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INVESTIGATION OF AN AFFORDABLE MULTIGRAIN THRESHER FOR SMALLHOLDER FARMERS IN SUB-SAHARAN AFRICA

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INVESTIGATION OF AN AFFORDABLE MULTIGRAIN THRESHER FOR SMALLHOLDER FARMERS IN SUB-SAHARAN AFRICA

A Thesis

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of

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by

David D. Wilson

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LIST OF ABBREVIATIONS

ADM	Archer Daniels Midland
FAO	Food and Agricultural Organization
GPS	Global Positioning System
LGB	Larger Grain Borer
MOG	Material Other than Grain
PHL	Post-Harvest Losses
PUP	Purdue Utility Platform
SCPI	Sustainable Crop Production Intensification
SSA	Sub-Saharan Africa
UNFAO	Food and Agricultural Organization of the United Nations

ABSTRACT

Wilson, David D. M.S., Purdue University, December 2015. Investigation of an Affordable Multigrain Thresher for Smallholder Farmers in Sub-Saharan Africa. Major Professor: John Lumkes.

As the global population rises, food security is among the most important grand challenges of our time. While agriculture has significantly developed in parts of the world, other parts are severely underdeveloped, inhibiting agriculture productivity, which is a necessary component of the solution to the food security challenge. Sub-Saharan Africa (SSA), in particular, has seen little growth in productivity, something that has been correlated to its low agricultural mechanization. One barrier to mechanization in SSA, where the average farm size is less than 2 Ha, is the cost of farm equipment. This leaves many farmers with just basic tools to perform farm operations. Threshing is a critical part of processing grains, which are staple crops in most countries. Traditional methods of threshing are time and energy consuming and can result in significant grain losses. Threshers that are available are imported, expensive, or too large for most farms.

This thesis investigated a locally appropriate and sustainable multigrain threshing machine as a means of improving the productivity and efficiency of smallholder farmers in SSA. An axial-flow threshing machine was designed for the threshing and cleaning of maize and soybeans. The thresher was 5.2 ft (1.6 m) long, 4.3 ft (1.3 m) high and 1.4 ft (0.4 m) wide. At an engine speed of 3000 rpm, the drum had a peripheral speed of 39 ft/s

(12 m/s), the sieve oscillated at 10 Hz, and air speed at the fan outlet was 29 ft/s (8.9 m/s). To simplify local manufacturing and minimize costs, only basic parts and materials, like rebar, angle iron, and pulleys, were used in the thresher. Tests of the thresher were performed using pre-weighed stalks of soybeans or un-husked corncobs. The crop was run through the thresher, and afterwards, weights of the grain and material other than grain (MOG) were measured in four different locations: on the ground, in the thresher, out the cylinder discharge, and in the grain bin. After initial tests, minor modifications were made to the thresher, and final tests were conducted. The final results showed that 96% of corn and 94% of soybeans were collected in the grain bin, with MOG amounts of 1.3% and 6.6% respectively. The feeding of material into the thresher, not the power or threshing capacity of the machine, restricted the feed rates. Grain feed rates of over 200 kg/h (corn) and over 20 kg/h (soybeans) were achieved. The results have demonstrated strong potential for the machine to be manufactured and used in SSA as a labor saving device for smallholder farmers to increase productivity and decrease losses.

CHAPTER 1. INTRODUCTION

1.1 Food Security, Agriculture, and Mechanization

As the world's population is set to increase significantly in the next thirty-five years, food security is a growing challenge. Much of the growth is projected to be in populations that already deal with poverty and under nutrition. By 2050, the world population is expected to increase from the current 7 billion to 9.2 billion. Currently, we are failing to fully nourish 925 million people (FAO, 2011). If massive increases of undernourishment are to be avoided, let alone reversed, something must change.

While the causes of food insecurity are complex, it is evident that decreasing poverty and increasing agricultural productivity will be major parts of the solution. Almost all of the projected population growth is expected to happen in less developed regions, with the least developed countries seeing the highest growth rates. Currently, 80 percent of the food supply in developing countries comes from smallholder farmers (FAO, 2011). The key to successful development of agriculture lies with these numerous farmers. If their productivity can be increased, there will be strong hope for the adequate nourishment of every person.

The UNFAO laid out a clear challenge for agriculture in *Save and Grow* ("A policymaker's guide to the sustainable intensification of smallholder crop production"), by presenting a paradigm of sustainable crop production intensification (SCPI), which "produces more from the same area of land while conserving resources, reducing negative impacts on the environment and enhancing natural capital and the flow of ecosystem services" (FAO, 2011). The lack of farm power is cited as a significant constraint to SCPI. Farms where only manual family labor is used, "survive at the margin of subsistence" (Bishop-Sambrook, 2005). With manual labor alone, a farmer can on average produce enough to feed three other people, but with animal power this number can double and with a tractor, it rises to 50 people (FAO, 2011).

India is an example of agricultural mechanization contributing to agricultural productivity. In the second half of the twentieth century, India saw remarkable changes in its agriculture. The green revolution, which completely reshaped the way farming was done across the globe, is often attributed to fertilizers, improved seeds, and irrigation, but Singh (2012) argues that another significant variable in revolutionizing agriculture in India was its mechanization. Between 1960 and 2010, India saw the number of tractors increase by more than 100 times, while at the same time grain yields nearly tripled. An analysis of the different states in India showed that there is a positive relationship between the power available to farms and the food grain productivity of farms. Singh notes however, that mechanization was first adopted by large farms (over 10ha) and then by medium size farms (4-10ha). This initial demand by a large number of such farmers is what started the agricultural machine distribution and service sector, which paved the way for smaller farms to begin to be mechanized. This mechanization first happened through services and renting from larger farms.

1.2 Sub-Saharan Africa

Of special note with regard to SCPI and mechanization is the region of Sub-Saharan Africa (SSA). Unlike other regions of the world, Africa's agricultural productivity has increased relatively little. As shown in Figure 1, cereal yields in 2013 were about 1600 kg per hectare, which is approximately one third that of Asia and South America and falls below the Least Developed Country average.

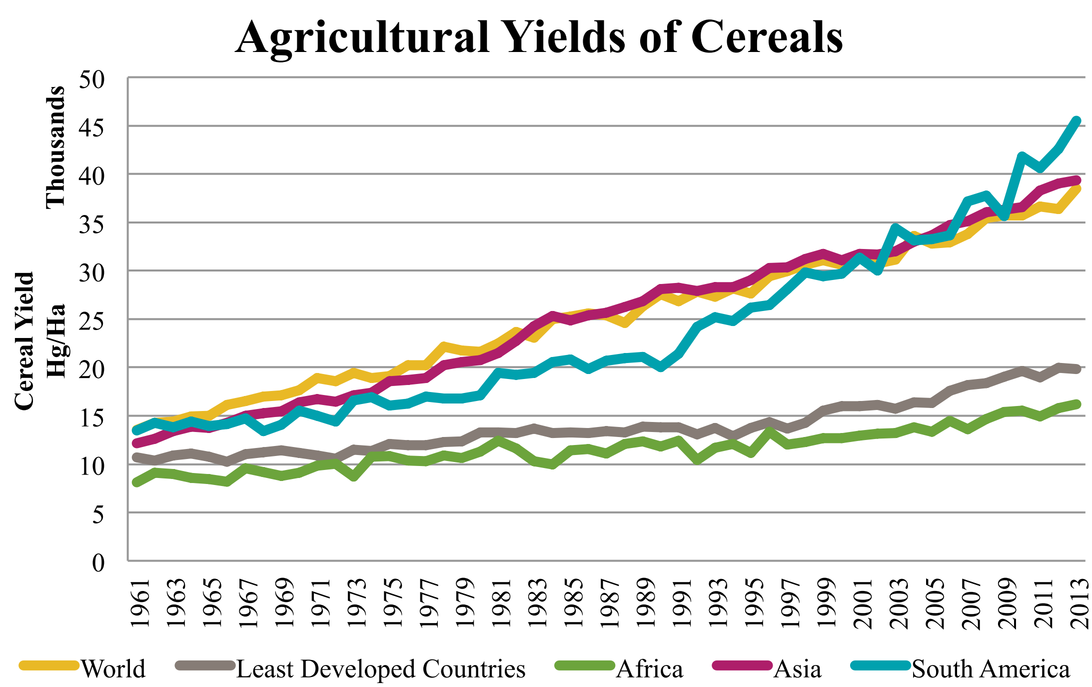

Figure 1 - Agricultural yields of cereals. Source: FAOSTAT

Farm power is central to agricultural production, and factors that reduce the availability of power on the farm are known as a source of poverty in SSA (Bishop-Sambrook, 2005). A 2013 report (Kienzle et al., 2013) stated that in West and Central Africa, mechanization is crucial for growth in the agricultural sector, while in East Africa, the lack of mechanization “is one of the most serious obstacles to expanded and sustainable utilization of the ample land and water resources for agriculture." According to the report, Africa has some of the most abundant resources for increased agricultural production, and yet, it also has "the lowest farm power base with less than 10 percent of mechanization services provided by engine-powered sources." This report also listed the sources of farm power in Africa as 25% from animals and 70% from human muscle power, often supplied by women, children, and the elderly using rudimentary tools and equipment.

