



Meeting	Product Design Specification (PDS)
Attendee	**Role**
Prof. D. Nash	University of Strathclyde: Academic Supervisor
Mr. W. McArthur	Simultech Scotland: Industry Representative
Kirk Johnston	Craobh Planting: Head of Communications
Isobel Chong Cheung	Craobh Planting: CAD Modelling
Kazuki Iida	Craobh Planting: Critical Analysis
Fraser Henderson	Craobh Planting: Reporting
Graeme Queen	Craobh Planting: Product Design

The group updated DN about site visits conducted:

- Dumfriesshire
    - Clarks Engineering
    - Forestry Commission
    - Jas P Wilson
- Carlisle
    - ECM
    - John Deere
- Edinburgh
    - Edinburgh Trams

Discussion centred around what had been gained and learnt from each visit. DN was then informed of upcoming visit to BSW in Fort William and what group hoped to take from this visit.

Figure 8: Example of use of revision lines.

As a new concept, initially implementing this method was a slight challenge for the group and the benefits of doing so were not apparent. However, as the project progressed and the number of documents produced grew exponentially, the group obtained a greater appreciation of the system's advantages and adopted the process fully. One particular challenge the group faced in the early stages of the project was communication regarding any specific document. Thus, it was decided to employ a document numbering process that gave each document a unique number, making reference to it much simpler. Figure 9 shows the use of document numbering within the meeting minutes section of the group's document sharing site.

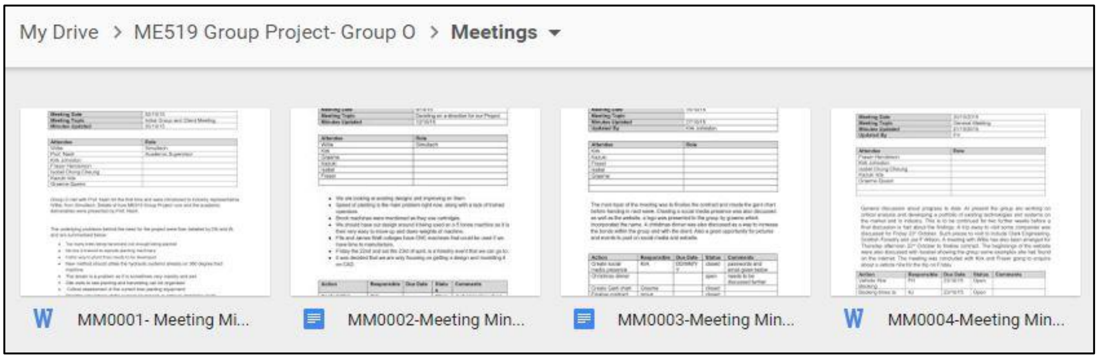


Figure 9: Document Numbering.

2.7 Project Plan

Initially the group utilised a Gantt chart, created in Microsoft Project, to plan and monitor tasks. The Gantt chart gave a visual aid for planning the project, enabling the group to allocate resources to each task. Management of the task, by the responsible group member, and reporting project progress to stakeholders was also aided. The project's critical path was defined, such that the project group understood which tasks were able to float and those that were essential to be completed on schedule.

The original plan set out at beginning of the project, shown Appendix A1 and Appendix A2 estimated completion of the critical analysis and conceptual design stages by the end of semester one. While individual task deadlines were allowed to float and thus certain components of critical analysis delivered "late", other components were delivered quicker than was originally anticipated, allowing for overall delivery to be on schedule. It was noted that the extra time spent on critical analysis and research enabled the following design steps to be completed quicker than expected.

2.7.1 Updated Plan

At the project midpoint the group felt that the original plan did not best represent the tasks to be completed in the second semester and thus the overall plan was modified to include the separation of design tasks to focus on the three specific areas for improvement identified during the critical analysis stage of the project. The updated plan is shown in Appendix A3 and Appendix A4. The planned durations are shown in the colour corresponding to the task categorisation, and their actual durations are shown by the corresponding black bars.

Several detailed design tasks were completed behind schedule as shown, due to an underestimation of the task sizes involved. However, to ensure these delays did not impact on other tasks such as the writing of the final report these following tasks were commenced ahead of schedule when group members were awaiting information relating to other tasks. Further, if a critical task was in danger of not meeting its scheduled delivery date, resources were reallocated from other tasks to ensure on-time delivery. One example of this was the creation of the CAD model of the existing Bracke P11.a. As the task was more time-consuming than thought, further resources were allocated to ensure it was completed as quickly as possible and to the quality required.

One task that was unable to be completed and took up much more of the group's time and resources than anticipated was 3D printing. However, the reasons for its lack of completion were out with the group's control. The challenges faced with 3D printing are further described in section 5.0.

2.8 Risk Management

A risk assessment was carried during the planning of the group project. This was essential in order to identify things that could have prevented the completion of deliverables on time. By considering risks during planning, proactive action could be taken to prevent the risks from occurring or ensuring better management of them if they did occur. There were a number of different risks that could have occurred, from time constraints to loss of members and personal illness or injury. A risk assessment chart was created. This was conducted to outline the risks, identify the severity of each one and consider how they can be prevented/managed. Table 3 outlines potential risks that threatened to affect the overall project progress.

Table 3: Table of proposed risks

Risk	**Probability**			**Impact**			**Effect on Project**	**Reducing the Risk**	**Contingency**
	L	**M**	**H**	**L**	**M**	**H**			
Time constraint		🟧				🟥	Not meeting the full requirements outlined in the contract	Ensure that progress is regularly monitored	Implement further resources on late tasks
3D printing availability		🟧			🟧		Not able to produce a scaled prototype	Liaise closely with department to identify when system will be operational	Outsource to another department
Not meeting with clients	🟩				🟧		Lack of communication and project may deviate	Maintain close correspondence	Arrange further meetings
Making site visits		🟧				🟥	Slower progression of the project	Maintain close correspondence.	Substitute visits with further on-line research
Group schedule/commitment to other classes	🟩				🟧		Project falls behind meeting deadlines	Good time management	Meet through video call rather than face-to-face
Injury/illness	🟩					🟥	Project falls behind meeting deadlines	Complete assigned tasks as soon as possible	Reallocate affected task and workload
Data storage loss	🟩					🟥	Loss of data, effects on time scheduling	Taking weekly back-ups	Recover lost work
Injury whilst on site	🟩					🟥	Project falls behind. Deadlines missed	Ensure correct safety equipment worn	Re-allocate work
Conflicting demands of industry and academia			🟥			🟥	Failure to complete project because trying to please both parties	Ensure all parties agree on the project requirements in the contract and stick to those	Lean towards demands that benefit quality of project

3.0 Critical Analysis

Prior to commencing the design phase of the project, time was set aside for the group to conduct a critical analysis of existing machinery as well as investigating the environment in which the final design would operate. Further to this, throughout the research phase, manufacturing companies and industry experts were contacted across Scotland and the north of England requesting knowledge and literature that would be otherwise unavailable on the public domain. To a certain degree this proved successful, however in a lot of circumstances, many documents were not released based upon intellectual property (IP) rights held by the company.

To make full use of the time and to involve the entire group, a meeting was held to identify main areas of research and the group divided so that each individual had one specific area to focus on. Following this individual research, each topic was presented to the group to ensure everyone had a clear understanding of each sector and so no one was unsure of any terminology or constraints to design later in the project.

3.1 Planting Environment

For many years, forests and woodlands in Scotland have provided an industry that has harvested and produced many different grades of timber for a multitude of different purposes. At present, the percentage of woodland covering the country’s terrain is relativley low at only 17% [4]. In many harvesting operations, trees are felled and not replanted resulting in a deficit and ultimately reducing potential stocks for future harvesting. Planting using mechanical methods is a lot less labour intensive, however the technology still does not exist to operate faster than manual planting. At present, manual planting consists of preparing the land using a machine operated disc trench cultivator. This machine unfurls the soil allowing for planters to follow the trench planting saplings at specified intervals. Using a mechanical planting machine allows for a more careful approach to planting, ultimately spot planting and only cultivating the soil where a sapling is to be planted.

According to data acquired from the Scottish Forestry Commission, quotas for re-planting suggest that 2500-3000 saplings are planted per hectare if the ground conditions allow [5]. This allows for a percentage loss of trees due to inclement weather or death through disease etc. At present, manual tree planting is faster and a lot more efficient than mechanised tree planting due to the need for re-stocking current machine designs. On average, manual tree planters can plant around 2500 saplings per day, therefore covering approximately one hectare in a shift. Planting distance in Scotland is between 1.5m and 2.5m and the most common tree species planted in Sitka Spruce [5].

Reasons for trying to implement mechanised tree planting includes the desire to try and reduce overhead costs, increase productivity and sapling survival rate. Also, although slower, the quality of planting using a machine is greater than that of manual methods. The machine is able to spot prepare the soil whereas manual methods involved firstly disc trenching the land [6]. The use of heavy machinery is potentially detrimental to the land over time as compaction and erosion occurs due to the weight. This can lead to decreased infiltration and decreased plant survival rates [7]. Soil compaction reduces pore space in the soil, resulting in a poor soil structure, also having an effect on soil water status. To eliminate this problem, mounding is required prior to restocking. As well as aerating the soil, more heat is absorbed throughout the day. As the temperature drops at night, this heat is released, minimising the risk of frost penetration in non-extreme weather conditions [5].

Throughout most commercial planting operations in Scotland the preferred choice of sapling is the Sitka Spruce, a non-native conifer, from Alaska. An important figure in tree planting is the YIELD CLASS figure. This non-dimensional figure is the mean cubic metres growth, for each hectare of tree species for each years growth [8]. Sitka Spruce has an approximate figure of 14 compared with Oak that has a yield class figure of 4. This suggests a fast growth rate in comparison to other trees. Deep, moist and well drained soils allow for optimum growth. These conditions are typical of those found in Scotland however these conditions do not favour machine access and so the requirements for a planting machine capable of performing well in these conditions is necessary. Wood produced from the tree is of a high quality for felling and processing for a multitude of industries [8].

Based on the soil conditions of Scotland, typically peaty, gley sites of highly varying gradient, trench mounding and brash raking is the current preferred method of ground preparation for replanting [5]. Once harvesting is complete, it is often typical to find dense brash left on the ground, which covers the soil required for planting new saplings. By trench mounding, soil is excavated to form mound rows suitable for planting before brash and other spoil is backfilled into the remaining trench. Brash raking takes place to form mats for use by the machinery to avoid compacting the soil [5].

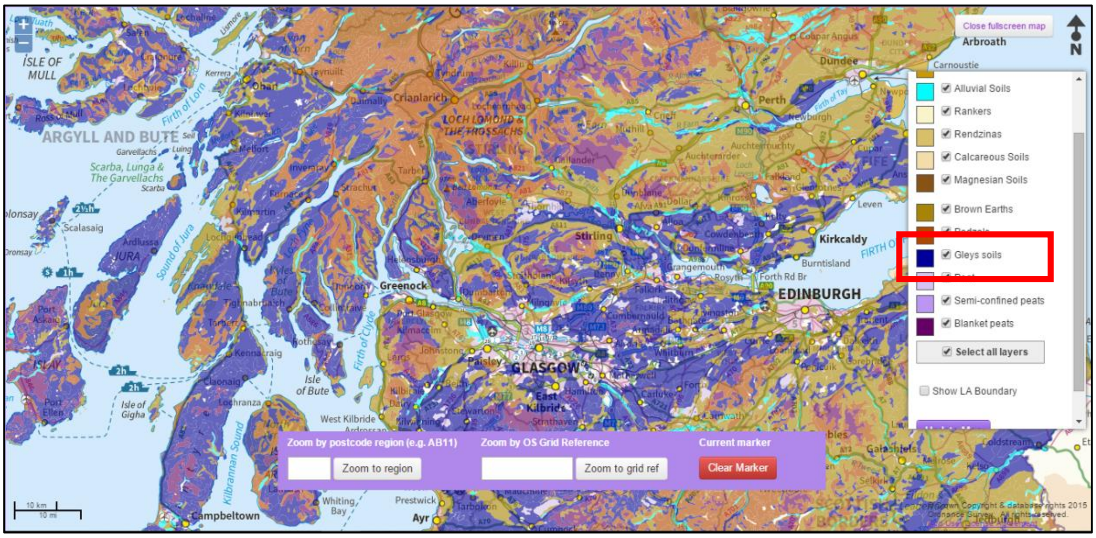


Figure 10: Soil map of Scotland illustrating wide variety of soil types across the central belt and lower highlands [55].

Across Scotland, it can be seen from Figure 10 that soil types vary significantly as a result of varying terrains and geographical locations. However across central Scotland and the lower highlands where pastures are more suitable for growth, gley soils dominate. Furthering this analysis, capabilites of land areas can also be identified using a classification system outlined by The James Hutton Institute [9]. This classification ranges from Class F1, outlining land with excellent flexibility for the growth and management of tree crops to Class F7, outlining land unsuitable for producing crops. Due to the variability in terrain and gradient, potential forestation sites must be carefully selected ensuring a number of limiting factors are accounted for. These include soil wetness, rock density and surface terrain. By making reference to Figure 11 illustrating land capabilities across a localised geographical area of Scotland, it can be seen that towards the West Coast, the land capabilities vary predominantly between F4 – F6, outlining land with limited flexibility for the growth and management of tree crops [9]. This may be due to steeper upland terrain introducing harvesting complications and also limiting species selection for planting. Soils primarliy found across these sites include gleys and peats.

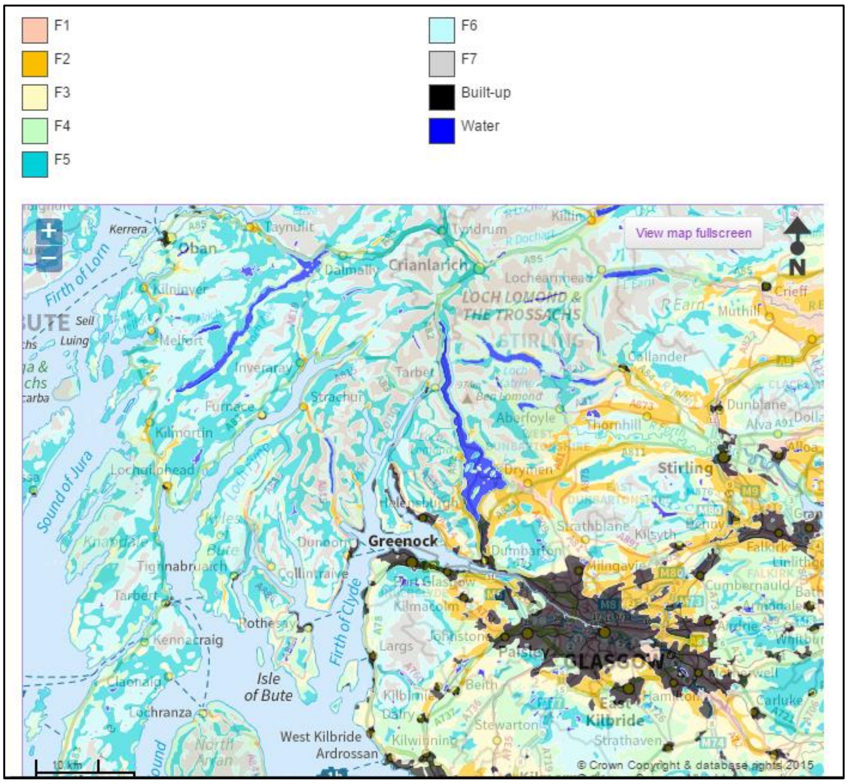


Figure 11: Land classifications around central Scotland [56]

3.2 Existing Planting Machines/Methods

3.2.1 Bracke P11.a

The Bracke Forest P11.a is a Swedish manufactured mechanical planting machine that is designed to operate as an attachment on a 360^{o} tracked excavator. This design delivers a combined scarification and planting procedure using hydraulic and electrical components for operation. The P11.a (Figure 12) is fully controlled in the excavator cab and functions by firstly inverting the soil to create a mound before compacting and finally setting the sapling into the soil. Saplings are directed into the soil using a mechanical dibble that is connected to a rotational carousel used to store the saplings in individual cavities. Productivity of the P11.a is approximately 300 plants per hour with the carousel able to store between 80 and 120 sapling cartridges [10].

Figure 12: Bracke P11.a [10].

Advantages of the P11.a is the versatility of planting on a multitude of terrains. Being attached to a tracked excavator allows for low ground pressure operation using wide tracks to increase overall surface area. This increases flexibility in being able to plant on soft soil sites as well as heavy brash sites where clearing may be required first. The excavator arm reach and manoeuvrability also allows for the planter to be operated from a variety of positions. In Scotland in particular, the terrain is particularly steep at certain re-forestation sites therefore flexibility is required to plant in this environment. As mounding is the preferred planting method to ensure deep rooting for tree stability, the scaring blade on the P11.a has the flexibility to vary the depth and compaction parameters depending on environmental conditions. Sites with a lot of residue brash on the ground, will require clearing before mounding can commence. The scaring blade can be operated as a mechanical rake to clear an appropriate site.

However, as mechanical planting machines have developed, rate of planting has not been comparable to manual planting methods. One disadvantage of the Bracke P11.a is the need for re-stocking the rotating carousel. This must be carried out manually by individually inserting sapling cartridges into the cavities. It has been found that reloading saplings on average takes 15-20% of the productive work time [6]. The process of individual spot mounding and compaction planting is a lot more expensive and time consuming than disc trenching an entire area and following this up with continuous manual planting. Spot mounding, however is of a higher quality and ensures deep root planting for maximised chance of sapling survival in the early critical life stages [5].

3.2.2 EcoPlanter

Developed in the early 1990's in Sweden, the EcoPlanter (Figure 13) used a harvester machine as its prime mover and operated using two planting heads to simultaneously plant saplings. This can be seen in Figure 13. Planting was conducted by firstly using two simultaneously rotating rotors to scarify the soil before planting two saplings alongside each other at an approximate distance of 2m apart [11]. Although the carousel capacity was relatively large with an average carrying capacity of 240 saplings, the rotovating process was relatively slow and planting in steep environments resulted in poorly planted saplings. Although planting capacity was increased using two simultaneously operating planting heads, overall productivity was decreased as sapling survival rates were relatively lower and manual re-stocking time was increased [11].

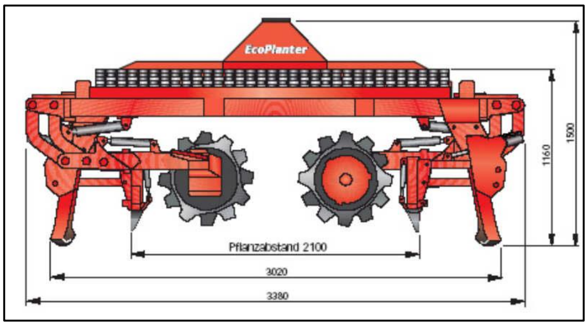


Figure 13: Valmet EcoPlanter [57].

3.2.3 Risutec

Planting and harvesting is a booming industry in Scandinavia. Of all the machines studied throughout this analysis, the majority are designed and manufactured in either Sweden or Finland. The Risutec PM and TK series planting machines are a range of attachments developed in Finland to attach generically to excavators in the 10 – 18 ton range [12]. Efficient for small scale planting operations, the PM series is fully mechanical with no requirement for hydraulic lines or electrics. This overall reduces operating costs as specially fitted prime movers are not required and the attachment is essentially 'clip in and go'. However, with a reduced sapling capacity and solid mounding blade, overall productive time use is reduced and as such limits full capabilities [13]. Figure 14 illustrates the variation between the PM series and TK series planting machines.

Where competition exists on the market, the TK series aims to match the capabilities of the Bracke P11.a for operation in large scale planting contracting. Unlike the PM series, the TK series has capacity for 120 – 198 saplings depending on the model with an adjustable planting depth [14]. Operating under similar control to the Bracke P11.a, the TK series has the ability to operate in a wide range of terrains, which is critical to the operational success of any planting machine. Where it has been identified that the Risutec is further advantageous to other existing machines is the stated features available as standard, such as a sapling tube monitor, sealing pressure monitor and watering system to name but a few [14]. However, with limited information available and no machines operating in the UK, it is difficult to identify whether these features overall benefit the planting operation or hinder overall productive working time with more technical features to potentially malfunction. The TK series planting machine can be seen in Figure 14.

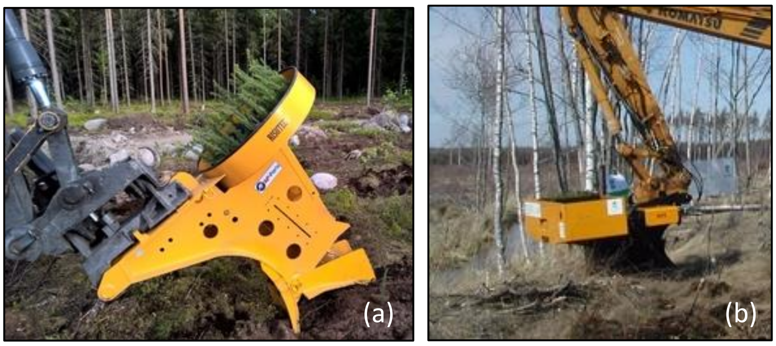


Figure 14: (a) Risutec PM series (b) Risutec TK series [12].

3.2.4 M Planter

Developing on the two headed planting machine concept, the M-Planter has the flexibility to plant two saplings simultaneously using a similar mounding procedure to the Bracke P11.a. The machine is operated from a 360° tracked excavator and is more suited to planting on larger operational sites with a larger carrying capacity. Mirrored in the rarity of using two headed machines in industry, it is debatable as to whether planting quality is jeopardised for productivity using two simultaneous planting heads. The machine works less selectively than a single headed machine suggesting that deep root planting is less substantial than using a single headed machine to individually spot mound.

3.2.5 Overall Comparison of Planting Machines

From the above analysis it is possible to conclude with an overall comparison of the market leading planting machines based on specifications and capacities. This can be seen in Table 4.

Table 4: Comparison of planting machines

Model	Seedling Capacity	Machine Weight (kg)	Prime Mover	Planting Capacity in each cycle
Bracke P11.a	80 - 120	1100	Excavator	1
EcoPlanter	240	-	Harvester	2
Risutec PM series	60	550	Excavator	1
Risutec TK series	120	1100	Excavator	1
M-Planter (single)	122	900	Excavator/Harvester	1
M-Planter (double)	162 - 244	1500	Excavator/Harvester	2

The large variations of seedling capacity and machine weight across the various machines. Overall weight is dependent upon the maximum capacity of the planting machine and will have an overall effect on the capability of the excavator as with a greater weight at the end of the boom, the centre of gravity of the excavator will move and as such decrease its overall stability. It is important to note that although there are evident variations between each of the machines, the functionality and operation of each machine is very similar. Each design spot mounds and plants a sapling through the same operational cycle and as such any variation in design will have an effect on all types of machine.

3.3 Future Concepts for Planting Machines

3.3.1 Eco-Friendly Tree Planting Robot

The Husqvarna Group [15] is a Swedish manufacturer of outdoor power products and a producer of watering products, cutting equipment and diamond tools for stone and construction industries. Through research and investigation conducted in Sweden, Husqvarna Group identified [16]:

- Manual planting is inefficient and can pose a risk for workers.
- No mechanical planting machine exists where human interaction is not required at some point in the operation.
- Environment conservation has become a more critical concern in recent times.

From these conclusions, industrial engineers at Husqvarna Group have designed an eco-friendly tree planting robot of four-legged design equipped with an extending arm and planting head. A CAD generated render can be seen in Figure 15.

Figure 15: Eco-friendly tree planting robot [15].

This robot concept has the capacity to carry up to 320 saplings in a single load and to reduce overall carbon footprint is steam powered [17]. Its small size facilitates efficiency and flexible manoeuvring through tough terrains besides reducing the ground pressure exerted on the forest floor. Saplings are fed into the machine at the front and loaded onto a revolving cartridge. When empty, the robot is required to return to a stock location where it is refilled and returned back to the planting site. Further renders can be seen in Figure 16 outlining the basic operating principles of the sapling planting system.

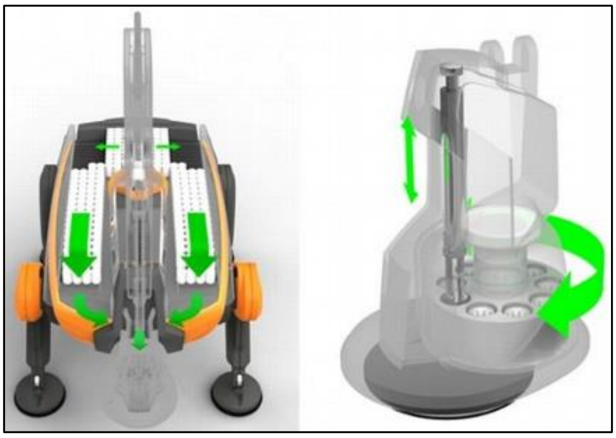


Figure 16: Sapling planting system [15].

As a prototype, this robot is still unavailable on the market however it is evident to see that these future designs are still incorporating design principles of existing machines. As part of this critical analysis, this concept provides an example of how machines may develop in the future and gives an opportunity to identify design areas that may be incorporated into design improvements of this project. However, from this concept, Husqvarna Group identified some areas where advancements had been made:

- It optimises its sapling storage by not leaving empty spaces in its skeleton.
- Its four-legged shape allows planting in any kind of terrain.
- It has some automated reloading process.

3.3.2 Tree Planting Drone

BioCarbon Engineering [18] is a UK company that has tackled the deforestation problem with a future concept based on a different technology. This small engineering company have developed a solution to major worldwide deforestation by re-planting on an industrial scale using Unmanned Aerial Vehicles (UAV's). The overall process involves gathering detailed terrain data to produce a 3D map of the land. From this, the UAV is able to then carry out precision planting activities and finally the land is monitored to provide assessments of the ecosystem health [18]. Figure 17 shows a rendered illustration of the process of planting using a UAV to drop capsules to the ground that then biodegrade and allow the seedling to grow.

Figure 17: Illustration of tree planting drone showing seedlings being dropped in caplets to the ground [18].

This method reduces the cost of traditional reforestation methods by 15% with the overall aim to plant up to one billion trees a year with this technology. It is not possible at present to provide any remarkable conclusions as the technology is still very elementary and requires a lot of further research, well out with the scope of this project however it is important to identify the various technologies using different approaches so as to be aware that one solution is potentially not the best solution.

3.4 Forestry Machinery

3.4.1 Harvester

A harvester is a piece of heavy machinery that is used to fell, cut to length, delimb and buck trees. The harvester is made up of the vehicle, which is a custom design based on an excavator, and then the harvester head. Harvester heads can be bought separately and attached to any kind of excavator arm. The main manufactures of harvesters and harvester heads are John Deere and Ponsse, John Deere being the principal provider in the UK and Ireland. Harvesters are used on level and steep terrain to fell trees and also for thinning operations [19]. Harvesters are built to be very robust and cope with many different types of terrain. The vehicle can be wheeled, tracked or walking; to increase the manoeuvrability between trees many of the modern harvesters are articulated. Harvesters range in size and design, this allows them to be used in a number of different environments; smaller harvesters are better suited for thinning or moving on a steeper gradient. Bigger vehicles are more suitable for thicker trees that will put more strain on the engine of the vehicle [19]. The development and use of these harvesters has made the forestry industry much safer and more efficient. Instead of having men on the ground using chainsaws, they are inside the cab of the harvester where trees cannot fall on them and they do not have to worry about chainsaw related injuries. The harvesters make felling more efficient by cutting the tree down, delimbing and cutting the tree to size. Another advantage of the harvesters is the advanced operating systems. These are used to monitor the machine performance as well as analysing the log dimensions and calculating how to cut it in order to gain the maximum amount of product. These systems rely on a number of different sensors and measuring systems found in the latest state of the art harvester heads.

Figure 18: John Deere harvesting equipment [19] [20].

3.4.2 Harvester Heads

The harvester head is the main point of interest; harvester heads come in a range of shapes and sizes and then can be used on many different types of machine [20]. An example of a harvesting head and prime mover can be seen in Figure 18. They are the part of the machine that does the felling, delimbing and cutting of the trees. The harvester head is powered by hydraulics; there is a hydraulic control valve in the harvester head that redirects the hydraulic fluid coming from the vehicle. The value is controlled by electrical signals sent from the driver. The fact that the head has its own control value is part of the reason it is so universal, as it only requires a hydraulic input and output line from the vehicle [21]. Although there are a number of different heads, each one consists of the same vital components:

- Chainsaw- this is a very powerful hydraulically powered chainsaw that is used to cut the tree at the base and cut it to length.
- Delimbing Knives- 2 or more curved knives that wrap around the trunk, the tree is forced through them, cutting off the limbs.
- Feed Rollers- at least 2 feed rollers that close around the tree to grip it and then force it back and forward through the delimbing knives.
- Diameter sensors- these are used to set the knives so that only limbs are being removed.
- Measuring wheel- used to measure the length of the trunk as the rollers feed the tree through.

The harvester once again makes the forestry industry much safer as again the driver remains in the cab of the harvester [20]. New harvester heads are constantly being developed to try and optimise the process and each tree. New designs use up to 6 knives for delimbing and up to 4 feed rollers to ensure that the tree is well gripped. New developments are also being made in producing sensors to determine the density of the wood, and therefore optimise the way it is processed to make the most of each tree. Harvester heads are becoming more and more complicated and this causes problems when they malfunction or break down [21]. Given the remote locations where these are used it is difficult to get the engineers out to site and even more difficult to replace parts in the adverse weather conditions.

3.4.3 Forwarders

A forwarder is a vehicle that normally works in conjunction with a harvester (Figure 19). It is designed to collect the logs felled by the harvester and take them to a designated area of the site for collection. The forwarder picks up the logs, using a custom boom similar to that of an excavator, and then drops them in the load area which is being pushed in front of vehicle, the logs are then moved at a designated area on the site. Picking the trees up does limit the size of the logs that can be moved by a forwarder but it can help save the soil on the site. The logs are not being dragged around the site which affects the soil quality [22]. Like the harvester the forwarders are articulated to help them manoeuvre around the site, they can also operate on wheels or tracks (although most are wheeled vehicles). Forwarders again increase the safety of the site as no one needs to be on the ground while the feeling and recovery process is taking place on the site. Forwarders range in size from small to large; the small forwarders have a typical load rating of 9-11 tonnes and these are best suited for thinning operations as they are small and easy to manoeuvre, only available as a 6 wheel vehicle. Medium forwarders have a load rating of 12-13 tonnes, these are the most versatile as they can be used in thinning and final felling operations. Medium Forwarders are available in 6 and 8 wheel configurations. The largest forwarders have a load rating of 15-19 tonnes and our mostly used when the terrain is difficult and long distances must be travelled. They are the most powerful forwarders meaning they can go places smaller forwarders cannot manage, always an 8 wheel configuration. The 8 wheels spreads the increased load better than 6 would, this helps prevent the vehicle becoming bogged down [22].

Figure 19: John Deere forwarder [22].

3.4.4 Skidders

The alternatives to forwarders are known as skidders. These are large heavy duty vehicle that is used to drag logs out of the forest this is known as skidding [23]. Skidders can be used instead of or alongside forwarders when removing logs, skidders are capable of removing much larger trees than forwarders. Typically, forwarders are tracked or four wheeled with a large turbocharged diesel engine to provide the power. They have articulated steering, the driver is protected from falling trees or broken cables by a steel cab. A skidder can also be used to remove tree stumps and create an initial path for other equipment, known as a skid path. One of the advantages of skidding is that the trees particles and seeds will cultivate the soil as it is dragged through the forest. Disadvantages include the damage to the remaining trees when thinning, as the logs are dragged against them removing bark etc. The skidder can also do a lot of damage to the top soil, as it creates large furrows. These furrows will affect the natural run off patterns in the forest and this increases the cost of rehabilitation and reforestation [24]. There are two main types of skidder used.

