Project Proposal and Feasibility Studies

ENGR 339/340 Senior Design Project
Calvin College
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Team 18: The Fröolja Project

The Fröolja Project

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For Review By:

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Executive Summary

South Sudan is the youngest nation in the world. After decades of civil war, South Sudan separated from Sudan and became an independent nation. The people there are among the poorest in the world, living on less than $1 per day on average. However, South Sudan is one of the most fertile nations in Africa, and their primary cash crop is sesame. Sesame seeds are used in foods around the world; however, the real value lies in the oil that can be extracted from them. Sesame oil is one of the most stable of all seed oils, which makes it very desirable for cooking. Currently, in South Sudan, very small quantities of sesame oil are extracted through inefficient manual processes. As a result, South Sudan exports the majority of their sesame seeds to countries in Asia who extract the oil efficiently and inexpensively, and then sell it back to South Sudan at inflated rates [1].

Team 18's solution to this problem is to design and build a prototype of a mechanical system that will extract oil from sesame seeds within South Sudan faster and more effectively (greater percent of oil removed from seeds) than current methods. The system will be a screw expeller with a rotating central worm shaft powered by the power take-off on a Massey Ferguson 385 tractor. The system will be used by farmers in Malakal on a 40-hectare cooperative farm. As seeds are fed into the system through a hopper, pressure will be applied to the seeds as they move through the system and are compressed by the worm shaft. Oil will be collected through perforated holes at the bottom of the worm shaft housing while waste product is expelled from the end of the machine through a choke. The waste product will contain some oil, but most of the oil in the seeds will be collected and used for cooking in the community, while the excess is sold for profit. The waste product can be further processed and used for animal feed [2].

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1 Introduction

The nation of Sudan went through many years of civil war and violence leading to the separation of South Sudan in 2011, making it the youngest nation in the world. Many of the South Sudanese people live in extreme poverty, less than $1 per day on average. However, South Sudan is one of the most fertile nations in Africa. As a result, much of their national income comes from the harvest and sale of their primary cash crop, sesame seeds. The seeds are used in foods around the world, however the real value in growing sesame seeds is the oil that can be extracted from them. Sesame oil is extremely stable chemically, making it very desirable for cooking around the world. Currently, in South Sudan, very small quantities of sesame oil are extracted through inefficient manual processes. As a result, South Sudan instead exports the majority of their sesame seeds to countries in Asia who extract the oil and sell it back to South Sudan at marked up prices [1].

> The Problem: Due to lack of infrastructure and split from Sudan, South Sudan is unable to capitalize on its abundant natural resources. Sesame seed oil production continues to be limited due to inefficient manual oil extraction processes.
>
> The Solution: The team's goal is to design a mechanical system for extracting sesame oil in South Sudan while accounting for environmental, economic, and social sustainability. This will generate more income for farmers by allowing them to produce large quantities of sesame oil for sale internationally.

To Team 18, sustainability entails ease of maintenance of the machine, economic payback, and the provision of an avenue for the local South Sudanese people to apply their skills towards profitable ventures while working together.

The idea for the project initially came from a detailed proposal created by Jeffrey Kibbie along with his close friend Monyroor Teng [1]. Mr. Kibbie is a seasoned entrepreneur and patented technologist. Monyroor is the pastor of the Sudanese Covenant Evangelical Church in Manchester, NH. Both men agreed to serve as mentors for the duration of the project and beyond. The customer for this project is James Tor Monybuny, Governor of the Upper Nile Region of South Sudan. Governor Monybuny is also the brother-in-law of Monyroor. Therefore, the project focused on creating a small processing system for use on a farm outside the city of Malakal, located in the Upper Nile Region of South Sudan. The farm was set aside for this project by Governor Monybuny.

South Sudan is a nation full of different tribal groups which have periodically been engaged in civil war. No civil war is currently taking place, however violence is common. The two largest tribal groups are the Dinka and the Nuer, which make up 35.8% and 15.6% of the population respectively [1]. Both of these tribes are heavily represented in Malakal, and it is the hope of Team 18 that the sesame oil extractor will be shared amongst farmers from different tribal groups to promote unity and peace between them.

Throughout the 2017 fall semester, Senior Design Team 18, also known as The Fröolja Project (Fröolja is Swedish for "seed oil"), worked to design a processor to extract the oil from sesame seeds. The machine would be used on a cooperative farm in the Upper Nile Region of South Sudan. This report describes Team 18's process of designing and determining the feasibility of the sesame oil extractor.

1.1 Team Background

Each member of the team has a unique background and brings a special set of skills and experiences to contribute to the success of the project.

Figure 1. Team Picture (left to right): Vermeulen, Kpodzro, Boelens, Anderson

Nathan Anderson

Nathan Anderson is a senior mechanical engineering student at Calvin College in Grand Rapids, MI. Growing up in Milan, MI, he began college at Spring Arbor University before transferring to Calvin to finish out his bachelor's degrees in engineering and physics. He attributes his passion for engineering to growing up with mechanical hobbies in an extended family with engineers, and to his family background in farming. These, coupled with the arts and athletics, have developed a determined approach to engineering in him. Nathan spent two summers at a Chrysler engine manufacturing plant as a quality intern and foreman where he learned how to work with various backgrounds at once and focusing on the big picture. He also spent several months at Extol Inc. as a applications lab intern, where he developed skills in the lab, testing and working with customers. Recently married, Nathan is passionate about the outdoors and sports; most notably spikeball, camping, and running where he competed in cross country and track from childhood onto the collegiate level.

Matthew Boelens

Matthew Boelens is in his senior year at Calvin College studying mechanical engineering with a sustainability designation and economics minor. He has a passion for sustainable user-centered design, new product development, and market analysis. Matt spent a summer working as an Engineering Intern at DISHER where he gained experience in prototype design and product development. He also gained experience in data collection and analysis as a research intern junior year in Calvin's Engineering Department. Additionally, Matt spent a month in Kenya learning about community development in rural and urban settings. Matt has competed on Calvin College's cross country, indoor track, and outdoor track teams in all four of his years at Calvin. Outside of school, he enjoys hiking, camping, cycling, and anything else that gets him outside.

Edwin Kpodzro

Edwin Kpodzro is a senior Mechanical Engineering student with a passion for human-centered product design, global engineering and research, and community development. He hails from Accra, Ghana. Edwin has had two internships at Dematic Corporation, where he spent a year as a Controls Engineering Intern before moving into his current role as a Research and Development Intern in Mechatronic Development. Edwin contributes his analytical skills in product sustaining, control systems, system analysis and testing, and written communication to the team's work. He enjoys a good game of soccer and spending time with his family.

Hendrik Vermeulen

A senior mechanical engineering student originally from South Africa, Hendrik has always had a passion for making things work better. Before his formal education in engineering, he had gained practical experience as a mechanic and sales representative at a bicycle store; there, he developed problem solving and leadership skills. While at Calvin, Hendrik worked at Herman Miller, as a New Product Development engineering intern for two summers, where he became proficient in using parametric modeling and FEA. Work at Herman Miller and experience on the Calvin College cross country and track and field teams have prepared Hendrik for teamwork and perseverance. Furthermore, in January 2017 Hendrik participated in a leadership class in Kenya where he became passionate about using his skills as a mechanical engineer to improve the lives of others.

1.2 Project Ideology

The motivation behind this project was to help others, spread compassion in South Sudan, and generate income for the community of Malakal. There were eight engineering design norms central to the decisions and outcomes of this project: cultural appropriateness, transparency, stewardship, integrity, justice, caring, trust, and humility. It is the responsibility of engineers everywhere to work in such a manner that the wellbeing of humanity is the primary goal. The purpose of the design norms listed above is to assist engineers in exercising their responsibilities. As a design team serving a customer, the members of The Fröolja Project maintained a policy of honest communication and thoughtful decision making.

2 Project Management

This section of the report describes the organizational structure of the project, how the team assigned tasks, scheduled meetings and events, and allocated budgeted time and monetary resources.

2.1 Team Organization

Primary roles were assigned to each team member to ensure continuous work on the various aspects of the project. Matt Boelens was assigned the role of Business/Finance and Website lead due to his prowess and experience in economic analysis gained from pursuing a minor in economics at Calvin. Hendrik Vermeulen is the Computer Aided Design (CAD) lead due to his experience in parametric modeling from his internships. Edwin Kpodzro is the Supply Chain and Technical Writing/Communications lead, utilizing skills he honed during his internships. Nate Anderson is the Project Coordinator (deadlines/dates/scheduling) and Building/Workshop lead, due to his experience in handling tools and farm equipment as a result of growing up on a farm. The team made it a point to distribute the workload according to the allocated roles above. However, the team communicated constantly to coordinate efforts and lend a helping hand to one another as necessary. The team was blessed with several mentors and resources throughout the project including Professor Renard Tubergen, Ben Hekman, Jeffrey Kibbie, and Monyroor Teng. The team is also planning on partnering with a non-profit organization as the team is unequipped to do the community development work. Partnering with a non-profit organization will also provide a home for the project, and project funds, upon the team's graduation from Calvin. Currently the team is in discussions with two potential partners: Africa Inland Mission (AIM) and Life in Abundance (LIA) [3, 4]. Figure 2 shows the current organization chart for the project (excluding the non-profit as it has not yet been selected or affiliated with the project).

Research and project documents such as meeting minutes were stored in folders on the team's Google Drive. Folders were created for subcategories of the project, and appropriate documents were placed in their allocated folders for all team members to access. Once all the work for the semester is completed, the information will be transferred from Google Drive to the Calvin \\S: drive.