Bishop-Sambrook (2005) states that the agricultural workforce has been negatively affected by three factors. First, the HIV/AIDS epidemic, a factor problematic in itself, has taken a significant number of the workforce. Second, the success of primary education has had the consequence of less labor available to family farms, because the children are attending school. Third, urban migration is taking a significant number of the youth away from the farm. Because of the low use of mechanization and other productivity-increasing technologies, agriculture stays at subsistence levels, and the young and enterprising in Africa do not see agriculture as an attractive employment or enterprise (Kienzle et al., 2013).

The farm power dilemma in Africa was summarized well in *Agricultural Mechanization in Africa: Time for Action*, the report of an Expert Group Meeting in 2008:

> "In general, animal and tractor power have both declined in African agriculture in the past few years, making agriculture yet more reliant on manual methods in a continent where constraints such as severe health problems and demographic shifts make manual labour a scarce and weak resource." (FAO & UNIDO, 2008)

1.3 Threshing and Shelling

1.3.1 Labor

One of the many crop production tasks that can be mechanized is the threshing or shelling process. Significant time and energy are spent on the process of threshing when manual means are employed. Traditional methods of threshing include laying the dried crop on the ground and trampling it by foot, hoof, or wheel; laying the crop on the ground and beating it with a stick; placing the crop in a bag and beating the bag with a stick; grasping stalks and beating them against a hard surface; and for shelling, rubbing kernels on the cob with the thumb or with another cob (Chakraverty et al., 2003; Hodges & Stathers, 2012; Lucia & Assennato, 1994; Proctor, 1994). After threshing is done, the grain still must be separated and cleaned. The simplest manual methods for doing this are sorting by hand and by winnowing, where the crop is tossed in the air, letting the wind separate low density material, like chaff, from higher density material, like grain kernels (Proctor, 1994).

There is little doubt that these processes are tedious and labor intensive. In Tanzania, it was found that more women were involved in these activities than men and that many of the activities were done manually, processes which the farmers considered “tiresome and take considerable time of all the household members” (Abass et al., 2014). In Ethiopia, most threshing is still performed by treading the crop or beating it, and “the working conditions are appalling, back breaking and time consuming” (Moges & Alemu, 2014). Often, the tedious work of threshing falls most heavily on women.

1.3.2 Post-Harvest Losses

Hodges (2013) emphasizes that reducing losses is dependent on adopting better post-harvest practices, which includes new technologies like threshing and shelling machines. Post-harvest losses (PHL) is defined as “a measurable quantitative and qualitative loss in a given product” that “can occur during any of the various phases of the post-harvest system,” which include drying, threshing, cleaning, storage and processing (Lucia & Assennato, 1994). It is important to evaluate both grain quality and quantity losses. Standard practice is to measure quantity losses by weight, which makes comparisons across time and space easier (Hodges & Stathers, 2013). Quantity losses can happen with both manual and mechanical threshing by grain being scattered, incomplete threshing, or discharging grain with material other than grain (MOG).

On the other hand, quality losses are more complicated and can be caused both directly and indirectly from threshing. The first and most obvious quality degradation occurs when contaminants are introduced. These can be either plant matter that hasn’t been separated out or foreign matter like dirt and rocks. Traditional methods of threshing are often done on the bare earth. This can increases the amount of contaminants significantly. Another direct loss of quality is broken grain. This type of damage is one which threshing is particularly prone to cause, because of the aggressive action required to detach the kernels from the pods or cobs. Additionally, broken grain is considerably more susceptible to further damage by molds and pests (Golob, 2009; Hodges, 2012a; Lucia & Assennato, 1994).

The larger grain borer (LGB) has been a growing problem in SSA, where it infests multiple crops. The standard recommendation to avoid or mitigate LGB infestation in corn is to shell the corn and store the grain in sacks (Golob, 2009; Jones et al., 2011; The World Bank, 2011). Bags of shelled corn can store three times the grain that bags of unshelled corn can (Golob, 2009). However, if threshing takes too much time, it may be postponed, causing spoilage, delaying the storing of the grain in sacks, and so incurring losses indirectly (Chakraverty et al., 2003). Golob (2009) emphasizes that threshing is important so that grain legumes can be treated with insecticide dust, since these crops, particularly beans and cowpeas, can be quickly infested.

An example of where threshing indirectly caused quality losses comes from the Iganga Farmers' Group in Uganda (Hodges et al., 2013). These farmers raised corn, and after harvesting it, they shelled the corn by beating the cobs with wooden sticks. The process was time-consuming and tedious, but it also resulted in significant grain damage. Because shelling took so long, it was delayed while farmers tackled more immediate tasks like land preparation for another crop. This delay meant that the grain quality could decline before it could be shelled and sold. However, this changed when access to a shelling machine became available. The farmers were then able to process their crop quickly, with less grain breakage, and had time to sort out any damaged grain. The result was a high quality grain that could be sold at a premium rate. For these farmers, it was the slowness of the threshing process that mainly created a low-quality product. The solution was a shelling machine that greatly reduced the time spent on the actual shelling of the corn.

1.4 Local Manufacturing

One of the biggest barriers to mechanization in SSA is the cost of equipment. Imported equipment must be marked up to cover the costs shipping and, in some countries, import duties and taxes. Often the supply chain for imported farm equipment is not well developed, and as soon as a piece of equipment breaks down, it never moves again. There is not economical way to get replacement parts, or when replacement parts are ordered, they take a long time in coming, making the machine useless for that season (Houmy et al., 2013). Jenane (2012) indicates that a leading cause for the low agricultural productivity of Africa is the missing focus on "adapting and extending proven mechanization to suit the needs of the local farmers."

Fortunately, importing is not the only option. In contrast, local manufacturing has many advantages. The cost to the customer for the equipment is dropped greatly, as shipping costs and import duties are removed. Manufacturing locally can increase the availability of suitable equipment and decrease its cost (FAO, 2011). Local manufacturing of equipment uses locally available skills and materials, which means upkeep of the equipment is not dependent on expensive and delay-prone supply chains (Kienzle et al., 2013). Equipment developed and manufactured close to its users is generally better suited to the users needs. Because there is better feedback, better equipment is produced (Wilson & Lumkes, 2015). "Local manufacture has the advantage of being able to respond directly and rapidly to the demands of the agricultural sector" (Sims et al., 2012). Local manufacturing also enables growth of the local economy.

1.5 Scope of Study

The research of this thesis focused on investigating the design, fabrication, and testing of a multigrain threshing machine suitable for smallholder farmers and local manufacturing in SSA. Threshers that can thresh more than one kind of crop will be more valuable to farmers or entrepreneurs that rent them. This machine was designed to thresh and clean corn and soybeans. Corn is a staple crop in many African countries, as evidenced by the fact that 71 million metric tons of corn was produced out of 182 million metric tons of total cereal production in Africa (FAO, 2015). Soybeans, although not a common crop in SSA, have similarities to other bean crops, like cowpeas, that are produced there. The availability of these two grains for testing in Indiana contributed to their selection. Grains are the staple food for most Sub-Saharan Africa's population and the majority of the grain harvested in SSA is produced and consumed by smallholder farmers (The World Bank, 2011). Therefore, the design was catered towards being used by smallholder farmers. To increase the access that these smallholder farmers have to mechanized threshing, a main driver in the design was affordability. To decrease costs for the consumer, an emphasis was placed on designing a machine that could be manufactured locally, using only parts and materials that can be easily obtained in SSA.

