Design of a Small Scale Root Crop Washer

BREE 495: Final Design Report

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Executive Summary

Adequately cleaning is a critical operation in the production and distribution of fresh produce. This is especially true for the smaller scale, local agriculture operations such as the McGill Student-Run Ecological Garden (MSEG) with less access to large scale cleaning operations. In an attempt to improve upon the traditional cleaning methods of root crop vegetables, MSEG has expressed a need for an innovative processing approach to the cleaning of their harvested organic produce to meet their special needs.

Applying engineering design concepts and analysis, this report outlines the development of a small scale root crop washer from computer model simulation to a working prototype. The methodologies of mechanical design, material acquisition, construction and prototype testing are addressed. Prototype success, assessed through adequate testing, has enabled the validation of the efficacy in the cleaning of root crop vegetables. Using these success parameters and the working prototype a scaled-up model will effectively be constructed by using food grade brushes, in order to meet the needs of MSEG and their agricultural practices.

1.0 Introduction

Our client, the McGill Student Ecological Garden (MSEG) is a student-run organization based at McGill University's Macdonald Campus that operates on a 5058.57 m^2 (1 ¼ acre) ecological farmland located in the Morgan Arboretum and near the Eco-residences. Every year, MSEG applies sustainable agricultural practices to produce local organic vegetable crops in hopes of expanding on and educating the community about ecological and organic agriculture.

MSEG's current practices involve exerting a substantial amount of manual labour, expended on activities which include, but are not limited to planting, harvesting and cleaning all of their produce. This summer, MSEG will be relocating the centre of their activities from the fields near Macdonald Campus' horticulture centre to farmland near the Macdonald Farm near on the opposite side of the AutoRoute 20. Previously, MSEG had been using a combination of the horticulture centre's barrel washer in addition to manual hand washing to process some of their root crops after harvesting to prepare them for sale. The barrel drum washer, while it is helpful in processing large quantities of harvest at a time, was deemed insufficient in preserving the much valued green tops that help boost the crop's marketability. Through their expansion, MSEG will not only be cut-off from the horticulture centre's barrel washer, but they will also have to deal with an increase of crop harvest due to larger fields at the Macdonald farm.

Figure 1 - The Horticulture Centre barrel washer

In the wake of the first planting season since they have relocated to the MacDonald farm, MSEG has expressed the need for an innovative cleaning method that can effectively, clean, produce and maintain the organization's current pace of actions. As per the previous design proposal, our goal is to develop a small scale root crop washer that can help MSEG improve the efficacy as well as reducing amount of physical labour put into the post-harvest cleaning of their root crops.

In order to better understand what the needs of MSEG are in more detail, a concise interview was conducted as well as a tour of their working area. The problems that MSEG are facing are:

- The lack of efficiency in regards to post harvest washing of root crops.
- Post-harvest washing treatment of the crops and their greens should be improved.
- Water and resource management should be improved since MSEG is a green and ecological group striving for ecologically sound developments.

Thus, the new washer design should improve how root crops are being processed with a special regard for the preservation of the green tops; it should also strive for more water and energy use efficiency. However, it will need to adhere to constraints such as durability/longevity and cost.

Summarized are the design criteria that was put together in the design proposal:

1. The machine must be able to wash root crops of **various sizes** (due to the variability in size and shape from crop to crop).
2. The machine must be able to be **easy to use** and fairly easy to **integrate**/**implement** into MSEG's routine.
3. The machine must **reduce the processing time** of each crop compared to MSEG's current methods.

4. **Water resource consumption** should be reduced to lesser amounts used compared to current methods.
5. The machine must be able to withstand wear from frequent usage.
6. The **crop impact**- particularly of the green tops must be **reduced significantly** and thus, would improve the crop's marketability.
7. The machine must be **safe** for users and be easy to maintain.

In the proposal, 3 different designs were focused on that were created in accordance to satisfying each of the design criteria. To evaluate the best design, all three prospective designs were compared to the reference barrel washer by employing a Pugh chart.

Table 1: Design comparison Pugh chart

		Reference	DESIGN OPTIONS		
Criteria	Weight	Barrel drum	Conveyor belt	Lever Tray	Rolling brushes
Durability	3	0	-1	-1	-1
Safety	1	0	-1	0	-1
Crop impact	3	0	1	2	2
Ease of use	3	0	0	-1	0
Cost	2	0	-2	0	0
Efficiency	3	0	0	1	-1
Resources	2	0	0	1	1
Manufacturability	2	0	-1	-1	-1
Maitenance	2	0	-1	-1	0
Portablity	1	0	0	1	1
Integration	1	0	0	-1	0
sum positives			3	12	9
sum zeros			5	2	4
sum negatives			-12	-11	-6
Total points		0	**-9**	**1**	**3**
Rank			**3**	**2**	**1**

The total ratings of each design option were determined in accordance to their evaluation based on meeting the design criteria. The rolling brush design option was found to be the best option compared to the other prospective designs.

In choosing the rolling brush design for prototyping purposes, a new set of objectives and constraints have to be determined to better understand how the project progression should be headed.

A simplified list of goals to be achieved in the final stages of our design were indicated as:

- The **re-evaluation** of the chosen design, including the actual design components and its specifications.

- **Sourcing** of the materials to be used to build a working prototype.
- The actual **construction** and testing of a prototype.

To achieve our objectives, new challenges and constraints were to be addressed, with a particular emphasis on the construction aspect of the prototype:

- The **time** needed to **source** materials and have them delivered.
- The **time** it takes to **build** and **test** the prototype.
- **Costs** associated with purchasing the parts.
- **Safety** considerations while building the prototype.
- Our **expertise** in operating heavy machinery.

A Gantt chart (See Appendix 2) was created in order to set solid deadlines for a multitude of specific tasks. It should be noted that some of the construction aspects of the prototyping were pushed back due to the difficulty in the actual sourcing and obtaining of the materials.

2.0 Analysis and specification

After the determination of the basic concept of design, the use of Computer Aided Design facilitated the progress of the design process. Specifications were defined within the software environment; then machinery design concepts and calculations were used to analyze the design and make adjustments as was necessary throughout the completion of the process.

The analysis process lead to identification of suitable assumptions which reduced the amount of calculations required for many of the elements of the machine system. These assumptions are listed following the overview of the design process.

2.1 Design process overview through Computer Aided Design (CAD)

The AutoCAD software was first used to produce the drawings. Although later on it was abandoned due to two main reasons: 1) difficulty to work with a multitude of smaller elements, 2) the need to enable easy dynamic adjustment of each part throughout the process. Figure 2 below shows the result of these drawings. At this point, the number of brushes to be used was set to two with a large diameter brush (10 cm) to enable good brush/crop contact on all sides.

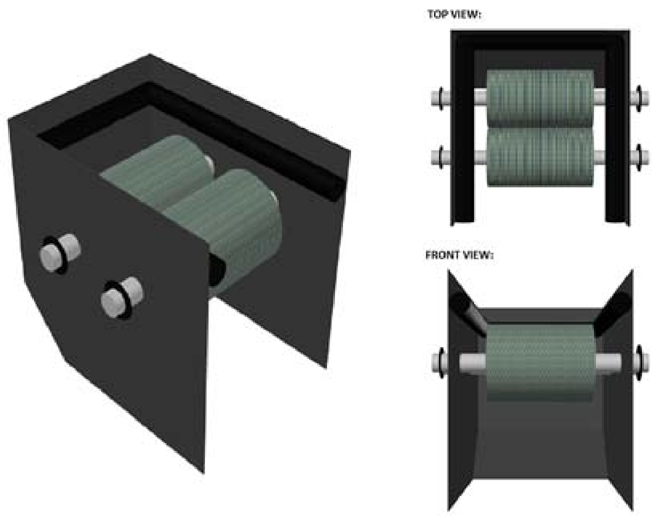

Figure 2 - AutoCAD drawing

To obtain optimal effectiveness of the brushes, and also to reduce splashing issues towards the operator of the machine, it was concluded that the two brushes need to be rolling in opposite directions, towards each other. To attain these result the v-belt transmission system shown in Figure 3 was purposed.