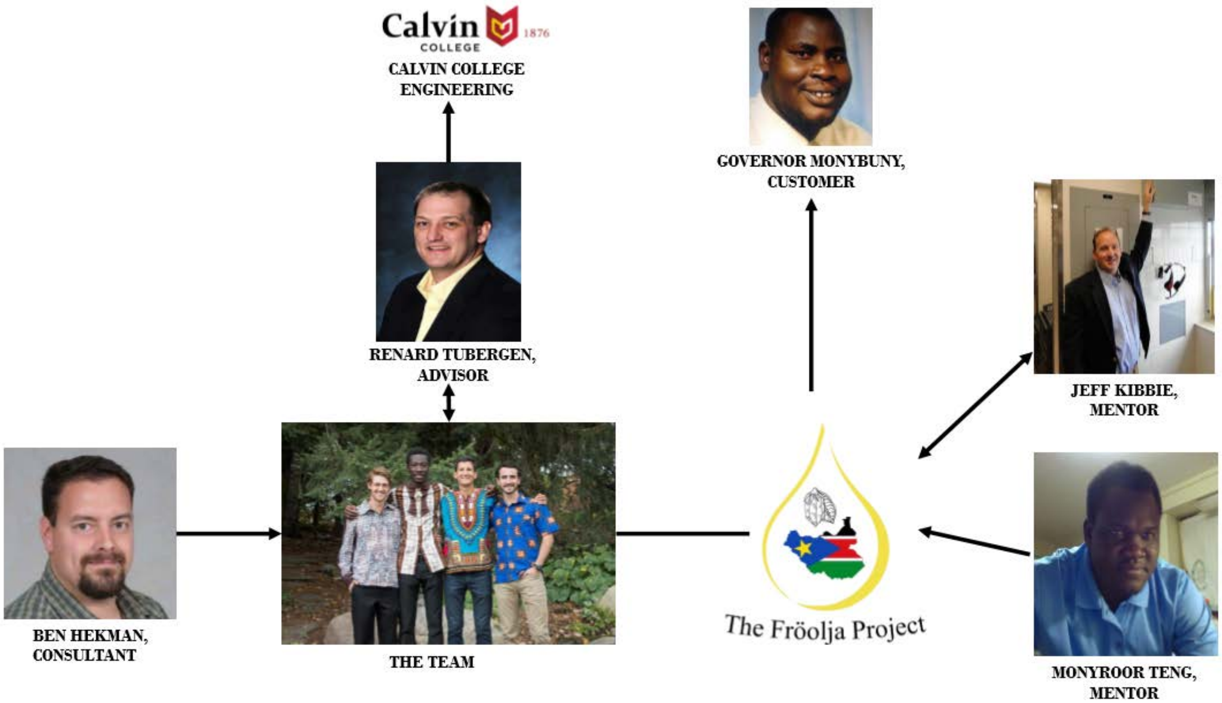

Figure 2. Organizational chart for the project

2.2 Schedule

A work breakdown schedule (WBS) and a project Gantt chart were created to guide the team's efforts and provide a better sense of the project timeline. The WBS and Gantt chart can be found on the project website [5].

According to the Gantt chart, the team's schedule for the fall semester was to define as much of the proposed system as possible. So far, the team is on track, having determined system components that will either be purchased or manufactured. As mentioned earlier, tasks were divided amongst team members according to strengths and experience. The spring semester will be dedicated to system integration and building of the prototype.

2.3 Operational Budget

A large part of the resources for the project (land, tractors, and labor) have been provided through donations from the United Nations and from the government of South Sudan. The team is also fundraising through crowd-funding platforms online and through donations from the business partners of the team's mentor, Mr. Jeff Kibbie. While the team is selecting a non-profit the Calvin College Engineering Department has agreed to set up a temporary account to keep the donated money. The project budget was managed by the Business lead, Matt Boelens, together with Jeff Kibbie. Members of the team provided information to Matt based on costs that came up in the execution of various tasks.

2.4 Method of Approach

Decisions were made through consultation with the mentors, industrial consultant, customer, and project advisor. Whenever the team came up with ideas, these were run by the aforementioned people to make sure the team was headed in the right direction.

The team based decisions primarily on cost, time, and availability of resources in South Sudan. Research topics were distributed based on parameters the team needed for the design. Different team members were assigned major topics to research, such as system flow rates, farm productivity, power sources, business models and analyses, among others. The information found was saved under the Research Folder in the team's Google Drive.

The team communicated primarily via email, and had an active WhatsApp chat where meeting times were scheduled and pertinent information was discussed. The team also allocated Tuesday nights as project work times as this was often when Skype calls with Jeff Kibbie took place, and Friday afternoons for meetings with Professor Tubergen, the project advisor.

3 Project Requirements

Prior to coming up with design alternatives, the team defined the system as thoroughly as possible. The team considered functional, physical, performance, and sustainability-related requirements. The system should be able to extract sesame oil effectively (maximum of 15 wt% oil in waste product) using a mechanical pressurizing process [6]. The system must be able to be transported from farm to farm. The system must also be corrosion-resistant and be constructed with food grade quality materials. A single cooperative farm is defined as 40 hectares. The farm served as the control volume that a single oil extractor device must process seeds for. As a result, the system must be able to process all of the sesame seeds produced by a 40-hectare farm in two weeks or less in order to prevent rotting of the seeds due to lack of infrastructure [7]. The system must be sustainable when evaluated from environmental, economic, and social perspectives. Environmental impact will be considered in the design of the system. Long term economic profitability is an absolutely necessity of the final oil extractor. The oil must be high enough quality to cook with and consume, while using ethical farming practices. Planting, harvesting, processing, and transportation must be financially reasonable for the process to exist.

3.1 Project Scope

It is the hope of Team 18 that through the solution provided, unity is promoted within the community of Malakal. However, after consulting with project mentors, it was determined that designing a solution around community development was outside of the project scope. The team consists of four mechanical engineers, and is therefore qualified to handle a technical design project. However, the team is not qualified to address and plan for future community development initiatives. As previously mentioned, in order to ensure that The Fröolja Project will have a positive impact on the community in Malakal, Team 18 is actively seeking a partnership with an established non-profit organization operating within South Sudan. The partnership will assist in legitimizing Team 18's involvement in South Sudan while also providing a place for The Fröolja Project to live following Team 18's graduation in May 2018. Hopefully The Fröolja Project will continue to grow and develop into an ongoing aid mission within South Sudan.

4 Design Alternatives

The team conducted research on mechanical processes for oil extraction in areas similar to South Sudan. Largely, the seed oil extraction process is either through a mechanical process or a chemical process such as solvent extraction [2]. Based on the cost and equipment associated with chemical processes and the instability of South Sudan, the team decided to focus on a mechanical process. Case studies conducted in developing countries such as India, Nigeria, Ethiopia, and Sudan showed that the mechanical processes used. Processes ranged from using a common mortar and pestle to traditional ghanis, hydraulic presses, screw expellers, and other types of mechanical presses such as the ram press [8]. The common mortar and pestle method was discounted because the process is slow, tedious, and cannot be performed on a large scale. However, other mechanical processes use the same concept of applying pressure to the seeds to force oil out, as will be seen in the follow sub-sections. Since a large quantity of seeds will be processed, the selected system requires a capability of processing about 2400 kg of seeds per day. The three alternatives considered were the ghani, hydraulic press, and screw expeller, and these decisions are discussed below.

4.1 Ghani

Ghanis are an ancient technology used primarily in India with the following functional components: a circular mortar with a pit in the center to hold the seeds and extracted oil, and a heavy pinioned or chained pestle angled in a hollow so that the pestle can rotate. The pestle is usually made in two pieces: one connected to a load beam and the other to a yoked animal, usually cattle. As the animal moves and exerts lateral pressure, the seeds are crushed to release oil. Although this method is largely inexpensive, it is only capable of processing approximately 34 kg of seed per hour (101 days for entire co-op with 10 hour days at 85% operation) [9]. Figure 3 shows the general concept behind a ghani.

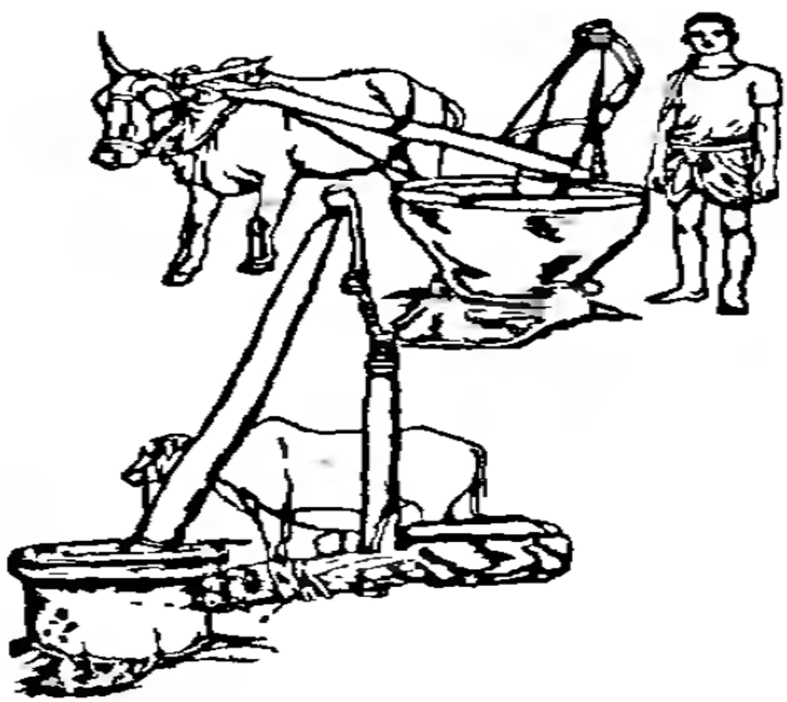

Figure 3. Two ghani designs [10]

4.2 Hydraulic Press

Hydraulic presses can also be used to extract oil from seeds. In this method of extraction, seeds are milled, cooked, and wrapped in filter cloths that are then pressed between the head block and ram of the press using hydraulic pressure. The filter cloths and waste material have to be manually removed from the press after the oil has seeped out. Hydraulic press oil mills were commonly in use as late as the 1950's before the last of them were replaced with continuous screw presses and continuous solvent extraction plants, both of which required far less labor and could process at much higher rates [11].