CHAPTER 2. THRESHING

2.1 Definitions

The following chapters will employ the following definitions, taken from *Engineering Principles of Agricultural Machines, Second Edition* (Srivastava et al., 2006)

- Threshing: breaking grain free from other plant material by applying mechanical force that creates a combination of impact, shear, and/or compression.
- Separation: separating threshed grains from bulk plant material such as straw.
- Cleaning: uses air to separate fine crop material such as chaff from grain.

Feed rates can be MOG feed rates, grain feed rates, or total feed rates. Material feed rates will be given as grain feed rates, unless otherwise specified.

2.2 Methods

2.2.1 Manual

Traditional methods of threshing, the same methods used over 3000 years ago in ancient Egypt (Quick & Buchele, 1978), are very basic but still employed in many developing countries. The grain output rates of traditional corn shelling methods in India were summarized by Singh, with the lowest rate being 4.5 kg/h (9.9 lb/h) for shelling using the backside of a sickle, and the highest rate being 40 kg/h (88 lb/h) when shelling by beating the cobs with a wooden stick (S. P. Singh et al., 2011). Lucia & Assennato (1994) state that “a worker can hand-shell only a few kilograms an hour,” while Proctor (1994) estimates 10 kg/h (22 lb/h). Proctor also estimated the hand threshing of rice by beating at 10-30 kg/h (22-60 lb/h), by trampling underfoot at 30-50 kg/h (60-110 lb/h), and by driving over the material with a vehicle at a few hundred kilograms per hour. Lucia & Assennato estimate rates for manual threshing techniques of various crops at 15-40 kg/h (33-88 lb/h) and claim that upwards of 640 kg/h (1400 lb/h) can be obtained by "treading out" with a vehicle. Chakraverty et al (2003) state that a worker can thresh crops like rice or wheat at 15-22 kg/h (33-49 lb/h) by hand-beating and 110-140 kg/h (240-310 lb/h) by the treading of an animal. However, when separating, cleaning and bagging are also accounted for, these rates drop to 12-18 kg/h (26-40 lb/h) and 80-120 kg/h (180-260 lb/h) respectively. By just using small hand tools for shelling corn, a worker can shell 8-15 kg/h (18-33 lb/h) (Lucia & Assennato, 1994) or 20 kg/h (44 lb/h) (Proctor, 1994). However, these tasks are still "tedious to use and have never achieved widespread popularity" (Hodges & Stathers, 2012). Small shelling equipment, usually driven by cranking or pedaling but can be powered, can increase rates to 14-100 kg/h (31-220 lb/h) (Lucia & Assennato, 1994) or 150-300 kg/h (330-660 lb/h) with two operators (Proctor, 1994).

Threshing and shelling losses by weight for small farmers are often minimal. For example, when shelling corn by hand, the operation is done over a basket and very little grain is lost. However, estimates of losses are difficult to make and much of the data comes from farmer surveys, which may contain bias. Hodges (2012b) lists values between 1% and 2.5%, noting that the low losses are expected, because of the manual and often contained process. However, other surveys listed by this author showed that losses from shelling maize were 6% in Ethiopia. Winnowing losses were 2.5% for rice in Madagascar and averaged 5% for cereals in Ethiopia.

2.2.2 Mechanized

At the other extreme of threshing and cleaning methods are modern combines. Combines are called such because they combine the reaping with the threshing, separating and cleaning (or winnowing) of grain. These machines have been equipped with real-time yield sensing and GPS guidance for years, and now engineers are working on making combines completely autonomous (Cho et al., 2014; Choi et al., 2014; Masahiro, 2013). However, the machines depend on the same basic principles as the most rudimentary methods: impact and shearing actions to thresh the crop and density differences to clean the crop. The following discussion on mechanized threshing will focus on stand-alone threshing and/or cleaning machines, not combines. However, there is significant overlap and many of the threshing machine designs have drawn on those of combines.

Powered threshing machines can either be hold-on or throw-in. Hold-on type threshers require a person to hold the grain stalks while the heads are threshed. These machines are not designed to handle stalks or significant MOG. Throw-in type threshers allow for the whole stalk to be fed into the machine, providing continuous material flow. Throw-in threshers have a higher throughput, but hold-on machines keep the straw from breaking. This is advantageous when the straw is used for feed or other applications. There are two main categories for throw-in threshers, based on the flow of the material through the threshing unit: tangential (or conventional) and axial flow. The tangential flow type is always fed tangentially, but an axial flow device can be fed either axially or tangentially. In both types, the crop is threshed between the rotating cylinder and the stationary concave. In general, losses decrease and grain damage increases with decreasing concave clearance, increasing concave length, increasing cylinder speed, and decreasing feed rate (Srivastava et al., 2006).

The traditional method of machine threshing has been with tangential flow. In this type, the crop enters the threshing concave tangential to the cylinder across the whole width of the cylinder. The crop travels only partially around the cylinder before exiting. Tangential flow threshers require high speeds to successfully detach most of the grain. In order to fully thresh a crop, combine harvesters that use tangential flow sometimes have secondary threshing cylinders (Srivastava et al., 2006).

Axial flow threshing has become more popular in the last half-century (Srivastava et al., 2006). Whereas in tangential flow threshers, the crop travels less than one full rotation around the cylinder, axial flow threshers move the crop helically around the cylinder multiple times. The threshing time is prolonged, giving repeated opportunities for grains to be threshed. Because of this, rotational speeds are less, and concave clearances are greater than in conventional threshing cylinders, which generally decreases damage to grains (Srivastava et al., 2006).

Two types of cylinder-concave combinations, rasp bar and spike tooth dominate in today's market. Rasp bar cylinders are drums with metal bars attached to the outside and aligned with the axis. These bars have corrugation or ridges, usually at diagonals. This is the most common type of cylinder-concave because the combination of impact and rubbing is able to thresh most crops under a variety of conditions. Spike tooth cylinder-concaves have overlapping, but offset, spikes mounted to both the rotor and that stator. These cylinders have a higher positive feeding action compared to rasp bar and depend on tearing and shredding actions to thresh. While grain damage in a spike tooth cylinder is less than with rasp bars, there is often excessive straw breakup. Spike tooth threshers are predominantly used for rice (Kepner et al., 1972; Kutzbach & Quick, 1999; Srivastava et al., 2006).

Straw separation occurs in a conventional combine on the straw walkers. Straw walkers are a series of saw tooth channels that are oscillating at different phases off of a crankshaft. As the straw moves towards the back of the combine, the grain falls through to the cleaning system. Straw walkers are fairly large and depend on gravity to separate the grain. Rotary separators, on the other hand, use centrifugal force. These systems have a rotor inside a concave, and the crop is made to travel helically along the rotor. Although requiring more power than straw walkers, rotary separators take less space, and they are not gravity, and therefore slope, dependent (Srivastava et al., 2006).

Rotary combines that have axial flow cylinders combine the threshing and separation process into one. At the front of the cylinders, there are rasp bars and open grate concaves and towards the back, there are beaters and separation grates. This system is simpler and has less separate moving parts. Rotary combines can have feed rates of more than 60,000 kg/h (130,000 lb/h) (Kutzbach & Quick, 1999).

The part of the combine or thresher where the cleaning takes place is often called the cleaning shoe. The cleaning is done by a series of oscillating sieves, and air flow is provided by a fan, usually paddle-type. The system utilizes the different terminal velocities of grain and small MOG, mostly chaff, to separate them (Srivastava et al., 2006).

2.3 Field Research in Ghana

In March of 2015, the author travelled to northern Ghana to research threshing machines that are made and modified there. The trip consisted of speaking to two farmers who each own and rent a thresher to other farmers, visiting three small local manufacturers, and meeting with an NGO that is focused on technology transfer and has subsidized the purchase of small agricultural equipment by farmers.

2.3.1 The First Farmer and Thresher

Figure 2 - A thresher in Ghana shelling corn. Source: Author.

One farmer had a threshing machine, shown in Figure 2, which he purchased in 2006. The man said that the machine has worked very well and has not required more maintenance than changing the engine oil, replacing a ring on the engine, and replacing the bolts on the threshing drum. However, the author observed other welding repair jobs on the thresher. The bolts partially mimicked spike teeth, but were only on the rotor. The rotor, shown in Figure 3, was about 11 inches (28 cm) in diameter and 13 inches (33 cm) long. There was one compartment for the threshing drum and another two seemingly for separation and discharge. Corn, soybeans, and millet were threshed in the machine, but each crop had its own concave grate and sieve. The thresher had an 8 hp (6 kW) engine. The farmer estimated that the machine could thresh 30 100 kg (220 lb) bags (probably of maize) in an 8-hour day with ten workers, which would be about 380 kg/h (840 lb/h) or 38 kg/man-hour (84 lb/man-hour).