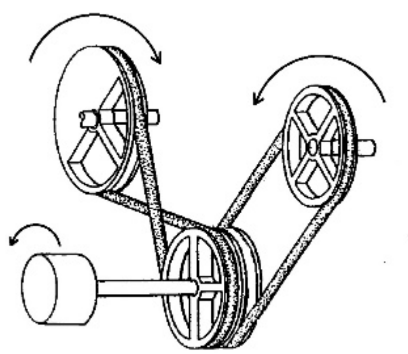

Figure 3 - V-belt transmission system

After prototyping the system, there were issues such as slight rubbing of the belt that was deemed unacceptable for long term use of the machine. This resulted in a new transmission system design that made use of a specially placed tensioner as show in Figure 4. A flat belt system was deemed necessary in this case due to both sides of the belt being in contact with the pulleys.

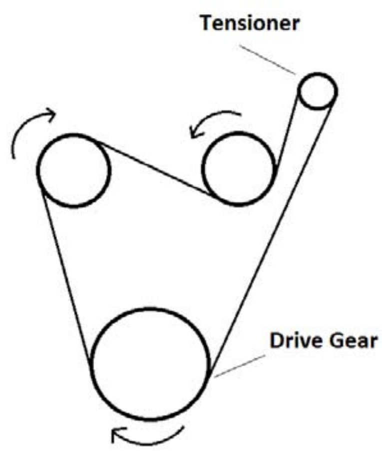

Figure 4 - Tensioner Transmission System

The PTC Creo software (previously known as Pro engineering) was adopted to create new set of CAD drawings to elaborate the progress of the design process and enable documenting detailed specifications. The first results are illustrated in Figure 5. At this point, to enable the adjustability of the system to accommodate the variety of the crop sizes produced by the client, an arrangement of slots were introduced to the location of one of the brushes, through which the respective bearings would be slide accordingly and tightened at desired locations.

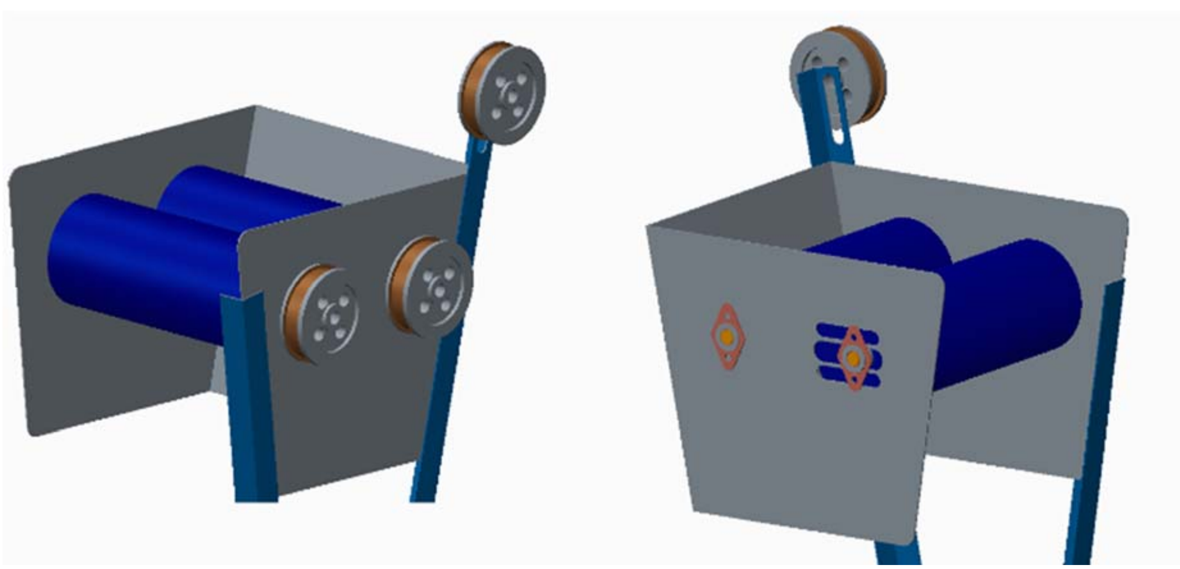

Figure 5 - First PTC Creo Drawing

Later on the use of a flat belt was also omitted. This was due to the slow speed of operation for this system, which would render the belt prone to slipping. Hence a sprocket gear system with the same transmission concept was adopted as the final choice.

Finally the side walls of the machine were simplified to enable easier attachment of safety covers for the gears, ease the process of machining, and allow a more stable mounting of the casing on legs. The final version of the CAD drawings are illustrated in Figure 6 with the addition of the crank shaft power source.

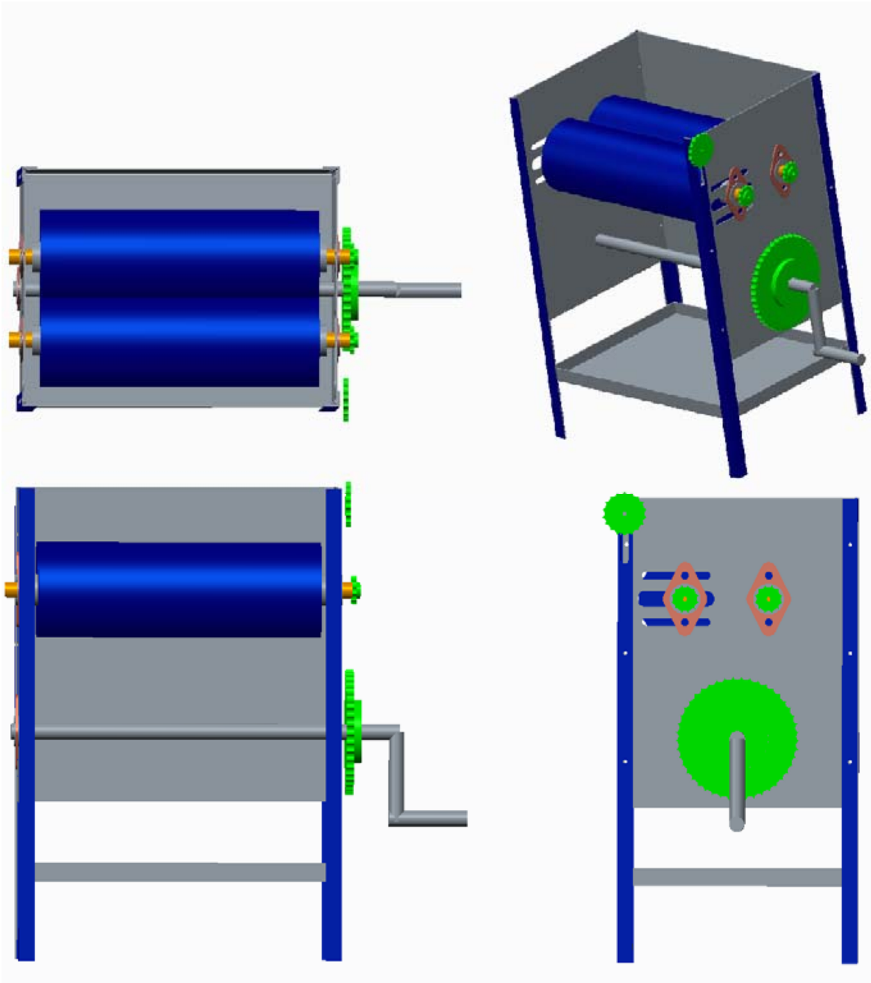

Figure 6 - Final PTC Creo Drawing

2.2 Assumptions

The purchasing of many of the system's parts from reputable sources and/or professional advice enabled a number of the assumptions to be made based on experience or proven functionality. This was helpful in adopting the parts in question as appropriate for the purposes of this project without further analysis.