3.4.5 Cable Skidders

Cable skidders have a high power winch at the rear with large funnel-shaped metal guards to protect the rear wheels [23]. An example can be seen in Figure 20. The winch/cable is wrapped around the trees and holds them as the skidder drags them to the landing area of the site. Cable skidders are becoming less popular because they are more labour intensive, the operator is required to attach the cables or someone else has to. Allow the cable and winch design is very useful when thinning and it is not possible to get a large vehicle close enough to pick up a tree [24].

Figure 20: John Deere cable skidder [23].

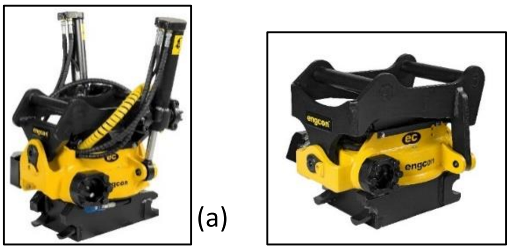
3.4.6 Grapple Skidders

Grapple skidders are becoming more and more popular; they have a hydraulic grapple bucket in place of a winch [24]. The bucket grabs and lifts the trees; the boom that attached the grapple bucket to the skidder can be single function or dual function. A single function boom has two hydraulic cylinders that allow movement in only one direction [23]. The dual function boom has four cylinders attached to it and this allows movement in two different directions, so as well as raising and lowering the grapple can be moved closer or further away from the skidder [24]. A third kind of boom allows for sideways movement in addition to the dual function booms movements.

Figure 21: Caterpillar grapple skidder [24].

3.4.7 Engcon Tiltrotator

Attaching a machine to the hitch of a 360° excavator restricts motion to only the positions that the excavator arm itself can reach. As a further attachment to increase manoeuvrability, the Engcon Tiltrotator is an add-on adaptor that can be attached between the fixed hitch on the excavator and the tool [25]. Through hydraulic actuation, motion of any attachment is increased through many different degrees, allowing the ability for the tool to be operated from a variety of different positions and ultimately increasing the precision and manoeuvrability of the tool.



(a) (b)

Figure 22: (a) Engcon Tiltrotator EC15B (b) Engcon Rotator EC15B-B [25].

Incorporating this attachment into the design of the tree planting machine would allow the potential for advanced movements, especially on variable terrain where the position of the excavator was critical. One of the design requirements throughout the project is that the planting machine operate on steep and uneven terrain. With a tilt-rotating hitch, position of the excavator becomes less critical as the moving head could compensate for any uneven positioning. However, looking specifically at the EC15B tiltrotator (from 360 kg) and the EC15B-R rotator (310 kg), weight is important [25] (Figure 22). By continuing to add a mass to the extended arm of an excavator, the centre of gravity of the entire machine changes. This is a particular issue on uneven terrain where the excavator relies upon its centre of gravity existing around the turntable between the tracks and the body. Excavator manufacturers outline the extremes to which their machines can operate and so it is important that these weights are not exceeded. By continually adding equipment to the digger arm, the maximum potential of the machines operational capabilities reduce.

3.4.8 Helac Powertilt

Extending on rotating actuators, the Helac Powertilt provides a tilting action up to 180^o full range using a sliding spline shaft. This device has the ability to provide additional movement to the excavator, ultimately increasing overall productivity by 50% [26]. The device is powered by the hydraulic pump situated in the excavator with flow provided from lines extending from the auxiliary circuit. With its relatively small size, the Powertilt is able to provide rotational motion up to 180^o around one axis converting linear piston motion into a shaft rotation in the spline housing [26]. By only providing one additional rotation around one axis, the overall weight of the device can be reduced, with the smaller size producing a more compact attachment.

3.5 Hydraulics

The role of hydraulics, in particular in this industry, was understood to be critical for power transmission enabling easily amplified power to be controlled from simply a joystick. The motion and functions associated with a 360° tracked excavator are all accomplished with the utilisation of hydraulic fluids, as are many forestry attachments. As a subject not well investigated through the academic curriculum thus far a short study was conducted.

3.5.1 Basic Principle

The underlying principle of a hydraulic system is rather simple: force is transmitted from the point where it is applied to another point via an incompressible fluid. More often than not the force is multiplied through use of geometry variations. Hydraulic systems are capable of transmitting high forces very quickly and accurately using relatively small pipes which can travel large distances and through awkward shapes. The principles of hydraulics were first explained by Blaise Pascal when he stated:

"Pressure applied to any part of a contained fluid transmits to every other part with no loss. The pressure acts with equal force on all equal areas of the confining walls and perpendicular to the walls." [27].

3.5.2 Hydraulic Pressure and Force

Hydraulic pressure P, is the force F, exerted on a unit area A, of a material by a fluid and is related as follows:

$$P = \frac{F}{A} \tag{1}$$

Hydraulic power $\dot{W}_{max}$, is a function of the hydraulic pressure P, and the flow rate Q, of the contained fluid:

$$\dot{W}_{max} = PQ \tag{2}$$

3.5.3 Hydraulics within Excavators and Forestry Machinery

Hydraulics are important in providing the power for many of a 360° tracked excavator's primary moving parts, such as the excavator's boom. The use of three hydraulic rams along the excavator's boom gives the operator maximum control over the intricate motions required of the boom. In many ways, the hydraulic rams act like the muscles in a human arm. An illustration of this can be seen in Figure 23.

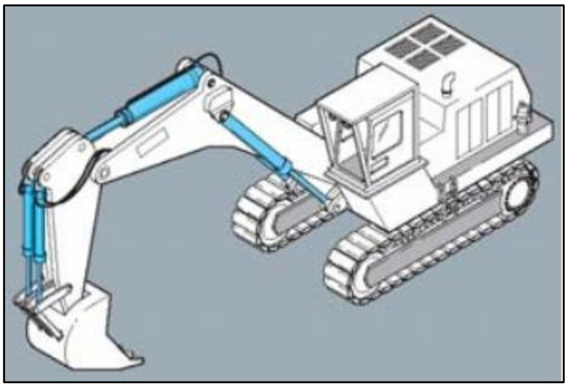


Figure 23: Hydraulic rams on excavator arm [58].

Not only are hydraulics utilised on the prime mover, the technology is also extensively used in attachments located at the end of the excavator boom. Many of the forestry machines and attachments mentioned previously use hydraulics to provide power. The Bracke P11.a tree planting machine utilises hydraulics to provide the power required in the scarifying blade, the delivery of the dibble to the ground and for the rotation of the carousel.

Hydraulics are common in forestry machinery due to their relative simplicity and the ease of maintenance they afford when compared with other power sources such as electrical and pneumatic. The utilisation of often small and flexible hosing for power transmission within a hydraulic system enables transmission of power to difficult to reach locations such as the end of the dipper on the excavator.

3.6 Industrial Contact

As part of continuous development for the project, it was suggested to the group by Mr McArthur that meetings and visits be organised to develop a broader understanding of the forestry industry and the machinery operated for harvesting and planting. It was also an opportunity for the group to present ideas to industry experts and obtain feedback on where further amendments could be made or where requirements were being met. The group had a proactive attitude in trying develop a solution that would be effective in the industry.

A list of companies that were contacted and visited include:

- Scot JCB
- John Deere Forestry
- Jas P Wilson Forest Machines
- Clark Engineering
- Forestry Commission Scotland office and planting site
- Edinburgh Trams
- ECM
- BSW Timber Group
- Dulnain Plant Hire/Christie Elite

A brief analysis of some visits made is covered below:

3.6.1 Scot JCB

Meeting with Andrew Campbell allowed for a short discussion about the use of 360^{o} tracked excavators in forestry operations. With a vision to design a mechanical planting machine as an attachment suitable for use on the excavator hitch, this discussion gave insight into how to make this design requirement possible and the problems that may be faced. One of the problems faced with implementing a tracked excavator in the forest is ensuring the machine can operate on the soft and often uneven terrain. This is overcome by using low ground pressure crawler tracks with a larger surface area to support the overall weight of the machine. This is further outlined in section 4.3.3. For the purposes of the design project, a JCB JS145 360^{o} tracked excavator was selected as the prime mover for the new attachment to be coupled to, with a universal attachment hitch as standard. Using a universal attachment hitch would allow for various manufacturers and models of 360° tracked excavators to act as the prime mover.

3.6.2 Forestry Commission Scotland

Further to simply understanding the mechanics and power systems of a mechanical planter and the machines used to operate them, a meeting was held with Bill Jones from the technical development department at the Forestry Commission. This allowed the group to develop a greater understanding of the ground terrain typical in forests and also the planting techniques and protocols followed at the present time. From the main issues discussed regarding current mechanical planting techniques, the most prominent were ensuring adequate manoeuvrability, ensuring the machine was able to operate on a variety of terrains and gradients and ensuring the sapling was planted in a rigid base with suitable compaction so as to maximise survival rate. Further to this, questions were raised regarding the present techniques used in planting in Scotland with a range of answers presented:

- Across a typical hectare, approximately 2500 – 3500 saplings are planted with the hope that after five years, at least 2500 will grow to mature trees for harvesting.
- Gap left between newly planted saplings is approximately 1.5 – 2.5 metres to allow for growth.
- The preferred plant for Scotland is the Sitka Spruce, having a quick growth period and typically harvested for timber production after 30 – 40 years.
- The direction of the planted sapling's roots is critical to its survival. Roots must face downwards in the vertical direction and not be curled upwards.
- The season during which saplings are planted is not critical, however the weather is. In inclement weather, frost penetration and high winds can be detrimental to the survival of a newly planted sapling.

3.6.3 John Deere Forestry

As part of the final design of the new planting machine, a simulation will be made for training purposes. To gain an understanding of how simulators operate in the forestry industry, a visit was made to John Deere Forestry where the group met Jock McKie to discuss the advantages of simulation for training and to also discuss the workings of forestry equipment (see section 3.4). The group were given the opportunity to use the simulator, at the same time getting a feel for the controls of harvester and forwarder machines used for harvesting forest plantations. Further to this, a tour was given of the site and the group allowed to view a range of machines up close to understand their workings. Documents specific to John Deere were distributed for further reading and to help develop a critical analysis specific to the project.

3.6.4 BSW Timber Group

Pursuing a further understanding into tree planting and the methods involved, a meeting was organised with Mick Bottomley, head of timber buying at BSW Timber Group, Corpach. Through an informative discussion, the group engaged in learning about the most effective methods of tree planting and some issues still present with mechanical planting machines. Of these issues, the most prominent included ensuring sufficient spacing between trees. This is most effective if the pattern is regular to maximise planting capacity per hectare. Further, a discussion was had about the mounding process and how this is critical to the survival of the sapling compacted into the soil. Finally, the group were introduced to JPP and bare root sapling cartridges, with bare rooting being cheaper and more suited to manual planting. After the discussion the group were given a guided tour of the sawmill to see the full operation of what happens to the tree once harvested.

3.6.5 Dulnain Plant Hire/Christie Elite Nurseries

Concluding the major visits made for the purpose of the project, the group were invited to Christie Elite Nurseries in Elgin where a short tour was given by nursery manager Brian McCamon. This allowed the group to see all the different sapling varieties planted across the UK and see them all at various stages in life. Important to note was the initial growing time required before the saplings were developed enough for planting in the wild and the amount of preparation carried out prior to travel to the various sites.

From here, an opportunity arose to view two Bracke P11.a planting machines (see section 3.2.1) in action at a local Forestry Commission site. Being able to see all the components in the machine allowed the group to develop an understanding of how the sapling is dropped from the carousel to the mound and compacted. However, from this it was observed that the complexity of the hydraulic and electronic systems in the machine were out with the capabilities of the group. Further designing these systems were out with the scope of the project, what with the final outcome to develop a model for simulation, not manufacture. This aside, it did present an opportunity in the project for developing a basic understanding of the on board systems. The knowledge of both the operator and site manager was valuable in understanding more about the workings of the most favoured planting machine in the industry at the present time.

4.0 Design

The design section of the project focussed on improving current mechanical planting devices and the creation of 3D CAD models suitable for use in simulation, to aid with future training of operators.

4.1 Identifying the Challenges

The extensive critical analysis conducted enabled the group to develop a strong understanding of the workings of existing forestry tree planting machinery, and the issues these devices currently face. There was an agreement reached between the group and the project clients that the Bracke P11.a was the current market leader and thus would be utilised as the basis for design going forward. The recurring challenges faced by current tree planting machinery devices were:

- The limited sapling capacity, leading to frequent reloading stoppages.
- Large reloading times, due to manual reloading process.
- Overall productivity of mechanical planting, compared with manual planting.
- Low quality of mound compaction, reducing overall high planting quality associated with mechanical planting.

4.1.1 Product Design Specification (PDS)

The requirements of a forestry tree planting machine were then formulated, through numerous group meetings, into a formal Product Design Specification (PDS). A PDS was used to ensure the quality of a design and ensure that the final product was fit for purpose. The specification created defined requirements for areas including performance, environment and weight amongst many others; and sets constraints which any subsequent designs adhered to. Treating this presentation as a Stage Gate process, section 2.2, code two amendments were recommended and incorporated, giving the finalised PDS as detailed in Appendix A5.

The PDS was then used as the reference point as the group defined a number of key functions required of any tree planting machine. The functions generated were:

- Scarification of soil/planting environment
- Storage on machine of saplings
- Delivery method of saplings to reforestation site
- Delivery of sapling to final planted position
- Maintenance of machine verticality
- Method of soil compaction after planting
- Movement of prime mover

4.2 Morphological Chart

Based on the functions derived in the PDS, a morphological chart was drawn up to allow these functions to be investigated in more detail by the design team. Extensive reference was made to existing machinery, considering all possible mechanisms for each function. The final morphological chart can be seen in Appendix A6.

The project definition and design requirements both state that the design shall be attached to a 360° tracked excavator, and thus it was decided that the movement of the prime mover shall be constrained to intermittently advancing, or spot planting. Not only is this easier for planting and the likely terrains, it also has great environmental advantages in only impacting small amounts of the overall terrain.

The three options for maintaining machine verticality when planting were discussed at length, and the group agreed that this challenge should be met with the incorporation of a Helac PowerTilt into the design [28]. This was the simplest of the three options investigated but was extremely effective in achieving verticality. It was also by far the lightest of the three options considered. With weight being critical to the success of the planting design, this gave greater freedom to other elements of the design.

From the generation of the morphological chart, the group investigated which functions were reliant on one another and began to group the functions together into sections for further design investigation. The first grouping for investigation was how the saplings were stored on the machine coupled with how they are delivered to site. The second key grouping of functions included the soil scarification, the delivery of the sapling into the ground and the subsequent soil compaction.

4.3 Power Design

4.3.1 Soil Bulk Density and Weight

One important consideration when mounding is considering the overall weight of soil being moved as this will have an effect on the performance of the excavator and attachments. When designing the scarifying blade, the minimum requirement of the blade was its capability of creating a mound by overcoming the resistive force exerted by the soil as the blade cut through. By considering the various soils conditions that the machine may be required to operate in, it is possible to estimate the approximate mass of soil being mounded in each operation based on the required volume of the mound. From there, the approximate force that the machine is required to overcome based on the weight of the soil can be calculated and therefore provide a basic analysis on the appropriateness of the machine and attachments. Further to this, a factor was included to represent further contaminants in the soil such as rocks and roots as in any environment, an ideal model would not represent the real conditions.

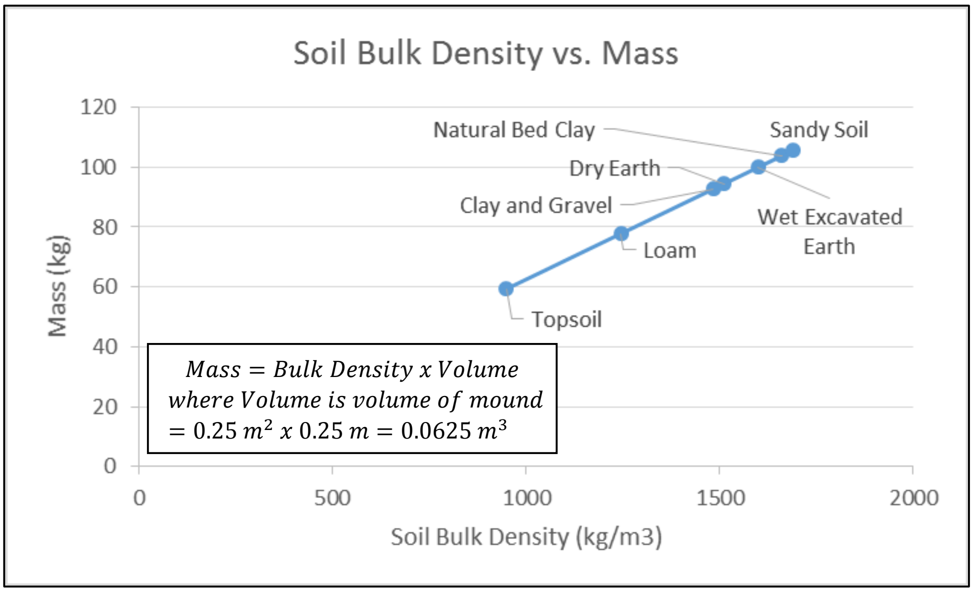


Figure 24: Plot of soil bulk density vs. mass.

Figure 24 [29] illustrates a range of typical soils that are suitable for planting in and allow root growth. As the soil bulk density increases, so too does the overall mass of the mound based on a constant mound volume. It is important to understand that the density of the soil will constantly vary. For example, when the soil is mounded, it will become more aerated and less compact, therefore reducing the bulk density however when the mound is compacted with the sapling inserted, the bulk density will increase as the soil becomes more compact. For this reason it is difficult to provide an accurate model of the properties of soil during the mounding process and as such the best way to design components is based on a worst case situation using a soil with the greatest mass.

$$W_s = m_s g \mu_s \qquad (3)$$

$$W_s = 110\ x\ 9.81\ x\ 1.2$$

$$W_s = 1295\ N$$

From this it is possible to show that the minimum force required to overcome the weight of the soil by the machine including any contaminants is approximately 1295 N. This will therefore form a design constraint ensuring that components designed are capable of overcoming this minimum force and is fit for service.

4.3.2 Machine Hydraulic Power Output and Breakout Force

Most modern excavators are driven predominantly by hydraulic components with the diesel engine in place to drive the hydraulic pumps. The hydraulic system in the JCB JS145 is made up of two variable displacement axial piston pumps delivering a total maximum flow rate of 124 L/min each. These pumps are used to supply hydraulic fluid to the entire mechanical system including the dipper, boom, drive motors and accessories which are supplied through auxiliary circuit line. Focussing on the planting machine attachment for this project, the auxiliary circuit is particularly important for providing a hydraulic flow to any attachments and consists of one flow and one return line that extends directly from the auxiliary hydraulic system. It is also important to note that the flow rate in the auxiliary circuit will directly influence flow to other components and have an effect on what further movements are possible in the excavator.

From technical data provided by JCB it was possible to calculate the maximum power provided by each of the hydraulic pumps using a simple equation relating pressure with flow rate [30]:

$$p_{max} = \frac{PQ}{\eta_{total}} \tag{4}$$

$$p_{max} = \frac{(Px10^5)\left(\frac{Q}{60000}\right)\left(\frac{1}{1000}\right)}{\eta_{total}}$$

$$p_{max} = \frac{PQ}{600\ \eta_{total}} \tag{5}$$

Where: P = 314 bar (maximum pressure available through relief valve)
Q = 124 L/min (maximum flow from axial pump)
η_{total} = 0.87 (average for axial hydraulic pumps)

$$p_{max} = \frac{314\ x\ 124}{600\ x\ 0.87}$$

$$p_{max} = 74.59\ kW$$

Another important consideration in excavator design is the breakout force that the machine can exert as the bucket is moved through the soil. In the case of this design, the standard equation to calculate this was used however the result was assumed very approximate in that more technical data was required by the group which was unobtainable from manufacturers meaning that the overall breakout force calculated was a lot more elementary and a detailed analysis out with the possibilities of the group. It is possible to note that from the technical data that was obtained from JCB, the maximum dipper breakout force possible by a JS145 excavator was listed as 6589 kilogram-force or 64616 Newton’s [31]. Breakout force F_B is stated as [32]:

$$F_B = \frac{P\ x\ \left(\frac{\pi}{4}\right) x\ D_B^2}{D_D}\ x\ (\frac{A\ x\ C}{B}) \tag{6}$$

In order to obtain all the relevant dimensions required for this evaluation, a visit was made to ScotJCB to briefly view a machine and measure critical distances between pins. Such dimensions can be seen in Figure 25 [32].

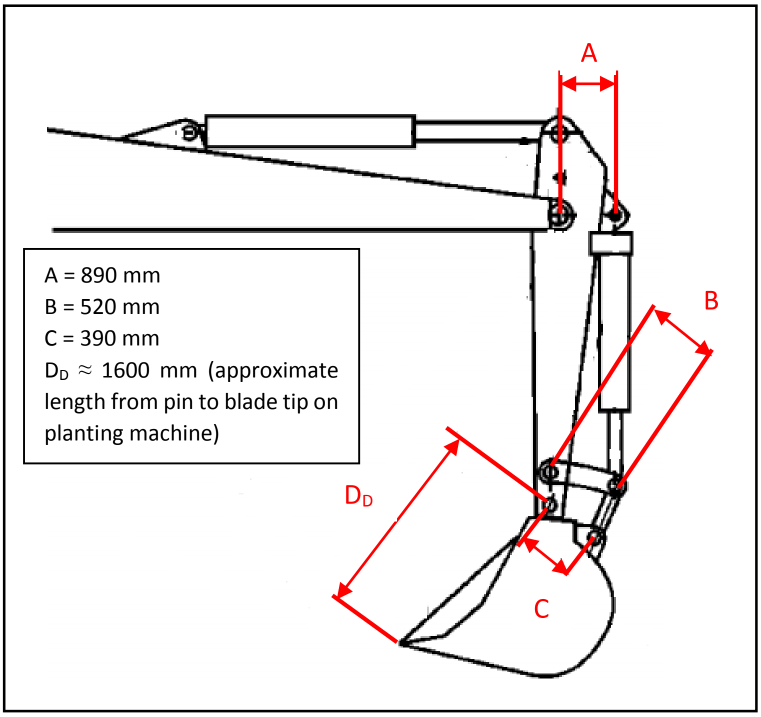


Figure 25: Excavator dipper dimensions.

Also assuming a maximum working pressure P from the relief valve equal to 314 bar with an assumed dipper cylinder diameter D_B equal to 40 mm [31].

$$F_B = \frac{31.4\ x\ \left(\frac{\pi}{4}\right) x\ 40^2}{1600}\ x\ \left(\frac{890\ x\ 390}{520}\right)$$

$$F_B \cong 16500\ N$$

This simplified approach provides an approximation and shows that the maximum breakout force of the excavator is limited when operating with an attachment of similar dimensions of a planting machine. The distance of the blade edge on the planting machine from the hitch pin is the major limiting factor for the maximum breakout force of the machine. The maximum breakout force as outlined by JCB suggests operation with a trenching bucket, typically a lot smaller and with a lesser offset from the hitch.

Selecting the appropriate machine for a specific purpose is critical to the success of the operation. During site visits made by the group, it was verified by industry experts, namely Jas P Wilson and ScotJCB that the most appropriate, and common, machine size for use in forestry operations ranged from 12 – 18 tons and so it was acceptable to suggest the JS145 (machine weight approximately 14.6 ton) to be suitable for this specific application.

4.3.3 Ground Pressure

Also a critical consideration for selecting an appropriate size of machine is the ground pressure. By increasing the size of machine based on lifting and breakout capacities, so also does the overall weight of the machine increase. In the forest, hard dry soils often give way to soft gley soils depending on the lay of the water table. For this reason, the operator must consider a machine capable of providing low ground pressure for use across a wide range of conditions. It is possible to calculate an approximate value of ground pressure for the prime mover and attachment operating with a typical track shoe width however, the applicability of the calculated value is site dependent and as such provides a means of reference only [33].

$$P_g = \frac{W_L}{R_{track}\ x\ L_{track}} \tag{7}$$

Where mean static ground pressure, P_g is unknown, wheel load, W_L combines the total mass of the prime mover and planting machine (based on P11.a (see section 3.2.5), track shoe width, R_{track} is the widest possible available from the manufacturer and the track level with ground, L_{track} represents the track length that is resting on the ground.

Wheel load, W_L = 14600 + 1100 = 15738 kg {Ref. [31]}
Track shoe width, R_{track} = 900 mm {Ref. [31]}
Track level on ground, L_{track} = 2865 mm {Ref. [31]}

$$P_g = \frac{15738}{0.9\ x\ 2.865}$$

$$P_g = 6100\ kgm^{-2} = 0.61\ kgcm^{-2}\ = 0.61\ bar$$

The value of ground pressure found above is representative of an overall weight combining the machine and the planting attachment with the widest track shoes available from the manufacturer. Based on a technical note published by the forestry commission [34] regarding mechanised forestry operations, this figure is representative of the typical range of machine operating in similar conditions where the forestry commission estimated tracked machines exerted 0.45-0.52 $kgcm^{-2}$ [34] dependent upon track width. In some circumstances, prime movers operating in the forest are equipped with custom tracks.

From the very beginning of the project, the group were made aware of the large differences that can exist in the size of machine selected and so these basic calculations provided a basis for what weight range to design the new planting attachment to with respect to the varying conditions that may exist in forestry operations.

4.3.4 Hydraulic Circuit

Ensuring that the excavator is capable of providing adequate power to any auxiliary attachments requires an understanding of the components required to provide flow from the pumps to the components that will provide motion to complete the task for which the machine was designed for. For this design, gaining detailed information again proved difficult and the group were forced to continue on with designing the device based on available information. Such information included the basic flow and pressure requirements of the similar Bracke P11.a planting machine and Helac Powertilt actuator. It can be assumed that the operating conditions of these existing machines would be similar to those of the new machine. It is also important to note that one requirement of this design outlined in the PDS was that it would be capable of attaching to a wide variety of tracked machines, each with varying power methods. These may include powering attachments from central, auxiliary or diesel pumps all sized according to the machine size and capable of providing varying magnitudes of flow and pressure. Another variable when considering what machine to attach the planting machine is the time of operation. If a planting machine is to be attached to a prime mover for full time planting operation then more capital will be invested into the machine so as to optimise output. Similarly, a prime mover being implemented on a planting operation for a short period of time will be fixed quickly for basic operation. These considerations have a significant effect on the overall operation of the attachments and the power that is available for operation. Under these circumstances, implementing a fundamental design is very complex and not practical. For this reason, the design was created more conceptually rather than creating a technical design. By focussing more on the conceptual design, a visual representation of the basic set up would be created allowing for a representative model to be created suitable for simulation.

From the obtainable manufacturer information, the required figures that would allow the group to create a conceptual circuit, can be seen in Table 5 . It can be seen that the operating pressure of the Powertilt component is greater than that of the Bracke P11.a. This is because the overall force required by the Powertilt is dependent upon the attachment that is to be rotated, while the Bracke P11.a only has to supply enough pressure to rotate the carousel for planting and pivot the blade for mounding. Similarly, the required flow rate corresponds to the number of hydraulic components in each device. In the Bracke P11.a, multiple hydraulic cylinders are required for a variety of applications while on the Powertilt, flow is only required for one rotational movement.

Table 5: Manufacturer data regarding operating pressure and flow rate

	Bracke P11.a	**Helac Powertilt**
Operating Pressure (bar)	125	200
Required Flow Rate (L/min)	100	20
Max. pressure and flow rate available from JCB JS145 is 314 bar and 124 L/min respectively		

Designing the flow circuit proved difficult with a lack of detailed information however it was possible to design conceptually for the potential worst case situation. From this it was decided that components should be specified to the information available and in many circumstances components may be over-sized. However, in a heavy industries design such as this, components should be of the highest quality with no margin for safety concern and as such there should be no compromise on design decisions that may jeopardise the life in service of the machine.

One of the biggest difficulties in conceptualising a circuit was how the flow would be received from the excavator to the leveller and planter machines. From section 4.3.2, it was understood that the auxiliary line provided the flow however it was required that individual control be available to the operator for controlling the leveller and planter. By installing only one auxiliary flow and return kit, the flow would need to be divided and regulated based upon the requirements of each device. Individual control of each machine would not be possible here due to the splitting of the fluid using only one spool valve controller.

Figure 26: Auxiliary flow outputs on excavator dipper.

To try to overcome this issue, Hytec Hydraulic Engineering Ltd were contacted with a view to obtaining a present method of providing individual control in excavator attachments. It was brought the groups attention that the only conventional way to do so without introducing complex remote control devices would be to install two auxiliary flow and return kits to the prime mover. An example of this can be seen in Figure 26. This would mean that any excavator using this equipment would require to be further specialised using third party auxiliary equipment. By using this information, a simplified hydraulic circuit was created using Hydraforce i-design 5.0 and can be seen in Figure 27.

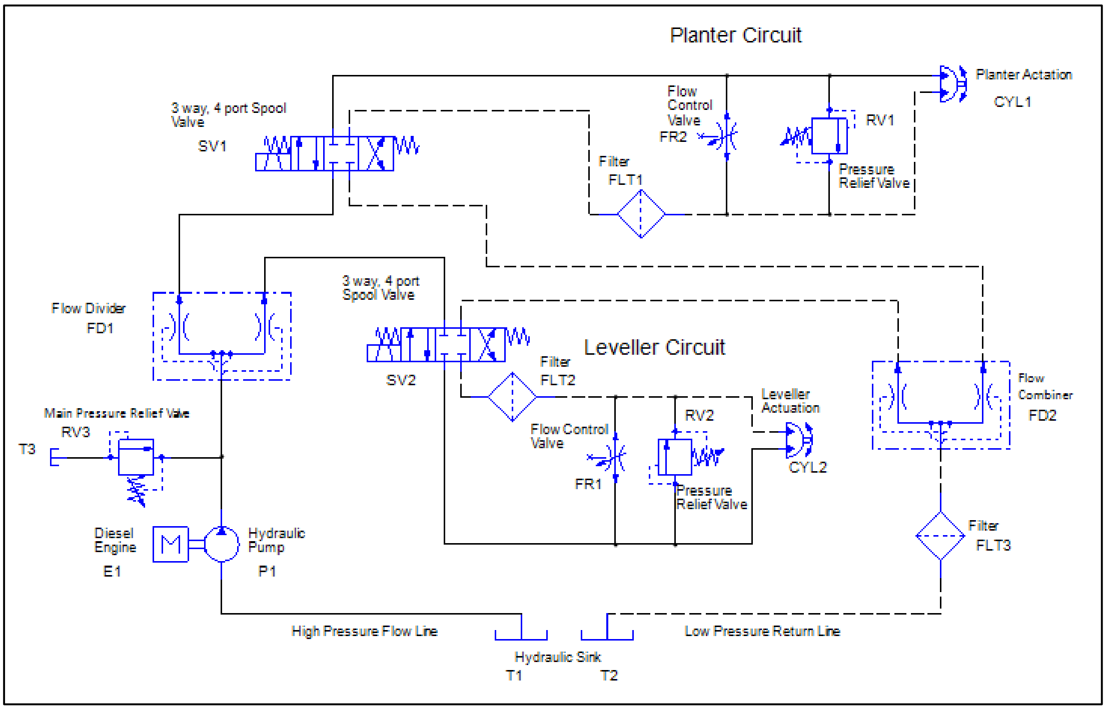


Figure 27: Conceptual auxiliary hydraulic circuit for planting machine and leveller.