In modern hydraulic presses, the required pressure to extract oil is about 15 to 20 MPa. These presses are able to process about 50 to 70 kg of seed per hour (69 to 35 days respectively for entire co-op with 10 hour days at 85% operation). However, this process is not continuous and has to be carried out in batches. Hydraulic presses are also generally more expensive ($8,000 for a 120 kg-oil/hr maximum rate) and require more maintenance compared to other oil extractors. In addition, the tolerances required to function at 15 MPa (over 2000 psi) are beyond the team's manufacturing capabilities and would likely end up buying most of the components, which would leave little to no engineering tasks. Figure 4 shows a modern hydraulic press.

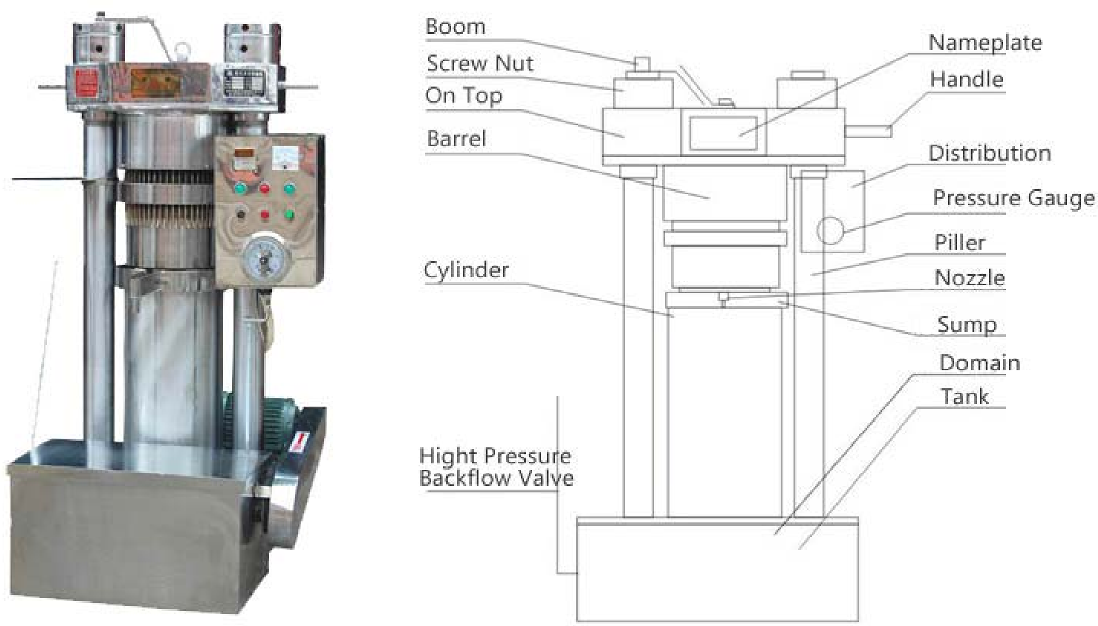

Figure 4. Hydraulic Press for Sesame Oil [12]

4.3 Screw Expeller

Screw expellers are the most used equipment for mechanical oil extraction based on their reliability. Raw materials enter one end of the system and waste material comes out of the other end. The machine uses friction and continuous pressure from the screw drives to move and sheer the seed material. Oil seeps through small openings at the base of the shaft housing that are not large enough to allow seed fiber solids to pass through. Afterward, the pressed seeds are formed into a hardened cake, which is removed from the machine. [13]

Compared to hydraulic presses, a screw expeller is more applicable to this project. The flavor of oil produced in a screw expeller is different, and the technology is simple as a result of few needed supporting equipment to keep the machine running. Initial investment costs are lower than hydraulic presses as well (approximately $7000 for a 250 kg-oil/hr maximum rate expeller). Figure 5 shows a typical screw expeller.

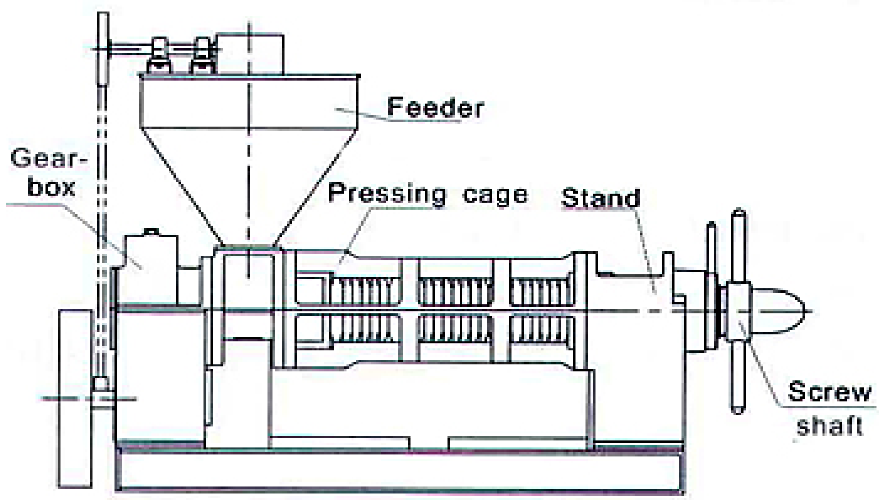

Figure 5. Screw Expeller [14]

5 Critical Design Decisions

The design alternatives were evaluated using the decision matrix shown in Figure 6.

WHAT MECHANICAL EXTRACTION METHOD SHOULD BE USED?			ALTERNATIVES					
			Ghani		Hydraulic Press		Screw Press	
Selection Criteria	Weight (1-5)	Multiply	Score	Weighted score	Score	Weighted score	Score	Weighted score
Cost (should have low initial cost)	5	x	5	=25	2	=10	4	=20
Ease of maintenance	5	x	3	=15	2	=10	3	=15
Continuous processing	5	x	2	=10	2	=10	4	=20
Maximum processing rate	4	x	2	=8	3	=12	4	=16
Simplicity	4	x	3	=12	2	=8	3	=12
	TOTAL SCORE	=	70		50		83	

Figure 6. Decision Matrix for Design Alternatives

The screw expeller was found to be the best design. The expeller fit the project's desired requirements of ease of maintenance by local South Sudanese people, continuous processing of seeds from the cooperative farms, a low initial investment cost, a simple design in terms of componentry, and a high maximum processing rate. The team decided to simplify the machine further by not including any electronic control systems and by modifying common expeller designs to fit the customer's needs and available resources.

5.1 Power Supply

The source of power for the system is a decision that was made based on cost and availability of technical maintenance in South Sudan. With scarce availability of electric power in the country, an electric motor was out of the question. Diesel fuel is an accessible resource in South Sudan and is inexpensive, selling at 0.62 USD/L in South Sudan compared to the 0.99 USD/L world average as of December 4, 2017 [15].

Fifteen Massey Ferguson 385 tractors were donated by the United Nations to South Sudan. One of those tractors was then donated to The Fröolja Project by Governor Monybuny. The power take-off (PTO) on the existing tractor was considered as a potential source of power for the screw expeller. As stated earlier, cost and availability of technical maintenance were the main design criteria in selecting a power source. In order to avoid the extra cost of purchasing an external diesel engine, the team settled on the PTO since the tractor from the United Nations is already available for the project, and local mechanics are available to service the tractor.

5.2 Component Sourcing

The team had to make decisions on what components to purchase or fabricate. The team realized that some of the components could be fabricated in the Calvin Engineering workshop, while others had to be purchased from vendors, or outsourced to outside machine shops to be fabricated. Complicated components of the system, such as the worm shaft and chamber assembly, will be purchased; the team is currently in contact with supplier Shreeji Expellers Incorporated [16]. The worm and chamber assembly are manufactured to extremely specific tolerances that the team cannot match in the Calvin workshop. Buying the pre-manufactured worm and chamber assembly would be more economical than trying to fabricate them. This would also allow the team to focus its time on technical aspects of the system that they are qualified to design. The external housing, hopper, and drive train will be fabricated in the Calvin Engineering workshop.

6 Seeds

Sesame is an annual, and occasionally perennial crop with an extensive root system, which makes the plant resistant to drought and very viable in the South Sudanese climate [17]. The current size of the land outside Malakal dedicated to the project is 40 hectares, which historically yields 30,000 kg of seed per year (one harvest per year, 729 kg-seed/ha) [18]. This is the maximum mass of seed that would need to be stored, but processing will begin as harvesting takes place. Sesame seeds need to be stored at a moisture content of no more than 6% [7]. In South Sudan, however, silos and grain storage structures are not readily available. Hence, seeds are mostly stored in makeshift structures such as sheds with tarps covering the seeds. The limited storage capability further validates the need for a continuous processing method such as the screw expeller method the team settled on. Sesame seeds are naturally hulled, and can be processed with or without the hulls. Whole sesame seeds are a somewhat better source of insoluble fiber because their hulls contain bran, but dehulled sesame seeds still deliver about the same amount of total dietary fiber [19]. In The Fröolja Project's oil extraction system, the sesame seed hulls will be removed manually by the farmers.

7 Power Transmission

As previously mentioned, power to the system will be provided by the PTO of a tractor. The power from the PTO has to be transformed to match the system's requirements using a drivetrain. In this section, the transmission of power from the tractor to the screw expeller is discussed in detail.

7.1 Fuel

The Massey Ferguson 385 tractor has a 85 hp 4 cylinder diesel engine [20]. This is beneficial because it provides the team with sufficient power to run the expeller while taking advantage of the inexpensive diesel prices and familiar componentry for maintenance by the South Sudanese.