These assumptions include:

- Shaft load considerations: due to the almost negligible loads caused by the flexing of the filament on the brush shaft, the load analysis on the shaft was omitted.

- Wall thickness: running a full vibrational analysis for the machine was out of the scope of this project and the experience of professionals enabled the choosing of proper wall thickness.
- Bearings specifications: were regarded appropriate since they were manufactured for working at much higher speeds and heavier loads than this project requires.

Other assumptions were made due to the nature of the machine system materials and method of use, such as:

- Torsion impact analysis: deemed unnecessary due to low functioning speeds and the manual nature of the power source.
- Load analysis on side walls: the chosen wall thickness for vibrational purposes rendered the walls to be overly qualified to handle the load of the brushes and bearings.

Machinery design analysis was carried out on the following subjects:

- Power transmission: to allow proper sizing of the gears to acquire desired speeds
- Leg support buckling: for sufficient and safe stabilizing of the system
- Bolt sizing: for sizing of drilling holes to accommodate safe mounting of the system
- Tolerances: to permit accurate determination of specifications required for proper drilling and milling, preventing future issues with fittings and sliding.

2.3 Power Transmission System

This analysis was done assuming the crankshaft is the primary driving component. The exact same process can be done in case a different power source was to replace the current system.

Assumptions:

60 RPM input speed of crankshaft

300 RPM max output speed

F=116N, max applied force possible by a male operator (NASA, 2008)

$$e = \frac{60rpm}{300rpm} = 5$$

Based on a maximum gear ratio of 5:1 guidelines, the sprocket system was chosen to use 36 tooth driving gear, two 9 tooth sprockets, for a #40 ANSI ½” pitch chain. This will accomplish a 4:1 ratio, resulting in a 240 rpm output. The augmentation to the gear ratio was a result of pitch diameters. A 45 tooth driving gear, adhering to the 5:1 gear ratio, with half inch pitch has an outer diameter of 7.54” compared to the 36 tooth that has an outer diameter of 6”. This size difference was a major consideration due to the spatial limitation of our machine.

$$n_{output} = 60 * \left(\frac{36}{9}\right) = 240\, rpm < \max rpm \;\therefore acceptable$$

$$T_{in} = F * handle\ length = (116N) * (0.0127\, m) = 1.4732\, Nm$$

$$T_{out} = 1.4732\, Nm \left(\frac{4}{1}\right) = 5.8928\, Nm$$

Additional analysis will be done assuming a motor is the primary driving component.

Assumption:

1/3 HP motor, 1725 RPM

300 RPM max output speed

$$e = \frac{1725rpm}{300rpm} = 5.75 \rightarrow round\ to\ 6$$

Using this ratio, it would be adequate to select a 9 tooth driving gear and 54 tooth sprocket, for a #40 ANSI ½” pitch chain. This will accomplish the 6:1 desired ratio.

As the gears are connected via a chain, the 16 tooth optimal interaction basis as outline in the textbook is not necessary for this application.

$$n_{output} = 1725 * \left(\frac{9}{54}\right) = 287.5\, rpm < \max rpm \;\therefore acceptable$$

$$T_{in} = \frac{(5252)(HP)}{n} = \frac{5252 * \frac{1}{3}}{1725} = 1.01\, lb\, ft * \ 1.356\ \frac{\text{Nm}}{\text{1lbft}} = 1.376\, Nm$$

$$T_{out} = 1376\, Nmm \left(\frac{1}{6}\right) = 8.2558\, Nm$$

2.4 Leg Support Buckling Analysis

To improve the stability of the machine, four angled leg post will be affixed of the corners of the machine. In order to ensure a safe support system a buckling analysis was completed to analyze the static mechanics of the legs

Assumptions:

Fixed-fixed system, C_{Design} = 1.2 (Table 4-2, Budynas, 2010)

SF=2, high operator interaction

Nominal force from washer weight

m=21.9 kg, w=214.839N to be distributed over 4 legs

1.5" x 1.5" x 1/8" leg angles

– ASTM A36 standard (McMaster-Carr 2014)

-Sy=248.21 MPa

-A=0.36 cm^2 (Table A-6, Budynas, 2010)

-I=0.074 cm^4 (Table A-6, Budynas, 2010)

-L=1.219 m

$$SF = \frac{Design\ F}{Nominal\ F} \rightarrow Design\ F = SF * Nominal\ F = 2 * 214.839N = 429.678N$$

$$Pcr\ for\ each\ leg = \frac{Pcr}{4} = \frac{429.678N}{4} = 107.419N$$

Apply the Euler formula for buckling for an individual leg element.

$$Scr = \frac{Design\ F}{A} = \frac{107.419N}{36mm^2} = 2.984\ MPa$$

$$\frac{Sy}{2} = \frac{248.21\ MPa}{2} = 124.105\ MPa > 2.984\ MPa$$

∴ Euler approach correctly characterized the leg angle, and will result in compression before buckling.

For buckling to occur the load would have to reach the critical load point. This point can be determined using the Euler column formula (Budynas, 2010).

$$Pcr = \frac{CEI\pi^2}{L^2}$$

$$Pcr = \frac{(1.2)(207\ GPa)(0.074\ cm^4)(\pi^2)}{(1.219m)^2}$$

$Pcr = 1488.2\ kN$ is the critical load for each leg

∴ For failure of the support system a substantial increase in the applied load is required.

2.5 Bolt dimensions

The main point of weight transmission to the leg elements will be transferred via the bolted sections of the corners. For each of the eight contacting faces there will be a total of 4 bolting points, making a total of 32 bolts to support and resist the shear forces of the machine.

$$\tau = \frac{F}{A_{cross\ section}}$$

Assuming each face has an equal load concentration equal to 1/8 of the applied force, distributed over 4 bolts cross sectional areas. A grade 5 bolt, with a standard tensile strength of 827 MPa (Bolt Depot, 2014), will be used to attach the members. The previously calculated design load is applied to include the safety factor deemed satisfactory for this machine design.

$$\tau = \frac{\frac{F}{8}}{4 * A_{cross\ section}} = \frac{\frac{F}{8}}{4 * \frac{\pi D_{bolt}^2}{4}}$$

$D_{bolt} = \sqrt{\frac{\frac{F}{8}}{\pi * \tau_{bolt}}} = \sqrt{\frac{53.71N}{\pi * 827MPa}} = 0.021\ mm$ < ¼" inches

∴ Using a ¼" bolt of grade 5 will adequately support the shear force applied in connecting the washer to the supporting leg system.