In designing a circuit that requires two flow and return hydraulic lines, the number of prime movers with the ability to operate both the planter and leveller effectively from the cab reduces as the third party equipment is not installed at manufacture unless specifically requested. It is possible to use Figure 27 to explain the basic control process for successful operation of each component.

- Powered by the excavator diesel engine, the hydraulic pump draws fluid from the tank around the circuit.

- The main pressure relief valve regulates the maximum flow pressure to the auxiliary circuit. The JS145 has a pressure relief valve regulating the system to 314 bar.
- With the introduction of two auxiliary kits, a flow divider is required to divide the flow equally with other components further along the circuit acting to control the flow rate and pressure.
- Each hydraulic line is then connected to a three way spool valve (detailed design of operation out with the scope of the project). It is important to note that both components will not be required to operate at the same time and so when one spool is open, the other will be closed, locking the fluid in that circuit and preventing motion. This therefore then allows the divider to distribute the flow unevenly in each circuit.
- With an uneven distribution of flow depending on what spool valve is open, the flow rate and pressure must then be regulated according to the requirements of each machine.
    - Planter circuit
        - Flow control valve limits to 100 L/min
        - Pressure relief valve limits to 125 bar
    - Leveller circuit
        - Flow control valve limits to 20 L/min
        - Pressure relief valve limits to 200 bar
- In the low pressure return line, it is appropriate to include a hydraulic filter so as to minimise contamination from the different circuits back to the hydraulic tank. This is a measure to maximise the life of the components,
- Before emptying back into the fluid tank, the return flows are then combined from the two auxiliary return lines.

Filters are required around the circuit to suitably safeguard the system from any contaminants and prolong the life of components. Connecting hoses vary depending on the location in the circuit. The high pressure flow line was sized to have a 19 mm inside diameter, equivalent to a Gates M3K hose, which would be substantial enough to carry flow at approximately 124 L/min and 225 bar. Beyond splitting the flow through the divider, it would be suitable to use hose with a 12 mm inside diameter, again equivalent to a Gates M3K hose so as to maintain the required pressure for operating both the actuator and the planter. M3K hose meets required standards ensuring suitability in high pressure applications and is flexible and easy to route to tight areas. One further benefit is that the hose is protected from collateral damage being braided with two layers of high tensile steel wire. A further critical consideration to design of hydraulic circuits is the implementation of high quality components. Operating under high pressure and flow conditions, failure risk must be minimised as far as possible to ensure safe working conditions for the operator. Quality of components will play a major role in minimising this risk and ensure life in service of the machine is extended.

It can be seen from Figure 27 that the planter and leveller are both represented in the circuit as single actuators. The leveller is a rotational actuator and as such only has one input and one output as represented by the circuit diagram with the required flow rate and pressure entering the chamber. As outlined in section 4.5.1 the leveller was incorporated with respect to existing solutions already on the market but sized accordingly with the enhanced planting machine design.

As previously described in section 3.6, when the group got the opportunity to view the Bracke P11.a in action, it was discovered that the power systems encapsulated within the machine were out with the ability of the group. Also, the scope of the project from the beginning stated that the group would aim to enhance existing planting machinery. After speaking with two operators, it was discovered that there were positive reviews on the internal hydraulic system in the Bracke P11.a. This was with regard to the response time of the cylinders and the accuracy of the computer control. From this it was decided, both as a group and with Simultech that with limited project time, enhancements would continue to be made to mechanical components to improve the overall hard process and not consider the equivalent software processes beside the basic design of major hydraulic components.

4.4 Unchanged Components

Further to identifying the challenges of design for the project, a series of components were modelled for the purpose of the final design but remained unchanged. These components were modelled following close resemblance to any drawings and documentation provided to the group. By analysing the existing Bracke P11.a planting machine, it can be simply represented by four main sections, namely the blade, dibble and casing, carousel and external machine casing. For the purposes of the project, the dibble, casing and external machine casing were all unchanged and modelled as per existing drawings. This decision was based on the opinions of Mr McArthur and a result of the visit to see the Bracke P11.a in operation where the operator was positive of the working of these components.

For the purposes of simulation, the full workings of the sapling planting system were not required and as such, the dibble was simplified. The only requirements for simulation is that the functions of the machine are available and the model can be animated. This simplification was also a result of a lack of information available explaining how the centre dibble system worked. When the group viewed the P11.a in operation it was not possible to fully dismantle the planting machine on site and so only select components were visible. Figure 28 illustrates the final model of the dibble mechanism alongside an orthographic projection outlined in Appendix A7. The sapling is ejected from the carousel and dropped through the central tube of the dibble. To insert the beak into the mound a hydraulic cylinder provides linear motion downwards where a second cylinder is used to control the opening and closing of the beak. When the beak is open, the sapling is inserted into the mound.

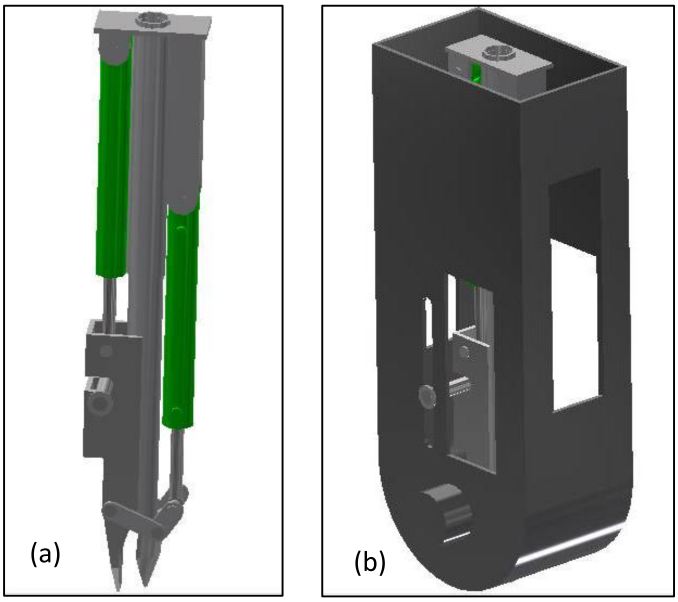


*Figure 28: Final CAD rendering (a) dibble mechanism,
(b) dibble mechanism located within casing.*

The second section unchanged in the model was the external machine casing. This was modelled to represent the existing machine with amendments made to accommodate the integration of each of the major sections. The casing was designed to protect the internal systems from any sudden impact and also the weather. It was further identified that the casing should also protect from dirt and grime during operation. Further, the external machine casing was designed in accordance with the existing Bracke P11.a in terms of material selection. It was identified that the machine casing was manufactured from a medium strength steel with a protective paint finish to minimise the risk of corrosion. This was reflected in the model with consideration of material choice, although not a critical aspect of a model destined for simulation. A final model of the machine casing can be seen in Figure 29 with a further orthographic projection available in Appendix A8.

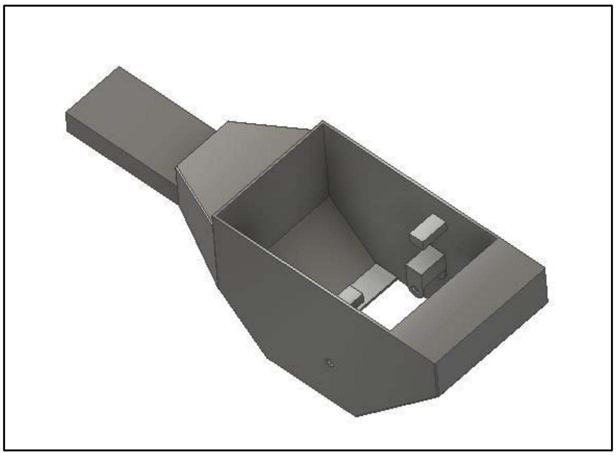


*Figure 29: Final CAD rendering of the external
machine casing.*

4.4.1 Dibble cylinder Design

This cylinder is enclosed within the dibble housing inside the main frame of the planting machine. This therefore made designing this cylinder more complicated what with a lack of detailed information available to the group. However, one constraint of this design was the overall size of the cylinder. The outside diameter of the cylinder was restricted to 50 mm therefore suggesting that the piston head diameter would have to be 40 mm considering a 5 mm wall thickness. The force exerted by the cylinder in this casing was approximated by considering the overall force it would have to overcome in punching a sapling into the mound. This force was assumed to be equivalent to the weight of the mound as it was observed that the dibble was not required to move soil in the mound but just exert a force capable of breaking the mound surface to create a divot for the sapling. By considering the bulk density of soil in section 4.3.1 the required force was assumed to be 1295 N.

$$P_{c2} = \frac{W_s}{A_{c2}} \tag{8}$$

$$P_{c2} = \frac{1295}{\frac{\pi}{4}\ x\ 0.04^2}$$

$$P_{c2} \cong 1.03\ MN/m^2 \cong 10\ bar$$

In the design of this cylinder, the stroke length was based upon the displacement of the dibble to insert the sapling the required distance into the mound. By considering the predicted size of the machine, the stroke length was selected to be 400 mm. A simple schematic can be seen in Figure 30.

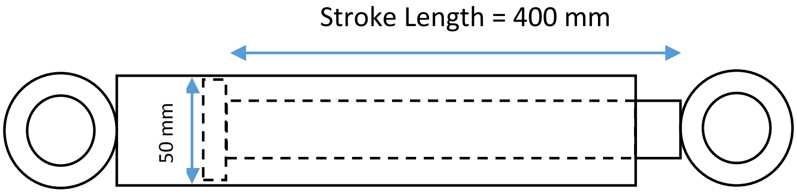


Figure 30: Dibble cylinder dimensions.

In a similar analysis, maximum buckling load was calculated to ensure the selected cylinder was of a suitable size for operation. Again, the Euler buckling theory was used with similar values as before however using a smaller cylinder, therefore piston rod diameter, d = 25 mm and buckling length, L = 800 mm. Maximum force to avoid buckling is:

$$F_L = \frac{K}{S} \tag{9}$$

$$K = \frac{\pi^2 EJ}{L_{c2}^2} \tag{10}$$

$$J = \frac{\pi d_{c2}^4}{64} \tag{11}$$

$$F_L = \frac{\pi^3 EJd_{c2}^4}{64L_{c2}^2 S}$$

$$F_L = \frac{\pi^3\ x\ 200x10^9\ x\ 0.025^4}{64\ x\ 0.8^2\ x\ 3.5}$$

$$F_L \cong 16900\ N$$

From this it is possible to identify that the approximate maximum buckling load on this smaller cylinder is 16900 N, which is again much less than the expected load through the cylinder. It can be assumed in this analysis that the cylinder is more than suitable for operation with the main operation to pierce a hole in the mound to insert a sapling.

4.4.2 Universal Hitch Analysis

Further to discovering the requirement for a universal hitch as a coupling point for any attachments to a 360° excavator, one was modelled based upon an existing design used frequently in forestry. This provided a mounting point for the computer simulation model and was not enhanced through the detailed design phase in any way. An orthographic projection of the universal hitch can be seen in Appendix A9. However, to ensure the hitch would be adequate for use in attaching the planting machine to an excavator, a simple FEA study was conducted to analyse the approximate maximum stress locations across the component and ensure minimal deformation occurred as a result of the applied loading.

Using ANSYS Workbench, the component was meshed accordingly using a fine relevance and small edge length to enhance the computational solution. Further, refinements were focussed around the fixing pin holes where the hitch would be rigidly constrained and the attachment mounts where loading would be applied. Fixed supports were introduced around the fixing pin holes to represent where the hitch would be rigidly attached to the dipper cylinder. A simplified load was applied around the attachment mount area to represent a typical loading scenario considering maximum breakout force as provided by the excavator, weight of the planting machine attached to the hitch and resistance force of moving the required weight of soil (see section 4.3.1). A simple free body diagram can be seen in Figure 31.

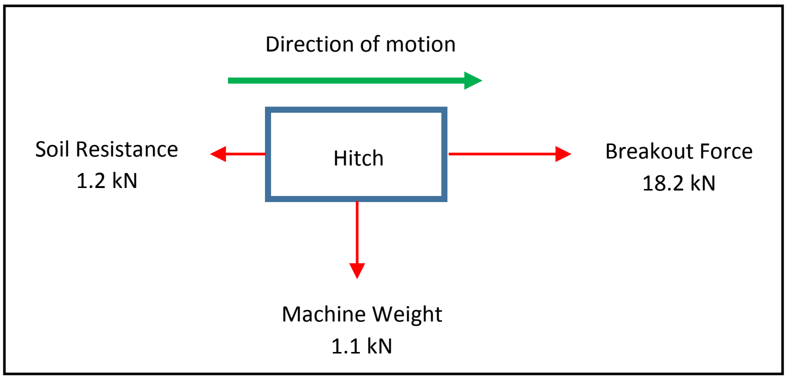


Figure 31: Free body diagram of hitch.

Results of the computational analysis can be seen in Figure 32 illustrating the maximum deformation and maximum principal Von-Mises stress as a result of the applied loading. It was found that the component deformed a maximum of 0.239 millimetres, suggesting negligible movement as a result of manufacturing from high tensile low carbon steel. Using this material, the yield stress is typically ≈400 MPa and the component was found to have a maximum stress of 243.8 MPa. Both maximum stress and deformation were identified to occur around the front face of the attachment mound at a location of least material usage. However, it is possible to note that the maximum stress identified in the hitch exists below the yield strength of the material and as such can be deemed safe for operational attachment of the planting machine.

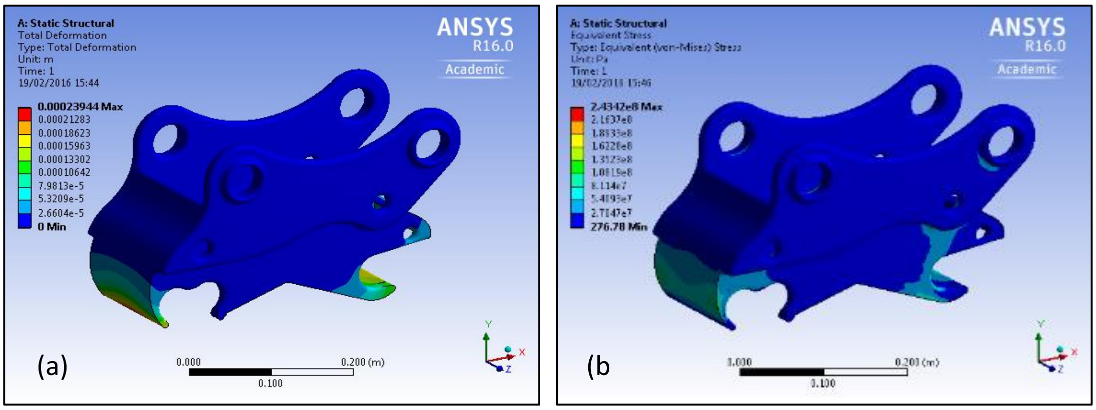


Figure 32: (a) Total deformation and (b) Von-Mises equivalent stress.

4.5 Design Improvement Focus

4.5.1 Hydraulic Leveller

4.5.1.1 Conceptual Design

In the early stages of the project design, members of the group met with representatives at ScotJCB to discuss what prime mover from the excavator range would be most suited to forest operations. The JCB JS145 excavator was selected for its mid-range weight and ability to perform a wide variety of tasks from the universal hitch located at the dipper. It is important to note that JCB was selected to provide a basis for design and because a local contact was available however the final design would allow for attachment to a wide range of mid weight excavators available from varying manufacturers. Throughout these meetings, the manoeuvrability of the attachment was discussed as it was outlined from the PDS that the device would be required to operate on a variety of terrains and gradients and would also be required to maintain verticality during planting. The problem presented to the group was that all the required movements would not be available from the excavator itself and an auxiliary rotating attachment would be required to provide further movements.

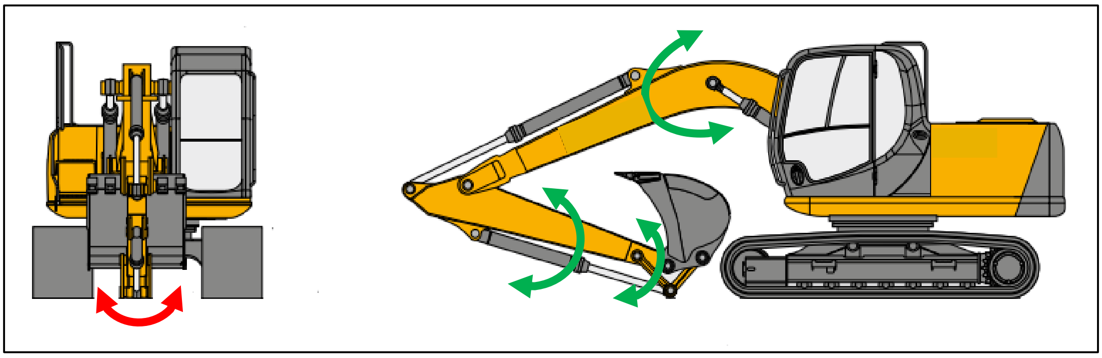


Figure 33: Excavator rotations.

Figure 33 illustrates the rotations and movements available from the prime mover (shown in green) and the rotation that is further required (shown in red), should the excavator have to plant on a gradient and still maintain verticality. From the critical analysis, two potential options were outlined, namely the Engcon Tiltrotator [36] and the Helac Powertilt [28]. Comparing the mechanisms and movements of both devices, and further identifying the additional rotations required, it was soon apparent that although a very versatile device, the

Tiltrotator was over specified for the requirements of the planting machine. Further to this, the Tiltrotator was also able to rotate any further attachments, however when planting, orientation of the sapling being inserted into the ground was irrelevant. Table 6 outlines the specs of the two devices for comparison.

Table 6: Leveller specifications

	Engcon Tiltrotator EC15B	**Helac Powertilt PT10**
Weight (kg)	360+	385
Tilt Range (degrees)	80	134
Flow Rate (L/min)	80	20

Overall, by considering the requirements of the levelling device, the Powertilt provides the required motion along one axis at a fraction of the power requirements of the Tiltrotator. From section 3.4.8 the Powertilt is also a lot smaller than the Tiltrotator meaning that it will be more easily integrated into the final design of the planting machine. This is an area where the group were able to conceptualise the requirements of the planting device, investigate the products existing in the market and design according to this, meaning time could be distributed to focus on more involved components requiring further design.

4.5.1.2 Detailed Design

Following on from the conceptual design of the leveller device, it was decided after investigation that with a device performing very effectively in the market at present that incorporating an existing component into the detailed design phase would prove more effective than designing a similar component from the beginning.

After considering the advantages and disadvantages of two existing leveller devices on the market, the most effective design for implementation was the Helac Powertilt due to its simple functionality, low weight and ability to actuate rotational motion over a larger angular range. After contacting Helac Inc. for more information, it was discovered that a lot of detailed information would not be available to the group for concern of infringing IP rights. However, as the scope of the project was to identify enhancements for existing planting machines, the group were able to conceptually design the leveller device based on information and develop a model based on basic dimensions and exploded drawings that were available on the public domain. These documents can be seen in Figure 34.

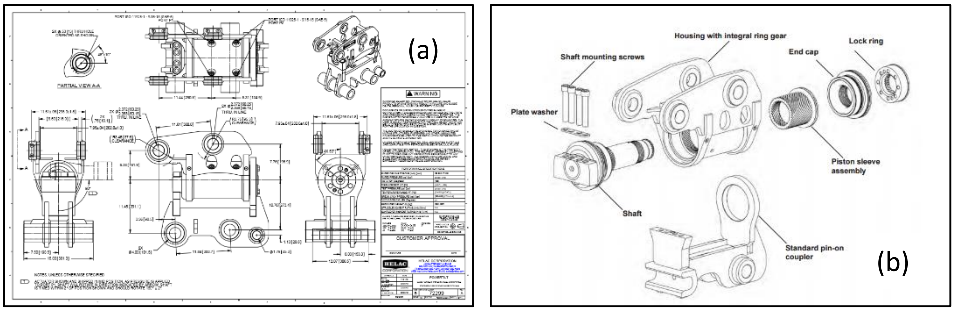


Figure 34: (a) Orthographic projection of leveller, (b) Exploded assembly of leveller [26].

It is important to note that for the purpose of modelling and with respect to the time constraint on the group for the project that the actuator was simplified but still designed so as to perform the required operation for the purposes of a proposed simulation model. With limited dimensions, the device was designed around the top housing with solid steel bars mounted in place of the pin holes. This was incorporated into the design so as to meet the criteria of attaching directly on to the universal hitch with little interaction from the excavator operator. The final modelled component can be seen in Figure 35 with a full dimension drawing available in Appendix A10.

Figure 35: Final CAD rendering of hydraulic leveller.

4.5.2 Scarifying Blade

4.5.2.1 Conceptual Design

The scarify blade is the component that makes first contact with the ground in the planting process. Its primary function is to prepare a mound of soil suitable for a sapling to be planted in. Second to this, the blade also acts as a compaction mechanism to ensure the sapling is secure in the mound. The potential challenges that the group identified after meeting with representatives in industry were that existing machines had no way of quantifying that the required mound volume was approximately uniform every time. It was identified that some existing machines were better at aerating and compacting the soil than others. As with any other existing designs, it was required that the blade should be strong and stiff and be able to overcome shock loading from roots and rock below the surface.

The sub-team looked to identify where possible improvements could be made to the most common existing design, namely the Bracke P11.a and sketched a number of possible concepts to be put forward for analysis and discussion. The most promising concepts selected for the blade design can be seen in Figure 36.

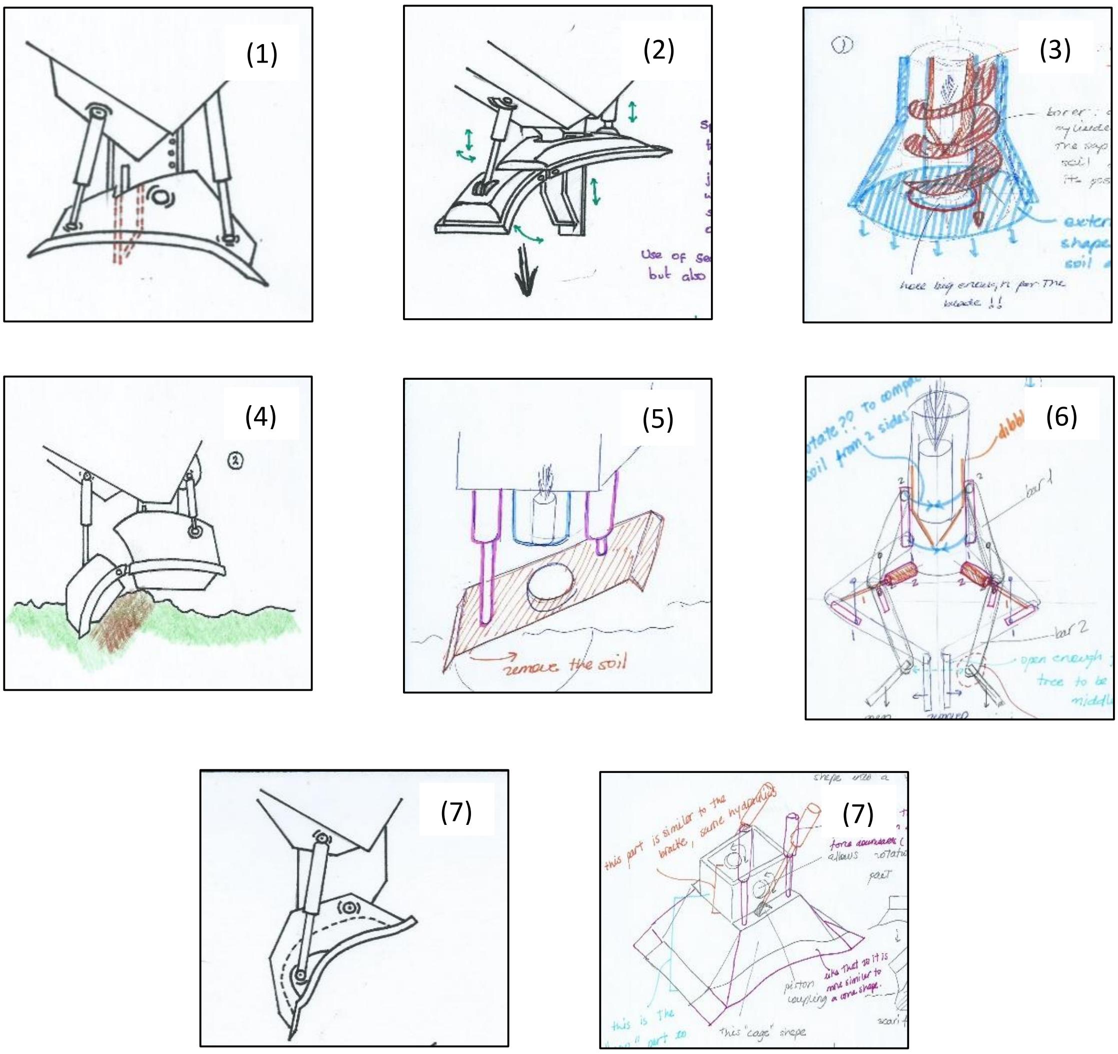


Figure 36: Scarifying blade conceptual designs.

It can be seen that a wide range of possible concepts were harnessed from the morphological chart and each try to consider the criteria of the PDS in a different way. Such examples from above include applying spill guards (4) to the blade to control the mound volume, using a rotating auger (3) to help with soil aeration. Design (5) considers the actions of the existing P11.a and simplifies the design to a flat plate controlled by two linear displacement cylinders.

From these concepts, a Controlled Convergence Matrix (CCM) technique was used from Stuart Pugh's Total Design [37]. This is an iterative concept selection technique where different designs are compared against a datum design and rated with respect to chosen criteria. Criteria was chosen based upon its applicability from the PDS. An example of one of the iterations carried out can be seen in Table 7.

Table 7: Controlled convergence matrix for scarifying blade

Controlled Convergence Matrix: Scarifying Blade							
CRITERIA	CONCEPTS						
	1	2	3	4	5	6	7
Operation on variable terrain		s	-	s	s	-	s
Capability of creating mounds with specific dimensions (20-30cm high and 0.25m^2).		s	-	+	-	-	+
Operation in adverse weather conditions	D	s	s	s	s	s	s
Corrosion resistance		s	s	s	s	s	s
Operation in various soil conditions	A	+	-	+	+	-	+
Resistivity to shock loading		s	-	s	+	-	s
Operation in dirty environment	T	s	s	s	s	s	s
Consideration of compaction and soil aeration		+	+	+	+	-	+
Access to components	U	s	-	s	s	-	s
Ease of Maintenance		-	-	-	s	-	s
Ergonomic design	M	s	s	+	-	-	+
Ease of operation		-	-	-	-	-	s
Life in service		s	s	s	s	s	s
Number of parts		+	-	-	-	-	s
Ability to perform localised scarification		+	+	+	s	s	+
Resistivity to temperature extremities		s	s	s	s	s	s
Weight		+	-	-	+	-	+
Response time		-	s	-	-	-	s
Sum of +		4	1	5	4	0	6
Sum of -		4	9	5	5	12	0
Sum of s		10	7	8	9	6	12
Score		0	-8	0	-1	-12	6

Along with further iterations, each time changing the datum, concept seven was a continued success following on similarly from the existing design of the P11.a but incorporating a hollow volume to help ensure the approximate target mound volume was achieved during every planting cycle. Further, the design also employs a serrated tooth edge along the leading edge to help achieve better aeration when the soil is being mounded as well as break the surface easier in colder climates when the ground is harder.

4.5.2.2 Detailed Design

Progressing to the detailed design phase for the blade design, the final solution from the CCM was carried forward for detailed design to ensure it would be fit for purpose in operation. From the conceptual design, criteria to focus on while finalising the design included:

- Ensuring structural rigidity was not compromised.
- Considering wear resistance to extend life in service.
- Ensuring the appropriate mound dimensions were formed while in operation.
- Considering aeration when mounding and compaction when inserting the sapling into the soil.

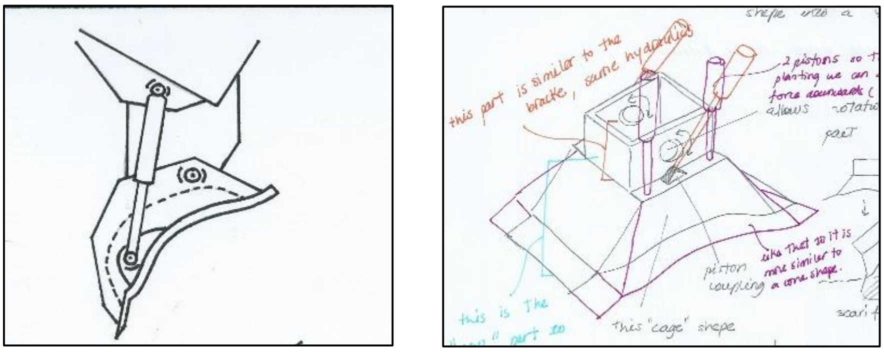


Figure 37: Final blade designs for detailed design.

Figure 37 illustrates the final solution that was developed as an enhancement to existing designs. It can be seen that the new design follows existing operational principles with the extension of the hydraulic cylinder to protrude the cutting edge and maximise penetration depth with the least force. The biggest design difference extends from the criteria outlined in the PDS stating that from Forestry Commission literature [5] a specific mound size and volume are favoured. This is to try to optimise the number of saplings planted over the entire land area and also help to ensure that sufficient soil surrounds the sapling root area to ensure suitable stability and maximise survival rate.

Taking forward sketches from the conceptual design phase, the final design was created on Autodesk Inventor 2016. This can be seen in Figure 38 with a detailed drawing outlining all major dimensions in Appendix A11.

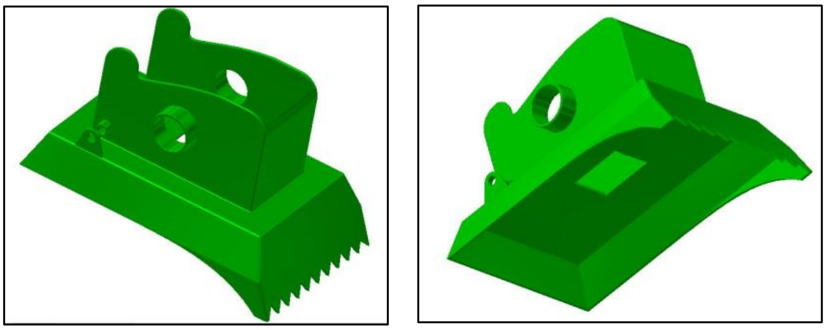


Figure 38: Final CAD rendering of scarifying blade.

From Figure 38 it can be seen that the optimised design is based loosely on existing shapes from similar planting machines. Throughout the critical analysis phase, where different machines were investigated, it was identified that the profile of the blade has very minimal variation across the different manufacturers. From this, the sub-group focussing on blade design decided to focus on enhancing the component using a similar profile as it was recognised from existing machines to be acceptable in operation.

The critical enhancement introduced into the blade was the hollow internal volume designed in line with following the mound size requirements. The prismatic trapezoidal volume of the blade was integrated into the design to both act as a gauge corresponding to the correct volume of mound required but also to better direct the soil while being inverted. One further design enhancement was derived from existing soil aeration machines. Figure 38 illustrates a series of protruding teeth across the primary mounding edge of the blade face. This was incorporated in to the design as a means of better aerating the soil during the mounding process so as to provide a better growing environment for the sapling once inserted into the ground. Similar to the design of earth moving buckets, teeth also provide a means of stability should the excavator be operating on a gradient and so this was established into this design also as a precautionary safety feature should the excavator require to be stabilised.