7.2 Drivetrain

The tractor's PTO is a live single speed shaft that rotates at a rate of 540 rpm at an engine speed of 1789 rpm [20]. The "live single speed" means that there is a set rate of rotation of the PTO that correlates to different engine speeds and that the PTO only turns while the clutch is engaged. Through research it was determined that the optimal rotational speed for the worm shaft is around 120 rpm [6]. Therefore, a power reduction drive train is needed between the PTO and the worm gear. Initially the team considered using a gearbox consisting of either spur or helical gears. However, since the rotational speed is so low, very large torques are generated, placing nearly 4000 lb_f on the teeth of the gears. These high forces would cause the gears to fail prematurely. A belt driven system was not a viable option due to slippage of the belt on the cogs and high-tension forces within the belt. This led the team to consider a chain driven system. Through the use of duplex chains, the system can be strengthened. A chain system also has a cost saving fail safe built in, as the chain is designed to break before the sprockets do (chains are much less expensive than the sprockets). Due to size constraints, the team decided to use a double reduction drive train system. The current design uses 08B-2 chain (duplex 08B chain) and has an overall reduction of 5:1 as shown in Figure 7 below. For full analysis of the drivetrain, see Appendix B.

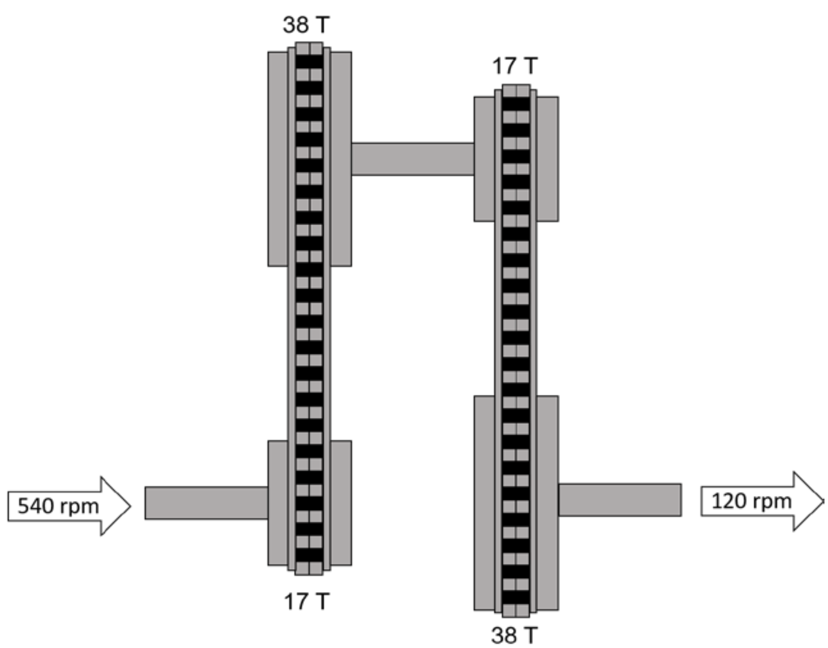

Figure 7. 5:1 Double Reduction Drive Train using Duplex Chains

8 Feeding Mechanism

In the initial stage of the oil expeller, seeds will be loaded into the hopper manually. A worker will monitor the seed level in the hopper and add seeds as needed. Injury due to overexertion is a concern with using manual labor to load the seeds; thus, efforts will be made to have the hopper height as low as possible in addition to switching out laborers.

The hopper will be constructed from stainless steel sheet metal with a transparent peephole and aid in feeding the seeds into the shaft housing to be crushed. A square prism, versus circular, will be used to avoid an "igloo effect" in the seeds, allowing for continuous flow. A stick with a bulb on the end will be used to pound the sesame seeds in the hopper to enable the continuous movement of seeds. Pounding the seeds will also aid in weakening their shells, reducing wear on the worm shaft. If a stick is not adequate, an attachment can be used to adjust the steady state volume of seeds at the base of the hopper.

9 Oil Extraction

As mentioned, an expeller system will be used to extract sesame oil from the seeds. As shown in Figure 8, as seeds are moved by the worm gear from the input to the output, the volume available is reduced, thus generating pressure and forcing oil out of the seeds. Small holes in the worm housing will allow for the oil to run out and be collected. The following sections describe this process in detail.

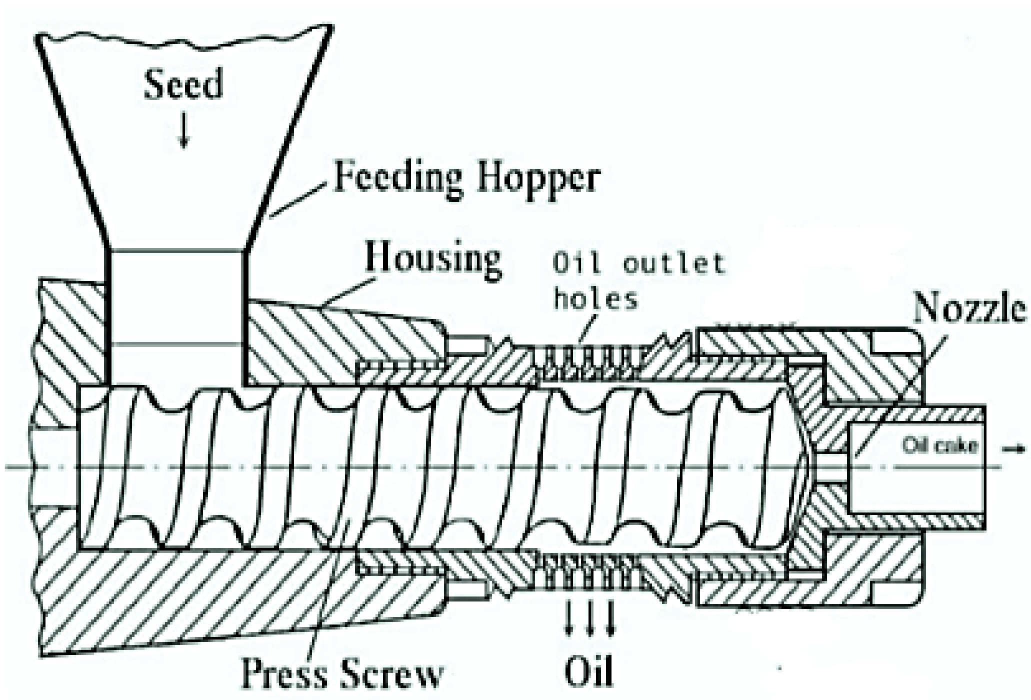

Figure 8. Sesame Seed Oil Expeller [21]

9.1 External Housing of Extractor

The housing will be made of sheet metal. The housing will be robust and capable of withstanding the forces generated internally as the shaft rotates. The immediate housing around the worm and shaft will have small perforations to allow the oil to percolate into a collector underneath the system; these holes will be small enough to allow for oil to flow through and for seeds to stay in the system.

The system will be towed behind a Massey Ferguson 385 tractor using a trailer. The external frame constructed to hold the system will be covered with sheet metal that is held together using rivets. Rivets were chosen because they will deter unqualified people from accessing the internal components of the system. However, if maintenance needs to be done, the rivets can be drilled out and the sheet metal panels can be removed to reveal the internal componentry. The sheet metal panels will be painted with weatherproof paint to protect against rust as well as improve the aesthetics.

9.2 Worm Screw

The worm screw is a tapered screw with varying pitches along the length of the screw. The pitch gets smaller moving from the input to output section, thereby applying more pressure toward the end of the extraction process to achieve the maximum amount of oil out of the ground-up seeds. The worm screw is made out of steel, with two options: case hardened and hard-faced. The purchased worm from Shreeji Expellers in India comes with spare parts [16].

9.3 Collection Bins

To collect the oil as it drips down from the perforations in the central housing, a sheet metal collection tray will be located directly beneath the worm shaft housing. The tray will be approximately 1 m x 0.3 m with 0.05 m walls extending upwards towards the central shaft. The tray will be angled to one side with a spout to pour the extracted oil into a larger collection container. This container will serve as the intermediate storage unit for the oil which, through a closable spout, can then be transferred into either a larger storage tank or numerous 5 L containers for shipping. The extruded waste material will be collected in buckets and periodically transferred to a larger storage container.

10 Expeller Flow Rates

This section describes the flow rates of substances through the expeller itself. In the Upper Nile region of South Sudan, a hectare of land will average a yield of 729 kg of sesame seed per annual harvest [18]. For the flow rates, it is assumed that one co-op (40 hectares) is to be processed over 2 weeks, with 6 work days in each week. The team is assuming a 10-hour work day, and 85% daily operation. Complete flow rates can be observed in Table 1.

Table 1: Expeller Flow Rates Summary and Assumptions [18]

FLOW RATES (mass basis)		
SEED	2431	kg/day
	286	kg/hr
	0.08	kg/s
OIL	911	kg/day
	107	kg/hr
	0.03	kg/s
WASTE	1519	kg/day
	179	kg/hr
	0.05	kg/s
Single co-op size	40	ha
Time per Co-Op	12	days
Work day	10	hrs/day
Operation	85%	per 10 hr day
Seed composition	50%	kgOil/kgSeed
Oil Yield (expeller)	75%	oil expelled/oil in seed

As previously stated, seeds will be manually loaded into the hopper and gravity fed into the shaft housing to be compressed, thus separating the oil from the seed waste. With the given assumptions above, the machine is targeted to process roughly 2400 kg of seed per day. This yields outputs of approximately 900 kg of oil and about 1500 kg of waste respectively per day. In practice, these numbers could change depending on any variation in the assumptions such crop yield rates (for example, droughts cause a low yearly yield). One contingency is that the oil yield percent is a logical estimate based on existing expellers. While the numbers may change slightly, this will not make the design any less functional. Only the time required to process seeds and the business analysis will be affected. The purpose of calculating these flow rates was to determine the size of worm shaft, and will also translate back to the power required through the drivetrain from the PTO.