2.6 Tolerances

Fits between parts, as a cylindrical member fitting in a cylindrical hole, influences the accuracy of relative positioning of members, the ease with which the members can be assembled and disassembled, and the ease with which they can slide with respect to each other (Junivall R.C. 2011).

Differential thermal expansion is often a factor but was assumed negligible for the case of this project. Following the guidelines of the USAS (ANSI) standards, a tolerance grade of 10-13 is applicable in the case of our machining process (milling). Considering the diameters, for the drive shaft this results in an average tolerance of 0.008 inch; for the brush shafts, a tolerance of about 0.007 inch; and for the bolts a tolerance of 0.004 inch is obtained (Appendix E-2, Junivall R.C. 2011).

The required tolerances for the holes on side walls can be considered as:

- Allowance fitting with a loose fit for the drive shaft
- Shaft tolerance fitting with a free fit for the brush shafts
- Hole diameter fitting with a free fit for the bolts

Hence the acceptable tolerances can be determined as follows:

Allowance (Drive shaft) = $C_a\sqrt[3]{d^2}$ = 0.0025

Shaft tolerance (Brush shaft) = $C_s\sqrt[3]{d}$ = 0.002

Hole diameter (Bolts) = $C_s\sqrt[3]{d}$ = 0.002

Since C_a = 0.0025 for loose fit, C_s = 0.0013 for free fit, C_h = 0.0013 for free fit (Junivall R.C. 2011) and the diameters of the drive shaft, brush shaft, and bolts respectively are 1 inch, ½ inch, ¼ inch.

The tolerances required for the appropriate fits all fall within the tolerance created by the machining. Although it should be mentioned due to slight rough edges created after machining process, a small amount of sanding of the milled sections was required to enable easy fitting and sliding.

3.0 Prototyping

3.1 Material Acquisition

Materials were acquired on basis of two key factors cost and delivery time. The project timeline was a major limiting factor and as such the materials ordered needed to be delivered as fast as possible.

The first pieces of equipment to be ordered were the cylindrical brushes. These components would dictate the rest of the dimensions in the machine design making them a material of primary concern. The framing width depended on the length of the brushes, and the brushes shaft diameter would set the requirement of the bearing bore hole and subsequent bearing order. Therefore before the brushes could be ordered, the building process was at a standstill.

To order food grade brushes that matched the design needs, many brush manufacturers were contacted through email. The difficulty of getting these companies to respond to our quote requests was not originally anticipated, and further stalled the building process. Of the many manufacturing companies contacted only a select few responded back, the first of them being the company Fiberbuilt. Their first quote comprised of a custom built stainless steel shaft brush whose prices ranged from $700 to $900. The correspondent from Fiberbuilt explained the high prices were due to the small inside diameter of the brushes and that it would be difficult to lower the quote cost. As a result, we did not pursue the Fiberbuilt brushes further; however the company's expert knowledge and advice did help in understanding what was necessary for this project. There were a small number of other companies that had some promising deals, but the majority of these companies sold in bulk which was unnecessary for this project.

As the time was a major limiting factor and no other company responded, the decision was made to order a set of smaller cylindrical brushes from a lab supply company through eBay. These brushes would be used to build a prototype to test the design processing ability. Depending on this prototype, a scaled up version could be built in the future with proper food grade brushes, using larger dimensions. These prototype brushes were normally made for chemical purposes, with a 1.27 cm (1/2 inch) steel shaft diameter and nylon fibers. Having successfully ordered the brushes, the rest of the materials could be ordered, and dimensioning of the CAD model could start.

The remaining materials were ordered with the expert help of Scott Manktelow from the Macdonald Shop. For the frame of the root crop washer, Scott presented two types of steel, cold rolled or stainless. For the purposes of a prototype, the cold rolled steel was chosen due to the significantly lower cost. Originally recommended was 0.635 cm (¼ inch) thick plate but after further deliberation, 0.3175 cm (1/8 inch) thick plate was concluded to be enough by Scott to be able to maintain the weight and vibrations of the machine. The option of painting the cold rolled steel was still possible as a method to reducing rusting, since the painted surfaced would not be directly interacting with the crops. The supplier, SNC-Lavalin, only sold the steel frames in 1.2192 by 2.4384 m (4 x 8 feet) plates, so the price was not overly economical for the amount of used for this design but proved to be the best option. To connect the steel plates in the shape of a box, Scott supplied angle bars, bolts and nuts as an alternative to welding the plates together, allowing for any necessary prototype adjustments.

The sealed bearings which house the brushes were purchased from Canadian Bearings. Four, 2-bolt flange mount self-aligning bearings with a 1.27 cm (1/2 inch) bore hole were required of the design. Two additional bearings were purchased, this time from McMaster Carr, for supporting the crankshaft. These were similar 2-bolt flange self-aligning type bearings but with a larger 1.905 cm (¾ inch) bore hole. Seal bearings were the optimal choice as the design involves water and dirt, and these bearings would help keep as much foreign particles as far away as possible from any moving parts.

As mentioned before, originally the design was conceptualized with the intent to use a v-belt pulley system. The slow speed that the crop washer would be operating at was determined to be a potential challenge to maintain effective contact and under the advisement of Scott it was determined that gear sprocket system yield an improved power transmission system. Conducting an analysis of the input and output requirements of the system, two 9 tooth gears for the brush shafts and one 36 teeth drive gear along with a #40 ANSI chain were purchased. An idler was also needed to maintain the chain tension, therefore a 17 teeth idler gear was ordered.

The crankshaft used was a 1.905 cm (¾ inch) steel rod that was residual material in the shop and donated to the project. This was then bent to have a usable handle for operational purposes. An extra 1.27 cm (1/2 inch) shaft was purchased as the original shafts of brushes were not long enough to support the gears once they were assembled with the machine and bearings.

A copper pipe was used for the water delivery system. One end of the pipe would be covered with a cap and the other would need a gate valve to control water pressures. Figure 7 below shows the water delivery assembly. Along the pipe, two copper T connectors to attach the flat spray nozzles both which has been purchased previously. The T connectors were bought from Reno Depot while the flat spray nozzles were ordered again from McMaster Carr. The flat spray nozzles were chosen over other types, as the angle of spray would have maximum water coverage over the length of the brushes to aid in the cleaning process.

Figure 7 – Water delivery assembly

Finalizing and ordering the brushes was the most arduous task in obtaining materials. Another major challenge in ordering other materials was communication with the manufacturing companies. Either the companies did not fully understand the order which may have in part been due to our lack of experience, or manufacturers simply took a long time to reply to our inquiries. When initially ordering with McMaster Carr, they refused to deliver to Canada unless it was to a business, meaning all orders had to go through Scott Manktelow. Each batch of orders was done one by one throughout the building procedure as we wanted to make sure each item was needed. In the future, more planning of material sources and most importantly time needs to be allotted for material purchasing and delivery.

3.1 Design Construction

Prototyping was a multiphase operation consisting of the CAD development and material acquisition process as outline in the previous section. In addition to these phases, construction was a major portion of prototyping design process. This included the assembly and machine of the following components: steel plates, crankshaft, sprockets and chain system, bearings, spray nozzles and brushes.