Compaction Test

Further to identifying the final design of the scarifying blade to be that of the hollow volume design, a simple experiment was set up to compare the compaction qualities of this enhanced design against the existing design implemented on the Bracke P11.a. The experiment was designed to illustrate basic soil compaction qualities of each design so as to draw a conclusion on the effectiveness of the new design. An illustration of the experimental setup can be seen in Figure 39. Two blade profiles were manufactured by 3D printing to 1:10 scale. By measuring the approximate displacement of each blade after applying a specified load, compaction characteristics of each design could be identified and compared across the two designs.

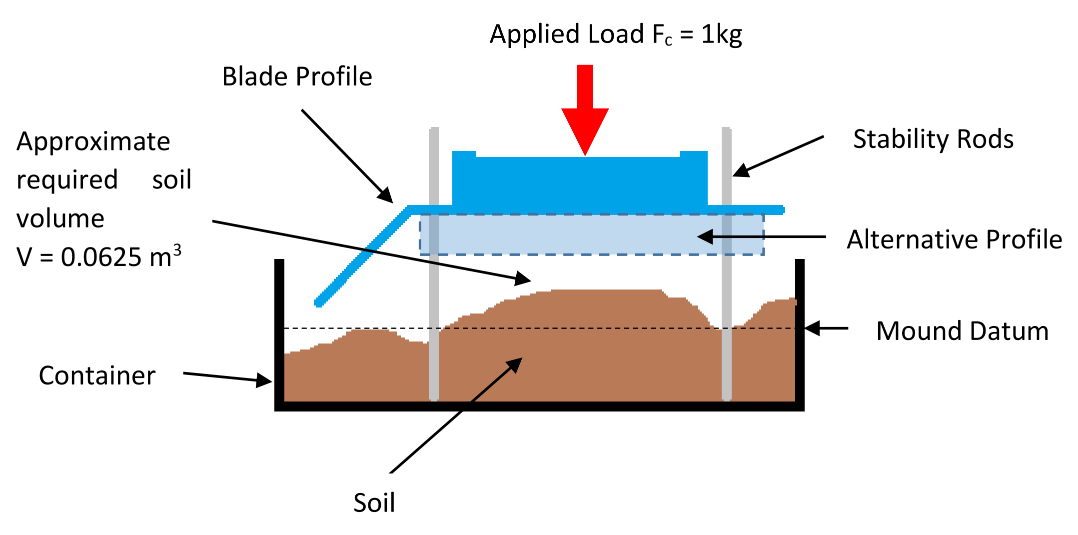


Figure 39: Experimental setup for compaction testing.

A specified volume of soil was formed using a 3D printed capsule that was designed to the required mound dimensions, $V_s = 0.0625\ m^3$, approximate $W_c = 0.037$ kg, before being mounded into the experimental container. This volume and weight were kept constant throughout the experiment. Stability rods were fixed to the base of the container and positioned so as to insert around all four corners of each blade profile. This ensured that the orientation of the profile was the same throughout each test. From the mound datum, the initial height of the mound was measured for each test and an applied load of 1 kg exerted onto the blade profile to create a compaction force on the soil. The final height of the mound was then measured and the absolute displacement of the blade profile calculated. This test was conducted five times for the two blade profiles so as to minimise experimental error and draw a more affirmed conclusion.

The results of this experiment can be seen in Figure 40. It can be seen that across the five tests, there was very little significant variance in the displacement between the two blade profiles. This may not be the case at full scale however as these models were printed to a reduced scale it may have had a result on the overall compaction capabilities of each design. Although these results do not show a significant variation in the overall compacted displacement for each design, it was evident to see that after each compaction test, the enhanced design had produced a more refined mound than that of the Bracke equivalent. This observation is important as it outlines that the refined design was more capable of producing a mound of similar compaction quality but with a more defined mound shape.

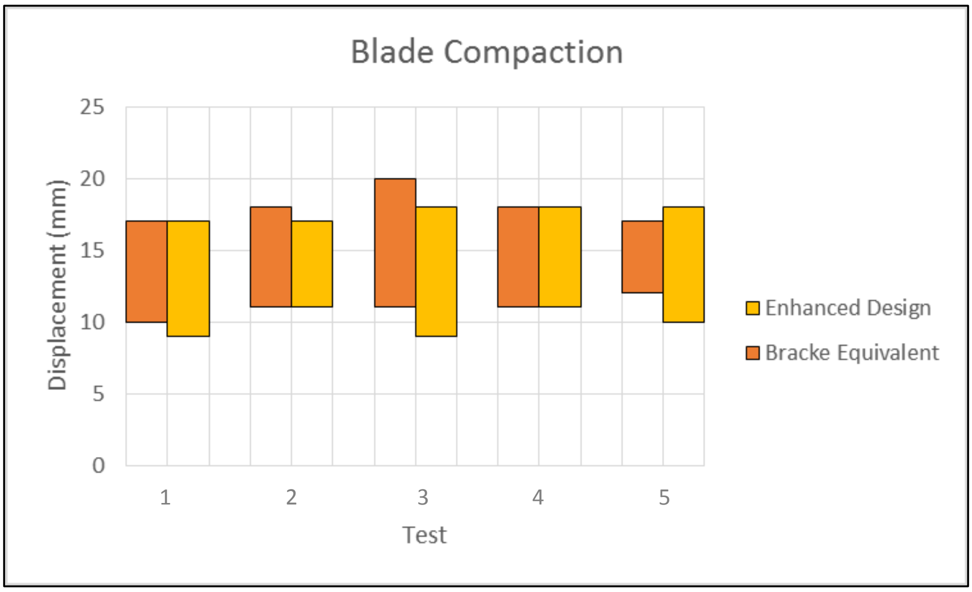


Figure 40: Plot of blade displacement during testing for various profiles.

From an early stage in the project, it was outlined to the group by the Forestry Commission that the shape and size of the mound was critical to the survival of a sapling. Having a more defined, protruding mound provides a more stable base for the sapling so as to be protected from the weather. From this small experiment, it can be concluded that the enhanced design performs with similar capabilities to that of the existing machine in terms of mound compaction displacement. This is understandable as the two blade profile are very similar however by adding the hollow volume section, each mound becomes more refined as the blade acts to control the volume of soil and as such prevent the mound from collapsing as the sapling is inserted.

By basing the design analysis for the blade around information available from Caterpillar [38] it is possible to identify the typical conditions expected to be operated in by the blade creating a mound. This can be seen in Figure 41.

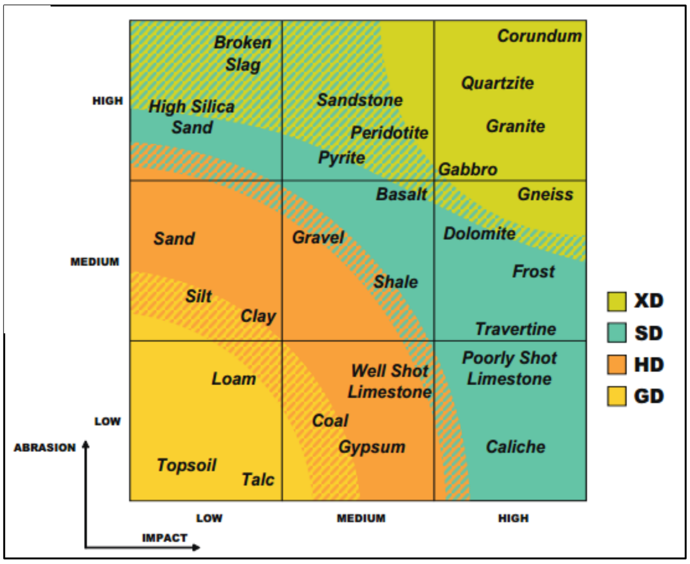


Figure 41: Soil conditions vs. bucket design [38].

It can be identified that the blade will be required to operate in conditions similar to those of general duty (GD) and heavy duty (HD) buckets on excavators. This provides a basis for design by suggesting that the blade should be able to withstand a suitable degree of shock loading and be further resistant to wear than other components. After making a site visit to view the existing Bracke planting machine, it was identified that all components classified as operating under high loads had been manufactured using 10 mm steel plate including any reinforcing bracings across the blade and mounting points. It is important to design for wear resistance and to minimise the amount of bending taking place in operation. One design technique employed here was designing to existing conditions. By identifying the existing thickness of the blade plate, it was assumed that this same thickness could be employed in the enhanced design as it was identified that the new blade profile would be operating under very similar conditions.

Important of the design of the blade was ensuring the position of the hydraulic ram was suitable to ensure effective operation and minimised risk of failure under high loading forces when mounding. From the visit made to Christie Elite Nurseries to see the Bracke P11.a in action, it was identified that the greatest loading conditions on the blade occurred during mounding. For this reason, an FEA analysis was conducted to investigate the most effective position for the hydraulic cylinders to be mounted. Two designs were analysed and can be seen in Figure 42. Design consideration (1) suggests mounting the cylinder pin close to the blade edge so that in the mounding position the cylinder is fully extended, retracting once the mounding cycle is complete ready for compaction. Design consideration (2) suggests mounting the pivot pin at a greater distance from the blade edge. At this position, the cylinder is fully retracted when mounding then extending for compaction.

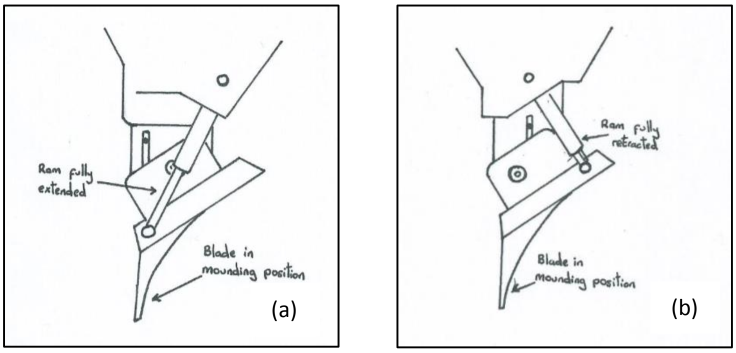


Figure 42: (a) Cylinder fully extended during mounding process (Design consideration (1)), (b) Cylinder fully retracted during mounding process (Design consideration (2)).

This analysis was developed to investigate equivalent stresses that occurred in the piston rod at two different positions after loading during mounding. It is important that stress in components is kept to a minimum, not exceeding maximum yield strength at any point during operation. Also critical to consider is potential impact loading that may occur in operation. When this occurs, stresses in machine components will be much higher but only applied over a short period of time. These stresses are difficult to predict however, ensuring maximum stress occurring through static loading is maintained well below yield ensures a safety factor for sudden stress fluctuations.

Using ANSYS Workbench, the component was meshed accordingly using a fine relevance and small edge length to enhance the computational solution. Further, refinements were focussed around the pivot pin holes and the piston rod. For each design consideration, support constraints and load conditions were identical, where fixed supports were applied around the pivot pin holes and loading was applied around the piston rod. Applied loads were simplified to consider only excavator break out force and soil resistance in the z-direction. In the y-direction, the approximate weight of the mounding blade component was also considered. A schematic of these loading conditions can be seen in Figure 43.

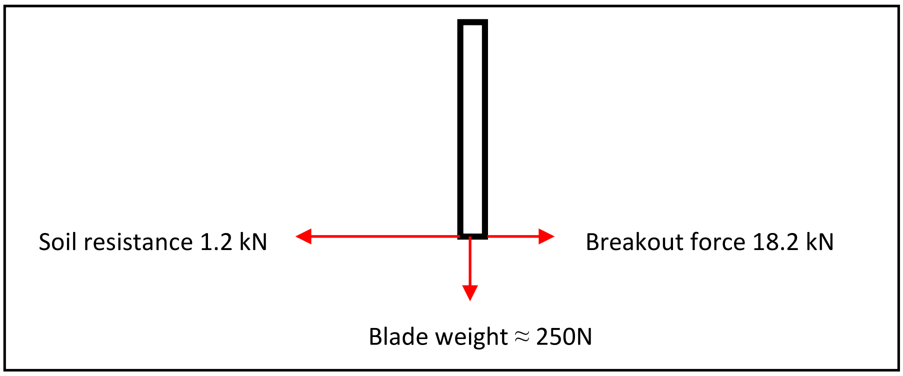


Figure 43: Free body diagram of cylinder with applied forces.

Although a relatively simple analysis, the results provided a means of confirmation of a design consideration important to the success of operation of various critical machine components. The results of the two design considerations can be seen in Figure 44. From these plots it can be observed that large stress variations exist depending on the position of the piston rod under the same loading conditions. As has been identified, it is critical to ensure a low stress magnitude across all machine components. Although it can be seen that the maximum stress magnitude of the two analyses is 332 MPa, which is lower than the material yield strength, it is important to consider a generous safety factor in case of impact loading.

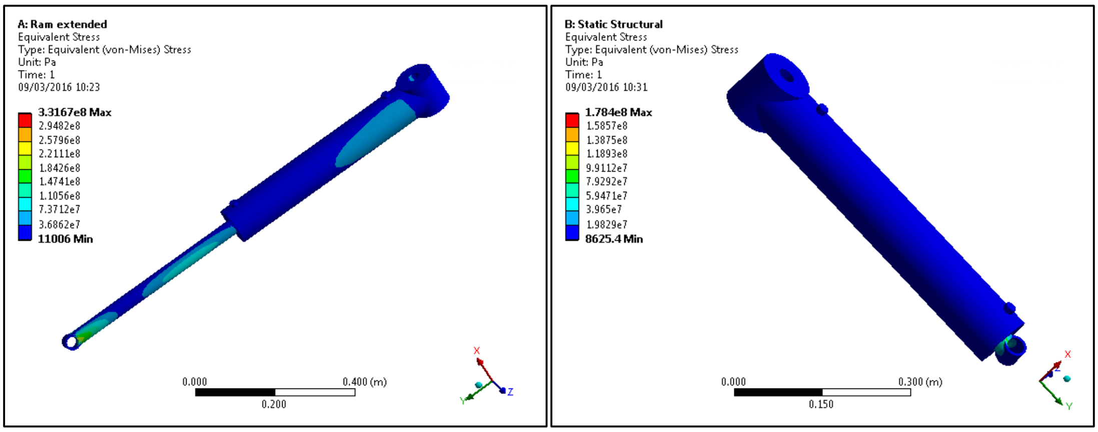


Figure 44: Plot of equivalent stress, (a) cylinder fully extended and (b) cylinder fully retracted.

It can be concluded that design consideration (2) is a more appropriate concept and follows a similar operating principle to the Bracke P11.a. By applying the greatest load to the cylinder in the retracted position, the rod is more constrained within the cylinder bore and as such has a greater resistance to deformation under loading. Another benefit of conducting the mounding process in the retracted position minimises the risk of contamination on the piston rod. When mounding takes place, the soil is being moved and as such creates a potential for debris to stick to machine components. In order for operation to be as smooth as possible, contamination risk must be negligible and as such conducting the dirtiest operation in the retracted position further reduces this risk.

4.5.2.3 Blade Cylinders Design

This cylinder requires to overcome the resistance of the soil as a mound is created and as such is the largest cylinder on the machine. Two cylinders were designed to operate to provide the actuated motion and also reduce the overall load on each cylinder. An important consideration in this design is the occurrence of compression loading on the piston rod. When mounding the soil, a compression force will be induced on each rod and as such, each cylinder should be designed in accordance to this, over-sizing if necessary to ensure risk of failure is minimised. For the purpose of this design, the cylinder was sized in accordance to the equivalent Bracke machine, knowing the approximate diameter of the piston head (80 mm) and assuming the cylinder to have to overcome the overall breakout force provided by the machine (16500 N). This then allowed for an approximation of the required supply pressure of the cylinder to be found.

$$P_{c1} = \frac{F_B}{A_{c1}} \tag{12}$$

$$P_{c1} = \frac{16500}{\frac{\pi}{4}\ x\ 0.08^2}$$

$$P_{c1} = 3.28\ MN/m^2 \cong 33\ bar$$

By designing to the specifications as outlined by the equivalent Bracke P11.a, it suggests that the cylinder will be more than suitable for the application and also considering the action of two cylinders operating to provide the same movement. Another important consideration in designing this cylinder is the stroke length of the piston rod. For the purpose of this design, the stroke length was designed to be 505 mm. A simple schematic can be seen in Figure 45.

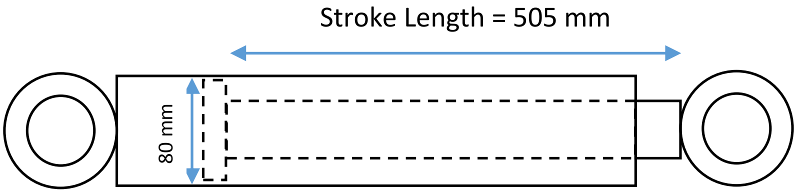


Figure 45: Blade cylinder dimensions.

By identifying the approximate working pressure of the cylinder it is also important to consider the piston rod diameter and ensure it is suitable for use in operation in terms of being able to operate without buckling. The Euler buckling theory can be used to calculate the maximum bearable force to avoid buckling [35]. Critical dimensions of this analysis include piston rod diameter, d_{c1} = 40 mm, buckling length, L_{c1} = 1010 mm, Young's modulus of steel, E = 200 GPa, factor of safety, S = 3.5. Further expressions used also include buckling load, K and inertia of the rod cross section, J. Maximum force to avoid buckling is:

$$F_L = \frac{K}{S} \tag{13}$$

$$K = \frac{\pi^2 EJ}{L_{c1}^2} \tag{14}$$

$$J = \frac{\pi d_{c1}^4}{64} \tag{15}$$

$$F_L = \frac{\pi^3 EJ d_{c1}^4}{64 L_{c1}^2 S}$$

$$F_L = \frac{\pi^3 \ x \ 200x10^9 \ x \ 0.04^4}{64 \ x \ 1.01^2 \ x \ 3.5}$$

$$F_L \cong 69500 \ N$$

It can be seen from the solution that the approximate maximum load to prevent buckling is 69500 N, which closely resembles the maximum breakout force that can be applied by the excavator without any attachments. However, it has been identified that the maximum breakout force as a result of the planting attachment is much lower than this and as such it can be concluded that the cylinders used to pivot the blade are suitable for operation. It is important to note that the cylinders were designed predominantly to ensure a suitable stroke length was available alongside an adequate force. As such, in other aspects of the design the cylinders appear oversized but this ensures a further factor of safety.

4.5.2.4 Material Selection

Throughout the design phase for any industrial application, appropriate materials must be selected for manufacture based on a wide range of properties and conditions that need to be met in order for the component to be successful in the operating environment. Referring back to the PDS developed earlier in the project, see section 4.1.1, a number of criteria were outlined relating to material choice for the design of the blade, and where materials selected must be:

- Corrosion resistant.
- Resistant to impact loading.
- Resistant to scratching and denting.
- Operable across a wide temperature range.
- Lightweight as far as possible, at the same time not compromising strength and rigidity.
- Malleable and formable for standard manufacturing processes.
- Readily available so as to reduce cost.

From the criteria outlined above, material choice is overall limited as it is important that the final design strives to meet all criteria. However, in the design of the blade, compromise is required. An example of this may include selecting a high strength, lightweight composite material such as a glass or carbon composite which would be ideal in a lot of applications however on the contrary to this, composite materials of this form require more complex manufacturing processes and are available only at a premium cost, therefore making metals a more favourable choice.

To aid the selection process for material design of the blade, and similarly other components, the CES Edupack database was used, helping to rank materials in an order with respect to the selected criteria. The first stage of selcting materials in a design analysis always involves outlining the properties of all possible materials in terms of two major criteria. This allows for an Ashby diagram to be developed allowing for a visual inspection of the basic suitability of materials. The plot was developed with density against Young's modulus. This can be seen in Figure 46.

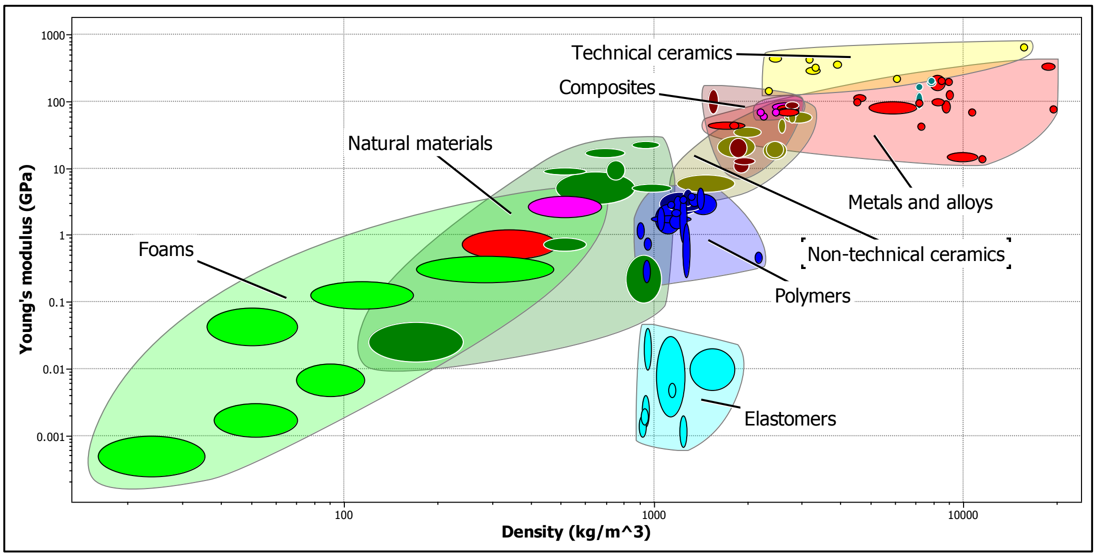


Figure 46: Density vs. Young's modulus for all common materials.

From Figure 46 it is possible to see visually that some materials are a lot more flexible and lighter than others. A simple inspection allows the designer to eliminate unsuitable materials and focus on the most appropriate material families. Another look at the criteria from the PDS yields the most appropriate materials to be composites and metals. Polymers would be suitable for some applications however in heavy machinery design stiffness and rigidity is vital under various loads in different environments. On the other hand, ceramics are a very stiff but brittle material that perform well in compression, however one of the criteria states the machine must be able to overcome impact loading and so this this material would again be unsuitable.

Figure 47 makes a comparison between metals and composites by considering Young's modulus against approximate price per kilogram. This is a good comparison as it shows that although the relative stiffness of the two types of materials are approximately the same, there is an order of magnitude difference in the price between conventional metals and more complex composites.

Investigating select materials further, carbon fibre and glass fibre reinforced composites CFRP and GFRP respectively are modern materials developed by laminating a series of layers of continuous fibres all bonded in an epoxy matrix. With a very high strength and stiffness, they are favourable in high strength applications and are capable of withstanding shock loading however, the manufacture process is very labour intensive and therefore more expensive. Manufacturing a component from composites is very complex as joining presents an opportunity for significant stress concentrations and any holes cut into the material reduces the failure strength.

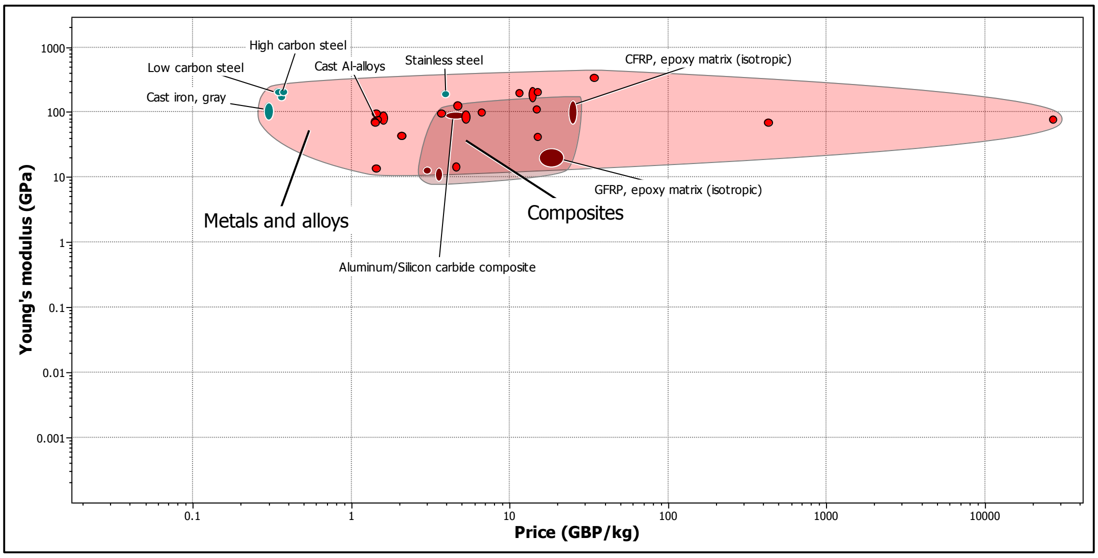


Figure 47: Plot of Price vs. Young's modulus for metals, alloys and composites

Identifying the various metals available, there is a very wide price range for a relatively uniform stiffness. To optimise the cost of manufacture and not compromise on strength and stiffness, carbon steel would be an appropriate choice as seen from Figure 47. By increasing the carbon content in the metal, the designer can optimise the surface treatments applied to the steel. A further advantage of using metals over composites is that composite materials are affected by moisture, heat effects and fatigue loading. Surface treating a more complex material like CFRP would considerably increase costs beyond need for an industrial machine therefore again making carbon steels more favourable in this particular design.

From information provided from brochures from manufacturers of heavy equipment, the material of choice is high strength carbon steel. One potentially detrimental concern of using this material is the effects of corrosion. In the varying environment that this planting machine will be required to operate in, moisture and temperature fluctuations will all affect the material in such ways to cause rusting or affect the machine structurally. Therefore, it is important in the design phase of the machine to consider how the materials used in design would be surface treated to maximise its life in service. Common methods that would present the best protection at the cheapest price may include galvanising or applying a hot metal flame coating, the latter having less effect on surface distortion of the metal. To finally finish off the component ready for assembly, a paint coating could be applied to create a further protection layer and to aid aesthetic appeal.

From this it is possible to conclude that the most suitable material for the blade design is high strength carbon steel. With a wide range of options for prior heat treatment processes before entering service provides an opportunity to ensure the material is well equipped for use in a varying environment at a cost effective price. It is also possible to conclude that although various materials meet all the criteria of the PDS, the high strength steel does so at a fraction of the price, and at a greater availability.

4.5.3 Sapling Reloading

Current sapling loading processes were found to be time-consuming due to the piecewise nature of loading [39]. That is to say, loading sapling-by-sapling. It has been estimated that modern planting machines occupy 15-20% of productive working time in a non-operative position as the operator manually loads the carousel with saplings [40] [41]. Whilst in the non-operative position, the machine's capital costs and operator's wage are still present while production of the machine is zero [42].

On a site visit to view a Bracke mechanical planting machine, the project group observed a reloading cycle completed by an experienced operator. It was noted that it took the operator 2 minutes 52 seconds to completely reload the Bracke's carousel. When averaged over the 70 saplings reloaded in each cycle this equated to roughly 2.46 seconds per sapling. Over a typical ten hour shift when operators are expected to plant as many as 1200 saplings this resulted in a total reloading time of 50 minutes, 8.2% of the productive working time of the machine. It was noted that time was small compared with those from literature and highlighted the importance of an operator with good experience to the performance output from mechanised tree planting.

4.5.3.1 Existing Concepts

Existing Carousels (Piecewise)

The piecewise loading utilised by modern planting machine is a low-tech and robust method which enables a degree of flexibility to planting operations. The low-tech nature of the devices ensure maximum machine availability by reducing the number of components which can possibly break down. Study found that there were two most common types of piecewise loaded carousels used in mechanised tree planting: rotary carousels and linked-cassette carousels. Examples of each type are given below.

<u>Rotary Carousels</u>: The two most common mechanised planting machines in use today, Bracke P11.a and Risutec, both utilise a piecewise loaded, rotary controlled carousel. Examples of these carousels can be seen in Figure 48. The Bracke carousel is composed of 72 cassettes arranged in two concentric circular arrangements, offset such that only one circle presents a sapling to the planting tube at any given time. The required rotary movement is applied to the carousel by a hydraulic ram connected to a feeding head. On the other hand, the Risutec device consists of 120 cassettes in three concentric circles. However, this carousel is only suitable for smaller saplings.

Figure 48: Rotary Carousels: (a) Bracke P11.a [10] (b) Operator manually loading Bracke P11.a carousel [10] (c) Risutec carousel [12].

<u>Linked-Cassette Carousels</u>: This type of carousel is evident on both the M-Planter and the EcoPlanter devices. Examples of which can be seen in Figure 49. It operates by having all the cassettes connected or banded together and using smaller rotational parts to create connected motion through all of the cassettes, again to feed a single location leading to the planting tube. The EcoPlanter device has the largest capacity of all current planting machines, holding 200 saplings [43], but these saplings must serve two planting heads. In comparison, each planting head of the M-Planter is served by a storage capacity of 122 saplings [44].

Figure 49: Linked-Cassette Carousels: (a) EcoPlanter (b) EcoPlanter Carousel [57] (c) M-Planter [6].

Process

Not only concerned with reducing the manual reloading time, the group investigated the whole process of a sapling's journey from germination through to planting into final location by machine. It was hoped that other areas or components of the process could also be made more efficient and thus increase the profitability of mechanised tree planting. First, the existing process had to be understood. Using a piecewise loaded carousel, such as the Bracke P11.a, the process can be seen in Figure 50.

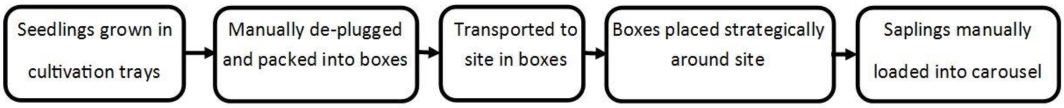


Figure 50: Original process associated with the Bracke P11.a.

Each of the other carousel concepts was considered with the entire process in mind and this was a key criteria in choosing a final concept going forward.

Other Carousel Concepts

Tray-wise Loading Systems

Tray-wise loading is the process of reloading a mechanical planter with a full tray of saplings [45]. Tray-wise loading greatly reduces the downtime of the machine and removes the number of steps that must be performed manually. There are two concepts that have currently been developed using tray-wise loading.

Mag-Mat: The Mag-Mat is a concept developed by students from Sweden. It is an improvement on the current carousel system employed by the Bracke P11a. The current carousel has a maximum capacity of 72 saplings. The carousel has to be reloaded by hand once empty therefore 15%-20% of productive working time is spent reloading. The aim of the Mag-Mat is to improve the efficiency of the Bracke planter by reducing the downtime of the machine, and increasing the capacity of the carousel. The final design of the Mag-Mat, which has been manufactured into a fully functioning prototype, can hold 320 seedlings. The 320 seedlings are loaded onto the Mag-Mat carousel in their cultivation trays, 8 trays in total are loaded with each one holding 40 saplings. The Mag-Mat then removes the saplings one by one. The only time planting needs to be stopped is when all 8 trays are empty and must be reloaded. These improvements greatly reduce the down time of the machine during planting and minimise the manual reloading required from the operator [39].

Figure 51(a): Mag.Mat prototype in action.

The Mag-Mat (Figure 51(a)) operates by selecting a full individual tray of saplings and raising it up, then a hydraulic de-plugger is utilised to push each sapling out of the tray one at a time. The ejected sapling lands in a channel, where it is then directed towards the planting hole. This process is repeated until the tray is empty, at which point the tray returns to its original position and a new tray is selected. Once all eight trays are empty the operator must reload the Mag-Mat with eight new full trays. The major benefits in utilising the Mag-Mat are the advantages in speeding up two parts of the process. First of all, the need to manual de-plug cultivation trays and pack boxes at the nursery is removed. Also, the number of interruptions to productive work are reduced through being able to reload more saplings, more than four times as many as the original Bracke carousel, at each individual reload. Each reloading cycle takes slightly longer but this is compensated by the reduction in number of reloading cycles.