11 Business Plan

The overarching goal of the sesame oil extractor system is to increase the quality of life of the community in Malakal, South Sudan. To increase the quality of life, this system was designed to increase the annual profit accrued by local area farmers thereby bringing more money to the local economy. A thorough business analysis of the sesame oil extractor system was performed in order to verify the system's profitability over the course of its 20-year lifetime.

11.1 Mission and Vision Statement

The Fröolja Project developed both a mission and a vision statement in order to guide decision making and constantly be aware of long terms outcomes for the project as a whole.

Mission Statement: The purpose of The Fröolja Project is the implementation of a mechanical sesame seed oil extractor intended to bring increased revenue to farmers within Malakal, which will in turn drive local economic growth.

Vision Statement: The long-term vision of The Fröolja Project is to increase the quality of life and promote flourishing within the community of Malakal, South Sudan. It is the goal of the project to promote community, collaboration, and understanding between the many different ethnic tribes of the region.

11.2 Industry Overview

The agriculture of sesame seeds is a lesser-known but still very large global industry responsible for $9.3 billion annually [7]. Sesame seeds are used in a wide variety of foods; however, the majority of seeds produced are crushed to extract oil. Sesame oil is one of the most commonly used seed oils in the world due to its stability at high temperatures, long shelf life, and healthy effects on the body. There are several different types of sesame oil produced globally, each with a different use. The most common form of sesame oil is extracted from dehulled, unroasted sesame seeds through cold pressing. This is the form of sesame oil that will be produced by The Fröolja Project's extractor. Referred to as the highest quality of sesame oil, this form is used as cooking oil for food preparation, primarily for frying. However, it can also be utilized in the production of cosmetic products and applied to the skin as anti-aging lotion. An alternative form of sesame oil is extracted from dehulled, roasted sesame seeds. The resulting oil is darker than the high-quality cooking oil. This oil is primarily added to food later in the cooking process as a flavor additive similar to soy sauce. The final form of sesame oil is produced by grinding hulled sesame seeds into a substance known as tahini, one of the primary ingredients in hummus [22]. While all of these forms of sesame oil are produced and consumed around the world, the oil extractor designed by The Fröolja Project will produce only pure, unroasted cooking oil. As a result, sesame cooking oil will be the focus of the business analysis.

Sesame seeds are a common cash crop and are produced by numerous countries around the globe. The four largest global producers of sesame seed according to the Food and Agriculture Organization of the United Nations in 2014 are shown below in Table 2.

Table 2: Largest Global Producers of Sesame Seed (2014) [18]

Country	Sesame Seed Production (tonnes)
1. Tanzania	1,138,920
2. India	811,000
3. Sudan	721,000
4. China	629,900
10. South Sudan	175,000

Following its separation from Sudan, South Sudan has not yet been able to fully capitalize on its abundant fertile land. There is much room for additional sesame seed production. South Sudan does not currently possess the infrastructure or means to domestically extract sesame oil. Instead, the vast majority of the seeds are exported to India where the oil is extracted and redistributed around the world. The largest global producers of sesame oil in 2014 are shown in Table 3.

Table 3: Largest Global Producers of Sesame Oil (2014) [18]

Country	Sesame Oil Production (tonnes)
1. India	542,000
2. Ethiopia	476,000
3. Nigeria	368,670
4. Tanzania	216,000
5. Burkina Faso	87,330

India is the largest global supplier of sesame oil as the country both grows sesame seed and imports additional seed for oil extraction [18]. Once the sesame oil is extracted and purified, it is sold and exported to nations all around the world, primarily in North America, Asia, and Europe. The largest importers of sesame oil in 2014, according to the Observatory of Economic Complexity, are shown in Table 4.

Table 4: Largest Global Importers of Sesame Oil (2014) [23]

Country	Sesame Oil Imported (tonnes)
1. United States	937,880
2. China	251,220
3. United Kingdom	174,180
4. Canada	160,780
5. Germany	137,330

11.3 SWOT Analysis

As a part of the effort to predict the success of The Fröolja Project’s sesame oil extractor in the international sesame oil market, a SWOT Analysis was conducted. The analysis focuses on identifying strengths, weaknesses, opportunities, and threats to a new business entering a market.

The primary strength of The Fröolja Project’s sesame oil extractor is that it would allow farmers in South Sudan to produce and sell their own sesame oil. This would be a drastic improvement from the current situation of selling their harvested sesame seeds to India, and then buying back India’s sesame oil at a marked-up price. The result is increased profit for farmers in South Sudan. Another strength of this oil extractor system is that it is designed to pay for itself after two harvests, and pay for a new system after four harvests. This promotes growth and expansion among the cooperative farms in Malakal. The system is also designed to be fully operated and owned by local farmers. The fact that farmers are now able to produce their own oil will develop feelings of ownership and pride, motivating them to care for the oil extractor and their farm, leading to a longer useful life of the machine.

The obvious weakness to the sesame oil extractor is that these farmers in South Sudan are attempting to enter into a global market that is already well established. It is likely that the majority of countries importing sesame oil already have partnerships and trade agreements with existing sesame oil producers. It may be difficult for South Sudanese farmers to develop international trade agreements and secure trade partners. It would also be challenging for South Sudanese farmers to market their oil internationally. Another weakness is that the sesame oil extractor system may not be used by farmers exactly as intended. The system relies on cooperation and mutual agreement between individual farmers. If farmers begin squabbling over ownership of the machine, then they will be unable to profitably operate the machine in the long term.

An exciting opportunity that The Fröolja Project's oil extractor hopes to capitalize on is the high level of consumer demand for authentic sesame oil. There are a growing number of consumers looking to purchase sesame oil with a known harvest and oil extraction location. The sesame oil extracted by this machine would be in very high demand around the world, with consumers willing to pay more for South Sudanese oil than for domestically produced oil in their respective countries. The Fröolja Project is also hoping to capitalize on the global sentiment of "helping the little guy." The hope is that many people around the globe would love to see the world's youngest nation thrive, and would be willing to contribute through the purchase of South Sudanese exports.

The greatest threat to the South Sudanese sesame oil industry are the leading global producers of sesame oil: India, Ethiopia, Nigeria, Tanzania, and Burkina Faso. Since the oil extraction processes in these countries are already well established and optimized, it is possible that they would be able to undersell South Sudanese sesame oil. Another threat is the ongoing tribal turmoil within South Sudan. The Fröolja Project's oil extractor is designed to be shared between a dozen or so farmers. If the tribes of these farmers begin feuding or warring, cooperative use of the oil extractor will cease to function and sesame oil production will stop.

11.4 Competitor Analysis

As previously mentioned, the primary competitors to South Sudan in the sesame oil market are the largest global producers listed in Table 4. Among those global producers, Ethiopia, Nigeria, Tanzania, and Burkina Faso are likely the closest competitors as they will also be selling African-pressed sesame oil. According to the USDA Foreign Agricultural Service's Global Agricultural Information Network Report from April 2016, sesame oil exports in Ethiopia account for almost one fifth of the nation's total export earnings with 75% of Ethiopia's sesame oil being exported annually [24]. Also, a 2016 report from Foraminifera Market Research indicates that the vast majority of Nigeria's sesame oil production is for domestic use, not international sale [25].

11.5 Market Analysis

The target market for South Sudan's sesame oil is North America, Asia, and Europe, with the majority of the focus on the United States. Additionally, the byproducts of sesame oil extraction, sesame oil cakes, are a popular food in Saudi Arabia when mixed appropriately with honey. The byproducts are also rich in protein and are commonly used in making animal feed [7]. This will be a secondary source of revenue for the South Sudanese farmers. Through the international trade website, Alibaba [26], market prices of several materials and goods relevant to the costs and revenue associated with the team's oil extractor were determined. These market prices are shown in Table 5. Additionally, much data was collected regarding fuel consumption, sesame oil consumption in South Sudan, fertilizer use, and tractor operating time. These values were used for calculating annual cost and revenue flows. The research values are shown in Table A1, located in Appendix A.

Table 5: Market Prices (Nov. 2017) [26]

Material	Market Price
Sesame Seed (per kg)	$1.18
Sesame Oil (Export, per kg)	$2.87
Sesame Oil (Shelf, per kg)	$20.00
Diesel Fuel (Sudan, per L)	$0.62
Fertilizer (per kg)	$0.55
Land (per hectare)	$1,000.00
Storage Container (per kg oil)	$0.11
Sesame Oil Cake (per kg)	$0.46

**All prices in US Dollars*

11.6 Bill of Materials

In order to determine the investment cost of the sesame oil extraction system, a bill of materials was created. This was done by listing all of the necessary system components and looking up typical parts costs online, primarily on McMaster-Carr's website [27]. The pricing for the expeller chamber was determined from a quote the team received from Shreeji Expeller Industries [16], the likely supplier of the worm shaft and housing chamber. The full bill of materials is shown below in Table 6.

Table 6: Oil Expeller Bill of Materials [27]

Assembly	Part	Quantity	Cost (each)	
Expeller Chamber	Chamer Assembly	1	$	1,600
	Worm Assembly	set	$	1,200
	Cone Assembly	set	$	780
	Main Screw Shafts	1	$	950
	Cage Bar Set	set	$	750
		Total	**$**	**5,280**
Gear Box	Shaft	3	$	30
	Bearings	7	$	50
	PTO shaft adapter	1	$	50
	17tooth sprocket	2	$	62
	38tooth sprocket	2	$	113
	Roller Chain	1	$	58
	Steel for Frame	2	$	44
	Sheet metal	2	$	68
		Total	**$**	**1,122**
Hopper	Sheet metal	3	$	69
Collection	Sheet metal	2	$	69
Storage	Metal for Frame	3	$	44
	Sheet metal	6	$	69
		Total	**$**	**894**
Contingency	25%		$	1,824
		Overall Total	**$**	**9,119**

The team added in a budget contingency of 25% since the exact costs will likely fluctuate slightly prior to purchasing the parts. Also, the above costs of parts are, largely, general prices. The costs of the specific materials ordered may vary slightly from the above typical values. Including the contingency, the total budget for a single sesame oil expeller is approximately $9,119.