The steel plates order for prototyping was delivered as a 121.92 cm by 243.84 cm (4 ft. by 8 ft.) steel plate. In order to make this manageable, it was first cut down to a 121.92 cm by 45.72 cm (4 ft. by 1.5 ft.) plate using a plasma cutter. This section was further sectioned into the three wall components using the band saw. Consulting the CAD model, the different bearing slots and dimensions were then marked on the two side wall plated for milling. To increase the milling efficiency, the two side wall pieces cut simultaneously with the exception of the tensioner slot, as it is only on one side of the washer (Figure 8).

Figure 8 - Metal prototype frame with milled slots

Having milled all the bearing slots, the leg angles and walls were marked for bolt holes. It was initially intended that the wall be welded together, but as the prototyping process is an ever evolving system bolt attachment proved to be a better option for any adjustments required. The bolt holes were machine using the drill press on a low speed, high torque setting. As is part of the learning curve, it was quickly realized that the initially degree of placement overlap would not allow the standard hex bolts to sit side by side. This issue was address with the inclusion of a carriage bolt, as they have a significantly less collar volume.

The different machine parts were then assembled into the final prototype design system. For the prototyping phase a crankshaft was machined from a 1.905 cm (¾”) hot rolled shaft to power the

current brush system (Figure 9). It allows for adequate energy production for the testing of the machine.

The final construction stage was the assembly of the water delivery system. This included a copper piping system, with two T fittings where the flat spray nozzles attached. A valve was attached to the end to control the water pressure and all for a more readily accessible shut off process. The valve used has a male fixture which would be difficult to integrate into a standard hose system. Using a standard washing machine hose, with two female hose couplings, it was possible to make the water system more universal. Figure 10 shows is an example of the prototype design running the with water delivery system.

Figure 10 - Root crop washer water delivery system

4.0 Economic Feasibility

Table 2: Prototyping Cost Analysis

Materials	**Quantity**	**Cost**
Nylon fiber, ½" steel shaft brushes	2 @ 35$/brush + shipping	100.00$
2 bolt flange mount bearings(½")	4 @ 10.45$/bearing	41.80$
2 bolt flange mount bearings (3/4")	2 @ 11.90$/bearing	23.80$
9 T gear	2 @ 11.88$/sprocket	23.76$
36 T drive gear	1 @ 55.71$/sprocket	55.71$
17 T idler	1 @ 16.54$	16.54$
#40 ANSI Chain	4 ft @ 3.53$/ft	14.12$
1/8" Cold Rolled Steel Plate	4x8	126.00$
Flat Spray Nozzles	3 @ 4.40$/nozzle	13.20$
Copper fittings	3 @ 4.98$/ fittings	14.94$
Copper hose connector fitting	1@ 16.99$	16.99$
Total		**446.77$**

Table 1 outlines the amount of money that has been currently invested in the prototype. Listed, are only the items that were considered to be the most important and influential in the building process. Some items that were not included are the extra steel rods for the crank and brush shaft, nuts and bolts, and copper piping that were provided by the Macdonald Shop.

The price of the cold rolled steel is the most expensive due to the fact that only such a large piece was allowed to be ordered. This price was minimized as much as possible by reducing the thickness from 0.635 cm to 0.3175 (¼ inch to 1/8), making it much lighter and cheaper for the prototype. Also by choosing cold rolled instead of stainless steel reduced the price by much more.

The bearings were relatively inexpensive, and price for the crank shaft bearing were even cheaper as it was decided that a self-lubricating bearing would be sufficient. Unlike the bearings for the brush, whose inner diameter spins with the shaft, the self-lubricating bearings turn the crank with grease. These bearings, although perhaps not as good quality as the brush bearings, have proven to be efficient enough to support the crank and help spin it with ease, and were less expensive.

The 36 teeth gears are much more expensive than the 9 teeth gear and idler as the pitch diameter and volume of a 36 teeth gear is much larger.

5.0 Design Testing

For the testing of the prototype two root vegetables of different shapes were processed using the machine. Carrot and beets were chose due to availability and size differentiation that would test the bearing adjustability of the machine. These vegetable were purchased from a local grocery store so an extra dirt layer was manually applied to better assess the clean ability of the machine. Once the simulated harvest conditions were prepared the crops were then processes by the crop washer with the operator both turning the crankshaft and washing the crop.

Figure 11 - Prototype testing of the root crop washer on carrots

The first crops to be processes were the carrots. As demonstrated in Figure 12, the washer effectively removed the surface dirt with minimal damage to the greens and skin.

Figure 12 - Carrots before and after processing with the root crop washer

The beets were then processed, after the bearing spacing was increased. The difficulty with the beets is the irregular shape. Additionally as the prototype brush fibers are only 1 inch in length, it is hard to attain a good overlap. This will be addressed with the inclusion of larger brush filaments in a scaled up model. The results of the cleaning process can be seen in Figure 13.

Figure 13 - Beets before and after processing with the root crop washer

As demonstrated by the comparison of the processed and unprocessed crops, it is obvious that the washer can effectively clean the surface dirt. It was observed that much of the cleaning was a result of the spray nozzles, which the brushes then moved off the crop and out of the machine bottom at a higher efficacy then a pure water application. The brushes also allow for the tougher dirt deposits to be removed as a result of the rolling friction interaction between the brush and vegetable skin.

For further comparison the processed vegetable were compared with clean, grocery quality produce. This was to analyse any potential skin damage that may have occurred during the processing operation. It should be noted that micro-abrasions would not be visible during this assessment and a longitudinal study of storage impact from processes should be done in tandem with similar unprocessed products.

Figure 14 - Comparison between the processed (right) and unprocessed (left) surface quality

As pictured in Figure 14, there is no major, visible damage to the root crop washer processed vegetables as compared against the grocery store produce. In regards to the carrots, the processes yielded a cleaner produce than what was obtain from the store. The beets had some slight abrasions, but this is due to the maneuvering during the cleaning process because of the short fiber length limitations.

6.0 Results

The testing of the prototype preformed was a good basis as a proof of concept, in addition to having a great deal of insight in regards to redesign and scaling up. The first point of modification would be in the addition of leg elements, not included during the testing phase. Leg elements increase the stability of the machine, improve the effluent flow through the bottom of the device as well as allow for movability through the attachment of wheels to the legs. Additionally, the test substantiated the need to integrate a front splash guard. An operator would be subjected to a high degree of spray due to the direction and flow rate of the nozzle. The addition of a plastic water guard would leave enough material to replace the back wall of the machine with a plastic piece. Currently the machine weighs 22 kg which could be further decreased by switching the back wall material. Another related redesign would be smaller nozzles to limit the flow rate of the system to less of a spray and more of a mist, similar to those seen in a grocery store produce section.

It is also important to note the safety considerations required for a scaled-up practical washer. It is of the utmost important that the operator is working in the safest conditions possible. This was in part included in the analysis portion of the report, for example the safety factor integrated into the buckling calculations. As the machine has a high degree of moving components, the gear system will need to be adequately covered to avoid unintentional interaction by the user, yet still allow for proper maintenance. For even better operational use, the MSEG worker will be adequately informed of how the machine functions, any maintenance requirements as wells as a contact if there are any concerns about operating the machine.

Based on the testing and efficacy of the washer a larger scale model is currently in development. Before undertaking another design process the redesign and material alterations were run through a cost analysis to assess the feasibility of reproducing the design within out allotted budget.