However, the prototype faced many challenges including a lack of mechanical availability due to the amount of complex parts and mechanisms included in the design.

Risutec Automatic Plant Container (APC): The Risutec APC is a tray-wise loading mechanical planter that was developed by Risutec Ltd. [46]. The APC can hold 16 full trays, with each tray holding 81 saplings. In total the Risutec can hold 1296 saplings when fully loaded. This huge sapling capacity is part of the reason that the Risutec APC is 1800 kg in weight. In addition to the sapling capacity of the machine itself, it comes with an additional portable storage rack that holds 12 more trays. This allows the operator to have access to an additional 972 saplings, per storage rack, on site [46].

Figure 51(b): Risutec APC in action [46].

The APC is made up of the scarification, mounding and planting block with the storage and loading system located on top. The storage and loading system is rectangular in shape with multiple levels for trays. The loading system is in the middle with the trays either side. The loading system consists of a cartridge that is loaded with nine plants at once. The cartridge then moves in a linear direction to drop the plants into the dibble for planting one by one. The cartridge is loaded by an electrically powered robotic arm that consists of nine clamps. The clamps are positioned on the arm so that they line up perfectly with a row of saplings in a tray. A computer selects a specific row to be loaded for planting, and orientates the robotic arm so that the clamps close around all nine saplings in the row at once. The arm then lifts up and moves to line up with the planting cartridge, when orientated appropriately the clamps release and drop all nine saplings in at once. The computer system then picks another row from the same tray and starts to remove it as the cartridge is emptied. As reloading is taking place, the scarification blade on the bottom of the planting block is used to form 4-5 mounds each evenly spaced 2 m apart in a semi-circular orientation. Then a tree is planted in each mound before the track excavator moves and creates more mounds [46].

Advantages of the Risutec APC include the massive storage capacity that allows over 1200 saplings to be stored, ready to be planted, at any time. This hugely reduces the down time of the machine; although the huge numbers of trays will greatly increase the time of reloading. The increased number of trays is not the only reason for the increase in loading time. The robotic loading system that the APC uses to load the planting cartridge does not have the required force to remove the plants from the trays; the operator must loosen each plant by hand before loading [46]. The reduction in downtime will however outweigh the increased loading time.

Disadvantages include each sapling needs to be loosened by hand in order for the automatic loading system to function. The loading capacity of the APC creates a very negative effect, the size that the APC needs to be to hold so many saplings is simply huge. When added on to the bottom planting column, the APC is tall, wide and extremely heavy. Having spoken with operators who use tracked excavators, the increased height and weight makes operating the machine more difficult.

Cultivation Trays used in Scotland

The employment of tray-wise loading, with regards both the Mag-Mat and Risutec APC designs, was based on the assumption that most nurseries in Sweden and Finland respectively use the same brand and design of cultivation tray. Thus, the group contacted a number of key nurseries in Scotland to investigate if there was a predominantly used brand or style of cultivation tray across tree planting in Scotland. The nurseries with whom correspondence was had were:

- Trees for Life
- Christie Elite
- Alba Trees
- Eadha Enterprise
- Bogancloch Hedging Plants

This correspondence enabled the group to reach the conclusion that the Scottish Forestry Nursery industry does not currently use a standard type of cultivation tray. Thus any tray-wise loading system would require a seismic shift in processes and operations not only in the planting industry but also within the nursery industry.

4.5.3.2 New Concepts

Fast Loader System

This concept was generated from analysing the time spent on each reloading cycle on the act of reloading itself. The Fast Loader concept aims to minimise the time spent in reloading by loading all 70 saplings simultaneously, utilising a "false floor" type arrangement. In this arrangement the Fast Loader would be composed of a middle plate representing the "false floor" and two other plates creating the outer structure of the system. The upper plate would include 72 cassettes arranged exactly on the existing carousel, which would be used for the storage of the saplings to be delivered to the Bracke P11.a. The "false floor" arrangement and its operation are illustrated in Figure 52.

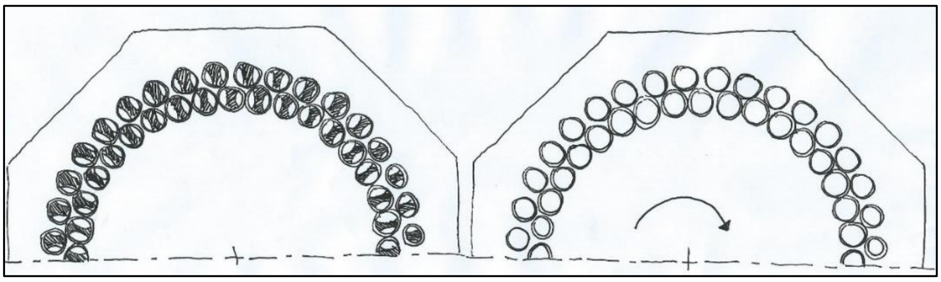


Figure 52: False floor concept.

The two outer plates of the Fast Loader system would be connected by bolt and nut connections, meaning that manufacture of the system would be as simple as possible. One key consideration for the design of the Fast Loader system is how the rotation of the middle plate would be controlled such that accurate orientation could be easily achieved and reloading completed successfully. A number of concepts were created and investigated and the three main concepts are shown in Figure 53.

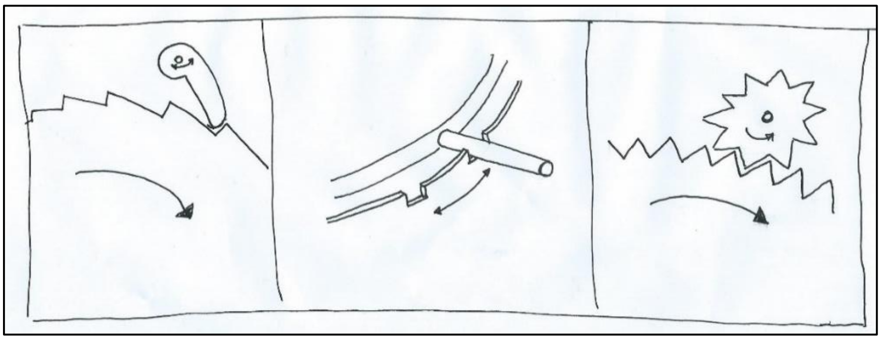


Figure 53: Rotation control concepts.

The decision was made to utilise the ratchet and pawl concept as it offered relative simplicity of design and manufacture coupled with excellent control of the rotation. The Fast Loader concept considers principally the reloading aspect of the overall process, but also offers opportunity to reduce the time spent within the nursery manual loading the saplings into boxes for transport to site. It does this by loading four Fast Loader systems for each day's planting at the nursery prior to transport to the planting site.

Bulk-Loading System

To further improve the reduction in time spent reloading, a bulk-loading concept was designed and investigated which incorporated a hopper which could be simply reloaded with a box of saplings each time it was emptied. The hopper could select one sapling to be presented to the planting tube on each occasion through the use of geometry and vibrations. However, the use of vibrations was cited as a potential downfall because of its possible impact on reducing the soil connected to the roots of each sapling. This would then have a detrimental effect on the planting quality delivered by the planting machine.

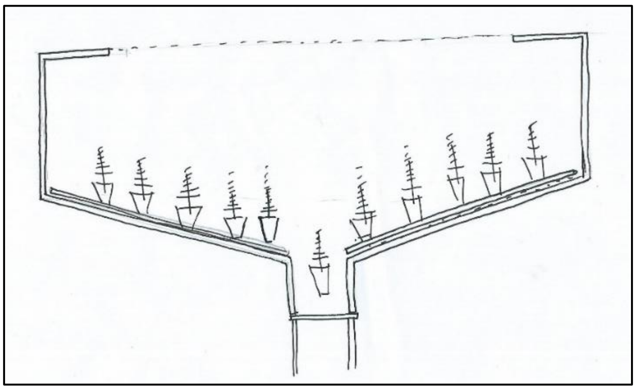


Figure 54: Hopper Concept.

This concept, shown in **Error! Reference source not found.** 54, also incorporated an air vacuum style delivery system to increase the time of delivery from carousel/hopper to ground of the sapling. Again, though, this may have detrimental effects on the condition of sapling before planting due to the external forces being applied to the sapling. This concept also only focuses on the reloading aspect of the overall process and has no scope for a reduction in the time spent manually reloading within the nursery.

4.5.3.3 Concept Selection

The concepts described above were compared via a Controlled Convergence Matrix (CCM) technique, as described in Pugh's Total Design [37]. The piecewise loading concept was chosen as the datum with it being the current method in use, and each new concept was rated against it through a variety of desired criteria. An example of one CCM iteration is shown in Table 8.

Table 8: Controlled Convergence Matrix

CONTROLLED CONVERGENCE MATRIX: SAPLING RELOADING				
CRITERIA	CONCEPTS			
	PIECEWISE	TRAYWISE	FAST-LOADING	BULK-LOADING
COMPLEXITY	D	--	-	--
IMPACT ON OVERALL PROCESS		++	+	+
SPEED OF RELOADING	A	-	++	++
NO. OF INTERUPTIONS		++	s	+
COST	T	--	-	--
WEIGHT		--	s	--
MAINTENANCE	U	-	s	--
OPPORTUNITY FOR BREAKDOWN		-	s	--
EASE OF OPERATION	M	s	+	-
SUM OF +		4	4	4
SUM OF -		9	2	11
SUM OF s		1	4	0
TOTAL SCORE		-5	+2	-7

This process was repeated with other concepts as the datum, and also with the omission of piecewise loading to enable pure comparison between the new concepts. The result each time was that a Fast Loader system would be most beneficial in meeting the intended goals, and thus it was chosen as the concept going forward.

4.5.3.4 Detailed Design

Middle Plate Thickness

A key consideration for the detailed design of the fast loading system is the mass of the system. As required to be manually lifted by the operator the mass of the system plus the mass of 72 saplings must be less than 25 kg, the maximum mass able to be carried by one man at above waist height according to manual lifting guidelines [47]. Using the largest mass of the saplings the group obtained the mass of 72 saplings was estimated as:

$$m_{sapling\ total} = n\ m_{sapling} \tag{16}$$

$$m_{sapling\ total} = 72x0.166 = 11.95kg$$

Thus FEA was utilised to optimise the thickness required for the middle plate of the Fast Loader system, in order that it could adequately perform its minimum function of supporting the saplings. The middle plate was modelled at a variety of thicknesses ranging from 2mm to 10mm, with a representative slice (1/36th) taken to minimise computational time and power required.

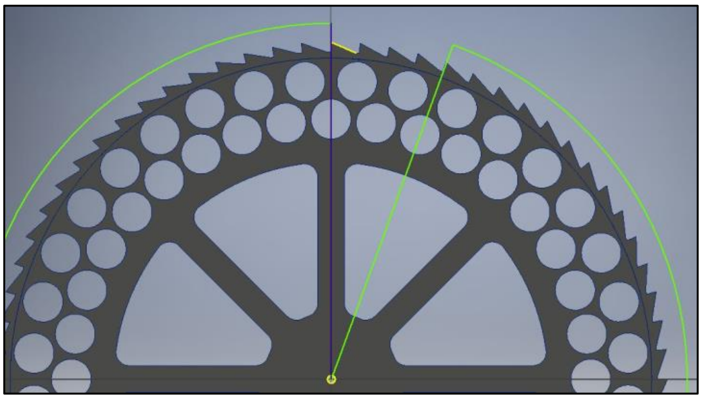


Figure 55: FEA slice diagram

The loads to be applied were calculated from the basis of the heaviest Sitka Spruce sapling the group obtained from Alba Trees. This sapling had a measured mass $m_{sapling}$ of 0.166 kg, which then a safety factor of two was applied to giving a theoretical worst case sapling mass of 0.32 kg on each middle plate section. When converted to a weight, multiplied by acceleration due to gravity (9.81 m/s^2), this gave a force $F_{sapling}$ 3.14 N acting at each sapling location. In order to accurately apply these forces through ANSYS, the areas interacting with each sapling were measured using Autodesk Inventor and thus the corresponding pressures calculated as:

$$P_1 = \frac{F_2}{A_1} = \frac{1.57}{727.951} = 2.16x10^{-3}\ N/mm^2 \tag{17}$$

$$P_2 = \frac{F_1}{A_2} = \frac{3.14}{1467.979} = 2.14x10^{-3}\ N/mm^2$$

$$P_3 = \frac{F_2}{A_3} = \frac{1.57}{740.028} = 2.12x10^{-3}\ N/mm^2$$

$$P_4 = P_5 = \frac{F_1}{A_4} = \frac{3.14}{990.207} = 3.17x10^{-3}\ N/mm^2$$

The pressures acting on areas 1 and 3 were calculated using half of the maximum sapling weight due to the fact that they encompass a half of the area used to hold a sapling. Frictionless supports were applied at the outer edges of the slice to model the rotational symmetry. These types of supports were also utilised to simulate the behaviour of the bearings, originally only in the centre but later also the outer bearings too. The middle plate was modelled from aluminium alloy to begin with, due to its high strength to weight ratio. The boundary conditions applied to the model are shown in Figure 56.

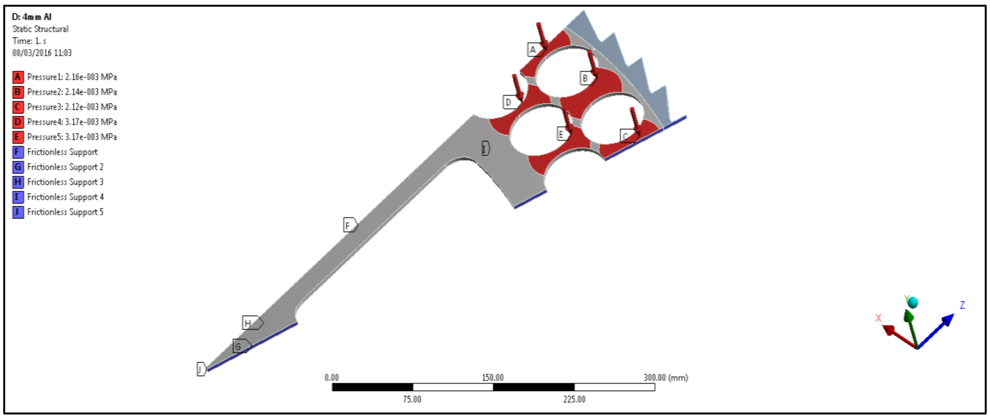


Figure 56: ANSYS middle plate boundary conditions.

Originally, bearing support for the middle plate was only considered in a central location and results showed excessive deformation even at the larger plate thicknesses. For example, the 4mm model exhibited a maximum deflection of roughly 14 mm which is excessive when considered against the 3 mm gap to the lower plate in the equilibrium position. The plots in Figure 57 and Figure 58 illustrate the deformation behaviour and equivalent stress distribution for the 4 mm thick model with only inner bearings considered.

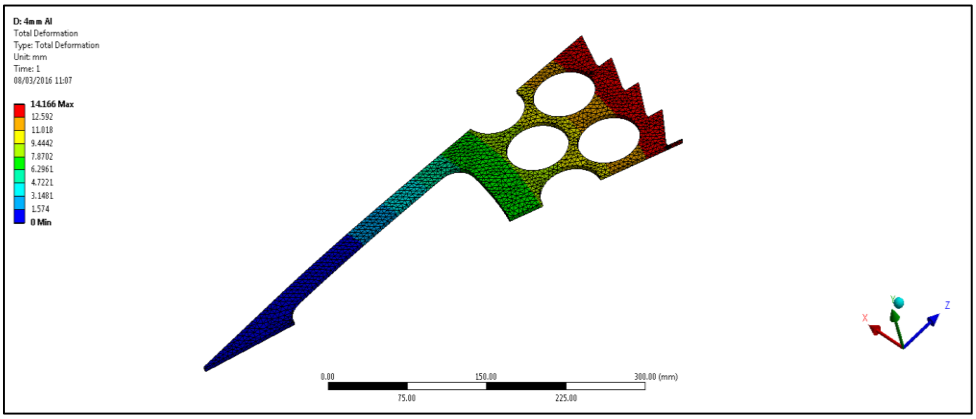


Figure 57: 4 mm aluminium deformation plat.

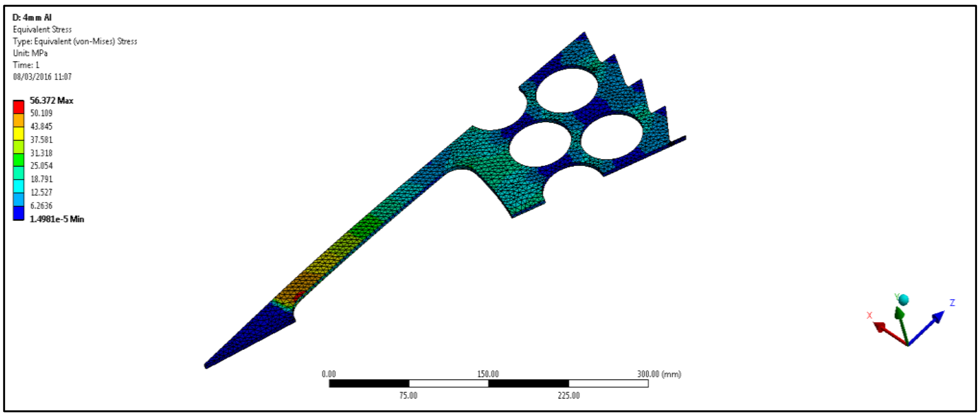


Figure 58: 4 mm aluminium equivalent stress plot.

If only central bearings were implemented the plate thickness required would be approximately 8mm, increasing the weight of the overall machine dramatically. Thus it was decided to incorporate additional bearings to support the middle plates at a radius just inside the cassettes. In order to minimise weight, plastic ball bearings were sourced from igus [48] and arranged as shown in Figure 59.

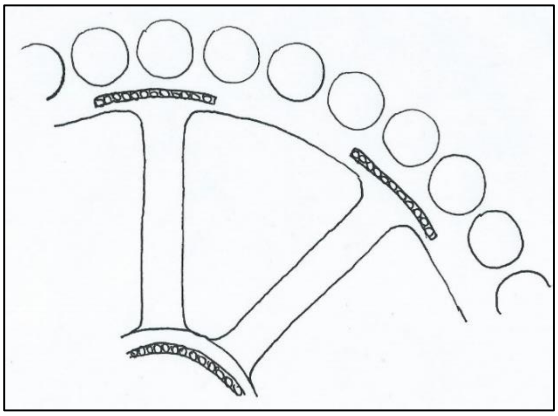


Figure 59: Outer bearings location.

The simulations were then conducted for all thickness variations with these bearings considered. Figure 60 and Figure 61 show the results of the simulations of a 4mm thick middle plate made of aluminium with outer bearings considered.

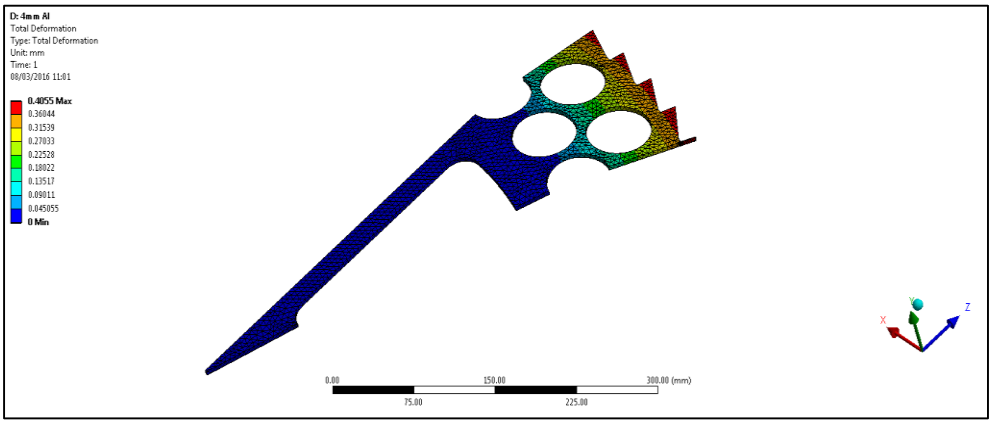


Figure 60: 4 mm aluminium with outer bearings: deformation plot.

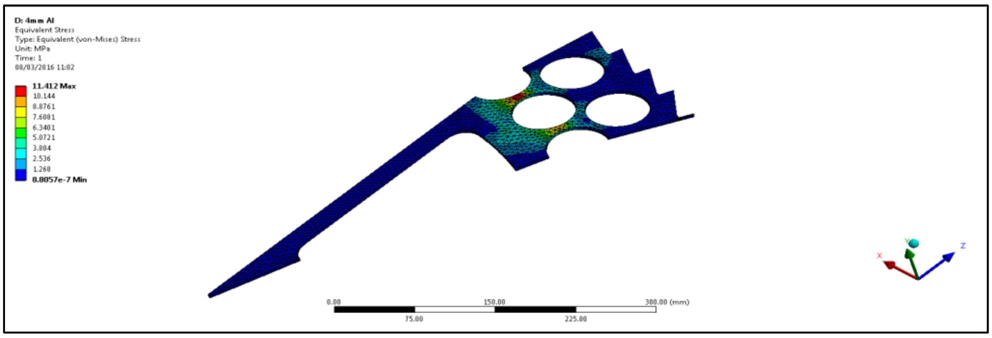


Figure 61: 4 mm aluminium with outer bearings: equivalent stress plot.

The added support of the outer bearings led to a drastic reduction in the maximum deformation experienced. For example, with outer bearings the maximum deformation in the case of a 4 mm thick middle plate was roughly 0.4 mm, reduced from 14 mm with no outer bearings. The magnitude and location of the maximum equivalent stress also changed with the introduction of the outer bearings. The location was now at the section which was supporting the sapling as opposed to at the joint between the spoke and central bearing section.

With these deformation and equivalent stress results deemed as acceptable, the mass of the entire Fast Loader system was calculated using 4 mm thick aluminium for the majority of its make-up. The values obtained are detailed in Table 9.

Table 9: Fast loader mass in 4mm Aluminium

Section	**Volume (mm^3)**	**Density (kg/m^3)**	**Mass (kg)**
Upper	10617041.19	2712	28.79
Middle	1581676.949	2712	4.29
Lower	2009279.183	2712	5.45
		Total	**38.53**

As this total mass of the Fast Loader systems well exceeds the 25 kg guideline for individual lifting without even including the mass of the 72 saplings, it was decided to carry out a material study to investigate other suitable materials to enable reduction in the mass of the Fast Loader system.

Material Analysis

The Fast Loader system will be subjected to a variety of environmental conditions, therefore ensuring full operational capability in these environments is of critical importance. Further, the loader may also be in contact with organic matter, oil, fuel and possibly even hydraulic fluid. The Loader must also be lifted and moved around the site by the operator, so the weight needs to be considered during material selection. The main requirements of the material are listed below:

- The material must maintain its structural integrity across a range of working temperatures.
- Must be water resistant.
- Low reaction with alkalis and acids.
- Scratch resistant and minimal friction are desirable.
- The surface finish and the colour of the product are not vitally important, although the colour scheme should tie in with the environment and the existing Bracke colours.
- Good surface hardness.
- Easily fabricated.
- Strong and lightweight.

Using CES Edupack, a range of suitable materials were identified based on operational capability. It was decided that metals or plastics would be the most suitable material choice based on strength and weight requirements. Initially aluminium was selected due to its lightweight properties whilst still being relatively strong. However as previously analysed, aluminium was too heavy to be considered suitable for use in the Fast Loader. The performance of three plastics was therefore analysed.

POM (Polyoxymethylene)

Polyoxymethylene (POM) has many desirable qualities for use in harsh environments. A good abrasion resistance and robustness is beneficial in an application where the loader will be frequently handled. POM also demonstrates good surface hardness, fatigue resistance and solvent resistance. These all increase the robustness of the Loader, helping to prevent damage and increase the product life. A low coefficient of friction is beneficial where saplings are required to drop from the loader under gravity. With a high resistance to water, the loader manufactured from POM would operate well in a variety of different weather conditions. POM is commonly found in a wide range of engineering applications, namely bearing and automotive design therefore suitable under different load conditions and robust.

However, POM is susceptible to damage from nitric acid and many other acids/alkalis; this is an issue when being used outside because nitric acid is found in acid rain. There is a chance that the acid rain could severely damage the Fast Loader. The other main issue with POM is that its UV resistance is very poor unless carbon black is used to stabilise it. This would limit the Fast Loader to being black in colour which is not ideal.

Acrylonitrile butadiene styrene (ABS)

ABS is suitable in a wide range of applications namely vehicle bumper design where a high impact resistance is required. This thermoplastic polymer is suitable in the loader design where robustness is a key attribute and a long product life is desirable. ABS can be used across a large temperature range, with very little change in performance. The main advantage when using it in a harsh outdoor environment, is that ABS resists acids, alkalis and solvents very well. Knowing that the Loader will be in contact with water and chemicals, it is beneficial to use a material that does not react easily. Forming ABS is a relatively simple process and complex shapes can be formed, namely by injection moulding.

However, ABS has limitations in manufacture and applications. To be suitable in outdoor applications, the polymer must be stabilised to increase UV resistance. ABS has poor resistance to fatigue which would affect the life time of each Loader. High friction and wear are common problems when using ABS, which would have an effect on the products life in service.

Polymethylmethacrylate (PMMA)

Commonly noted as a thermoplastic glass alternative, PMMA is commonly found in a range of outdoor applications and in high moisture environments. These all suggest that PMMA performs well in a harsh outdoor environment. PMMA has excellent UV resistance and no stabilisation or further treatment is required. PMMA shows good hardness, stiffness and it is abrasion resistant with high tensile strength. All these characteristics suggest that the loader would be extremely robust and hard wearing were PMMA the chosen material. It also has excellent surface finish and gloss, so it is an aesthetically pleasing material to use.

The limitations when using PMMA include poor fatigue resistance and solvent resistance. This may cause a decrease in the product life.

Comparison

Table 10: Plastics comparison

	PMMA	ABS	POM
Price	1.68 £/kg	1.53 £/kg	1.58 £/kg
Density	$1.18x10^3$ kg/m^3	$1.04x10^3$ kg/m^3	$1.4x10^3$ kg/m^3
Young's Modulus	2.7 GPa	2.21 GPa	2.5 GPa
Yield Strength	57.8 MPa	42 MPa	60.7 MPa
Poisson's Ratio	0.365	0.391	0.37

A comparison of the selected polymer properties can be seen in Table 10: Plastics comparison In terms of the shown characteristics PMMA can be seen as the strongest with a Young's modulus of 2.7 GPa although it is slightly more expensive than the other two materials. The lightest material is ABS but it is also the weakest, this shows that density and strength are related. From the data in the table PMMA is decided upon as the best material for purpose. Then all the other characteristics that have been mentioned were considered. There are a few disadvantages to PMMA, in areas where ABS and POM perform better. For example the ABS and POM are more scratch resistant and have better fatigue resistance. ABS is the best performer in terms of resistance to chemicals; this is a strong advantage over the other materials. The main disadvantage of ABS and POM are the need to stabilize them before they can be used outside. Outside use is the main characteristic of the material needed. This reason and its superior strength have led to the PMMA being chosen as the material for the Fast Loader.

PMMA Fast Loader Optimisation

Following on from the decision to utilise PMMA as the main structural material for the Fast Loader system, it was decided to re-run the FEA analysis to optimise the middle plate thickness under these new conditions. Again, the same loading conditions were applied and the middle plate was modelled at a variety of thickness with a PMMA material model. The deformation plot for the case of a 4mm thick middle plate made from PMMA is shown in Figure 62.

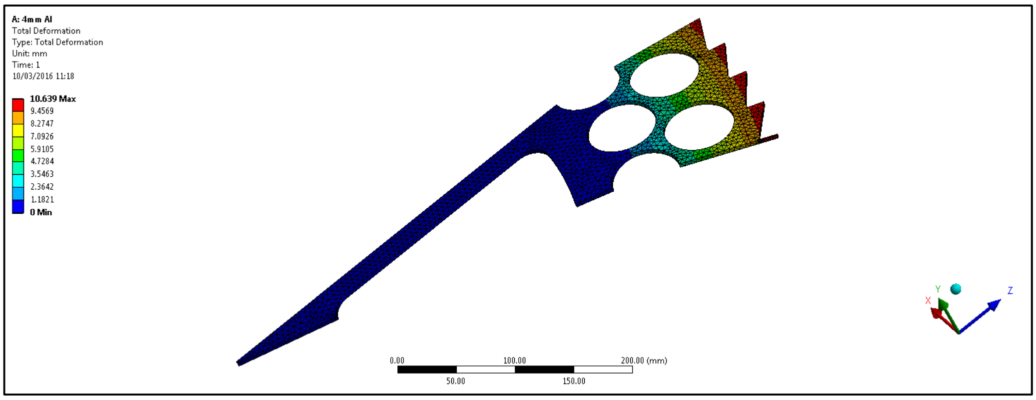


Figure 62: 4mm PMMA middle plate with outer bearings: deformation plot.

Once more, the deformation at the outer edge of the middle plate was considered to be excessive, with maximum values of more than 10mm. This set of analyses showed that for satisfactory deformation and equivalent stress performance the middle plate would be required to be at least 8mm thick PMMA.

However, with weight again paramount to thinking, it was decided to incorporate further bearing supports at the outer radius to enable weight minimisation. The added bearings were incorporated in a style similar to the outer bearings previously described, but at a radius between the outer cassette holes and the radius of the ratchet teeth.

In order to validate the inclusion of the outermost bearings, and again optimise the middle plate thickness, the FEA was again re-run for this latest configuration. The outermost bearings were, as with the other bearings, were modelled as frictionless supports. The deformation plot, for 4mm thick middle plate made of PMMA incorporating two outer bearings, is shown in Figure 63.

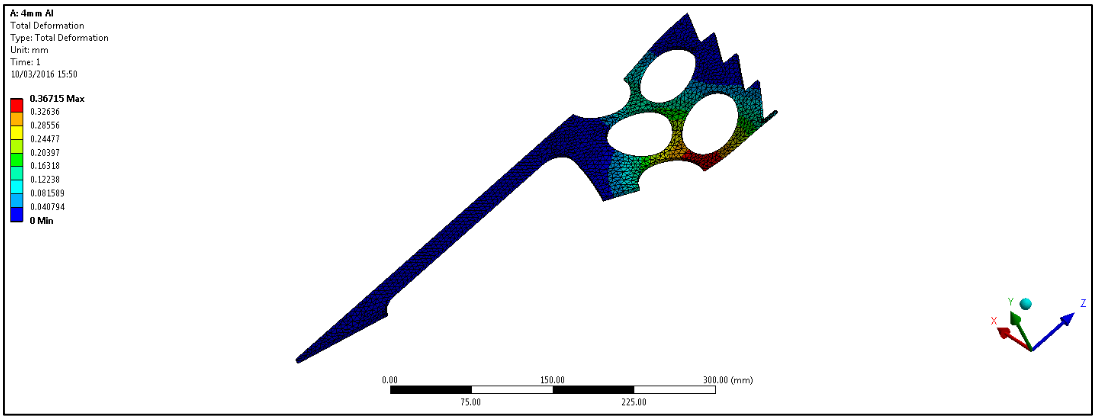


Figure 63: 4mm PMMA middle plate with outermost bearings: Deformation plot.