11.7 Business Strategy

Given the control volume of a single sesame oil extractor machine processing all of the sesame seeds produced on 40 hectares of farmland in one growing season, the annual profit experienced by the farm cooperative is $34,234 (US Dollars). The calculated cost and revenue streams for the farm cooperative are shown below in Table 7.

Table 7: Single Farm Cooperative Statement of Income (with Expeller)

Costs		Annual Revenue	
Year 1 Costs		Sesame Oil	$30,928
PEC (Expeller, yr 1)	$9,119	Sesame Oil Cakes	$8,347
PEC (seeds, yr 1)	$159		
PEC (Tractor, yr 1)	$15,000		
PEC (Land, yr 1)	$40,000		
TOTAL	$64,278	TOTAL	$39,275
Annual Costs		Annual Profit Per Co-Op	$34,234
Diesel Fuel	$2,639	Estimated Breakeven (yrs)	2
Maintenance	$912		
Fertilizer	$242		
Storage Barrels	$1,248		
TOTAL	$5,041		

**All prices in US Dollars*

The Fröolja Project's budget approximates the cost of a single oil extractor system at $9,119. The initial cost of sesame seeds for planting was determined assuming a typical planting density of 3.37 kg seed/ha. The cost of the Massey Ferguson 385 tractor used to power and transport the oil extractor was estimated at $15,000. Also, the cost of the farmland was assumed to be an initial payment at the estimated cost of $1,000 per hectare. These initial investment costs sum to $64,278. The annual costs for operating the oil extractor were calculated assuming a diesel fuel consumption rate of 0.20 L/hp*hr with a tractor output power of 70 hp during use. The team also assumed a maintenance cost equal to 10% of the total capital investment of the oil extractor. According to the World Bank Database [28], the average rate of fertilizer use in Sudan is 11kg/ha. This rate was used to determine annual fertilizer costs. The price of plastic storage barrels was determined from Alibaba, and the quantity needed was determined by the quantity of sesame oil produced annually. This yielded a total annual cost of $5,041.

In order to determine the annual quantity of sesame oil produced by a single 40-hectare farm, a harvest yield of 729 kg/ha was used from the FAO/WFP Crop and Food Security Assessment Report [18]. Also, a seed composition of 50 wt% oil was assumed along with an oil extractor effectiveness of 75%. Together, this yielded an annual production of 10,887 kg sesame oil. Through the team's South Sudanese resource, Pastor Monyroor Teng, it was determined that a single family in South Sudan consumes approximately 11 kg of sesame oil annually. Assuming that 10 families live off the 40-hectare cooperative farm, the 110 kg of sesame oil used by the farmers and their families per year was subtracted from the total sesame oil production to yield a net sesame oil production of 10,776 kg per year. Assuming all the oil is sold at the current market price of $2.87/kg, a revenue of $30,928 is obtained. Coupling this with the 18,145 kg of dried sesame cake by-product sold at a market price of $0.46/kg, a total annual revenue of $39,275 is received by the farmers. Subtracting the annual costs yields an annual profit of $34,234 for a single 40-hectare cooperative farm utilizing The Fröolja Project's sesame oil extractor. Figure 9 depicts the 10-year cash flow for the 40-hectare cooperative farm utilizing the oil extractor.

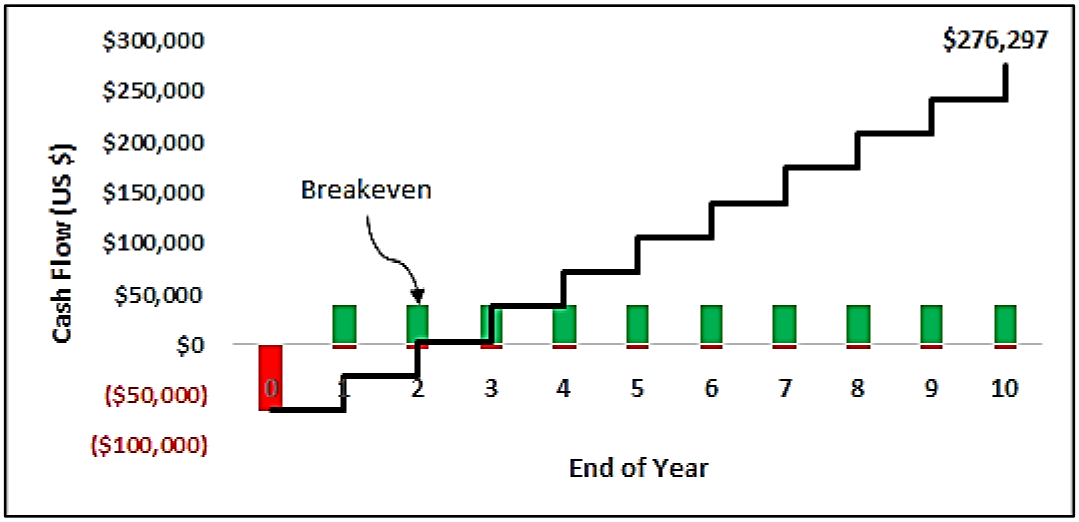

Figure 9: Cash Flow Diagram using Expeller

As shown above, the farm will break even during only their second harvest. The projected total profit at the end of year 10 is $276,297 and the projected total profit at the end of year 20 is $620,402. For comparison, the cost and revenue streams of a 40-hectare farm in South Sudan selling only harvested sesame seeds were calculated and are shown in Table 8.

Table 8: Single farm Cooperative Statement of Income (without Expeller)

Costs		Annual Revenue	
Year 1 Costs		Sesame Seed	$34,258
PEC (seeds, yr 1)	$159		
PEC (Land, yr 1)	$40,000		
		TOTAL	$34,258
		Annual Profit Per Co-Op	$26,579
TOTAL	$40,159	Estimated Breakeven (yrs)	2
Annual Costs			
Fertilizer	$242		
Storage Barrels	$3,328		
Shipping	$4,108		
TOTAL	$7,679		

**All prices in US Dollars*

The cost of seeds, land, and fertilizer are the same for both farms. However, when not producing oil there is an additional annual cost of $4,108 for importing sesame oil from India. The annual revenue of $34,258 is experienced when selling the 29,032 kg of sesame seeds produced annually at the market price of $1.18 per kg. Figure 10 depicts the 10-year cash flow for the 40-hectare farm selling harvested sesame seeds, not oil.

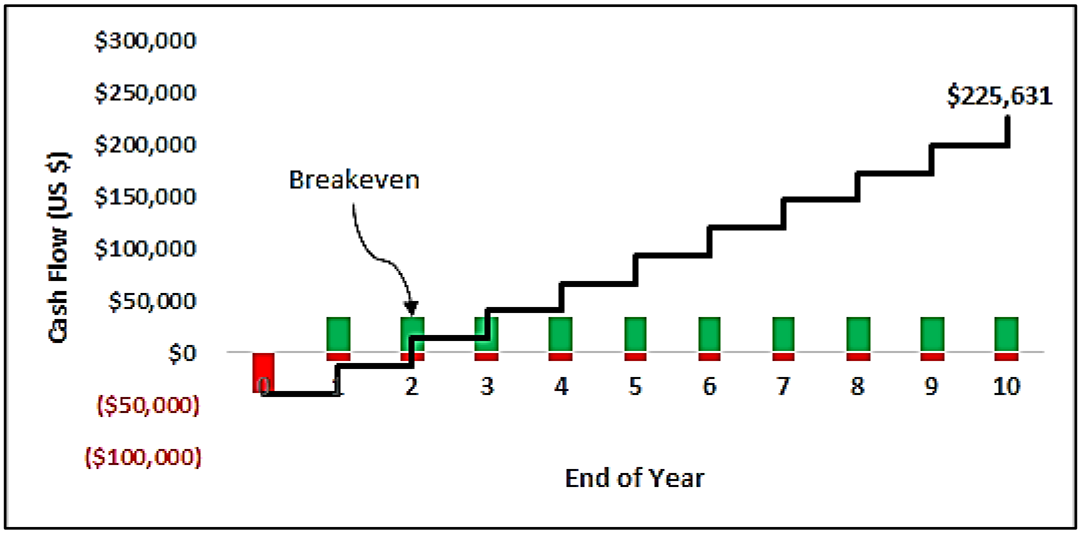

Figure 10: Cash Flow Diagram without using Expeller

Simply exporting the harvested sesame seeds would yield an annual profit of $26,579 for the farm. The total profit after 10 years would be $225,631 and the total profit after 20 years would be $491,421. It is clear that the implementation of an on-site oil extractor is beneficial to the local cooperative farmers as this would increase total profit by $128,981 over the 20-year lifetime of the oil extractor.

11.8 Marketing Strategy

Informal market research conducted by the team showed that consumers are willing to pay more for sesame oil that has a verified origin location. A key aspect of the marketing strategy will be capitalizing on the fact that the sesame oil is extracted on-location by South Sudanese farmers. The primary target market would be middle and upper-class cooking enthusiasts in North America who desire to use more authentic and specialty ingredients than are offered in large, discount grocery store chains.

12 Deliverables

Throughout this project, it has been important for Team 18 to be aware of the fact that there are two customers: the Calvin College Engineering Department and Governor Monybuny. This has been a source of slight conflict as sometimes each customer asks for something different from the team. However, it is the team's goal to satisfy both parties at the conclusion of the project in the spring.

12.1 Fall Semester

There have been a number of items submitted during the fall semester including a project schedule in the form of a Gantt chart, a Work Breakdown Structure, and a number of industrial mentor meetings. However, the primary deliverable in the fall semester is this Project Proposal and Feasibility Study.

If all goes according to plan, the team will be able to deliver a working prototype of the system to Governor Monybuny in South Sudan by early October 2018.