Table 3: Scale Up Cost Analysis

Materials	Quantity	Cost
6” Nylon fiber brushes	2 @ 200$/brush	460.00$
2 bolt flange mount bearings(1”)	4 @ 12.77$/bearing	51.08$
2 bolt flange mount bearings (3/4”)	2 @ 11.90$/bearing	23.80$
9 T drive gear	1 @ 11.88$/sprocket	23.76$
54 T gear	2 @ 66.08$/sprocket	132.16$
17 T idler	1 @ 16.54$	16.54$
#40 ANSI Chain	4 ft. @ 3.53$/ft.	14.12$
1/8” Stainless Steel Plate	4ft x8ft	379.99$
Flat Spray Nozzles	3 @ 4.40$/nozzle	13.20$
Copper fittings	3 @ 4.98$/ fitting	14.94$
Copper piping	10ft	6.58$
Copper hose connector fitting	1@ 16.99$	16.99$
¼ HP Motor	1 @ 88.99$	103.25$
Total		1256.41$

The above Table shows the cost breakdown of the materials that would be needed when scaling up the project from the prototype. The prices of these items were obtained by company quotes, research through McMaster Carr and Canadian Bearings, and visits to Reno Depot.

The first price change from the prototype would be in buying the brushes. Currently for the prototype, a non-food grade nylon fiber brush was used because of the difficulties of getting a good quote for a custom brush from manufacturing company. Fortunately, a quote for $200 polypropylene filament brush were attained from the manufacturer TANIS. For MSEGs root crop washer, these polypropylene brushes are perfect in terms of their material and cost. Compared to other quotes, these were the cheapest and best fit the requirements for the crop washer.

The new brushes have a shaft diameter of 2.54 cm (1 inch), meaning all brush bearing sizes would have to be changed to larger mount bearings. The bearings for the crank shaft could be kept the same, not needing to change the pricing on those bearings. If a motor is to be integrated as a power source, these bearing sizes might have to change, or a 1,905 cm (3/4”) rod could still be used.

When scaling up the machine if there was a motor being integrated, the gear ratios would be changed from 4:1 to 6:1. This new ratio would mean, two 54 teeth gears and a 9 teeth gear would be necessary to rotate the brushes. The size of the 54 teeth gear are much larger than any of the gears that were used on the prototype, increasing the overall prices of the gears by a relatively large amount.

Ideally, a stainless steel plate would be best for food grade applications. Stainless steel prevents rust and would increase the overall longevity of the machine. However, the price of the stainless steel plate would be much higher than the cold rolled, and again ordering from SNC-Lavalin, would mean having to order the large 121.92 cm by 243.84 cm (4 ft. by 8 ft.) plate. To save money and time on delivery, the remaining cold rolled steel from the prototype can be used. The cold rolled plates would have to be painted to prevent rusting and the paint would make it much more applicable for food purposes. If the cold rolled steel is used over stainless, plastic can also be used for the back and front cover to shave off some extra weight, and to provide some protection to the users from extra spray from the water.

The flat spray nozzles on the prototype, when testing, showed to spray at a higher pressure than originally desired. Although these nozzles could be used, a new set of nozzles would be preferred for scaling up. To save on water usage, misting or fogging nozzles would be the preferred type. The prices on misting nozzles vary from $6 to $16 on McMaster Carr, so are not very expensive. They would, however, need to have the same diameter as the fittings to be connected to the piping properly. Apart from changing the nozzles, the rest of the material can be easily obtained from Reno Depot on a moment's notice.

To power the machine, a ¼ horsepower motor has been considered. If, however, MSEG is shown to prefer manually powering the machine by hand crank or bicycle, this is a price point that can be neglected.

The plastic over and back for protection and reducing weight have already been discussed but there are several other materials that have been considered to make the crop washer more user friendly.

When adjusting the brushes for different crop sizes, the bolts on the bearing need to be untightened and tightened every time. Hand bolts could be used to make adjusting the bearings much easier, but these bolts also prevent the bearings to be completely and securely tightened. This could be fixed by adding a hook with adjustable wrenches for the user, making altering brush widths much simpler. The final design would also be mounted on angle legs connected to wheels to make the machine mobile and sturdy when being used.

7.0 Safety, Risk and Failure Analysis:

Should a scaled up version of the prototype be developed, several safety concerns should be addressed prior to finalizing the design. It should be noted that since the machine will contain moving parts such as rotating gears, sprockets and chains, it should adhere safety standards S493.1 for agricultural machinery outlined by the American Society of Agricultural and Biological Engineers (ASABE Standards S493.1, 2003). A complete outline of these guidelines can be references in the appendix. Such adherences will be applied to a scaled up model.

In the case of our design, a casing would be made around the gears, sprockets and chain to prevent any user-machine contact. Ideally, the casing would protect the moving components from water, be durable enough to withstand any weathering, and is easily detachable for maintenance purposes. A good choice of material would be aluminum due to its innate water-resistance and light weight.

8.0 Conclusion

The objective of this root crop washer design was to address the needs of the McGill Student-Run Ecological Garden by alleviating the processing impact of cleaning fresh root crop vegetables. Through design analysis, computer modeling and finally prototyping the conceptualized machine design was developed as an effective solution. Having achieved successful testing and results of the prototype processing operation, a larger scale model with appropriate mechanic improvements is in development. It is the intention that this larger scale be a long term solution integrated into the MSEG agricultural operation. Additionally this project will serve as an alternative engineering design application for future students within the department of Bioresource Engineering.

9.0 Acknowledgments

We would like to extend a special thanks to our supervisors and mentors who made this project and machine design possible. Thank you to Dr. Grant Clark, Dr. Valerie Orsat, and Scott Manktelow for their mentorship throughout this project. They imparted us with invaluable technical and machining knowledge. The project would also not have been possible without the generous support of the McGill University Sustainable Projects Fund and the help of Lilith Wyatt and Jameson Jones-Doyle. Collaboration from the McGill Student Ecological Garden and their constant willingness to support the project was greatly appreciated.