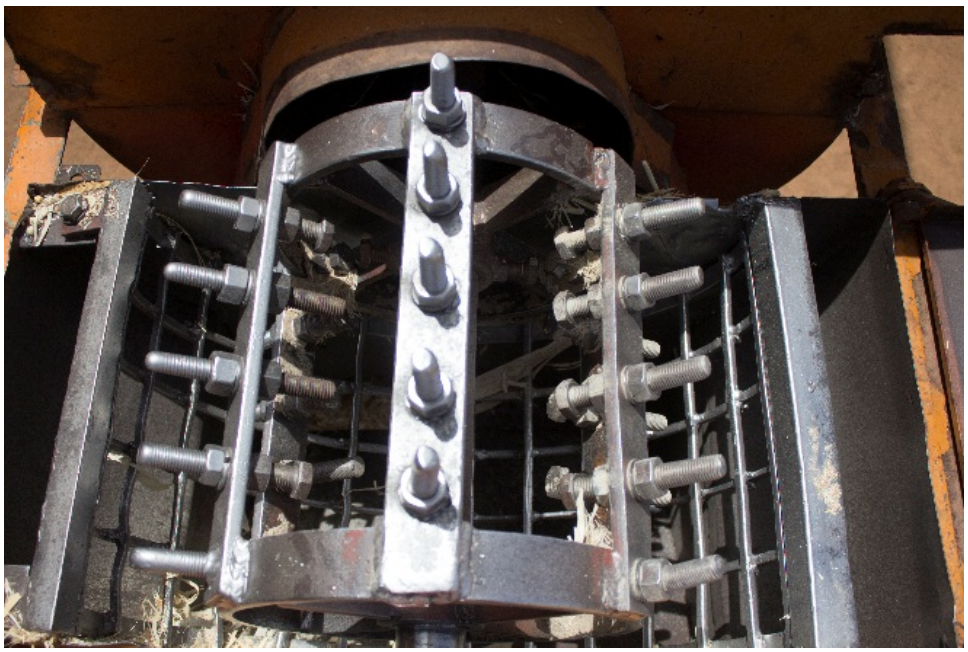

Figure 3 - The threshing cylinder and concave of the first thresher. Source: Author.

The farmer also showed how the single sieve needed to be cleared continually during use. If it wasn't, then small pieces of unwanted debris (cobs, etc.) would get into the grain and some of the grain would come off the end of the sieve. This happened because the sieve would overfill with MOG, blocking grain from falling through. As shown in Figure 4, many of the shelled cobs were falling onto the sieve. Therefore, the owner said that someone needed to be there clearing off the sieve.

The farmer suggested permanently attaching the thresher to a moto-trike, a three wheel motorized vehicle, usually imported from China. The issue for him was that the thresher had to be towed to the farm. This occupied his one vehicle. Then, if the thresher was finished and the vehicle was being used somewhere else, the thresher had to wait until the vehicle became available. Attaching the thresher to a moto-trike would allow the thresher to be easily transported to the farm or between farms without needing the use of another vehicle. He also said it should be detachable so that it can be parked away from the thresher.

Figure 4 - A thresher in Ghana threshing corn. The cleaning sieve becomes overloaded with corncobs, causing grain loss. Source: Author.

2.3.2 The Second Farmer and Thresher

Another farmer had a thresher that had been imported from India. The thresher was purchased in time for the past harvest season and had cost 6240 Cedis, or about $1650. This was the subsidized cost, 30% of original. It was similar in size and design to the first thresher and was equipped with a 10 hp (7.5 kW) diesel engine. It was estimated that this thresher could shell 150 100 kg (220 lb) bags of corn in an 8-hour day. This would be 1875 kg/h (4130 lb/h) or 188 kg/man-hour (413 lb/man-hour), if ten workers are again assumed.

2.3.3 A Local Thresher Manufacturer

Processors is a business located in Tamale that manufactures threshing machines (see Figure 5). The owner has been manufacturing since 2000. It takes him two weeks to make one thresher, with nine workers (but not working too hard). The threshers can shell maize and can thresh soybeans, but can't thresh millet. The owner estimated that his machines could thresh 150 100kg (220 lb) bags/day. The cost of the thresher last year with the fan was 7000 Cedis ($1850) new while the shaker model was 6000 Cedis ($1580). The manufacturer cited that there were Brazilian threshers that cost 70,000 Cedis ($18,500) and didn't even have a fan underneath. The owner also mentioned that someone had copied his thresher, but at lower quality standards and that this had hurt his brand. Some of the problems encountered with Processor threshers were said to be that studs wear and break, bearings are not greased and so fail, and the shaft can shear if the thresher is overloaded.

Figure 5 - A threshing machine made by Processors, a small manufacturer in Tamale, Ghana. The owner is shown with the thresher. Source: Author.

2.3.4 Thresher Rental

Both of the farmers and the owner of Processors rent their machines to other farmers. The rate charged is an in-kind payment of one bag of grain out of every ten threshed. The two farmers are benefitted because their crops are quickly and easily threshed. However, they are also generating income by renting the machine to other farmers. The other farmers benefit because they have significant cost-savings by renting the machine for a day or two, compared to hiring many workers for longer stretches of time. They also get the benefit of mechanized threshing without having to make the investment.

Renting services have been successful in mechanizing agricultural production in many places. In India, where mechanization happened first on larger farms, it came to smaller farms through the renting of equipment. Diao (2014) summarizes multiple examples of farm equipment hiring services, including ones from Indonesia, the Philippines, and

Thailand where farmers rented threshing machines and/or services. However, threshing services in Ethiopia have high rates, due to limited availability (Moges & Alemu, 2014). This demonstrates that small farms can benefit from mechanization without having to actually purchase the equipment. If threshing machines are available locally, and at a price that medium sized farms can afford, then the impact will reach the smallholder farmers, if the local equipment-owning farmers are as enterprising as those visited in Ghana.

2.3.5 Conclusion

All of the threshers examined were large enough to require towing by a truck. Although the threshing rates were relatively high, the machines were also fairly expensive. The threshers available in Ghana fit a certain need of mid-sized farms, but there is still a large gap for the many smaller farmers. Few smallholder farms can utilize the full capacity of these machines. Even with the same service model, a smaller machine that doesn’t require a truck to tow to the field could be used on smaller farms. Processors demonstrated the advantages of local manufacturing with lower costs, a sustainable private business, and local materials and repairs.

2.4 Research Contribution

Based on what was learned in Ghana, an opportunity was identified to provide access to mechanized threshing for smallholder farmers. Given that the entry barrier is high cost, the primary contribution of this thesis is a multigrain thresher design that is locally manufacturable, utilizes locally available materials, and is appropriately sized for smallholder farmers.

CHAPTER 3. MULTIGRAIN THRESHER DESIGN

3.1 Design

Based on the background research, the focus of this project was to design a threshing machine that was smaller and more affordable than the machines seen in Ghana. The thresher capacity would be more appropriately sized for the smallholder farms, which dominate much of SSA. The thresher was designed so that it could be powered by a variety of sources, such as an electric motor where electricity is available, a mobile power platform like the Purdue Utility Platform (PUP), or an engine attached to the thresher. This flexibility would decrease the cost of the unit, because it would not require the purchase of an engine with the thresher, unless the end-user doesn't have access to a source of rotary power. Another way the design lowers costs is by using only commonly available parts and materials. The materials used in the design include 1.25 x 1.25 x 0.125 inch (31.8 x 31.8 x 3.18 mm) angle iron, 3/8-inch (9.5 mm) rebar, sheet metal, and plate steel. Parts requiring purchasing include pulleys, belts, bearings, bolts and nuts.

3.1.1 The Threshing Cylinder

An axial-flow threshing mechanism was selected because of its advantages in simplicity and efficiency. First, axial-flow tends to have less breakage, because it can be run at slower speeds and still get high threshing efficiencies. Slower speeds require less balancing and improve life-expectancy. Second, axial-flow performs most of the separation of grain from MOG in the threshing cylinder, requiring less complicated mechanisms for further separation and cleaning. The cylinder was designed for larger MOG to travel helically around the rotor and exit out the chute at the end. Rasp-bars were used because of their ability to thresh a variety of crops and crop conditions.