12.2 Spring Semester

The spring semester deliverable, for Calvin College, is a final design report detailing the optimal design. The team also aims to provide a working prototype that has been tested for functionality.

12.3 Prototype

For Governor Monybuny and South Sudan, the primary deliverable is a fully functioning and tested prototype. Team 18 has been promised by the governor that 40 hectares of sesame seeds will be planted in May 2018, and will be ready for harvest and processing near the end of October 2018. The team is waiting for written documentation from the governor's office. It is the team's goal to deliver the prototype to the farm in Malakal before then. Due to shipping, the prototype will need to be completed by the end of July 2018 at the latest.

13 Testing

As previously mentioned, The Fröolja Project aims to deliver a working prototype at the end of the spring semester. To accomplish this, testing has to occur early enough to resolve issues that will need to be uncovered well ahead of the delivery date to South Sudan in October 2018. To accomplish this, the prototype will be operated for 4 hours, processing about 1000 kg of dry seed and producing roughly 375 kg of oil. The team believes this test will prove the functionality of the expeller and expose any major problems. After processing the seeds, the team will test ease of disassembly and cleaning, as this will have to occur often. The oil produced will be tested for quality through color and content of foreign particles. The team will also test to verify whether the system meets cold pressing standards, for which the oil has to remain below 50 C (122 F) [29]. This will be tested using an infrared camera to measure the temperature of the oil leaving the expeller as well as the temperature of the expeller housing.

14 Conclusions

The mechanical analysis performed this semester has led the members of The Fröolja Project to the conclusion that the sesame oil expeller system described in this report can be built and will function as designed. The projected earnings of the implemented system show that South Sudanese farmers will benefit financially from its use. A look at the project schedule indicates that the team is on track and ready to begin system construction at the start of the spring semester. In conclusion, Team 18 has determined that The Fröolja Project is indeed feasible given the progress of the project thus far.

Team 18 began the fall semester hoping to design a mechanical system to extract the oil from sesame seeds in South Sudan. One of the initial requirements of the system was that the waste product has a maximum 15 wt% of oil. Given that the unprocessed composition of sesame seeds is 50 wt% oil, in order to meet this criterion, the designed expeller must remove 70% of the oil contained within the seeds. A study conducted by The Institution of Engineers, Sri Lanka on similarly sized expellers shows a typical oil extraction rate of 88%. So, reaching the required 70% should be a matter of optimizing the machine once built in the spring. Another requirement was utilizing food grade materials. Stainless steel is a corrosion-resistant material that will not give off any harmful chemicals into the sesame. All of the system components in direct contact with sesame are capable of being stainless steel. The system must be capable of processing

290 kg of seeds per hour, and the machine from which the worm shaft and housing are being purchased is designed to process 300 kg of seeds per hour. The analysis performed on the drivetrain confirmed that all shafts, chains, and sprockets transmitting the input torque are strong enough to withstand yielding with a safety factor of 2. Additionally, Team 18 is set to order critical parts before the end of fall semester, which would allow construction to begin at the start of spring semester. Even though the prototype will be constructed from both purchased parts and manufactured components, Team 18 is confident that the full system will be able to be integrated and assembled as the manufactured components have been designed to fit into the purchased parts.

The entire purpose of this project is to bring more profit to South Sudanese farmers. The business analysis indicates that farmers will indeed be experiencing greater profit each year than they would be without the use of The Fröolja Project's oil extractor. Without the oil extractor, farmers experience an annual profit of roughly $30,700 and with the extractor they will see an annual profit of roughly $34,200. Therefore, Team 18 concludes that, from a financial perspective, The Fröolja Project is feasible.

15 Acknowledgements

The team would like to express gratitude to the mentors for this project, Jeff Kibbie and Monyroor Teng, whose genuine love and concern for the South Sudanese people led them to envision this project. Jeff and Monyroor's advice and the information they provided gave the team direction and helped to make decisions. The team also thanks the customer, Governor James Tor Monybuny and the people of Malakal, for their willingness to collaborate and see this project come to fruition. For his valuable input, the team also thanks their industrial consultant, Benjamin Hekman of Dematic Corp. Professor Tracy Kuperus in the International Development Studies department at Calvin gave the team great advice regarding international development; many thanks to her. Tess Anderson Photography graciously volunteered to take all the team pictures. The team would like to thank the project advisor, Professor Renard Tubergen, for his invaluable input throughout the semester. Sincere thanks to family and friends for their support and encouragement. Finally, the team would like to thank God for providing an avenue for us to use our engineering education and calling.

Appendices

Appendix A: Business Plan

Table A1: Cost/Usage Data

Data		
Single Household of Farmer	Oil Purchases (#/yr)	12
	Oil Purchase Quantity (L)	1
	Oil Consumption (kg/yr)	11.064
Single co-op Farm	Households per co-op (#)	10
	Oil Consumption (kg/yr)	110.64
Total	Number co-ops (#)	1
	Oil Consumption (kg/yr)	110.64
Single Co-Op Production	Sesame Seeds Produced (kg/yr)	29166.67
	Net Seeds Produced (kg/yr)	29031.87
	Sesame Oil Produced (kg/yr)	10886.95
	Net Oil Produced (kg/yr)	10776.31
	Fuel Consumption (L/hr)	28
	Operating Time (hrs/yr)	102
	Tractor Operation, Other Use (hrs/yr)	50
	Maintenance Cost (% of CI)	10.00%
https://data.worldbai	Fertilizer Consumption (kg/ha)	11
	Sesame Oil Cakes Produced (kg/yr)	18144.92
	Fuel Consumption (L/hp*hr)	0.2
	Tractor Output Utilized (hp)	70
	Tractor Output (non expeller use) (hp)	70

In Table A1 above, the information on the consumption of sesame oil in South Sudan was obtained from the project's South Sudanese resource, Pastor Monyroor Teng. From that information, consumption quantities were extrapolated to a cooperative farm. The quantity of sesame seeds produced by a farm in one year was calculated from the size of the farm, 40 hectares, and the average yield data from the World Food Programme (729 kg-sesame seed/ha) for South Sudan [18]. The quantity of sesame oil produced per year was calculated by multiplying the quantity of seeds produced by the composition of seeds (50 wt% oil) and the effectiveness of the expeller (75%). The net production quantities subtract the quantity of seeds and oil used for consumption by the cooperative farm each year. The rate of fertilizer use was taken from a World Bank survey [28]. The fuel consumption rate for the tractor was calculated by multiplying an estimated fuel consumption constant for tractors (0.2 L/hp*hr) by the reported power output of the specific tractor to be used in this system (Massey Ferguson 385). The operating time was determined from the team's assumption that all of the seeds produced for the 40-hectare farm would be processed in two weeks (12 working days). The value for tractor operation (other use) was estimated based on potential tilling and harvesting times. Finally, the mass of sesame oil cakes produced was calculated by subtracting the mass of the extracted oil from the mass of the seeds being processed.

Appendix B: Drive Train Analysis

Initial drivetrain calculations, including minimum shaft diameter, torque on shafts, force in roller chain (on teeth of sprockets), power transmitted, and rotational speed of shafts, were done using Engineering Equation Solver (EES). An input power of 14.91 kW (20 hp) was used as recommended by Shreeji Expeller Industries [16]. The input rotational speed was selected to be 540 rpm as it is the standard speed of the PTO on the Massey Ferguson 385 tractor being used [20]. Material properties for the shafts were selected to be the same as the PTO adaptor being used to connect the PTO to the drivetrain [27]. These properties are subject to change as more analysis is done and final parts are purchased. Figure B1 shows a detailed diagram of the drivetrain, which sheds more light on the nomenclature used in the calculation equations and system analysis. A summary of the results can be seen in Table B2, Table B3, and Table B4 below.

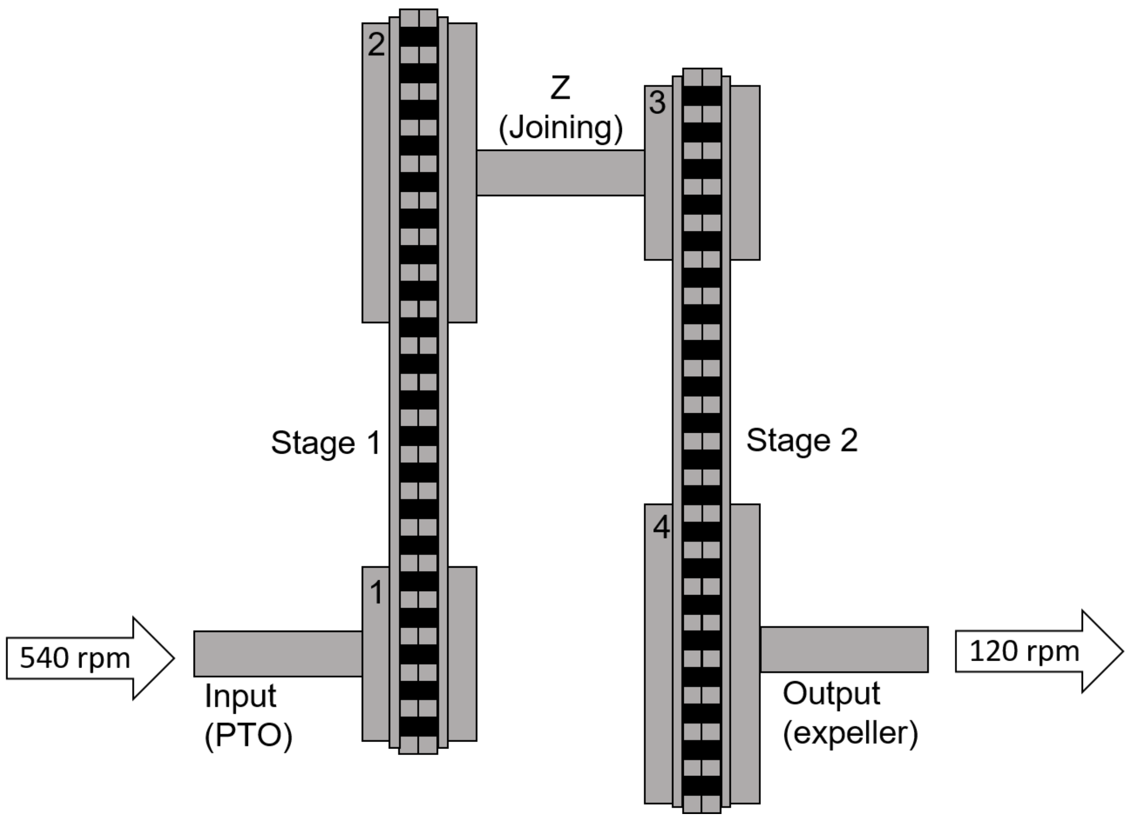

Figure B1. Detailed Diagram of Drivetrain

Table B1. Drivetrain Sprockets [30]