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Appendix 1

ASABE Safety Guidelines

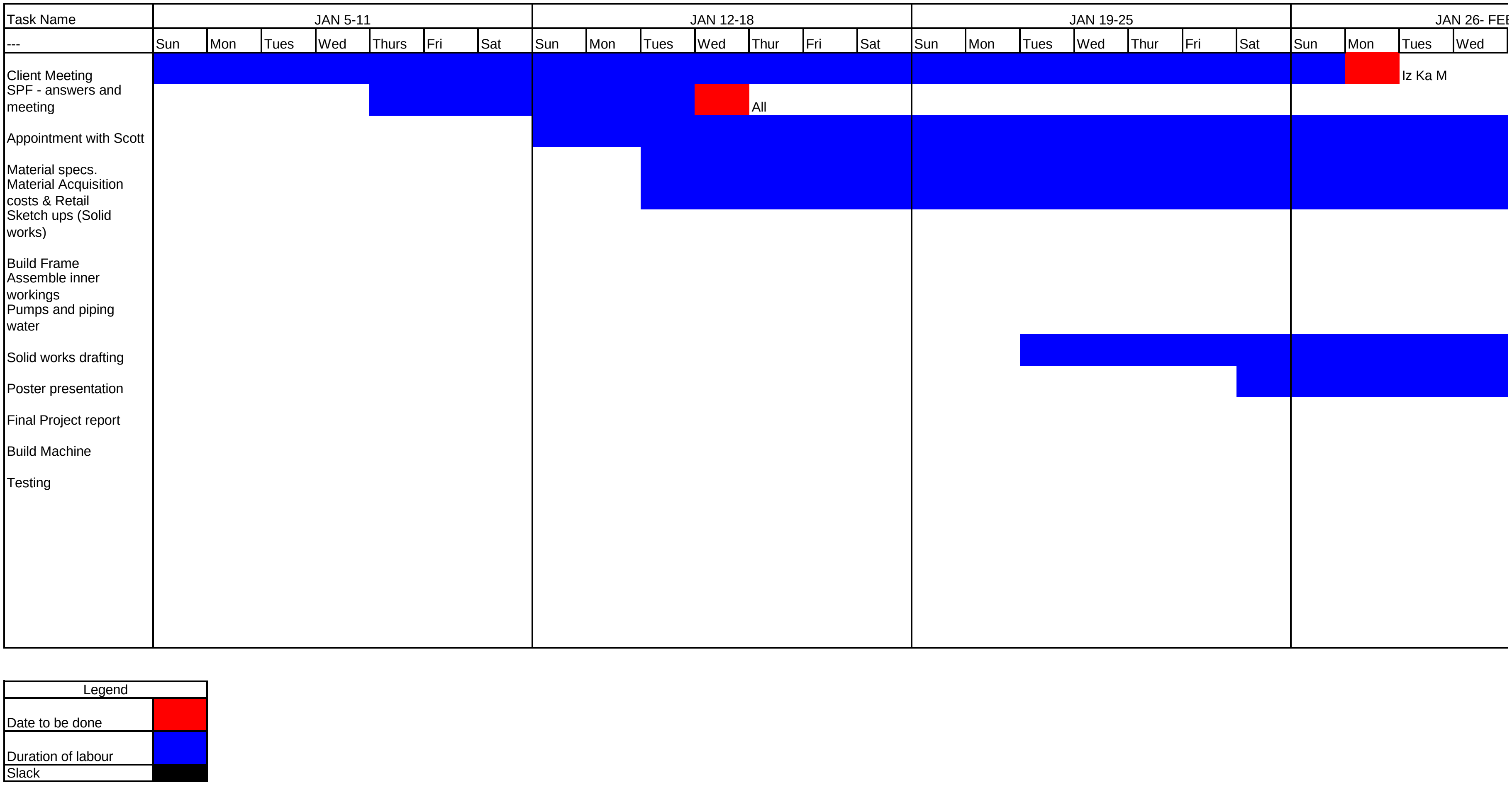
1.1 This Standard provides general guidelines for guarding for agricultural equipment so as to ***provide a reasonable degree of personal safety for operators and other persons during the normal operation and servicing of such equipment****. (S493.1.1.1).*

According to S493.1., guarding will be needed for our proposed design since it will include the following:
4.2.3 **Nip-points**, (a pinch point where a belt, **chain** or cable comes into contact with a sheave, **sprocket** or **idler**).
4.2.4 Outside faces of pulleys, sheaves, sprockets and gears.
4.2.5 **Revolving shafts**, universal joints, and other revolving parts with projections such as exposed **bolts**, keys, pins or set screws. Revolving shafts excluded are:
4.2.5.1 Smooth shafts revolving at less than 10 rpm.
4.2.5.2 Smooth shaft ends protruding less than one half the outside diameter of the shaft.
4.2.6 Surfaces which create **shearing** or **pinching** hazards
Guards are specified as protective device such as railing, fencing, framing or the likes that can ensure the operators' safety and must adhere to certain requirements outlined in ASABE standards S493.1. Listed below are requirements relevant to our design:

5.1 Guards shall be **sufficiently strong**. Unless it is clearly inappropriate, they shall, without cracking, tearing or permanently deflecting, withstand a perpendicular static load of 1 200 N.
5.4 Guards shall **be rigidly fixed**, have **no sharp edges**, **be weather resistant** and retain their strength under extremes of temperature, taking into account the intended use.
5.5 Guards shall be designed in such a way that **normal operation** and **service** of the machine can be readily carried out.
5.6 Guards **shall normally be attached** to the machine such that they cannot be removed without the use of a tool. They may be able to open up, in which case they should remain attached to the machine in some way, for example by means of a tether, hinge, slide, linkage or other suitable means, and should be provided with a convenient means to keep them closed.
5.7 Guards may be formed of a welded or rigid mesh or grille. The size of the opening permitted depends on the distance between the guard and the hazard/hazardous area. The design of the guard shall be such that it is not possible to distort the mesh or the grille during operation.