The inclusion of the outermost bearings can be seen to have caused variations in the size and location of the maximum deformation experienced on the middle plate. The maximum is reduced, on a 4mm middle plate, from more than 10 mm to 0.367 mm and the location moved from the outer radius of the middle plate to a location closer to where the saplings are supported and the furthest from the bearing locations radially. In order to optimise the thickness of the middle plate, the results were run for a variety of thicknesses between 2mm and 10mm and the maximum deformation magnitudes plotted in Figure 64.

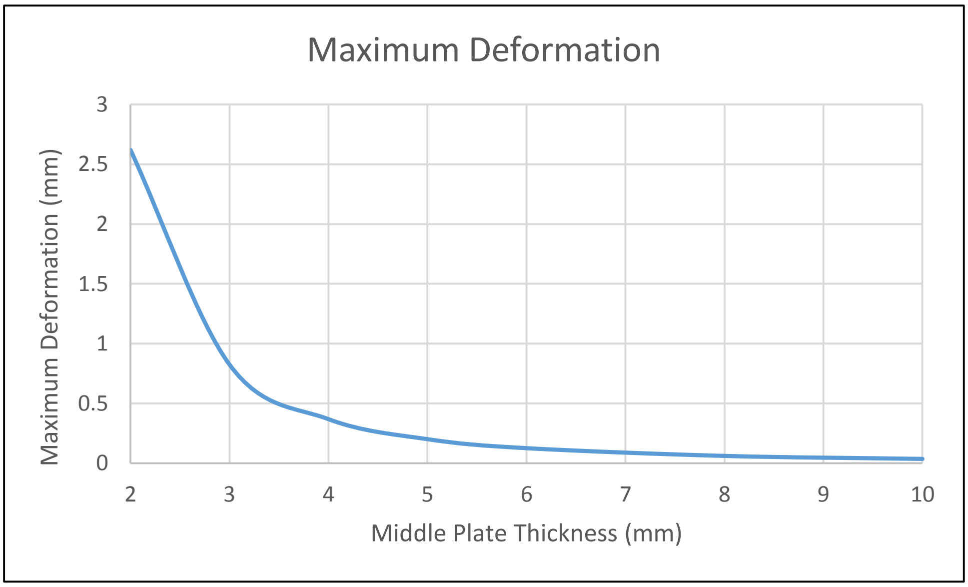


Figure 64: Plot of maximum deformations vs. PMMA middle plate thickness.

This plot was used to define the optimal thickness as 3mm for the middle plate when using PMMA as the main structural material. 3 mm was also chosen as the thickness for the other two main components of the Fast Loader system, as these components have less load to support. Thus the final mass of the system was calculated and are shown in Table 11.

Table 11: 3mm PMMA Fast Loader Mass

Section	**Volume(mm^3)**	**Density (kg/m^3)**	**Mass (kg)**
Upper	7981829.952	1180	9.42
Middle	1238579.141	1180	1.46
Lower	1528170.046	1180	1.80
		Total	**12.68**

When added to the 11.95 kg mass of saplings for each reloading cycle, this overall mass of Fast Loader system is deemed acceptable versus the recommended limit of 25 kg.

Torque Handle Sizing

The incorporation of three concentric bearings adds value in more ways than simply supporting the middle plate. The bearings are used to reduce friction and resistance to the rotary motion required to “load” the Bracke P11.a carousel. Thus the effort required to turn the middle plate through 5° as required would be minimal and easily achieved by any operator. However, with regards to sizing the handle needed, the worst case scenario was considered. In this circumstance the bearings and their effects are ignored, with the middle plate considered to be directly contacting onto the lower part of the Fast Loader system and the torque required to overcome the friction forces present calculated in a full loaded case. From above, the mass of the middle plate is 1.46 kg and the mass of 72 saplings equates to 11.95 kg. Thus the overall mass acting onto the lower part of the Fast Loader system was 13.41 kg. When converted to a weight this was 131.55 N. Incorporating a coefficient of friction of 0.54 [49], the force due to friction required to overcome was calculated as 131.55 x 0.54 = 71.037 N. Assuming load acts at a pitch circle diameter midway between the sapling cassettes (radius=0.417m), the torque T required to rotate the middle plate:

$$T = F_f d \tag{18}$$

$$T = 71.037x0.417 = 29.62\ Nm$$

The average man can apply 100 N of force comfortably, so thus the length of handle required was calculated:

$$d_{handle} = \frac{T}{F_{appied}} \tag{19}$$

$$d_{handle} = \frac{29.62}{100} = 0.296\ m$$

From this it was decided to design a handle of total length 600 mm which was 300 mm in length either side of the central axis of the fast loader.

Ratchet and Pawl Concept

Ratchets and pawls are mechanical devices which allow rotation in a single direction and not in the other direction [50]. The ratchet part is composed of a rotational gear with angled teeth, and the pawl is a component which rests against the ratchet in order to restrict its motion [51]. In the Fast Loader system, the required rotation during each reloading cycle was 5° and therefore the ratchet was designed to have 72 teeth. Thus during each reloading cycle the operator simply turns the device through one click.

The maximum possible torque required to rotate the middle plate was calculated previously as T=29.62 Nm. Thus it was possible to determine the maximum possible torque experienced by the torsional spring within the pawl resisting rotation. With the torque applied at a pitch circle diameter of 0.5 m, roughly the radial location of the pawl, the force experienced by the end of the pawl was calculated:

$$F_{pawl} = \frac{T}{d} \tag{20}$$

$$F_{pawl} = \frac{29.62}{0.5} = 59.24N$$

Considering the pawl itself has a lever arm of length 0.11m, the maximum torque experienced by the pawl was defined as:

$$T_{pawl\,max} = F_{pawl}d \tag{21}$$

$$T_{pawl\,max} = 59.24x0.11 = 6.52Nm$$

Utilising a basic spring calculator [52], and values suitable to the dimensions of the designed pawl it was capable to design a torsional spring capable of resisting maximum torques as high as 128.6N-m. These values are well in excess of the maximum possible torque calculated above, and thus the pawl design was deemed satisfactory.

Upper and Lower Part Connection

The upper and lower parts of the Fast Loader system were designed to be connected together through the use of four M8 bolt and nut connections, spaced equally at 90° intervals. These bolted connections would require to be able to resist the torque loading applied when using the Fast Loader. Taking the maximum torque loading possible as calculated above, T=29.62 Nm, this loading was split over the four bolts to give the torque experienced by each as 7.405 Nm. At the pitch circle diameter of the bolts' location this translates to a force of:

$$F_{bolt} = \frac{T_{pawl}}{4d}$$

$$F_{bolt} = \frac{29.62}{4\,x0.56} = 13.22N$$

Using M8 bolts, first the inside diameter at the minimum diameter of the threads was calculated to enable definition of the minimum shear supporting area. From [53], this was defined:

$$D_{bolt\,min} = D_{bolt\,max} - 1.082532P \tag{22}$$

$$D_{bolt\,min} = 8 - 1.082532x1.25 = 6.65mm$$

Where P is the pitch of the thread. Using this minimum diameter, the minimum area was defined:

$$A_{bolt} = \frac{\pi}{4} D_{min}^2 \tag{23}$$

$$A_{bolt} = 34.7mm^2$$

However, with the bolt arrangement passing through both the upper and lower plates of the Fast Loader system the components carrying the shear are doubled. Thus the area experiencing the loading is doubled to $A_{bolt} = 69.4mm^2$. Next, the shear stress experienced at each bolt location was calculated:

$$\tau = \frac{F_{bolt}}{A} \tag{24}$$

$$\tau = \frac{13.22}{69.4} = 0.19MPa$$

Often, shear strength is not specified for common bolt materials. However, it is safe to compare experienced shear stresses with 60% of the material's ultimate tensile strength to check for integrity [54]. For an 8.8 grade M8 bolts, the ultimate tensile strength (UTS) is 830 MPa [53], thus 60% of UTS is 498 MPa. It can be seen from these numbers that the four M8 bolts are more than sufficient for the small amount of shear stress experienced due to the torques induced by rotating the Fast Loader's middle plate.

Orientation

A key consideration in the design of the Fast Loader system was how it would attach to the existing Bracke P11.a carousel. It was critical that the Fast Loader system could orientate onto the Bracke carousel such that both sets of cassettes line up perfectly and reloading can occur successfully. The design solution to this challenge was to tack weld nuts onto four radially equal locations as shown in Figure 65.

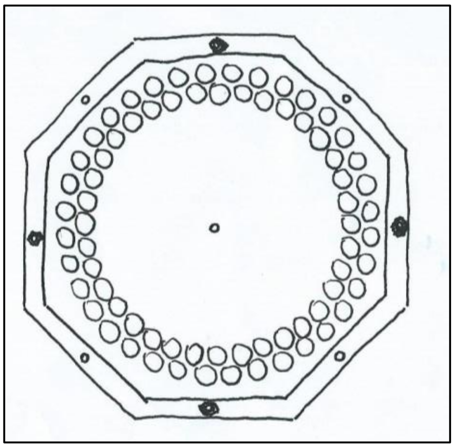


Figure 65: Tack welded bolts (4 in black).

These nuts would then be utilised to enable a variable diameter shaft with threads at each end to be threaded into location and used to guide the orientation of the Fast Loader system as shown in Figure 66.

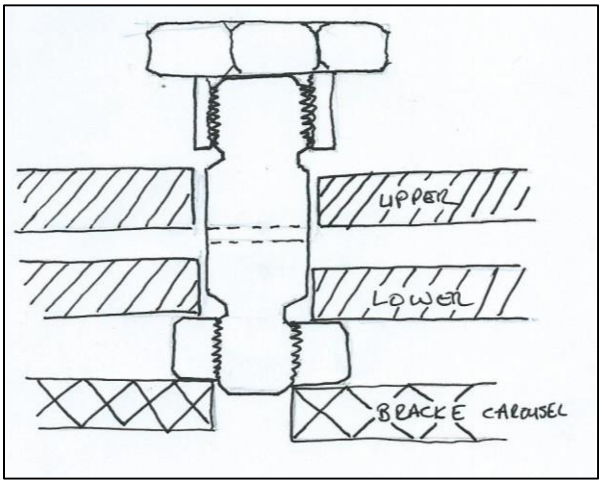


Figure 66: Nut, varied diameter stud and quick release star knob diagram.

Finally, the Fast Loader system could be fixed in the correct orientation through the use of four quick-release star grips, threaded onto the top end of the variable diameter shafts. These quick-release star grips work by tilting over a threaded spindle, then being brought into a straight position and turned a fraction of overall rotation to achieve the required clamping. Thus the time to fix the orientation is minimised. Similarly, the quick-release works in much the same way but in reverse enabling rapid removal of the Fast Loader system. The operation of the quick-release star knobs is shown in Figure 67.

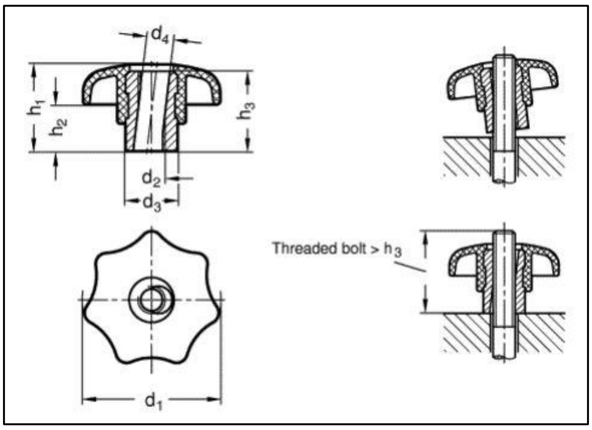


Figure 67: Quick-release star knob operation [59].

4.5.3.5 Final Fast Loader Design

With the materials defined and the thicknesses optimised, the torque handle and pawl separately sized, and the internal and external connections verified; the Fast Loader design was finalised and the concept modelled using Autodesk Inventor. The final 3D CAD model is shown in Figure 68 with a further assembly drawing illustrated in Appendix A12.

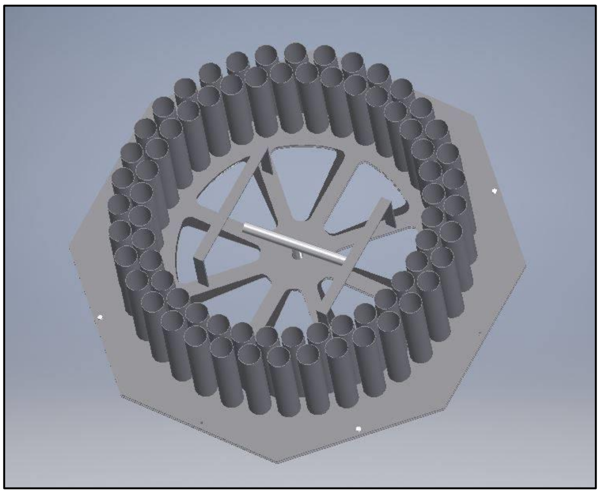


Figure 68: Final Fast Loader system

Figure 69 illustrates the internal workings of the Fast Loader, namely the ratchet and pawl concept utilised to control the rotation of the middle plate when loading saplings to the Bracke P11.a carousel.

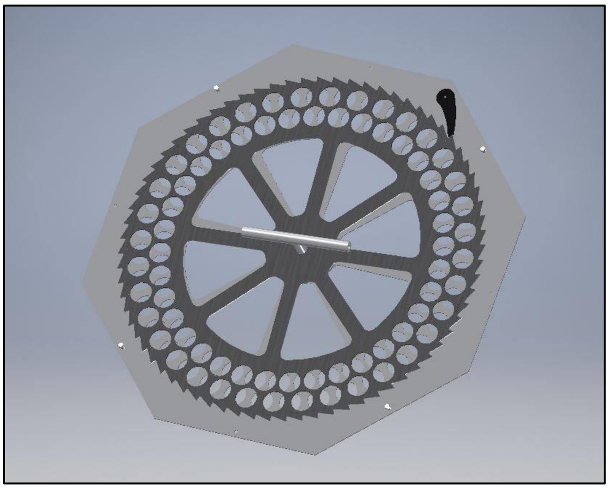


Figure 69: Final Fast Loader ratchet and pawl

The Fast Loader design enables the operator to minimise the time spent on each reloading cycle as it gives the ability to simultaneously load 72 saplings if desired. The exact timings have not been able to be defined in order to quantify exactly the improvement made, however if the concept was to be manufactured into a prototype it would be recommended that a time study such as this was conducted.

It would also be recommended that more than one Fast Loader would be manufactured for each planting machine such that prior loading could be completed at the nursery before sapling delivery to site. The benefit of prior loading would be further process time savings associated with the manual loading of saplings into boxes currently conducted at forestry nurseries across Scotland. With experienced operators able to plant approximately 1200 saplings in one working day, 17 Fast Loaders would be required to be pre-loaded ahead of each day's work. However, due to the physical scale of the Fast Loader system, it is anticipated that this would be unrealistic and would cause numerous transport problems between nursery and planting site. Thus the group recommend the manufacture and use of four Fast Loader systems with each enhanced planting machine, coupled with existing sapling storage boxes to transport the remaining saplings required each day. Critical to ensuring the process optimisation would be the employment of a further worker whose principle role would be to reload the Fast Loader system as the excavator operator continues to plant saplings. Although an added expense, this extra pair of hands could be utilised to monitor planting quality as operations continue and the Fast Loader system remains loaded. This is a task which is commonly completed when the planting machine is non-operational by the excavator operator, adding cost and time to the overall planting process. Further work is required to define the optimal transport system required for the use of Fast Loader systems and also to quantify the improved performance of the concept with regards sapling reloading time versus the existing manual reloading process. A cost analysis should also be conducted to validate the employment of a further worker within the process.

4.6 Final Models for Simulation

4.6.1 Existing Bracke P11.a Model

As the simulation is being used to train new operators on using a mechanical planter, it was decided to produce a full 3D model of the original Bracke P11.a. This allowed Simultech the choice between the original and the enhanced, they could also produce a simulation of both if desired. The final assembly was compiled on Autodesk Inventor 2016 and can be seen in Figure 70.

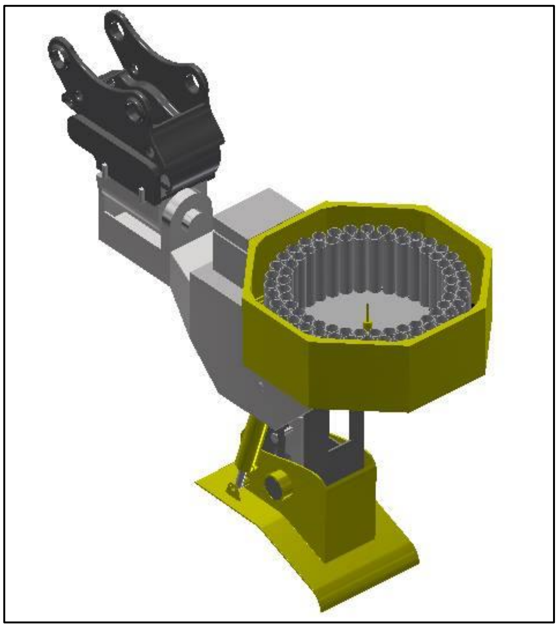


Figure 70: Final CAD rendering of existing Bracke P11.a planting machine

4.6.2 Craobh Planting Enhanced Model

Once the individual components of the Bracke P11.a and the improved design had been modelled they were assembled in Autodesk Inventor 2016 to create the final enhanced design. The final project model can be observed in Figure 71. Concluding the modelling of the planting machine, each of the final designs from the various design phases, including the unchanged components, scarifying blade and Fast Loader were all combined together to create a working prototype that would be suitable for simulation. In order to create a working model, all aspects of design throughout the project were considered including hydraulic and material design to ensure that the overall design solution would be suitable for working in a forestry operation. It is important to note that where all machine components were considered on a conceptual level, only critical moving components were further developed in a more detailed design process. These components were in line with the required outcomes from the problem statement in the earlier phases of the project. The model files have been handed to Simultech where they will be forwarded into simulation.

Further an exploded assembly of the final planting machine design is illustrated in Appendix A13.

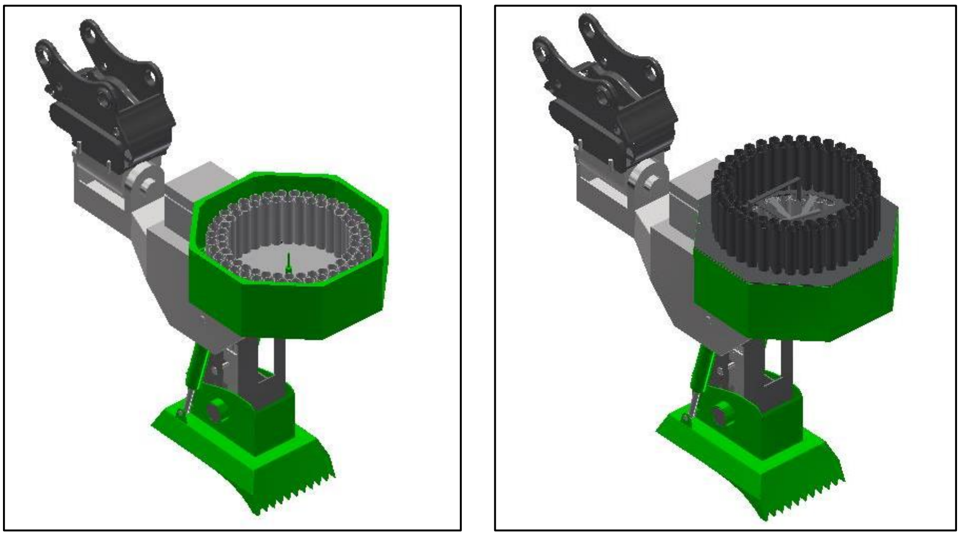


Figure 71: Final CAD renderings of enhanced planting machine with and without Fast Loader system.

5.0 Reflection

Reviewing the success of the project both in terms of technical achievement and group interaction presents an opportunity to reflect on overall performance and identify where objectives were met and where improvements could be made with further investigation. Although the main focus for the project was on developing an enhanced mechanical planting machine for use in simulation, a critical aspect to its success was how the team functioned, how decisions were made and how objectives were met.

5.1 Design Process Reflection

In the early stages of the design, it was critical that the opinions of every group member were heard to ensure that all design ideas were considered. After each visit made to external companies, the group were able to sit down and discuss what each member had learned from the information voiced by industry experts. By understanding what each member had gained from the visits, it allowed for a comprehensive critical analysis to be developed. It is also important to note that to ensure effective time management in this information development phase that each person took on a different topic of research. Ensuring that the entire group understood the various technologies, each member was responsible for explaining to the others what had been learned. This development phase, considering both independent learning and group learning through visits to various places allowed for each individual to gain an understanding of the technologies behind the project in hand at the same time establish an effective method of communication between everyone.

From this initial research and understanding of the various existing technologies the group were able to devise a comprehensive specification of capabilities of the enhanced design for the planting machine. This was devised with the help of Prof Nash and Mr McArthur to ensure that proposed deliverables were within the scope of the project and the ability of the group. As a project similar to this had never been carried out before within the university, it was important that the group were able to define some underlying fundamentals of forestry design however it is also important to note that designing for simulation meant that full detailed design similar to that for manufacture. For this reason, the group decided to focus on the enhancement of critical moving components of the forestry machine, looking in particular at the loading and discharging of saplings from the machine and also the mechanism required to provide sufficient mounding and compaction capabilities to the soil for enhanced protection of the sapling. Although important to the generation of an enhanced planting machine, the complex control through hydraulics and electronics was not developed any further from conceptual design. It was learned through speaking to operators of existing machines that these systems operated well at present and as such, time was directed at developing fully the critical moving components. However, this would provide a basis for future investigations perhaps looking solely at the electronic control of the machine to be integrated with the final designs of this project.

5.2 Project Management Reflection

Throughout the detailed design phase, the group were able to present sections along the way to Prof Nash, Mr McArthur and various companies who were all able to direct any issues with the proposed designs in the right direction and identify further areas for the group to develop upon. By maintaining a continuous communication link between industry experts and the projects clients, objectives could remain precise and the group could focus on ensuring the deliverables were in line with the requirements of the project scope. This also ensured that the group remained efficient in carrying out tasks and each member had a specific focus.

Scheduling of tasks was a critical concern throughout the project. To ensure that tasks remained on target and deadlines were achieved, a Gantt chart was devised with all the required tasks, as specified in the contract, outlined alongside theoretical start and completion dates. It became apparent as the project progressed that the progress chart would require constant monitoring and updating to ensure that deadlines were not missed and that extra time was available in the event of a delay. Identifying all major occurrences throughout the duration of the project, only two delays were significant enough to pose a threat to the completion of the project. Firstly, it was suggested to the group that a visit be made to view the existing market leading planting machine in operation. This however proved difficult as the machine was constantly operating across a large geographical area and travel arrangements could not be accommodated due to constraints out with the control of the group. In February, the machine was operating within a respectable travel distance and as such the group were able to make a visit three months behind schedule. If the group had been able to complete this visit earlier in the year then benefits would have been felt throughout the critical analysis phase and the design process enhanced.

Critical to the success of this project was effective team management and ensuring that at no point any member was unsure of a task. This meant that communication was vital and was made more complicated with the inclusion of an Erasmus student and a Japanese student both on exchange. However, it was identified that with clear communication and an instant messenger chat page set up online, that effective decision making discussions could be had both in company and independently. Identifying the scale of the project and the number of components to be designed, it was decided early on that effective time management could be established by splitting design sections into sub groups. This allowed for team members to focus on specific aspects of the design and become fully engaged in the phase relevant to them. On a regular basis, meetings were held with the whole group to discuss progress and identify further areas of development. It is important to note that the final design incorporated integrated parts and as such the group had to remain responsive in engaging in all sections of design so as in the final assembly, components would fit together accordingly. With limited time to the final deadline, effective time management was critical to the success and completion of all aspects of the project. With other deadlines and commitments around the same time as the project deadline, it was imperative that each group member monitor the progress of each other to ensure that no aspects of the design quietly lapsed.

By developing a design suitable for simulation, it presented the group with the opportunity to design using CAD software. As outlined early in the project, the strengths and weaknesses of each individual were outlined to identify the most suitable roles for the right people. All CAD design was conducted on Autodesk Inventor to accommodate for the expertise of two of the group members on said software. Around this, the other group members were able to focus time on developing other aspects of the design to ensure that all deliverables were completed by the due date. By accommodating for group members, it was identified that the design phase was more efficient and less time was required learning new software and developing new skills. Once again, by maintaining a clear line of communication between members, this phase developed with only minor flaws, which were always quickly corrected and the final design presented to the project clients.

Towards the end of the project, other commitments to study and personal circumstances became more apparent as the workload increased trying to meet the final deadline with all aspects of the design accounted for. Other engagements from group members were identified well in advance, allowing for contingency plans to be employed. In some circumstances this would include accepting a slight delay in non-critical work being carried out. Where it was identified that tasks would have a direct influence on further stages in the design, group members were swapped into different roles and to complete different aspects of the design work. This was made possible by engaging in a comprehensive study of the design and operating industry as a full group early in the project. An example of this occurred in the design phase where two group members were focussed on the enhancement of sapling reloading. These members required information from external sources. However by reallocating to the Head of Communications this task was completed quicker, allowing the other member to focus on other tasks.

As outlined throughout the reflection, risk management was a critical element of effective project management ensuring that any issues that did occur were mitigated immediately to minimise disruption. As outlined in section 2.8 potential risks were outlined early on in the project so as the group were made aware of issues that may arise and to ensure that contingency plans were available should an issue arise. On the whole, this was managed effectively by the group aside small delays as outlined.

In the beginning, the group was devised of five members, however this decreased to four in semester two as Kazuki Iida left the group to return home after a one semester exchange. Allowing Kazuki to manage a project phase in semester one enabled a more involved engagement in the project. As the project progressed on to semester two with detailed design, the lesser number in the group meant distributing a greater workload over the remaining team to match the number of tasks required to be completed ahead of the deadline. However, this was recognised well in advance and as such did not present itself as a major issue at the start of semester two.

5.3 3D Printing Challenges

Lead times for manufacture of 3D printed components presented a significant delay for the small experimental analysis set up to measure the performance of a variety of different blade types. Drawings were provided to the department at the beginning of week three and the final components not finished until the middle of week six. However, overall quality of the models was substandard to what was required for the testing. It was also made aware to the group that one model had failed to print at all and that to fix this, the model would have to be redesigned or the printing outsourced elsewhere. Taking the advice of outsourcing, the rapid prototyping centre within the DMEM department were contacted and the drawings handed over on the basis that a quote would be given for the cost of the printing. For reasons beyond the control of the group, two follow up emails went unheard before the group approached the department to be told that only laser cutting would be suitable for the profiles. This was a significant setback in the design of the blades and as such had an impact on the progress of the final design.

These setbacks had a significant influence on the progress of design, however it was proved that the team were able to overcome such issues effectively so as not to affect any further areas of the project. From learning of the outcome from DMEM, the group reconvened to make a decision about the blade profiles for testing. It was decided that the cost of laser cutting could not be justified for the reason that the blade profiles being printed may not have actually been the final design and so would not represent the project after testing. Further, having waited up to five weeks for any progress, the project time constraint hindered further development. From this, the low quality profiles were reworked by members of the group to produce profiles that would be adequate for the purposes of testing at a fraction of the original cost.

5.4 Academic vs. Industrial Representatives

The nature of the project involved both academic and industrial aspects, with a key stakeholder representing each. Presenting the progress of the project and the work in a manner appropriate for these two audiences was a challenge for a group composed of students more familiar with the academic style. However, close collaboration during the numerous site visits conducted enabled the group to establish a close working relationship with their industrial representative and thus communication was generally clear and productive. By participating in numerous and varied site visits the group further established useful contacts in not only the forestry but also heavy engineering industries, whose experience and guidance proved invaluable throughout the design process.

5.5 Further Investigations

Based on the final design of the project, it provides a solid foundation to speculate on further design work that could be conducted in future project investigations. Firstly, it was identified that the group would focus effort on enhancing major critical moving components of the planting machine with only a conceptual design being focussed on the hydraulic control and electronic design within the control system. From this it is possible to suggest that future investigations could be outsourced across different faculties, focussing solely on the electronic design. This was identified from an early stage as being out with the scope of the present group.

With the end objective to operate this design in a simulation environment, less of an emphasis was placed on constraints of manufacture such as considering materials and machining processes. If this design was to be carried into manufacture phase then it would present an opportunity for further detailed investigation to ensure an economic production process was available.

If this project was to be continued with a further investigation, it would be important to pass on the developed knowledge and information gained through meeting with a wide variety of industry experts. This could be done through continuing with a strong presence on social media and making the new project group aware of the wide contact base that was developed throughout the duration of this project. It proved invaluable to the current group having the ability to contact relevant companies to gain information on certain topics and receive advice at times of uncertainty.

Further investigation would be possible in relation to the challenge of reducing machine downtime required for sapling reloading. Focus should be given to increasing the reliability and reducing the weight challenges faced by current tray-wise loading concepts, as these concepts have the best potential for increasing the overall productivity of mechanised planting. However, collaboration with nurseries around Scotland would be required in order to gain agreement on the standardisation of cultivation trays required for successful tray-wise reloading. The Fast Loader concept developed within this report requires further attention to the design of the transport system, enabling optimal time reduction in the overall reloading process. Also, a prototype should be manufactured to allow quantification of the time reduction enabled by simultaneous reloading of 72 saplings as opposed to manual piecewise reloading.

6.0 Conclusion

On the whole, the project has been a success. Through following a strategic design approach to the initial problem, the group were able to develop a solution, based on existing designs, suitable for use in simulation. By focussing on critical moving components of the planting machine, each member was able to practice knowledge learned from previous years at university as well develop a new understanding of engineering principles in a more refined field. This, on top of effective team management and an effective working relationship between all members and clients overall enhanced the outcome of the project.

From this, the final design, as well as models of existing components, will be handed over to Simultech Scotland for further enhancement before being developed into a simulation model for the purposes of training and development in the field of forestry engineering. The final design can be compared with the existing Bracke design to show where design enhancements have been made with respect to improving the overall planting process. Both designs will be made available to Simultech, with a view to further future projects continuing to develop the machine and the various components.