The threshing rotor (Figure 6) is made of four quarter-inch thick steel disks (R1), eight pieces of angle iron (R2), and one-inch (25.4 mm) shaft (R4). The disks were cut with a plasma cutter, but they could be cut with a cutting wheel on a grinder and/or a torch. To mimic conventional rasp bars, which are common on axial-flow combines (Srivastava et al., 2006), 3/8-inch (9.5 mm) diameter reinforcing bar, better known as rebar, was used (R3). The rebar was oriented such that the parallel diagonal ribs on it assisted in the movement of the crop material axially along the cylinder. Because the rebar will wear with use, it was made to be replaceable by welding to the heads of 3/8-inch (9.5 mm) bolts, which were clamped to the rotor through holes in the angle iron. By removing the nuts on the bolts, the rebar can be removed and replaced with another piece also welded to bolt heads. The overall diameter of the rotor was 9 3/8 inches (23.7 cm).

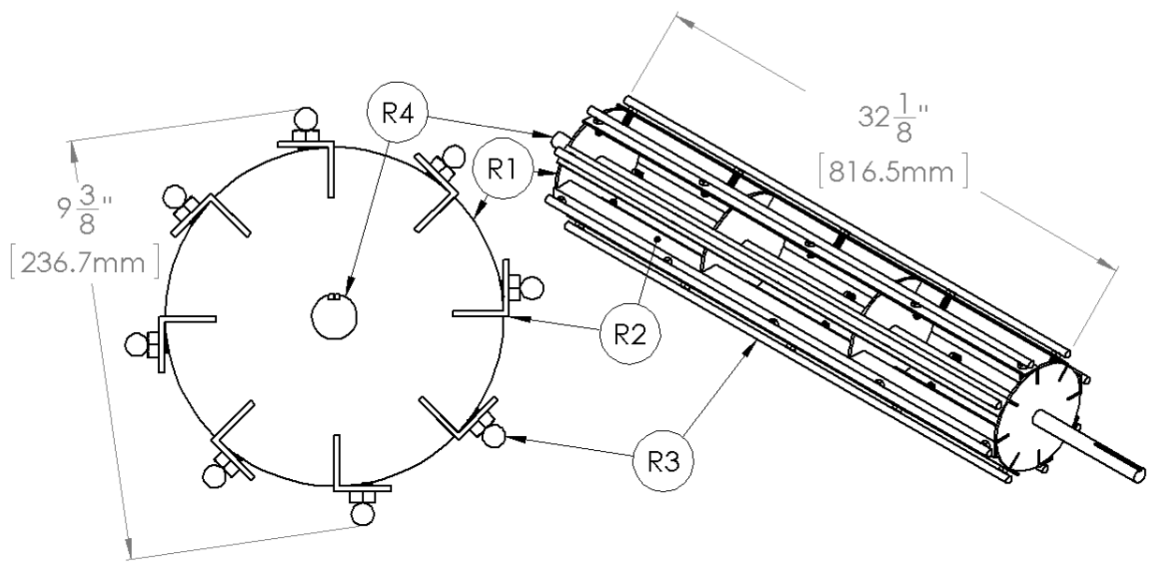

Figure 6 - Drawings of the threshing cylinder (or drum or rotor). Source: Author.

The upper concave (Figure 7) is removable but is fixed in place relative to the rotor when the machine is running. The upper concave has an opening in its top and an input chute (UC1). The chute was constructed so that it hinges and can be swung open for cleaning. The curved surface of the concave and the ends are made from 14 gauge (1.9 mm) sheet metal (UC2). Angle iron runs along the edges (UC3) with short angle iron pieces (UC4) completing the square where the concave bolts to the frame. Half-inch nuts were welded on the inside of the holes in the short angle iron pieces. Bolts went through four upright pieces of angle iron in the frame and into the nuts, holding the upper concave firmly in place. To help the crop material move axially along the cylinder, rebar was placed helically on the inside surface of the upper concave (UC5).

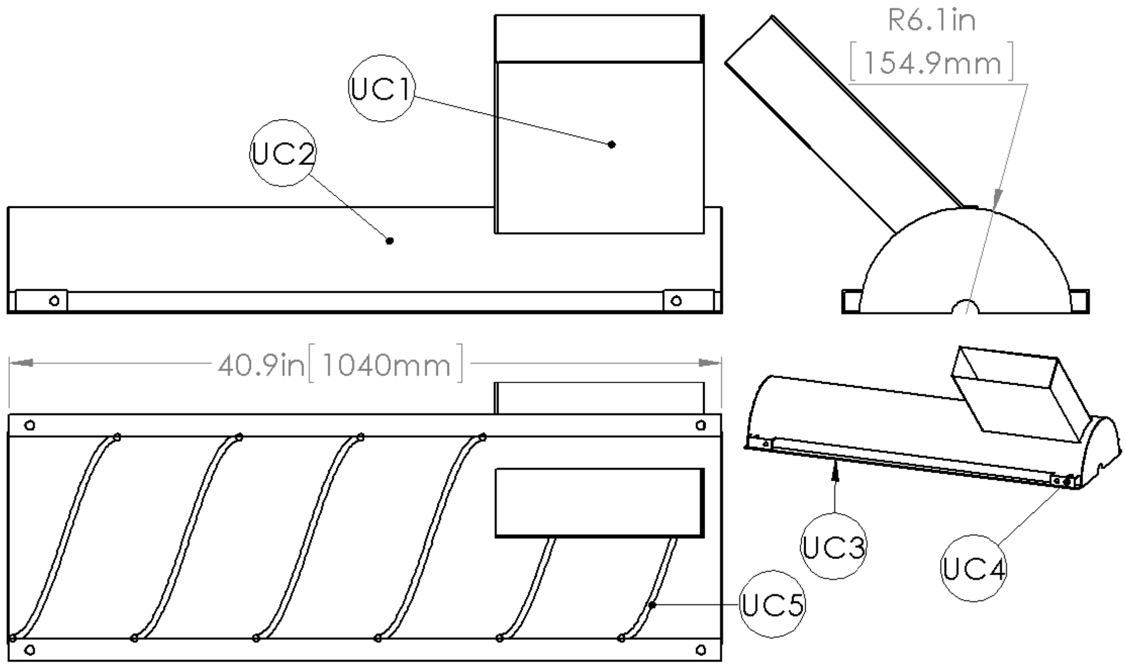

Figure 7 - Drawings of the upper concave of the threshing machine. Source: Author.

The lower concave (see Figure 8) was predominantly made of 3/8-inch (9.5 mm) rebar running axially (LC2) and tangentially (LC1). The long and straight pieces of rebar (LC2) were spaced at 5/8-inches (16 mm).

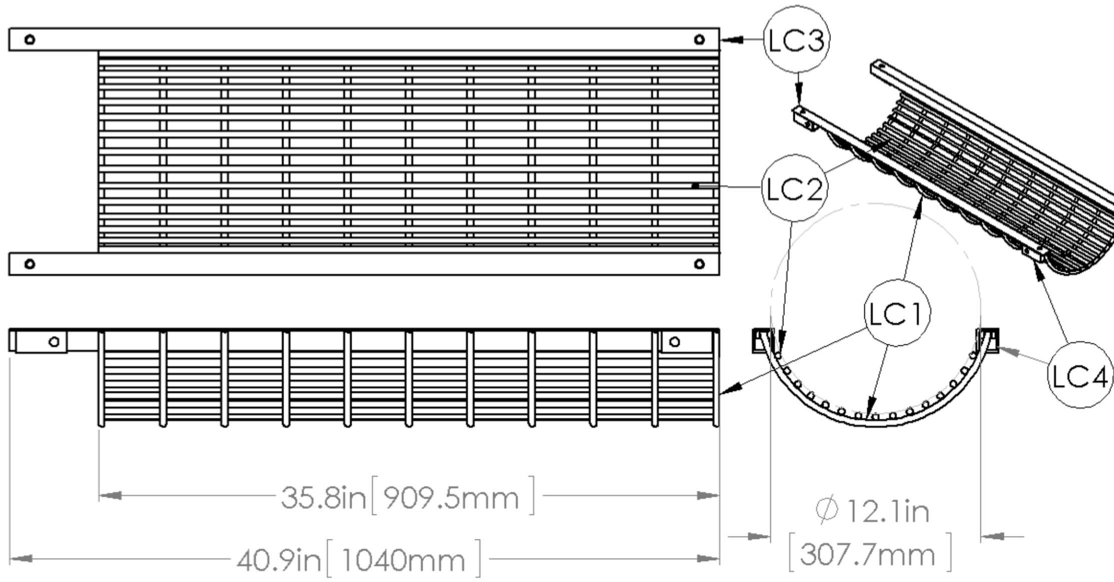

Figure 8 - Drawings of the lower concave of the thresher. Source: Author.