Appendix 2

Gantt chart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Build Machine
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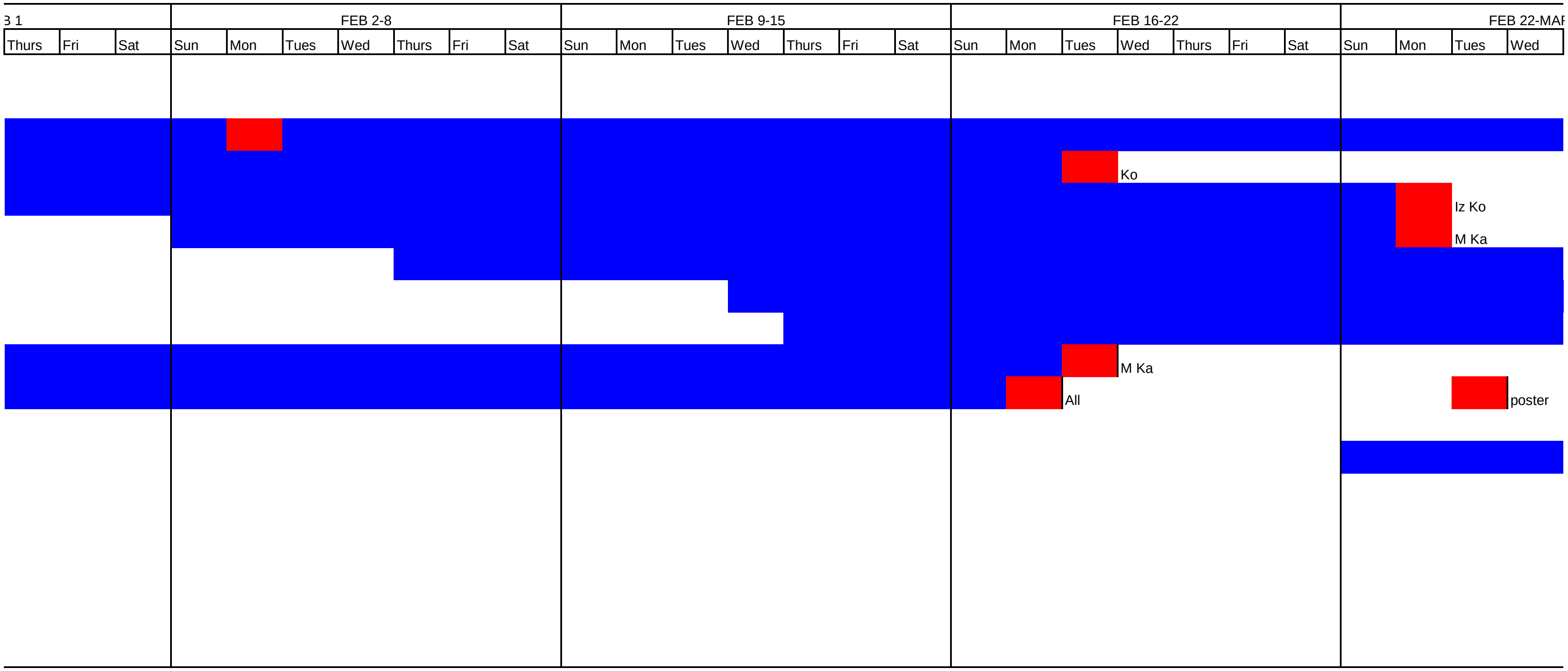
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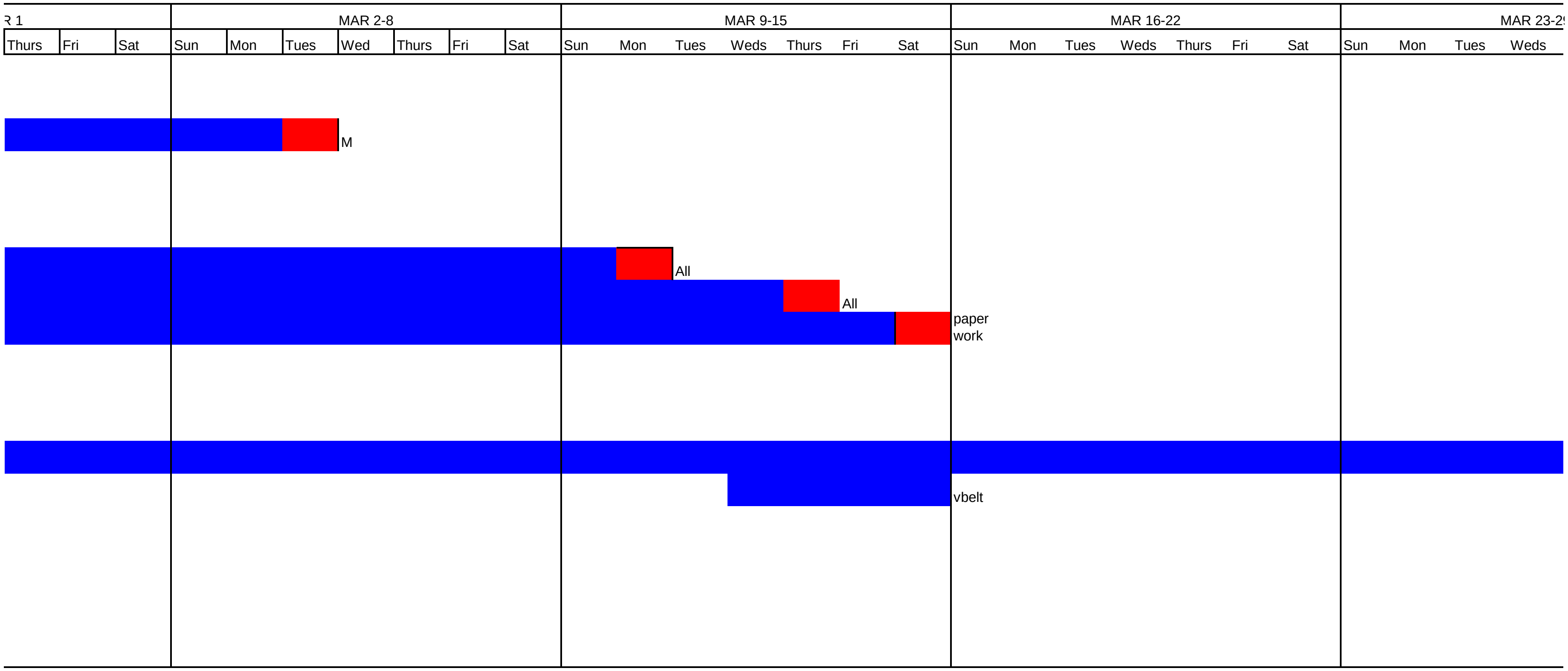
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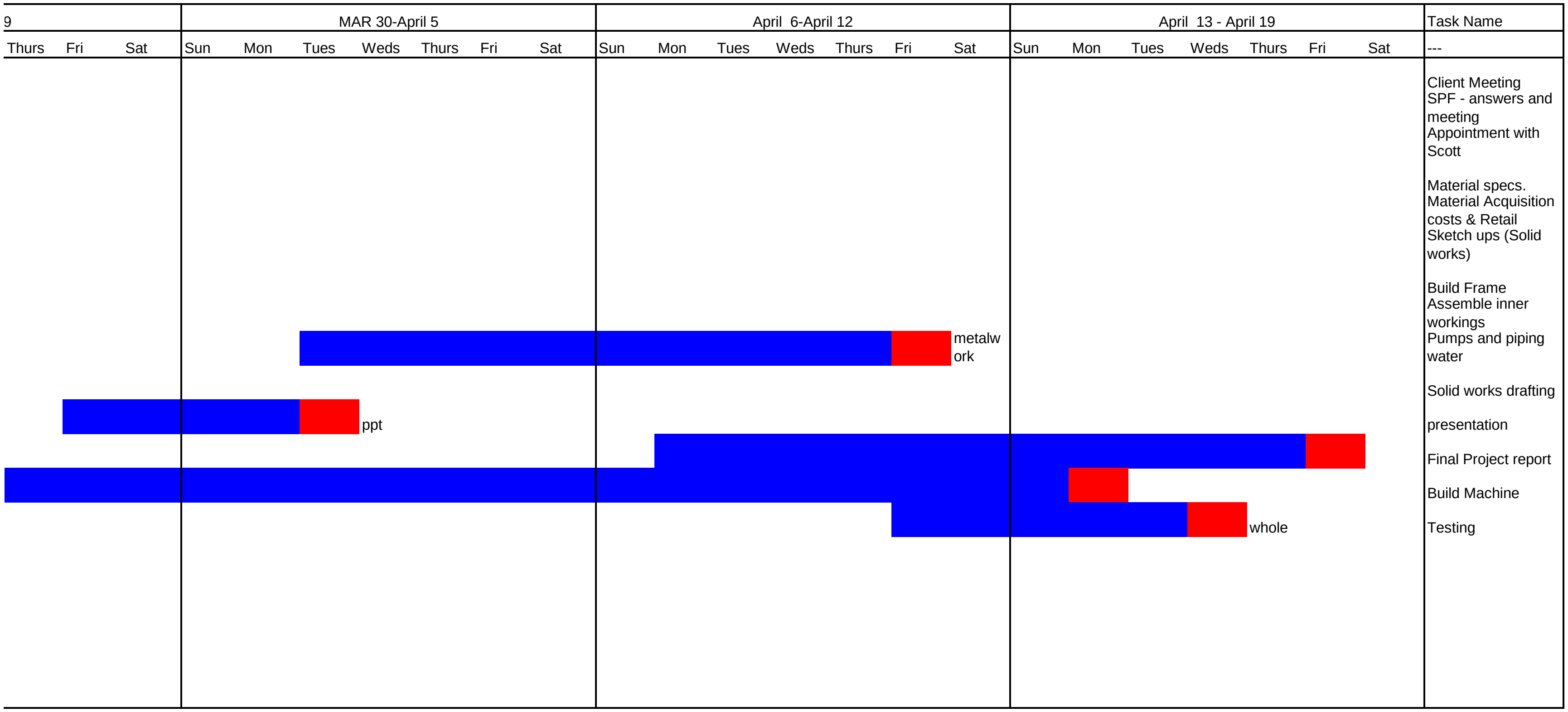
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Pumps and piping water
Solid works drafting
presentation
Final Project report
Build Machine
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