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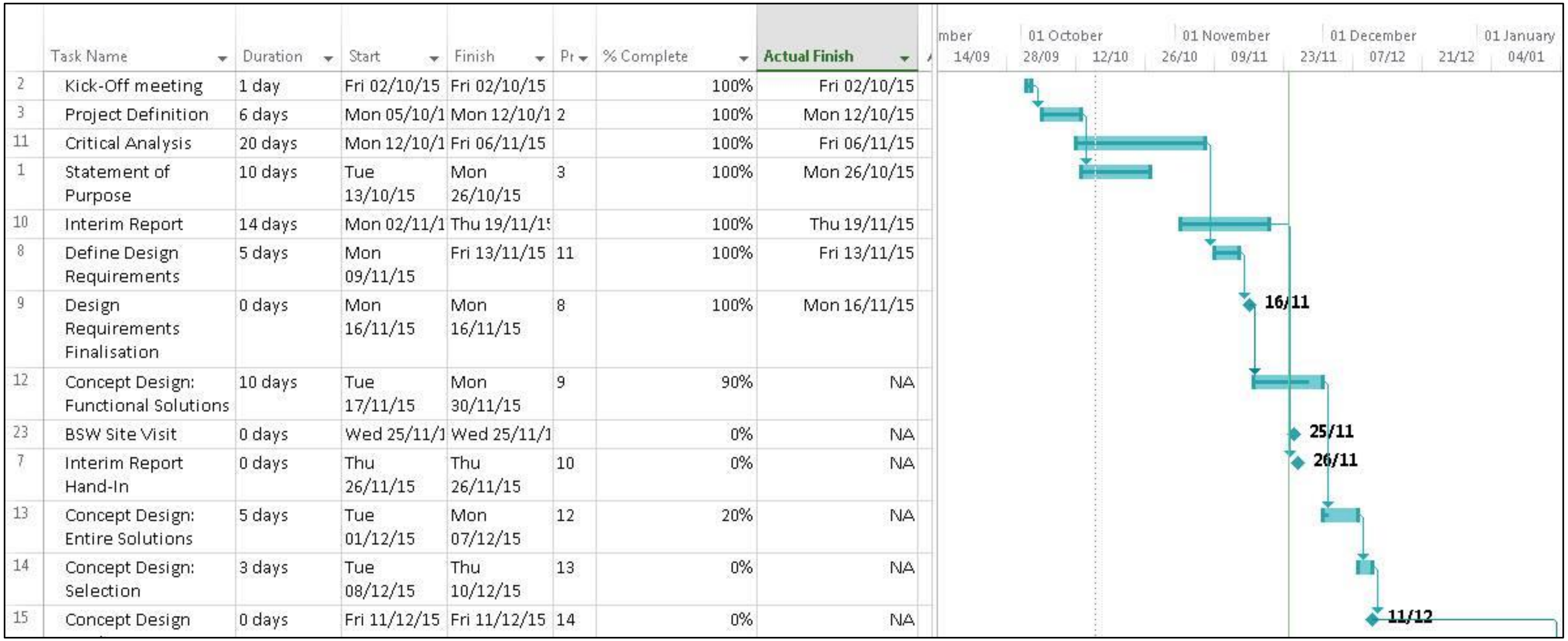
Appendix A1: Original Plan (Semester One)



	Task Name	Duration	Start	Finish	Pr	% Complete	**Actual Finish**
2	Kick-Off meeting	1 day	Fri 02/10/15	Fri 02/10/15		100%	Fri 02/10/15
3	Project Definition	6 days	Mon 05/10/1	Mon 12/10/1	2	100%	Mon 12/10/15
11	Critical Analysis	20 days	Mon 12/10/1	Fri 06/11/15		100%	Fri 06/11/15
1	Statement of Purpose	10 days	Tue 13/10/15	Mon 26/10/15	3	100%	Mon 26/10/15
10	Interim Report	14 days	Mon 02/11/1	Thu 19/11/1		100%	Thu 19/11/15
8	Define Design Requirements	5 days	Mon 09/11/15	Fri 13/11/15	11	100%	Fri 13/11/15
9	Design Requirements Finalisation	0 days	Mon 16/11/15	Mon 16/11/15	8	100%	Mon 16/11/15
12	Concept Design: Functional Solutions	10 days	Tue 17/11/15	Mon 30/11/15	9	90%	NA
23	BSW Site Visit	0 days	Wed 25/11/1	Wed 25/11/1		0%	NA
7	Interim Report Hand-In	0 days	Thu 26/11/15	Thu 26/11/15	10	0%	NA
13	Concept Design: Entire Solutions	5 days	Tue 01/12/15	Mon 07/12/15	12	20%	NA
14	Concept Design: Selection	3 days	Tue 08/12/15	Thu 10/12/15	13	0%	NA
15	Concept Design	0 days	Fri 11/12/15	Fri 11/12/15	14	0%	NA

Appendix A2: Original Plan (Semester Two)

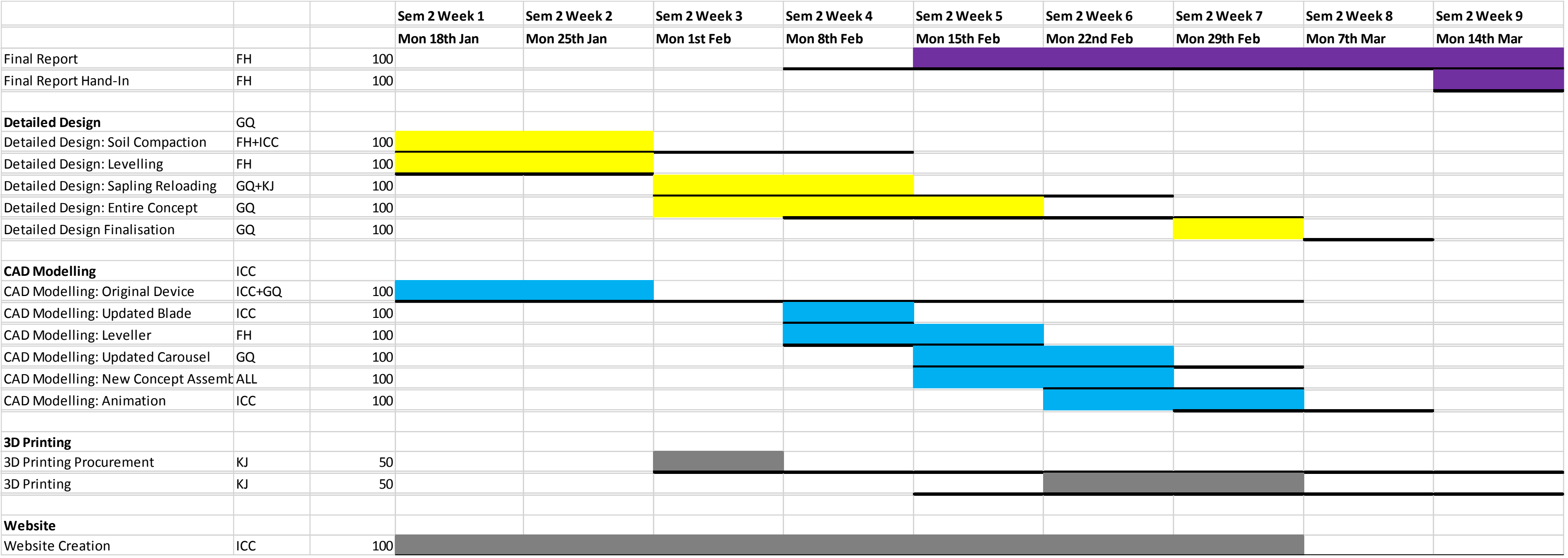
15	Concept Design Finalisation	0 days	Fri 11/12/15	Fri 11/12/15	14	0%	NA
4	Website Creation	44 days	Mon 18/01/1	Thu 17/03/1		40%	NA
5	Detailed Design: CAD Modelling	10 days	Mon 18/01/16	Fri 29/01/16	15	0%	NA
20	Design: Design Calculations	10 days	Mon 18/01/16	Fri 29/01/16	15	0%	NA
6	Detailed Design: FEA Analysis	8 days	Mon 01/02/16	Wed 10/02/16	20,5	0%	NA
16	Detailed Design: Material Selection	8 days	Mon 01/02/16	Wed 10/02/16	20	0%	NA
25	3D Printing Procurement	5 days	Mon 01/02/16	Fri 05/02/16	5	0%	NA
22	Detailed Design: CAD Model Update	4 days	Thu 11/02/16	Tue 16/02/16	6,16	0%	NA
18	Final Report	24 days	Mon 15/02/1	Thu 17/03/1		0%	NA
21	CAD Automation/Animati	5 days	Wed 17/02/16	Tue 23/02/16	22	0%	NA
17	3D Printing	7 days	Wed 24/02/1	Thu 03/03/1	19,2	0%	NA
19	Detailed Design Finalisation	0 days	Wed 24/02/16	Wed 24/02/16	21	0%	NA
24	Final Report Hand-In	0 days	Fri 18/03/16	Fri 18/03/16	18,4,	0%	NA

Appendix A3: Updated Plan (Semester One)

				Sem 1 Week 3	Sem 1 Week 4	Sem 1 Week 5	Sem 1 Week 6	Sem 1 Week 7	Sem 1 Week 8	Sem 1 Week 9	Sem 1 Week 10	Sem 1 Week 11	Sem 1 Week 12	Xmas Hols
Task	**Responsible**	**Complete (%)**		**Mon 5th Oct**	**Mon 12th Oct**	**Mon 19th Oct**	**Mon 26th Oct**	**Mon 2nd Nov**	**Mon 9th Nov**	**Mon 16th Nov**	**Mon 23rd Nov**	**Mon 30th Nov**	**Mon 7th Dec**	
Project Definition														
Kick-Off Meeting	ALL	100		⬛										
Project Definition	ALL	100		⬛										
Critical Analysis	KI	100			🟥	🟥	🟥	🟥						
Statement of Purpose	ALL	100			⬛	⬛								
Conceptual Design														
Define Design Requirements	GQ	100							🟩					
Design Requirements Finalisation	GQ	100								🟩				
Concept Design: Functional Solutions	GQ	100								🟩	🟩			
Concept Design: Focus Finalisation	GQ	100										🟩	🟩	
Reporting														
Interim Report	FH	100						🟪	🟪	🟪				
Interim Report Hand-In	FH	100								🟪				

Key	
Critical Analysis	🟥
Conceptual Design	🟩
Detailed Design	🟨
CAD	🟦
Reporting	🟪
Administrative	⬛

Appendix A4: Updated Plan (Semester Two)



			Sem 2 Week 1	Sem 2 Week 2	Sem 2 Week 3	Sem 2 Week 4	Sem 2 Week 5	Sem 2 Week 6	Sem 2 Week 7	Sem 2 Week 8	Sem 2 Week 9
			Mon 18th Jan	Mon 25th Jan	Mon 1st Feb	Mon 8th Feb	Mon 15th Feb	Mon 22nd Feb	Mon 29th Feb	Mon 7th Mar	Mon 14th Mar
Final Report	FH	100					🟪	🟪	🟪	🟪	🟪
Final Report Hand-In	FH	100									🟪
Detailed Design	GQ										
Detailed Design: Soil Compaction	FH+ICC	100	🟨	🟨							
Detailed Design: Levelling	FH	100	🟨	🟨							
Detailed Design: Sapling Reloading	GQ+KJ	100			🟨	🟨					
Detailed Design: Entire Concept	GQ	100			🟨	🟨	🟨				
Detailed Design Finalisation	GQ	100							🟨		
CAD Modelling	ICC										
CAD Modelling: Original Device	ICC+GQ	100	🟦	🟦							
CAD Modelling: Updated Blade	ICC	100				🟦					
CAD Modelling: Leveller	FH	100				🟦	🟦				
CAD Modelling: Updated Carousel	GQ	100					🟦	🟦			
CAD Modelling: New Concept Assemb	ALL	100					🟦	🟦			
CAD Modelling: Animation	ICC	100						🟦	🟦		
3D Printing											
3D Printing Procurement	KJ	50			▨						
3D Printing	KJ	50						▨	▨		
Website											
Website Creation	ICC	100	▨	▨	▨	▨	▨	▨	▨		

Key	
Critical Analysis	🟥
Conceptual Design	🟩
Detailed Design	🟨
CAD	🟦
Reporting	🟪
Administrative	▨

Appendix A5: Product Design Specification

As harvesting rates of round wood continues to exceed planting rates of new saplings, there introduces a gap in the forestry machine market for a product capable of reforesting areas at a similar rate to those used for deforestation. At present, few planting machine designs are used in the industry. Amongst those, the P11.a manufactured by Bracke Forest is a machine designed to operate as an attachment to a 360° tracked excavator.

With an opening in the market and a demand for large areas of Scotland to be reforested with saplings for future harvesting, craobh planting aim to enter this niche with the aim of identifying weaknesses in current machines in production and conducting a thorough design exercise, introducing ideas to increase productivity and efficiency of the mechanical planting machine.

This Product Design Specification (PDS) was drawn up by the group following a critical analysis phase of the current industry. After discussion, the main issues outlined as areas for improvement included:

- Increasing seedling carrying/planting capacity. The Bracke P11.a has the ability at present to carry 80-120 saplings.
- Increasing planting rate with a faster mounding and sapling insertion process. The Bracke P11.a currently plants with a productivity of approximately 300 plants per hour.
- Optimising overall weight of the machine with no compromise on productivity or structural integrity. The Bracke P11.a weighs 1100kg.
- Maintain verticality of planting to ensure maximum survival rate of sapling on inclined terrain.

Amongst the mains areas for improvement, craobh planting aim to identify the overall current situation in forestry and the machines available to develop an optimised machine capable of outperforming current competitors and reducing the overall downturn of planting capabilities in Scotland.

1.0 Performance

1.0 Shall be able to plant a sapling vertically.
1.1 Shall be able to operate on variable terrain, with varying gradients up to 30°.
1.2 Storage capacity shall be minimum of 200 saplings at one time.
1.3 Shall be capable of planting 2,500-3,000 saplings in one day.
1.4 Shall be able to plant 2,700 saplings per hectare.
1.5 Shall be capable of creating mounds with specific dimensions (20-30cm high and $0.25m^2$).
1.6 Shall be able to plant saplings of varying heights.
1.7 Coupling hitch shall be designed to be suitable for connection to various prime movers.
1.8 Shall increase productive work time by reducing overall time required for reloading sapling cartridge to ≤10 % of productive work time.

2.0 Environment

- 2.0 Product shall operate to full capacity in adverse weather conditions.
- 2.1 Shall be corrosion resistant in both functionality and material selection.
- 2.2 Shall be able to operate to full capacity in all soil conditions typical to Scotland.
- 2.3 Must be able to resist impact loading, caused by tree stumps and rocks.
- 2.4 Shall operate to full capacity in a dirty environment.
- 2.5 Shall be resistant to general forestry equipment wear and tear.
- 2.6 Product should perform to full capacity and not be damaged by temperatures in the range of -20°C to 70°C.
- 2.7 Shall consider compaction issues, with regards soil aeration and also mound compaction.
- 2.8 Shall only perform localised soil scarification, as opposed to across site trenching required for manual planting.

3.0 Maintenance

- 3.0 Shall require minimal maintenance with exception of light lubrication if and when required.
- 3.1 Design shall incorporate easy access to mechanical moving components.
- 3.2 Where screws, bolts and washers are used, British standards must be complied with.
- 3.3 Aftermarket sales and services shall be made available.
- 3.4 Maintenance shall only require general tools.

4.0 Materials

- 4.0 The chosen materials shall be resistant to wear and tear e.g. scratch and panel dent resistant.
- 4.1 Materials chosen shall be resistant to corrosion and rusting.
- 4.2 Materials chosen shall retain structural integrity in environments with temperatures ranging from -20°C to 70°C.
- 4.3 The materials shall be as lightweight as possible, however structural strength and rigidity must not be compromised.
- 4.4 Environmentally friendly materials shall be used for manufacture.
- 4.5 The materials chosen shall be malleable and formable in manufacture.
- 4.6 Readily available and commonly used materials for manufacture would be preferable.

5.0 Weight

- 5.0 Must not weigh more than 1500kg.
- 5.1 Product weight must not affect performance of tracked excavator.
- 5.2 Weight of design shall be reduced as far as possible, however structural strength and rigidity must not be comprised.
- 5.3 Lashing point shall be incorporated to enable easy transportation.

6.0 Size

- 6.0 Size shall be kept to a minimum, in order to reduce cost and power required and increase manoeuvrability.
- 6.1 Connection dimensions constrained by proportions of universal attachment hitch.
- 6.2 Size of scarifying blade is constrained by dimensions of mound required (see ‘Performance’)

6.3 Size of product will be constrained by sapling storage requirements (see 'Performance')

7.0 Shipping

7.0 Shall be transportable with 360° tracked excavator.
7.1 Shipping of saplings shall be considered to incorporate easier reloading of planting machine.
7.2 Lashing point shall be incorporated to enable easy transport.

8.0 Quantity

8.0 Must be able to entice custom through a full rental package. 5 units to be manufactured and made available across Scotland for contract hire.
8.1 Virtual design package to be made available for simulation training.

9.0 Competition

9.0 Dominance of manual planting within Scottish market.
9.1 Mechanised planting market led by Bracke Forest.
9.2 Shall improve on compaction issues experienced using Bracke machine.
9.3 Shall improve on sapling storage capabilities of other mechanised planting machines (around 120 saplings at one time).
9.4 Shall improve on abrasion issues with current Bracke carousel sapling delivery.

10.0 Market Constraints

10.0 The device shall be marketed on a trial basis within Scotland and, if successful, will be marketed worldwide.
10.1 Connection to excavator shall be through a universal attachment hitch found on a 360° tracked excavator.
10.2 Availability of standard parts (screws, nuts, bolts, etc) shall be considered during design.
10.3 Availability of hydraulic parts shall be considered during design of joints etc.
10.4 Prime mover shall be a 360° tracked excavator.

11.0 Customer

11.0 Customers shall be from the forestry industry and general groundworks contractors.
11.1 Product shall be suitable for simulation by Simultech Scotland.
11.2 Performance shall be prioritised over aesthetics.

12.0 Safety

12.0 All moving components shall be appropriately covered.
12.1 Design must meet all industry safety regulations.
12.2 Sharp edges shall be avoided or covered where possible.
12.3 Risk of injury when loading saplings shall be kept to a minimum.
12.4 Attachment of planting machine shall be considered to prioritise safety and conducted by an experienced operator.

13.0 Standard Specifications

13.0 At present no British Standards exist for planting.
13.1 Must conform to procedures and specifications currently in place using existing techniques.
13.2 Must follow existing health and safety standards, in place both by machine manufacturer and planting contractor/landowner.

14.0 Ergonomics

14.0 Must be able to operate using standard controls in the cab of the excavator with little or no additional training.

14.1 A clear line of sight from operator to planter attachment must be imposed to ensure maximum observation.

14.2 When reloading sapling cartridges, the machine at rest must be at an appropriate working height.

14.3 The operator must be able to easily access the carousel for sapling reloading without risk of injury or difficulty.

14.4 Moving components must have easy access with the aim of being able to conduct most maintenance in the field.

15.0 Time Scale

15.0 Refer to Gantt chart

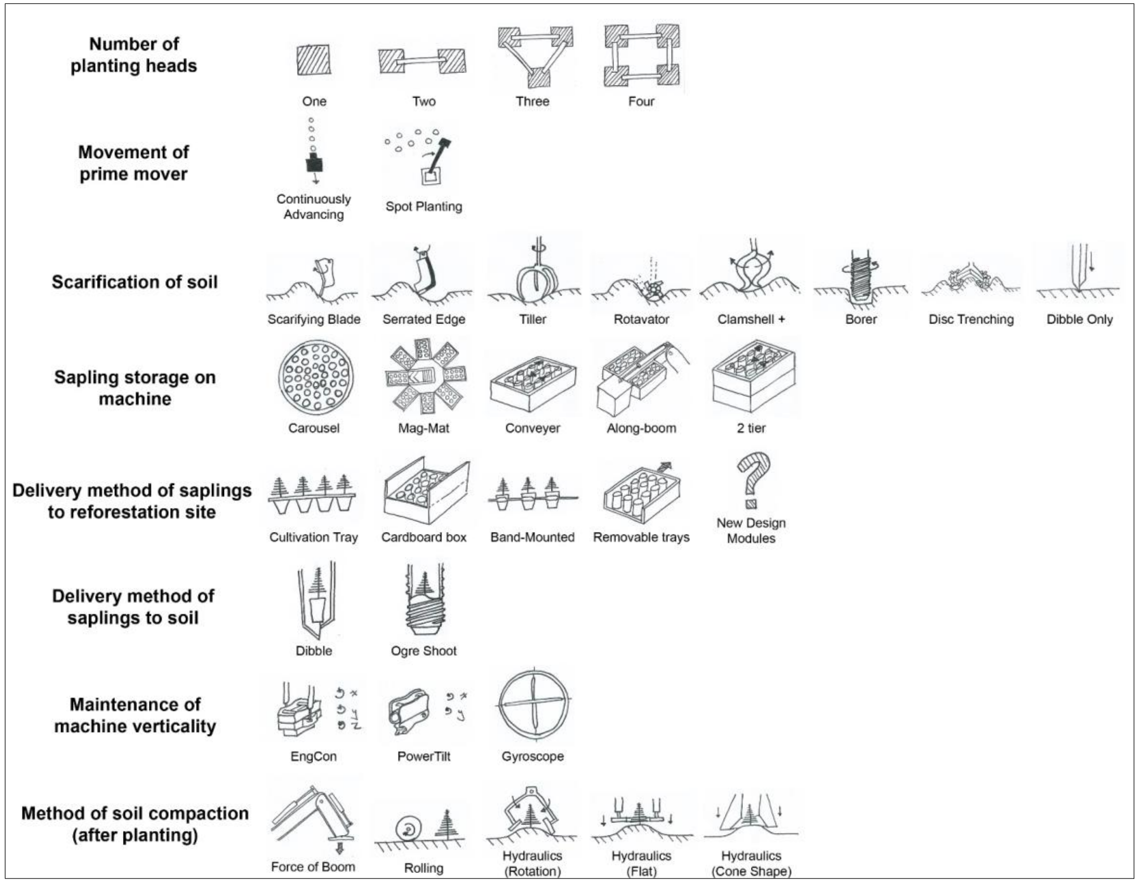
15.1 Interim Deadline – 26 November 2015

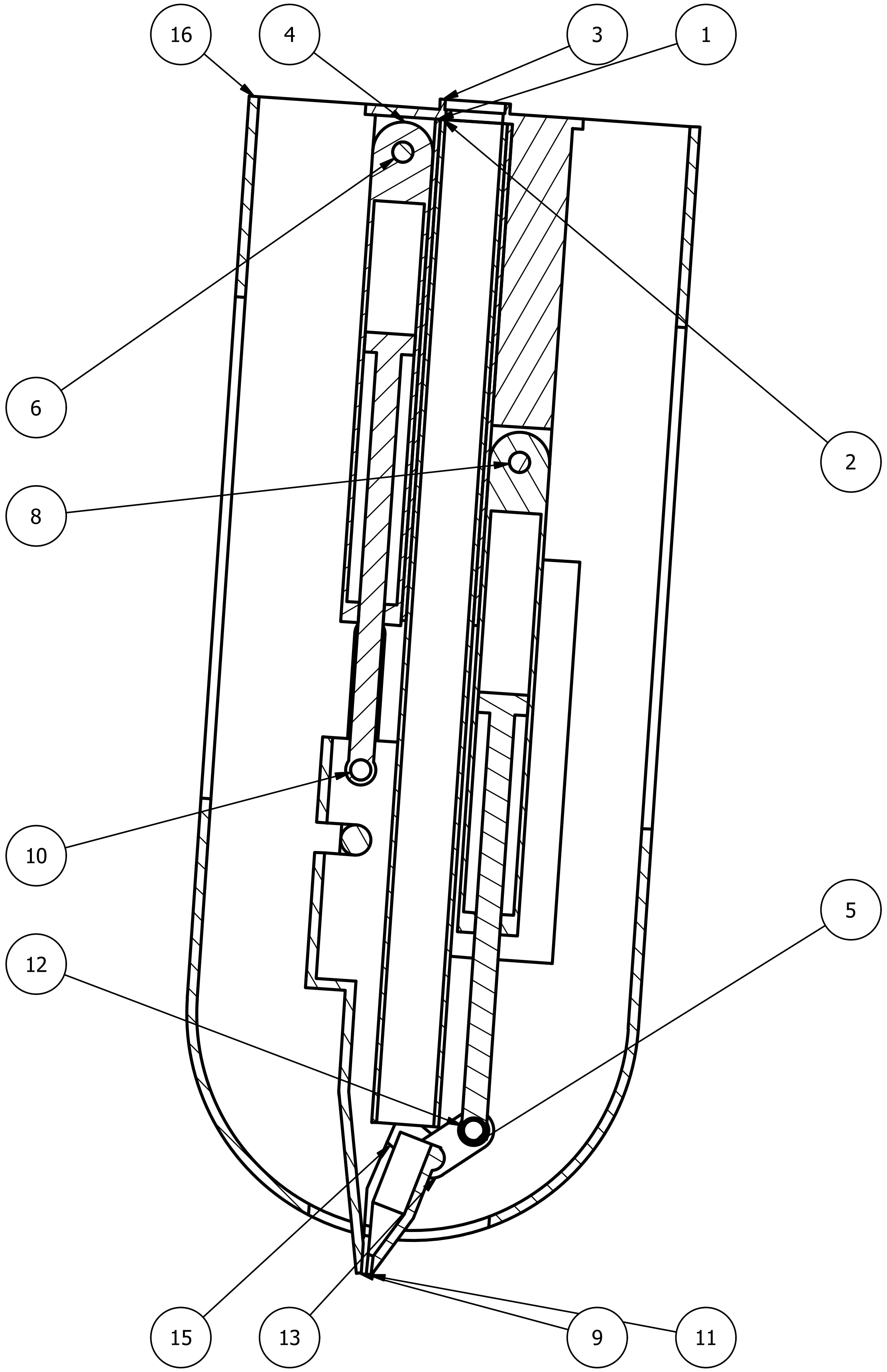
15.2 Final Deadline – 21 March 2016

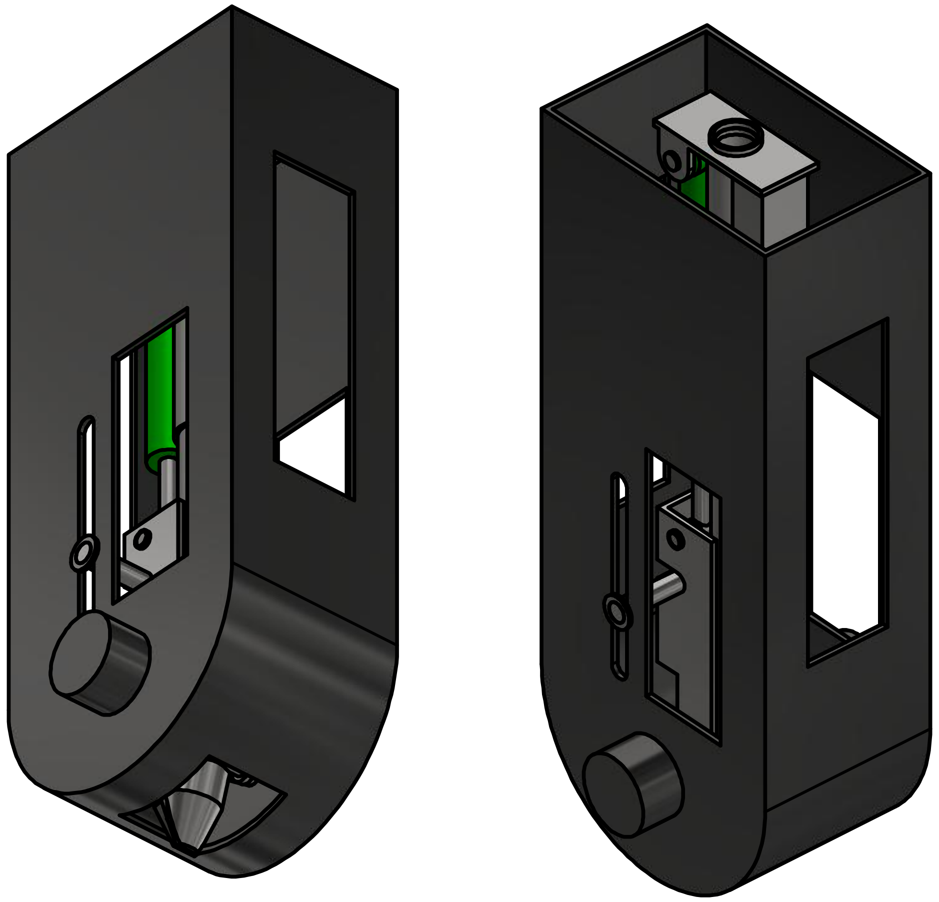
16.0 Product Life in Service

16.0 Product must be operational for a minimum of 15 years

Appendix A6: Morphological Chart







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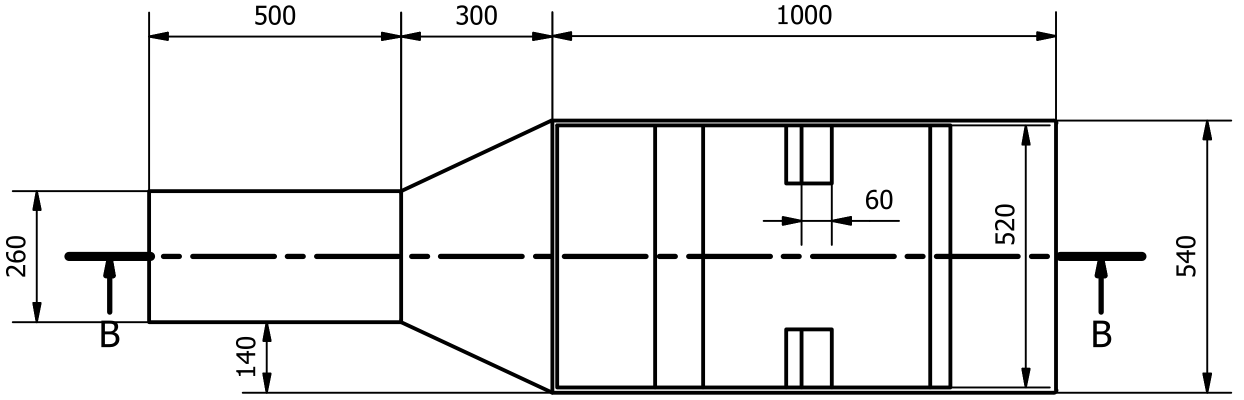
2	1	Internal pipe	Steel, High Strength, Low Alloy
3	1	Dibble base	Steel, High Strength, Low Alloy
4	2	Dibble cylinder external part	Steel, High Strength, Low Alloy
5	2	Dibble cylinder internal part	Steel, High Strength, Low Alloy
6	1	bolt 1	Steel, High Strength, Low Alloy
7	3	nut 1	Steel, High Strength, Low Alloy
8	1	bolt 2	Steel, High Strength, Low Alloy
9	1	Punta 1	Steel, High Strength, Low Alloy
10	1	bolt 3	Steel, High Strength, Low Alloy
11	1	Punta 2	Steel, High Strength, Low Alloy
12	1	Punta 2 bar connector	Steel, High Strength, Low Alloy
13	2	Punta 2 connector	Steel, High Strength, Low Alloy
14	2	Punta 2 nut	Steel, High Strength, Low Alloy
15	2	joint 2 for punta 2	Steel, High Strength, Low Alloy
16	1	Dibble external casing	Steel, High Strength, Low Alloy
17	2	nut pin punta 1	Steel, High Strength, Low Alloy

Author Isabel Chong Cheung	Edition date 15-03-2016	UNIVERSITY OF STRATHCLYDE
Checked by Fraser Henderson	Type Assembly drawing	

Scale 1:6	Title craobh planting machine	Material	Identification
	Sub-title Dibble and casing		Sheet Num. A7



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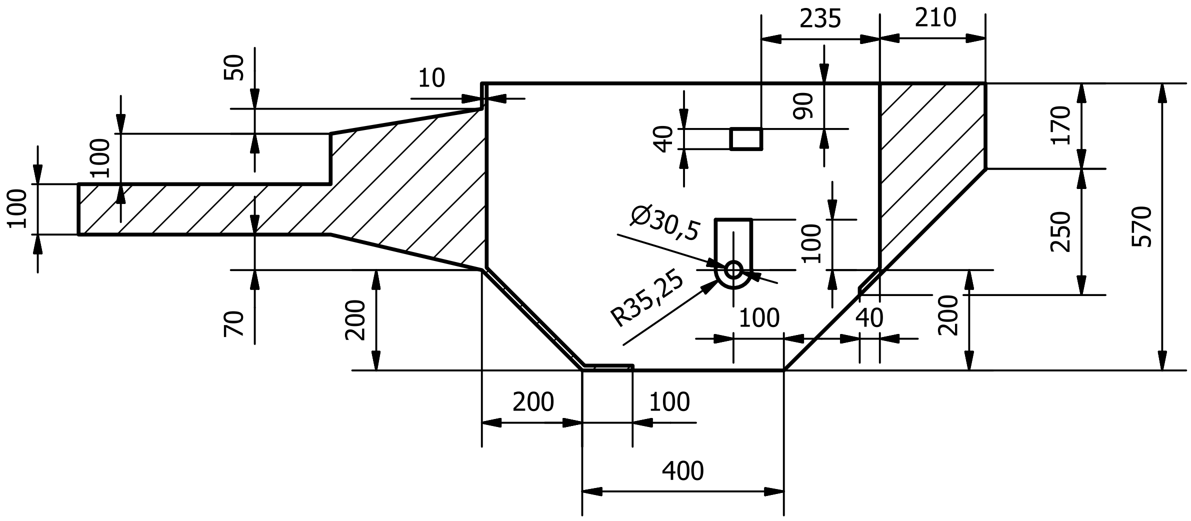