Like the upper concave, the lower concave had angle iron along the edges (LC3) with short angle iron pieces (LC4) with nuts for holding the concave in place. However, instead of the bolts going through bolts in the frame, slots were made in the upright pieces, so that the concave could move up and down. For easy adjustment, as shown in Figure 9, a nut was welded on the inside of a vertical hole in each of the short angle iron pieces, and a bolt was run through vertical holes in the upper concave into this nut. When the horizontal bolts clamping the lower concave to the frame were loosened, the vertical bolts could be tightened or loosened to raise and lower the concave respectively. A diagram of this mechanism is shown in Figure 9.

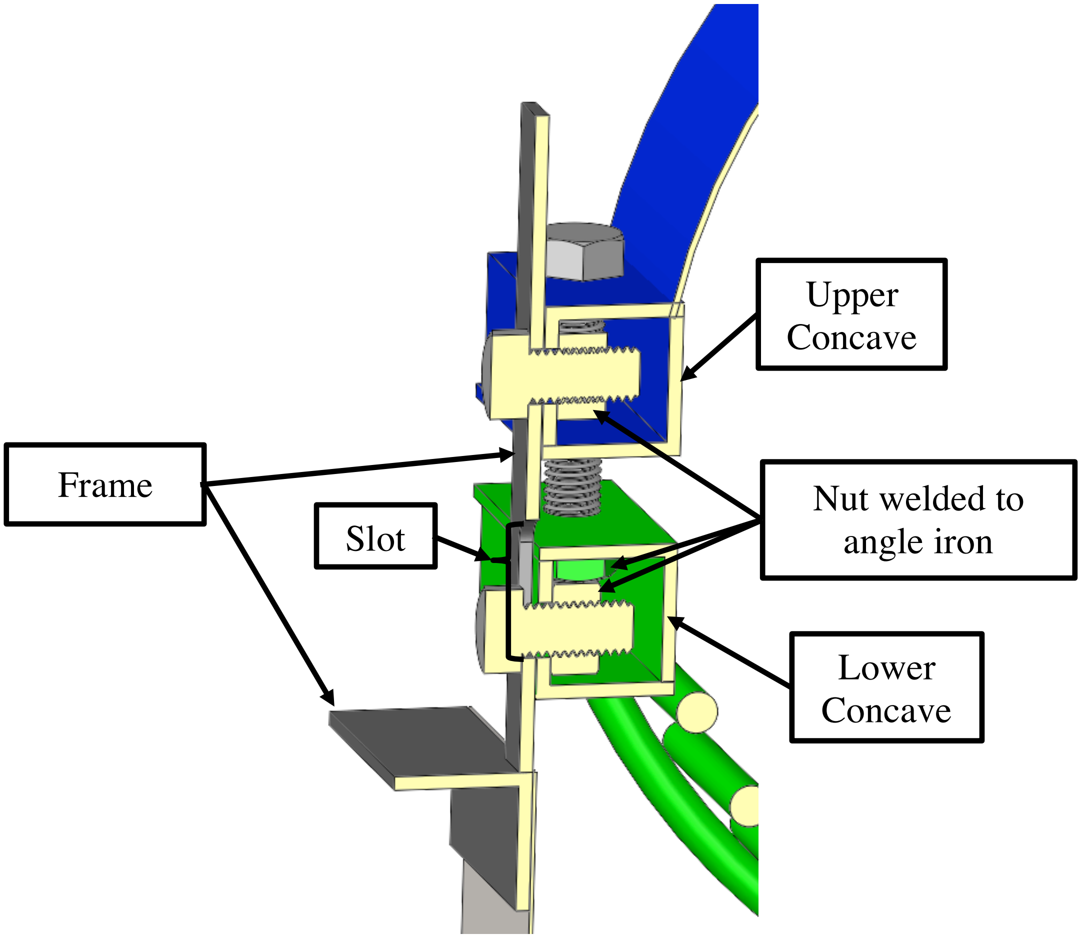

Figure 9 - Concaves attachment to the frame. The horizontal bolts clamp the concaves to the frame. The vertical bolt adjusts the lower concave height, when the horizontal bolts for the lower concave are loose. Source: Author.

The concave was designed to be adjusted vertically to change the minimum concave clearance. The closest point between the outside edge of the rasp bars of the rotor and the innermost rebar of the lower concave could be adjusted from a minimum of 1/4-in (6.4 mm) to a maximum of 1-in (25 mm). These values were based on those given in literature for soybeans (3/8 - 3/4 in, 0.95 - 19 mm) and corn (7/8 - 1 1/8 in, 22 - 29 mm) (Kepner et al., 1972; Kutzbach & Quick, 1999).

3.1.2 The Cleaning Shoe

The cleaning shoe was made to separate the grain from medium and small sized MOG that falls through the lower concave. This was done by a combination of shaking and airflow. Two key components of the cleaning shoe were the oscillating sieve and the fan. The oscillating sieve had a simple, three-sided angle iron frame that was surrounded by a sheet metal (20 gauge, 0.9 mm) enclosure and that had a piece of perforated steel laying across it. According to Stroshine (2011), grain can be separated by its intermediate diameter using round-hole type sieves. For corn, the average intermediate diameter is 8.15 mm (0.321 in) with a standard deviation of 0.71 mm (0.028 in), and for soybeans, the average intermediate diameter is 6.43 mm (0.253 in) with a standard deviation of 0.51 mm (0.020 in) (Stroshine, 2011). This data came from averages of measurements from ten varieties for each crop. Perforated steel with 3/8-inch (9.5 mm) holes was selected for use with the thresher because it would separate 97.3% of the corn, assuming a standard normal curve. Five-sixteenth inch (7.9 mm) holes would be ideal for separating soybeans, since that size would allow 99.9% of soybeans through. However, for the prototype, only 3/8 inch (9.5 mm) perforated steel was used to separate both the corn and the soybeans. The perforated steel had an open area of approximately 40%. A piece of sheet metal was set at an angle underneath the perforated steel as a shelf to keep material falling through the sieve from landing on the fan. The sieve was hung by straps cut from rubber B-sized V-belts in such a way that the perforated steel sheet sloped (7 degrees, 12.3% grade) down towards the end of the thresher and the bottom of the sheet metal enclosure sloped (10 degrees, 17.6% grade) towards the front of the thresher. A camshaft was used to accomplish the shaking motion of the sieve (see section 3.1.3.1 and Figure 19). The sieve oscillated at 6 Hz with a total displacement of approximately ¾-inch (20 mm). The shaking motion was approximately horizontal and parallel to the axis of the threshing drum.

The fan, composed of the rotor and shroud, was attached to the frame below and at the front of the sieve, so as to drive air through the sieve and out the back. A single piece of sheet metal (20 gauge, 0.9 mm) was cut, rolled, and bent to form the shroud. The rotor was made of blades attached to a one-inch (25.4 mm) steel shaft. The blades were made of 14-gauge (1.9 mm) sheet metal and short pieces of angle iron to support the sheet metal. The shaft, angle iron, and sheet metal were all welded together. The diameter of the fan blades was 7.125 inches (181 mm), and the diameter of the inside of the shroud was 7.5 inches (190 mm), leaving a clearance of 3/16 inches (4.8 mm) between the blade and the shroud. The fan pulled air from the open sides and forced it out of the rectangular exit of the shroud. The fan shroud fit inside the sheet metal enclosure of the oscillating sieve with enough clearance for the sieve to move forwards and backwards around the shroud.

Material falling out of the lower concave of the cylinder fell onto the oscillating sieve. The slope of the perforated steel and the shaking action were designed to move the MOG towards the back and off of the sieve and to assist grain to fall through the MOG and perforated steel. The fan was used to separate the light MOG falling through the sieve from the grain, blowing the chaff out the back but letting the grain roll down the bottom of the sieve towards the front and into a collection bin.