Sprocket	Number of Teeth	Pitch Diameter (mm)	Supplier	Product Number
1	17	69.12	Martin Sprocket	D08B17
2	38	153.79	Martin Sprocket	D08B38
3	17	69.12	Martin Sprocket	D08B17
4	38	153.79	Martin Sprocket	D08B38

Table B2. Drivetrain Shafts [27]

Shaft	Power (kW)	Torque (N*m)	Rotational Speed (RPM)	Min. Dia. (mm)
Input (PTO)	14.914	263	540	16.50
Z (Joining Shaft)	14.845	585.2	241.6	21.54
Output (Expeller)	14.777	1302	108.1	28.12

*Note that no supplier has been selected yet.

Table B3. Roller Chain [31]

Chain	Force in Chain (N)	Length (mm)	Supplier	Product number
Stage 1	10655	864.3	Nitro Power Products	RC08B-2R-10FT
Stage 2	23708	864.3	Nitro Power Products	RC08B-2R-10FT

*Note the selected chain has a tensile strength rating of 38700 N providing a safety factor of 1.6.

EES Code (Drivetrain)

ENGR SENIOR DESIGN
TEAM 18
THE FROOLJA PROJECT
DRIVE TRAIN CALCULATIONS

INPUT SHAFT (PTO) Source: https://www.engineeringtoolbox.com/torsion-shafts-d_947.html

$$P_{in} = 20 \cdot \left| 745.7 \cdot \frac{W}{hp} \right|$$ PTO Power

$$\omega_{in} = 540 \text{ [rev/min]}$$ PTO speed

$$\tau_{PTO} = 0.577 \cdot 75000 \cdot \left| 6895 \cdot \frac{Pa}{psi} \right|$$ http://www.matweb.com/search/datasheet.aspx?matguid=193434cf42e343fab880e1dabdb143ba&ckck=1

$$J_{PTO} = \frac{3.142 \cdot Dia_{PTO}^{4}}{32}$$ Polar Moment of Inertia PTO

$$P_{in} = 0.105 \text{ [min/(rev*s)]} \cdot \omega_{in} \cdot T_{PTO}$$ Torque in PTO

$$\tau_{PTO} = \frac{T_{PTO} \cdot \frac{Dia_{PTO}}{2}}{J_{PTO}}$$ Minimum Shaft Diameter of PTO

GEAR 1 Catalog Number D08B17 from Martinsprocket.com

$$N_1 = 17$$ Number of teeth on first gear

$$P_{D,1} = 69.12 \cdot \left| 0.001 \cdot \frac{m}{mm} \right|$$ Pitch Diameter of first gear

$$F_1 = \frac{T_{PTO}}{\frac{P_{D,1}}{2}}$$ Force on first gear

$$F_{lbf,1} = F_1 \cdot \left| 0.2248 \cdot \frac{lbf}{N} \right|$$

GEAR 2 Catalog Number D08B38 from Martinsproket.com

$$N_2 = 38$$ Number of teeth of second gear

$$P_{D,2} = 153.79 \cdot \left| 0.001 \cdot \frac{m}{mm} \right|$$ Pitch Diameter of second gear

$$F_2 = F_1$$ Force on second gear

$$F_{lbf,2} = F_2 \cdot \left| 0.2248 \cdot \frac{lbf}{N} \right|$$

JOINING SHAFT (Z)

$$T_Z = \frac{F_2 \cdot P_{D,2}}{2}$$ Torque in Joining shaft

$$\omega_z = \omega_{in} \cdot \frac{N_1}{N_2}$$ Speed of joining shaft

$$\tau_Z = 0.577 \cdot 75000 \cdot \left| 6895 \cdot \frac{Pa}{psi} \right|$$

$$J_Z = \frac{3.142 \cdot Dia_Z{}^4}{32}$$ Polar moment of inertia of joining shaft

$$P_Z = 0.105 \ [min/(rev*s)] \cdot \omega_z \cdot T_Z$$ Power in Joining shaft

$$\tau_Z = \frac{T_Z \cdot \frac{Dia_Z}{2}}{J_Z}$$ Diameter of joining shaft

GEAR 3 Catalog Number D08B17 from Martinsprocket.com

$$N_3 = 17$$ Number of teeth of third gear

$$P_{D,3} = 69.12 \cdot \left| 0.001 \cdot \frac{m}{mm} \right|$$ Pitch diameter of third gear

$$F_3 = \frac{T_Z}{\frac{P_{D,3}}{2}}$$ Force on third gear

$$F_{lbf,3} = F_3 \cdot \left| 0.2248 \cdot \frac{lbf}{N} \right|$$

GEAR 4 Catalog Number D08B38 from Martinsproket.com

$$N_4 = 38$$ Number of teeth on fourth gear

$$P_{D,4} = 153.79 \cdot \left| 0.001 \cdot \frac{m}{mm} \right|$$ Pitch diameter of fourth gear

$$F_4 = F_3$$ Force on fourth gear

$$F_{lbf,4} = F_4 \cdot \left| 0.2248 \cdot \frac{lbf}{N} \right|$$

OUTPUT SHAFT (EXPELLER)

$$T_{expeller} = \frac{F_4 \cdot P_{D,4}}{2}$$ Torque on expeller shaft

$$\omega_{expeller} = \omega_z \cdot \frac{N_3}{N_4}$$ Speed of expeller shaft

$$\tau_{expeller} = 0.577 \cdot 75000 \cdot \left| 6895 \cdot \frac{Pa}{psi} \right|$$

$$J_{expeller} = \frac{3.142 \cdot Dia_{expeller}{}^4}{32}$$ Poler moment of inertia on expeller shaft

$$P_{expeller} = 0.105 \ [min/(rev*s)] \cdot \omega_{expeller} \cdot T_{expeller}$$ Power in expeller shaft

$$\tau_{expeller} = \frac{T_{expeller} \cdot \frac{Dia_{expeller}}{2}}{J_{expeller}}$$ Diameter of expeller shaft

$P_{expeller,hp} = P_{expeller} \cdot \left| 0.001341022 \cdot \frac{hp}{W} \right|$ Power in expeller shaft in hp

$Reduction = \frac{\omega_{in}}{\omega_{expeller}}$ Overall gear reducton (5:1)

Chain Length

$Pitch = 0.5 \cdot \left| 0.0254 \cdot \frac{m}{in} \right|$ Pitch of chain

$C = 10 \cdot \left| 0.0254 \cdot \frac{m}{in} \right|$ Center distance in m

$C_{pitches} = \frac{C}{Pitch}$ Center distance in pitches

$K = 11.17$ From Table 5 on Page 236 in Roller Drive Chain Selection by Renold Jeffrey

$L_{pitches} = \frac{N_2 + N_1}{2} + 2 \cdot C_{pitches} + \frac{K}{C_{pitches}}$ Chain length in pitches

$L = L_{pitches} \cdot Pitch$

ISO Chain drive info: http://www.globalspec.com/learnmore/mechanical$_{components}$/chains$_{sprockets}$/sprockets$_{roller,chain,metric}$

Nitro Roller chains: https://www.nitropowerproducts.com/metric-roller-chain

Nitro Roller Chain Reccomended Care: http://www.rollerchain4less.com/assets/images/PDF%20Files/Nitro%20Roller%20Chain%20Care.pdf

Unit Settings: SI C kPa kJ mass deg

$C = 0.254$ [m]	$C_{pitches} = 20$	$Dia_{expeller} = 0.03145$ [m]
$J_{PTO} = 1.139E-08$ [m^4]	$J_Z = 3.308E-08$ [m^4]	$K = 11.17$
$\omega_{in} = 540$ [rev/min]	$\omega_Z = 241.6$ [rev/min]	$Pitch = 0.0127$ [m]
$P_Z = 20783$ [W]	$Reduction = 4.997$	$SF = 1.4$
$T_{expeller} = 1823$ [N*m]	$T_{PTO} = 368.2$ [N*m]	$T_Z = 819.3$ [N*m]
$Dia_{PTO} = 0.01846$ [m]	$Dia_Z = 0.02409$ [m]	$J_{expeller} = 9.609E-08$ [m^4]
$L = 0.8643$ [m]	$L_{pitches} = 68.06$	$\omega_{expeller} = 108.1$ [rev/min]
$P_{expeller} = 20687$ [W]	$P_{expeller,hp} = 27.74$ [hp]	$P_{in} = 20880$ [W]
$\tau_{expeller} = 2.984E+08$ [Pa]	$\tau_{PTO} = 2.984E+08$ [Pa]	$\tau_Z = 2.984E+08$ [Pa]

Sort	1 F_i [N]	2 $F_{lbf,i}$ [lbf]	3 N_i	4 $P_{D,i}$ [m]
[1]	10655	2395	17	0.06912
[2]	10655	2395	38	0.1538
[3]	23708	5330	17	0.06912
[4]	23708	5330	38	0.1538

Click on this line to see the array variables in the Arrays Table window

No unit problems were detected.

Calculation time = 31 ms

Appendix C: References

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