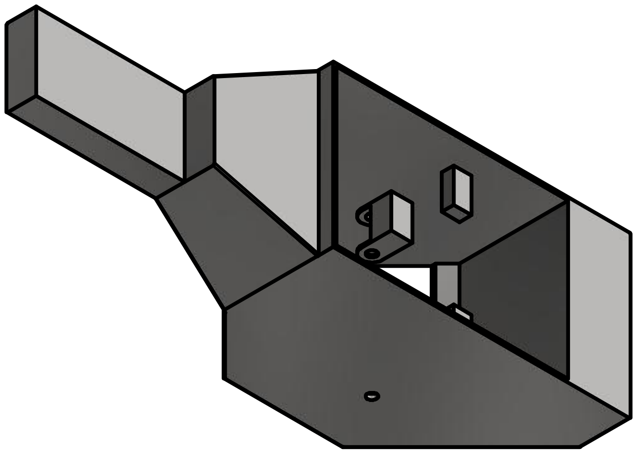

Author Isabel Chong Cheung	Edition date 15-03-2016	UNIVERSITY OF STRATHCLYDE		
Checked by Fraser Henderson	Type Part drawing			
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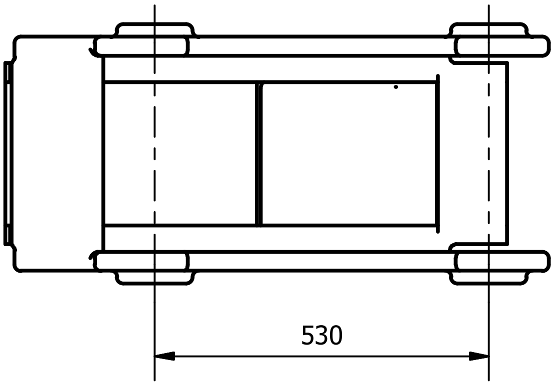
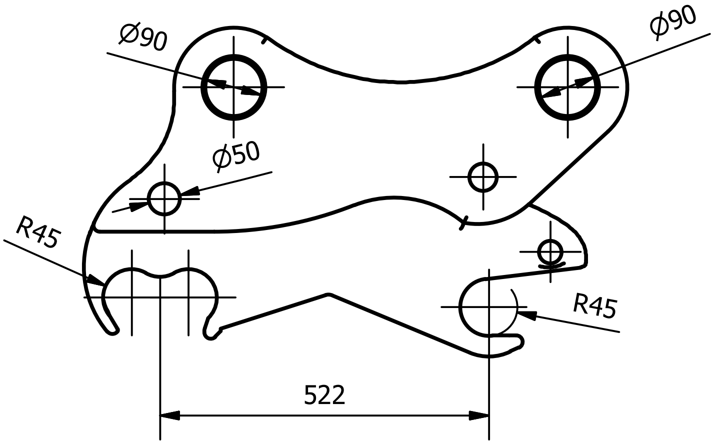
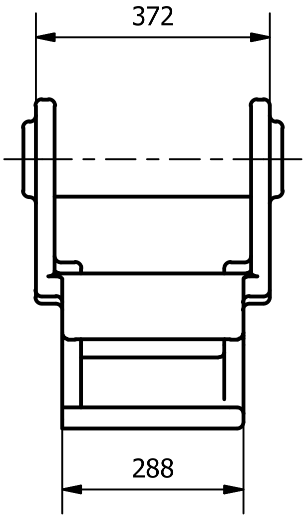
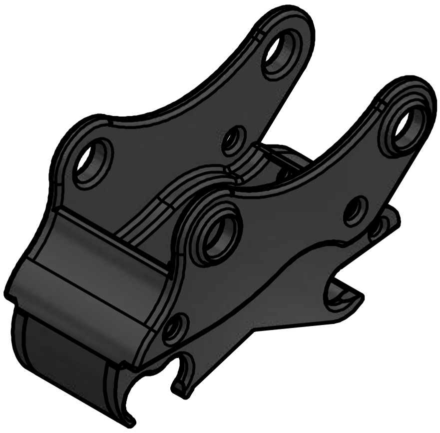
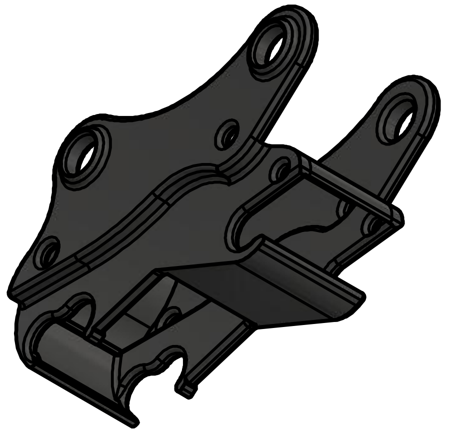
	Sub-title External casing			Sheet Num. A8











Author Isabel Chong Cheung	Edition date 15-03-2016	UNIVERSITY OF STRATHCLYDE	
Checked by Fraser Henderson	Type Part drawing		
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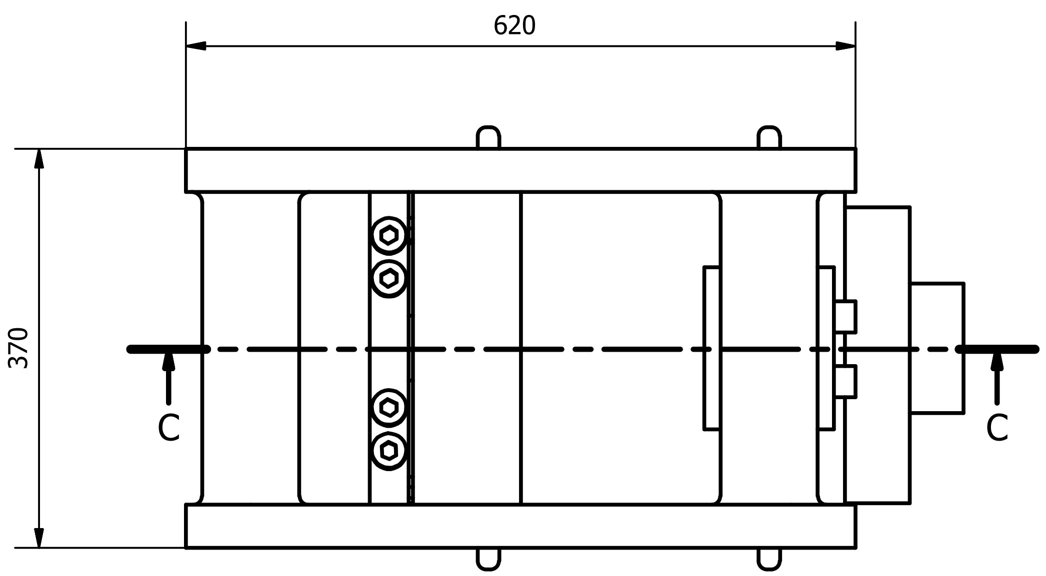
	Sub-title Universal hitch		Sheet Num. A9



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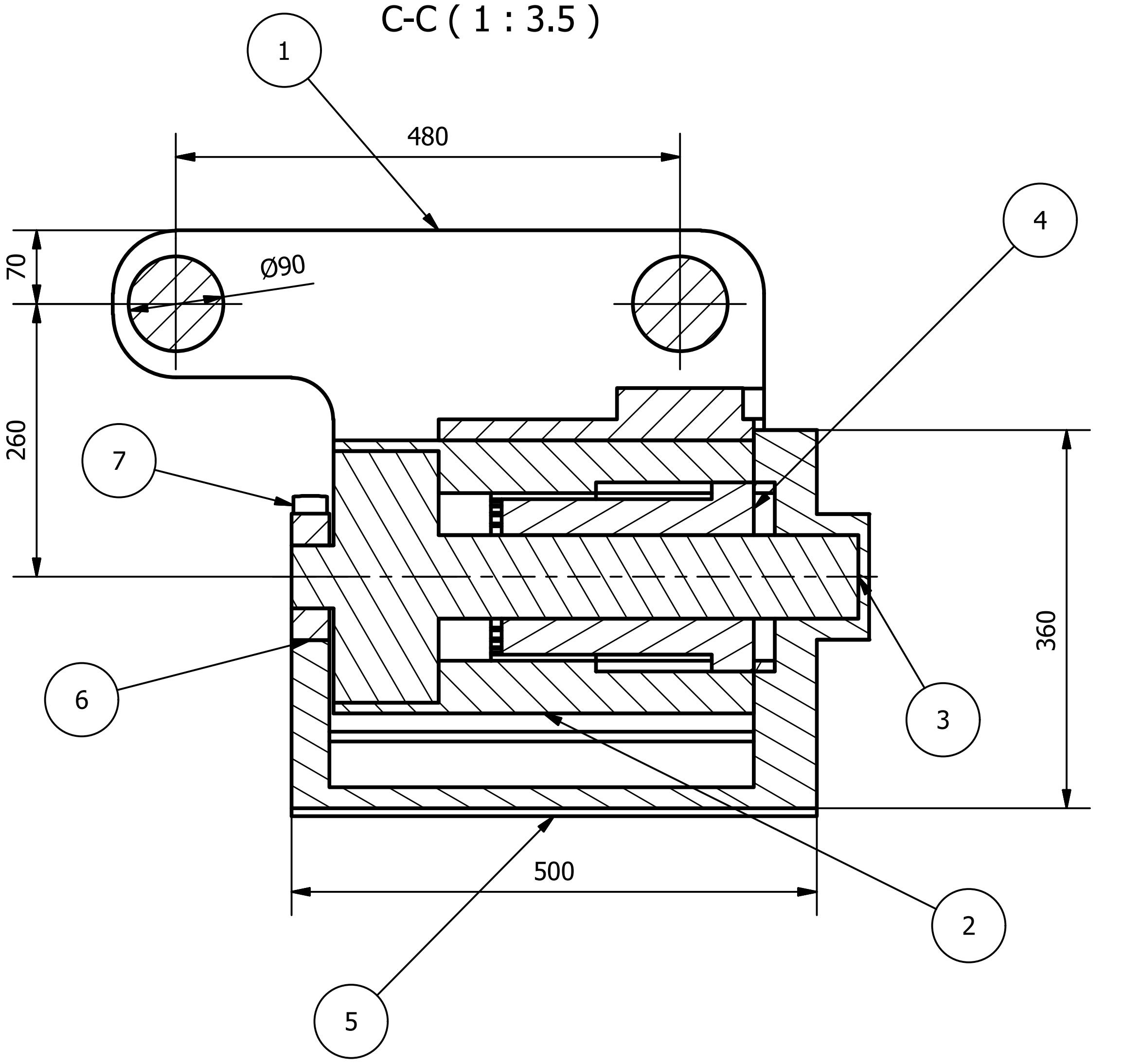
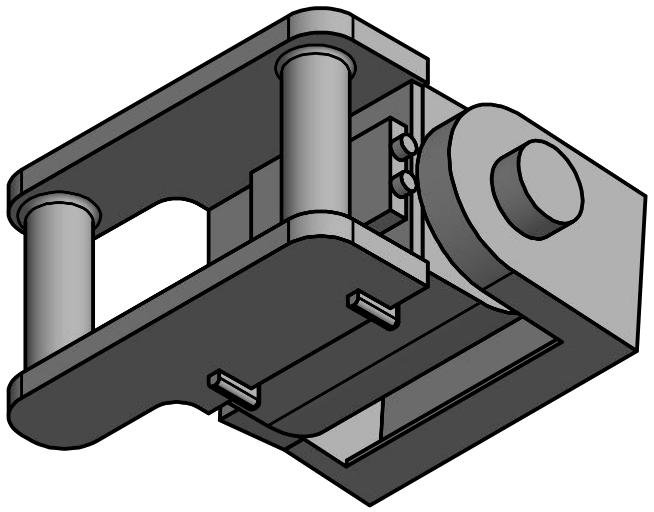
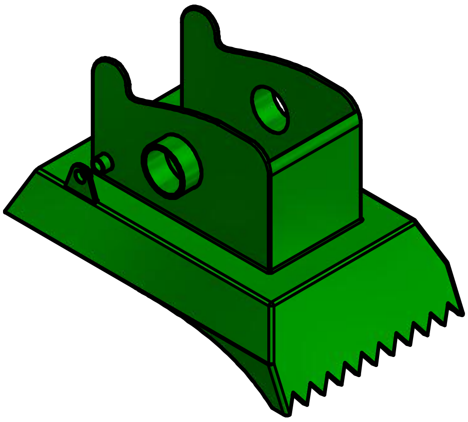


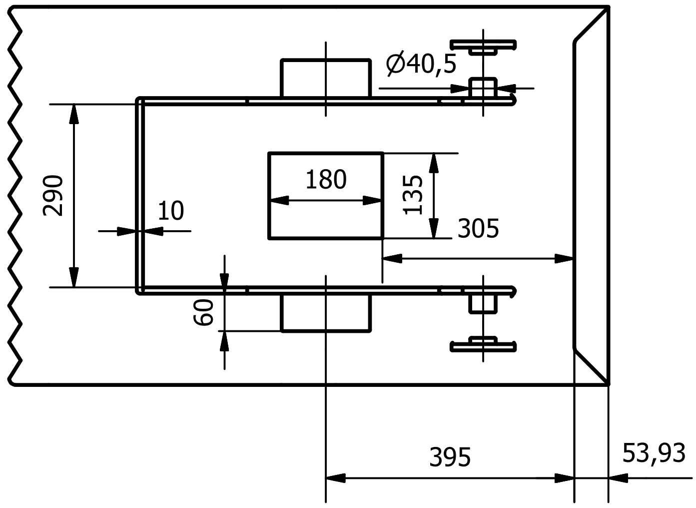


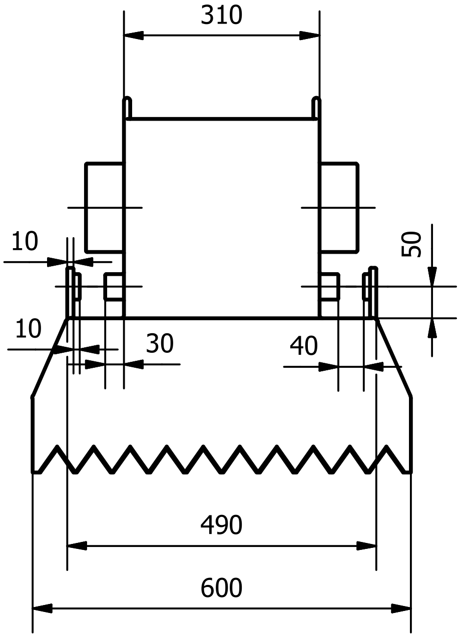
PARTS LIST			
ITEM	QTY	PART NUMBER	MATERIAL
1	1	tophousing	HS carbon steel
2	1	shafthousing	HS carbon steel
3	1	shaft	HS carbon steel
4	1	pistonsleeve	HS carbon steel
5	1	lowercoupling	HS carbon steel
6	1	endbearing	HS carbon steel
7	4	bolt	HS carbon steel

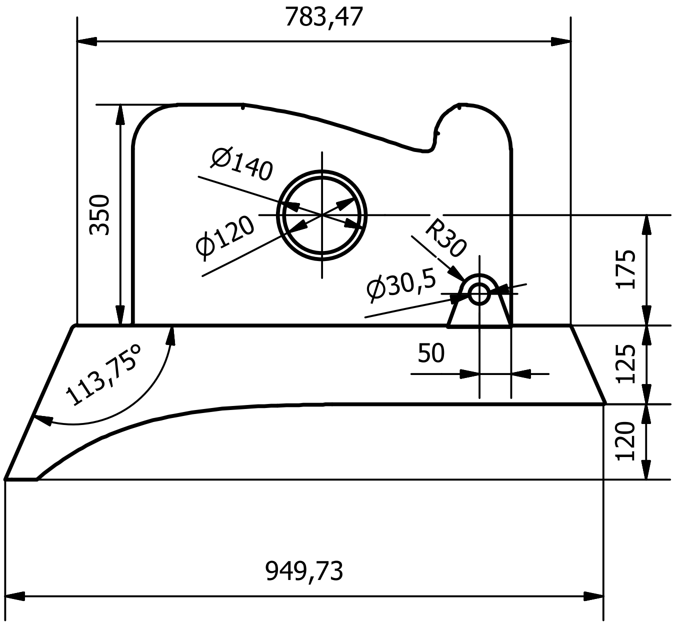
Author Isabel Chong Cheung	Edition date 15-03-2016	UNIVERSITY OF STRATHCLYDE
Checked by Fraser Henderson	Type Assembly drawing	

Scale 1:3.5	Title craobh planting machine	Material	Identification
	Sub-title Hydraulic leveller		Sheet Num. A10





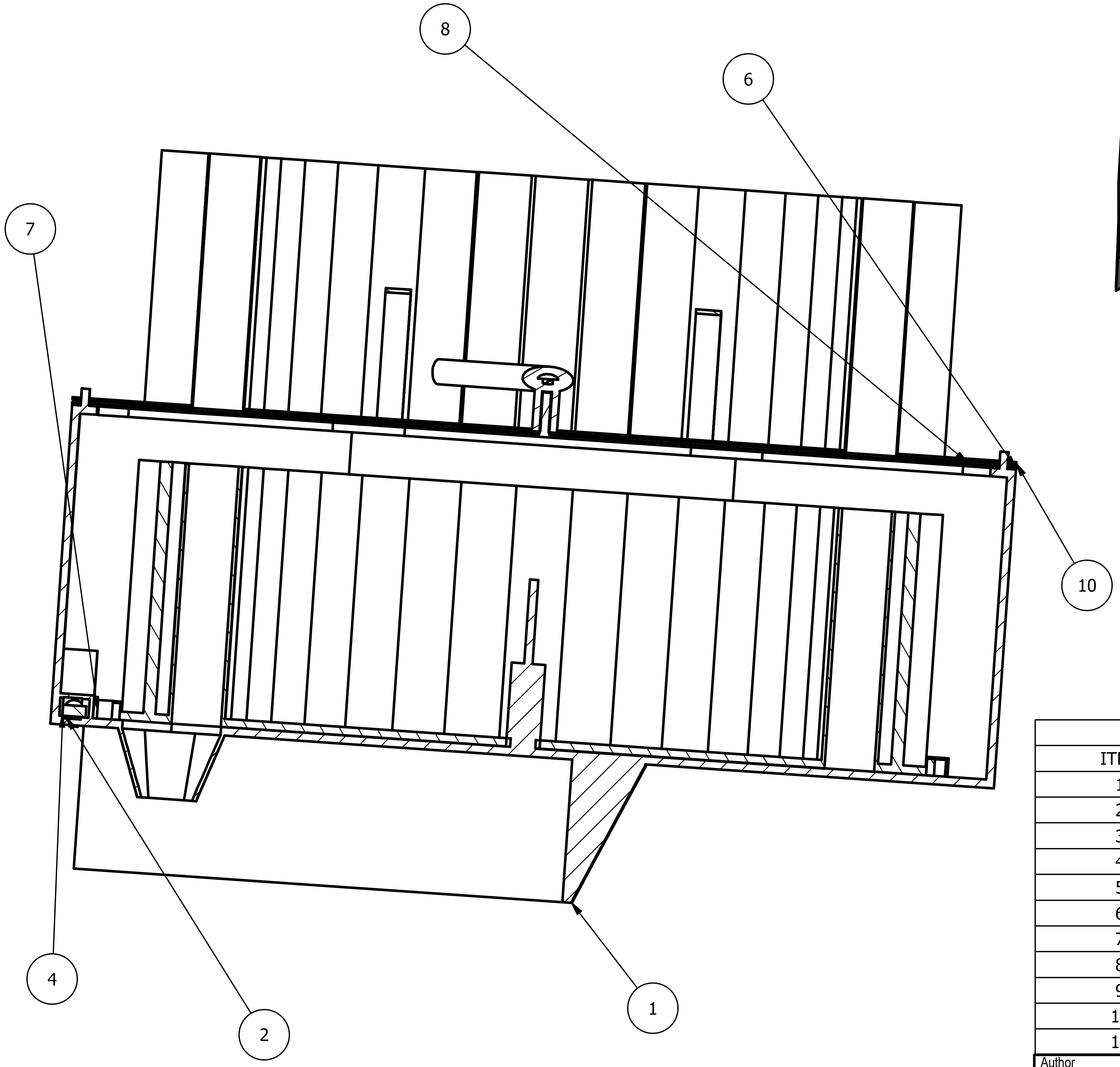


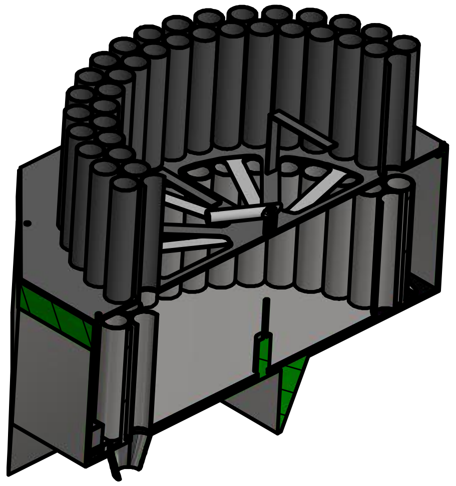


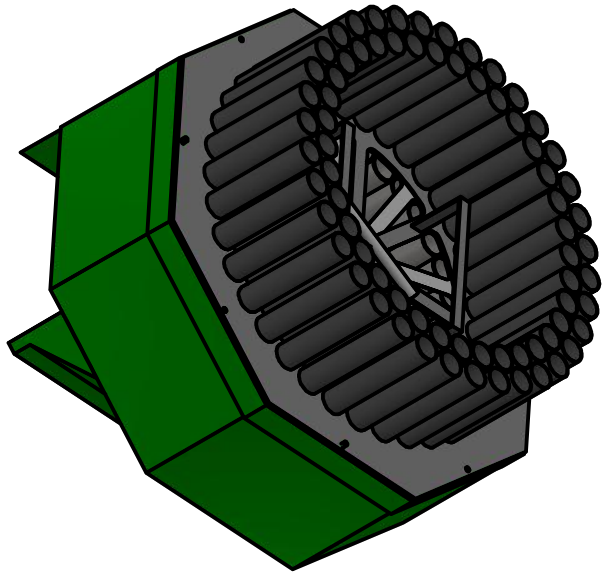
Author Isabel Chong Cheung	Edition date 15-03-2016
Checked by Fraser Henderson	Type Part drawing

UNIVERSITY OF STRATHCLYDE

Scale 1:12	Title craobh planting machine	Material HS Carbon Steel	Identification
	Sub-title craobh planting scarifying blade		Sheet Num. A11







PARTS LIST

ITEM	QTY	PART NUMBER	MATERIAL
1	1	Carousel External Casing	Steel, High Strength, Low Alloy
2	1	Carousel Ram Outer Cssing	Steel, High Strength, Low Alloy
3	1	Carousel Ram Inner Piston	Steel, High Strength, Low Alloy
4	1	Carousel Feeding Head Update	Steel, High Strength, Low Alloy
5	1	Carousel Feeding Head Upper	Steel, High Strength, Low Alloy
6	1	New Design Bottom Part	PMMA Plastic
7	1	Carousel Top	Steel, High Strength, Low Alloy
8	1	New Design Middle Part	PMMA Plastic
9	1	Pawl	PMMA Plastic
10	1	New Design Top Part	PMMA Plastic
11	4	Carousel Simplified Bolt	Steel, High Strength, Low Alloy

Author
Isabel Chong Cheung

Edition date
15-03-2016

Checked by
Kirk Johnston

Type
Assembly drawing

UNIVERSITY OF STRATHCLYDE

Scale
1:6

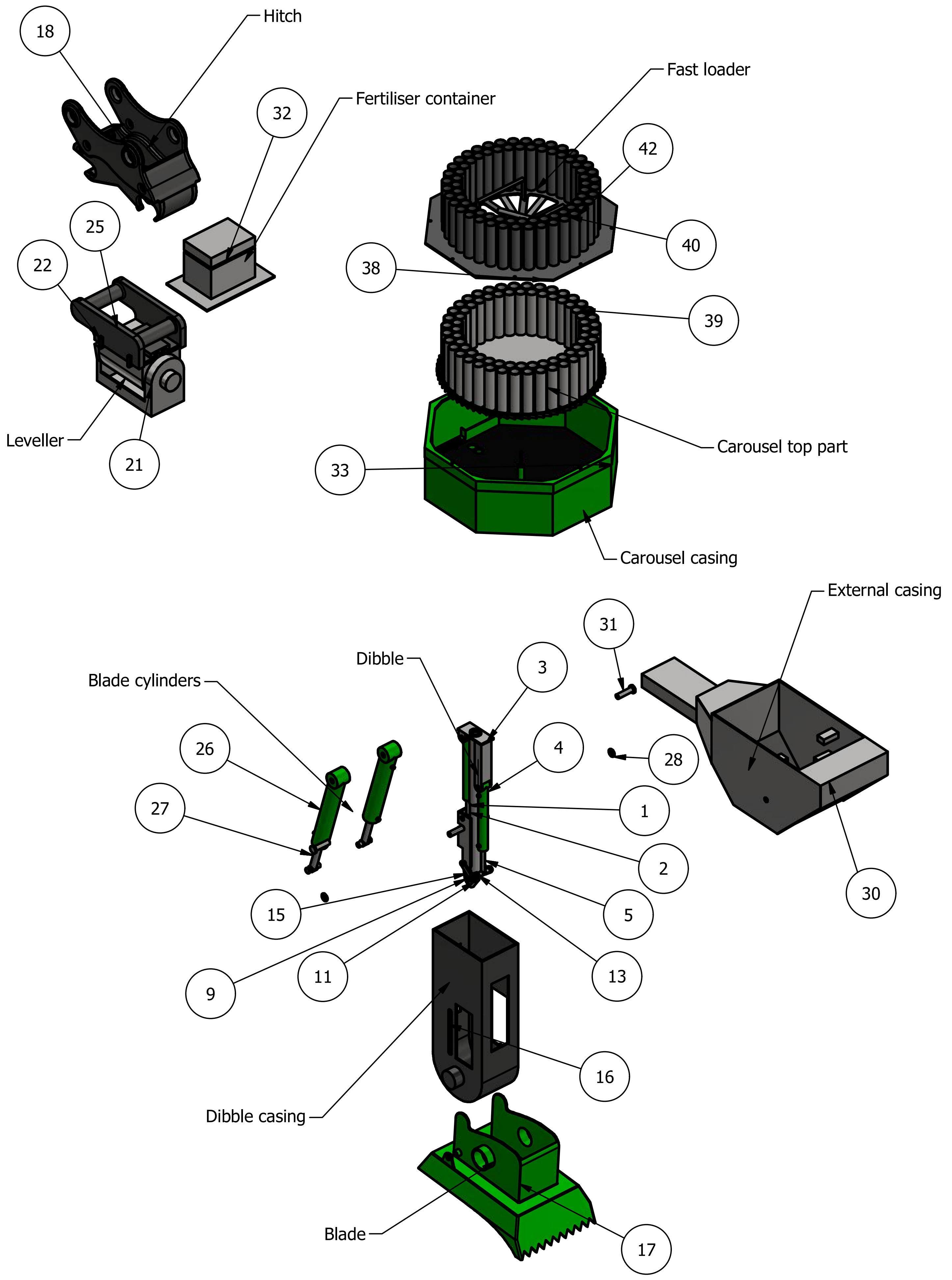
Title
craobh planting machine

Material

Identification

Sub-title
Carousel and fast loader

Sheet Num.
A12



PARTS LIST

ITEM	QTY	PART NUMBER	MATERIAL
1	1	External pipe	Steel, High Strength, Low Alloy
2	1	Internal pipe	Steel, High Strength, Low Alloy
3	1	Dibble base	Steel, High Strength, Low Alloy
4	2	Dibble cylinder external part	Steel, High Strength, Low Alloy
5	2	Dibble cylinder internal part	Steel, High Strength, Low Alloy
6	1	bolt 1	Steel, High Strength, Low Alloy
7	3	nut 1	Steel, High Strength, Low Alloy
8	1	bolt 2	Steel, High Strength, Low Alloy
9	1	Punta 1	Steel, High Strength, Low Alloy
10	1	bolt 3	Steel, High Strength, Low Alloy
11	1	Punta 2	Steel, High Strength, Low Alloy
12	1	Punta 2 bar connector	Steel, High Strength, Low Alloy
13	2	Punta 2 connector	Steel, High Strength, Low Alloy
14	2	Punta 2 nut	Steel, High Strength, Low Alloy
15	2	joint 2 for punta 2	Steel, High Strength, Low Alloy
16	1	Dibble external casing	Steel, High Strength, Low Alloy
17	1	Craobh planting blade	Steel, High Strength, Low Alloy
18	1	Hitch2	Steel, High Strength, Low Alloy
19	1	leveler bearing2	Steel, High Strength, Low Alloy
20	4	leveler bolt2	Steel, High Strength, Low Alloy
21	1	leveler coupling2	Steel, High Strength, Low Alloy
22	1	leveler housing2	Steel, High Strength, Low Alloy
23	1	leveler piston2	Steel, High Strength, Low Alloy
24	1	leveler shaft2	Steel, High Strength, Low Alloy
25	1	leveler tophousing2	Steel, High Strength, Low Alloy
26	2	Main ramp external part	Steel, High Strength, Low Alloy
27	2	Main ramp internal part	Steel, High Strength, Low Alloy
28	2	Nut pin punta 1	Steel, High Strength, Low Alloy
29	2	bolt pin main ramp	Steel, High Strength, Low Alloy
30	1	external casing	Steel, High Strength, Low Alloy
31	2	bolt for main ramp and external casing	Steel, High Strength, Low Alloy
32	1	box	Steel, High Strength, Low Alloy
33	1	Updated Base and Casing	Steel, High Strength, Low Alloy
34	1	Carousel Ram Outer Cssing	Steel, High Strength, Low Alloy
35	1	Carousel Ram Inner Piston	Steel, High Strength, Low Alloy
36	1	Carousel Feeding Head Update	Steel, High Strength, Low Alloy
37	1	Carousel Feeding Head Upper	Steel, High Strength, Low Alloy
38	1	New Design Bottom Part	PMMA Plastic
39	1	Carousel Top	Steel, High Strength, Low Alloy
40	1	New Design Middle Part	PMMA Plastic
41	1	Pawl	PMMA Plastic
42	1	New Design Top Part	PMMA Plastic
43	4	Carousel Simplified Bolt	Steel, High Strength, Low Alloy

Author
Isabel Chong Cheung
Edition date
15-03-2016
Checked by
Kirk Johnston
Type
Assembly drawing

UNIVERSITY OF STRATHCLYDE

Scale
1:30
Title
craobh planting machine
Material
Identification
Sub-title
Full assembly
Sheet Num.
A13