3.1.3 The Driveline

3.1.3.1 Driveline Components

The driveline needed to accept rotary power from an external source and transmit it to the drum, oscillating sieve, and fan, each of which needed to be driven at different speeds. Belts and pulleys were used for the driveline because of their simplicity, low-cost, and flexibility. Because of the high speed reductions required for the drum and oscillating sieve, an intermediate shaft with an initial reduction was placed between the engine and each of the driven components. This made for a total of four, 1-inch (25.4 mm) shafts, each supported by two pillow block bearings. Each shaft was placed so that all the pulleys and belts could be removed without removing any of the bearing mounts. The orientation of the threshing drum as perpendicular to the other rotating shafts added complexity to the driveline. This provided another advantage to using belts since belts can be twisted. Figure 10 shows the driveline layout.

For the prototype, a 6.5 horsepower (4.8 kW) gasoline engine was used. The engine was mounted to a simple angle iron frame that pivoted at the base of the thresher. The engine was supported by the belt between the engine and the intermediate shaft (D1), allowing the weight of the engine to tension the belt, but also served as a clutch and a torque limiter. The reduction between the engine and the intermediate shaft was 3.1:1. A simple idler pulley was used to tension the belt between the intermediate shaft and the fan (D2). The ratio between the two was 0.8:1. A belt was fit securely onto the pulleys between the intermediate shaft and the oscillating sieve shaft (D3), providing a reduction of 2.9:1. For the 2.3:1 reduction to the threshing drum (D4), a quarter-drive turn was used. In accordance with recommendations, the small pulley was placed close to parallel with the tensioned side of the belt (“V Belts and Their Drives,” 1961).

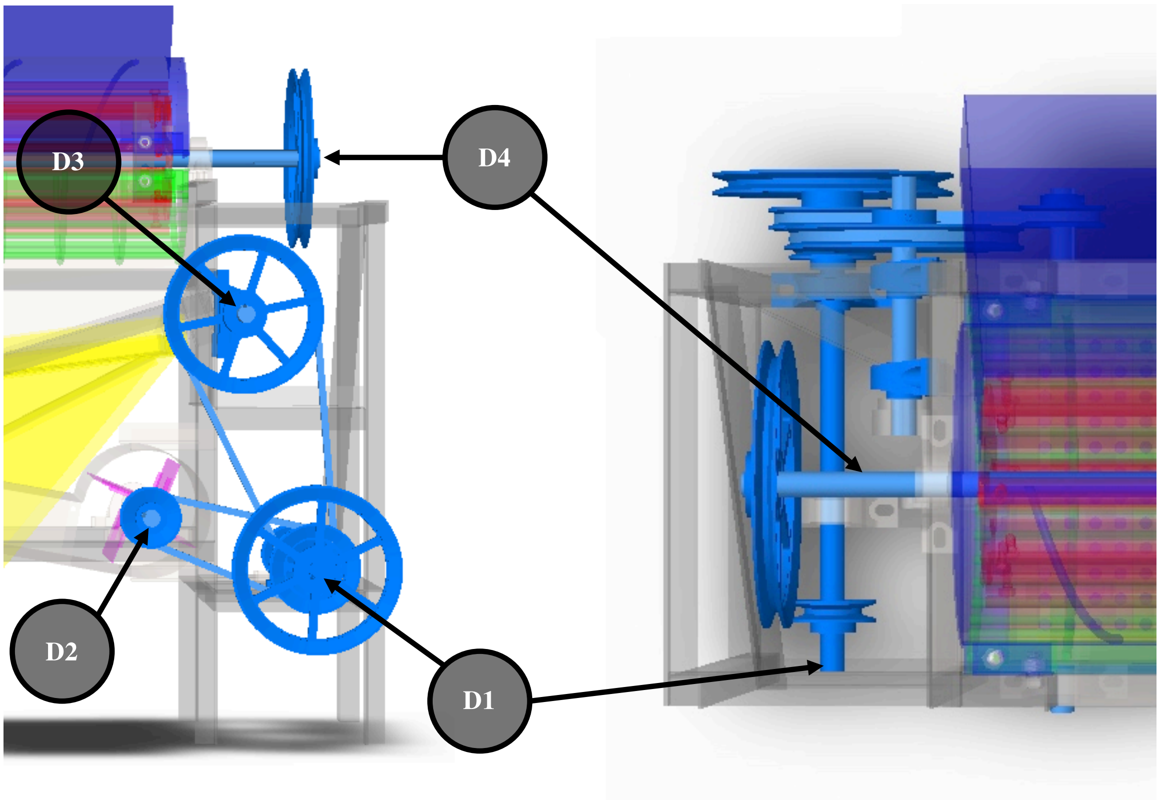

Figure 10 - The thresher driveline from the side (left) and from above (right). Shown are the shafts and pulleys for the driveline. Source: Author.

The belt could be tensioned by putting it on the pulleys when the small pulley was centered below the large pulley and then sliding the small pulley to its outer position. However, the belt had a tendency to jump off of the pulleys during initial tests, so a spring-loaded idler was added at an angle close to the small pulley on the slack side of the belt, as shown in Figure 11. This arrangement successfully kept the belt on the pulleys.

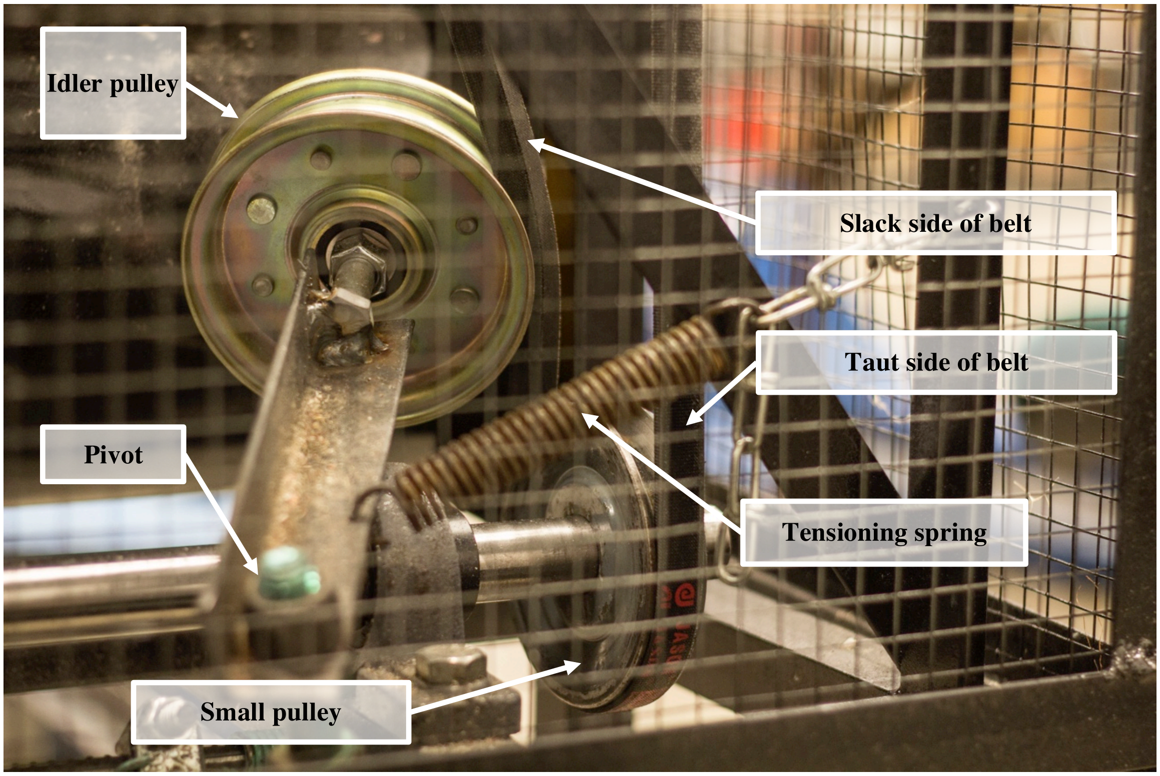

Figure 11 - The tensioning mechanism for the belt driving the threshing drum. Source: Author.

3.1.3.2 Driveline Speeds

Original reduction ratios were calculated assuming an engine speed of 3000 rpm. A list of the initial selection of the pulley dimensions, ratios, and resulting rotational speeds are summarized in Table 1.

Table 1 - The driveline pulley diameters and resulting ratios and speeds, given an engine speed of 3000 rpm. IS = intermediate shaft. Source: Author.

	Driving (inch)	Driving (cm)	Driven (inch)	Driven (cm)	Ratio	Total reduction	Speed (rpm)
Engine/IS	2.5	6.4	7.75	20	3.1	3.1	968
IS/drum	4	10	9	23	2.3	7.0	430
IS/sieve	3.5	8.9	10	25	2.9	8.9	339
IS/Fan	5	13	4	10	0.8	2.5	1210

The desired speed for the threshing drum was calculated using the overall diameter of the drum and the desired peripheral speed. Kepner (1972), assuming a conventional combine cylinder, lists typical cylinder peripheral speeds for corn as 42-67 ft/s (13-20 m/s) and for soybeans as 50-67 ft/s (15-20 m/s). Chakravery (2003) provides examples of rasp-bar threshers for soybeans with the minimum peripheral speed given as 36 ft/s (11 m/s) and the maximum as 57 ft/s (17 m/s), but he notes that "there is no specific cylinder-concave configuration that can be recommended for a crop for the best threshing effectiveness." The values provided by Chakravery are also likely referring to a conventional cylinder, not a rotary cylinder. Therefore, the design speed for the threshing drum was selected to be on the low end of the values given in the literature, because of its axial-flow design, which requires lower speeds for the same amount of threshing when compared to conventional cylinders. The overall reduction of 7:1 for the threshing drum provided a rotational speed of 430 rpm and a peripheral speed of 35 ft/s (11 m/s).

A study on wheat separation in combine sieves was used to estimate an effective sieve oscillation frequency. The study found oscillation frequencies in the range of 5.5 to 6.4 cycles per second to provide the best separation (Chakraverty et al., 2003). The desired shaft speed was selected to be 360 rpm (corresponding to 6 cycles per second) and, given the actual pulley diameters, the final expected speed was 339 rpm.

The terminal velocity of corn varies from 7.9 to 12.8 m/s (26 to 42.0 ft/s) and soybeans varies from 9.1 to 18.2 m/s (30 to 60 ft/s) (Stroshine, 2011). The desired air speed from the fan was just below the minimum terminal velocity of the grain being cleaned. The air speed in the cleaning shoe depended on many factors including the clearance between the fan blades and shroud, inlet restrictions, and outlet restrictions. However, without a complex model incorporating all of these factors, there was insufficient information to accurately predict the required fan speed for the desired air velocity. While it was known that the rotational speeds for the other components would need to be adjusted after testing, it was expected that, because of the lack of information, the fan speed would require the most adjustment in order to achieve optimal air speed. The initial ratio of 0.8 was chosen based on rough estimations of the ratios for the fan on one of the threshers seen in Ghana. The overall reduction for the fan of 2.5 would run the fan at 1210 rpm.

3.1.4 Frame and Assembly

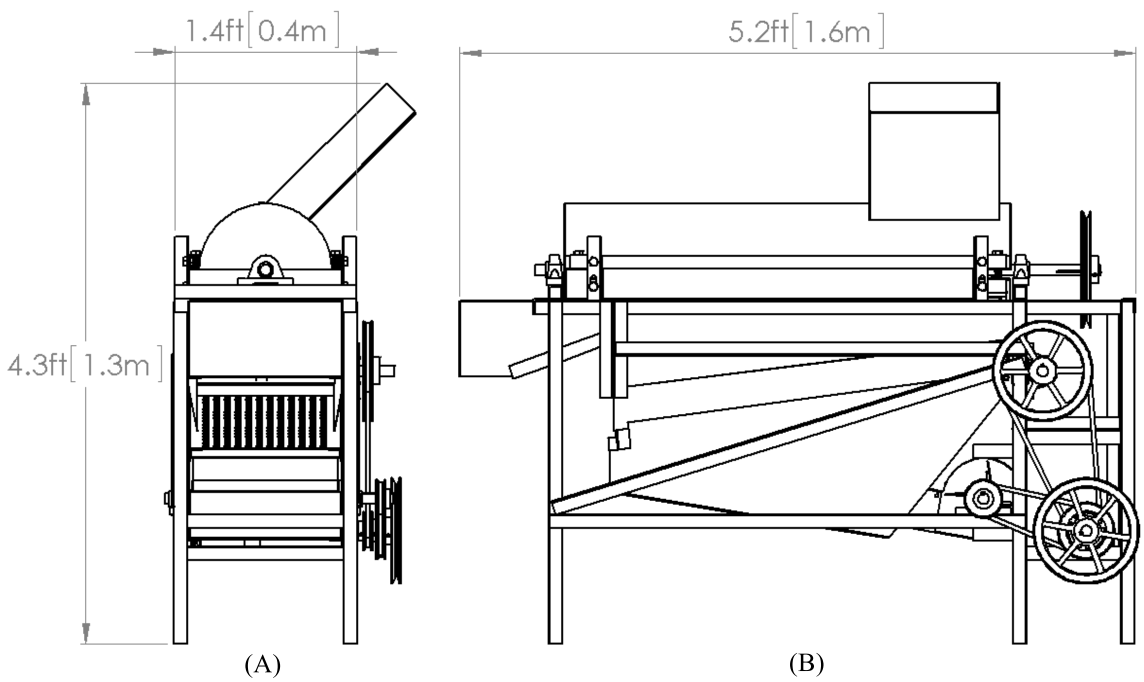

Figure 12 – A drawing of (A) the end view and (B) side view of the final thresher design. Source: Author.

The frame, shown in Figure 12, was made out of angle iron and was designed to support the threshing drum, concaves, oscillating sieve, fan, and driveline components in place, along with sheet metal to enclose the areas of the thresher where the grain and MOG needed to be contained. All of the angle iron members had only right angle cuts for easy manufacturing. As shown in Figure 13 and Figure 14, the threshing drum was at the top of the thresher, enclosed above and below by the upper and lower concaves. The cleaning shoe, composed of the oscillating sieve and fan, sat directly below the threshing cylinder. All of the driveline components were located at the front of the thresher.

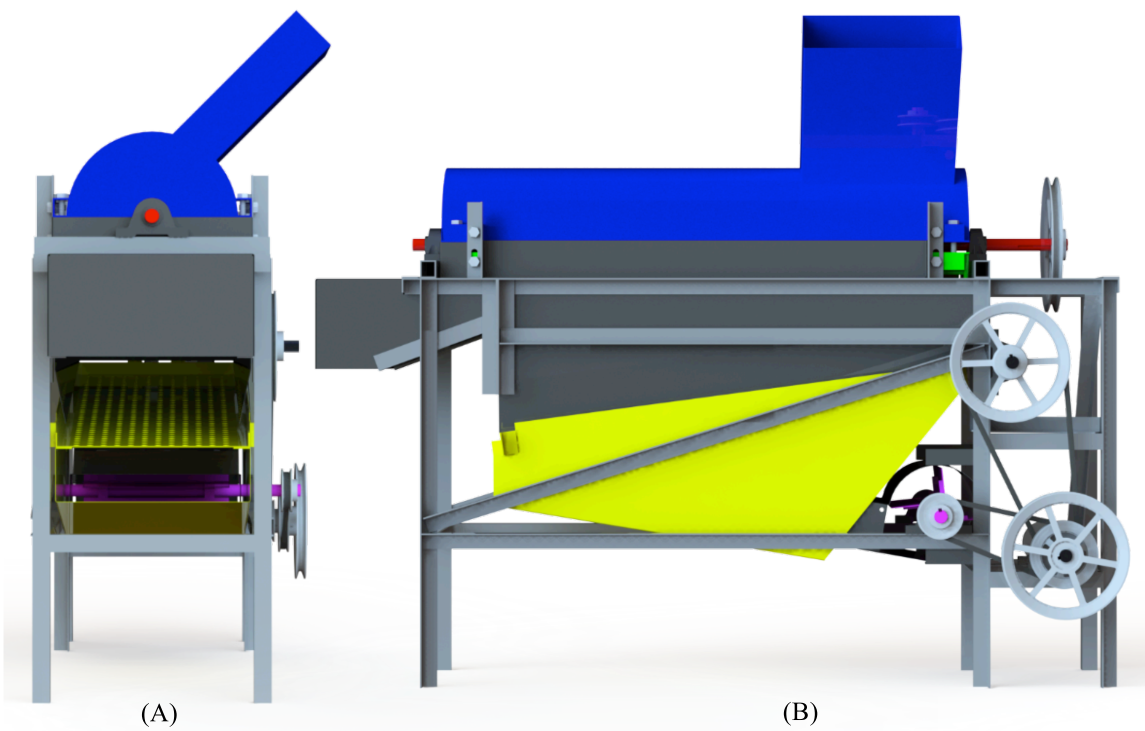

Figure 13 - A rendering of (A) the end view and (B) side view of the final thresher design. Source: Author.

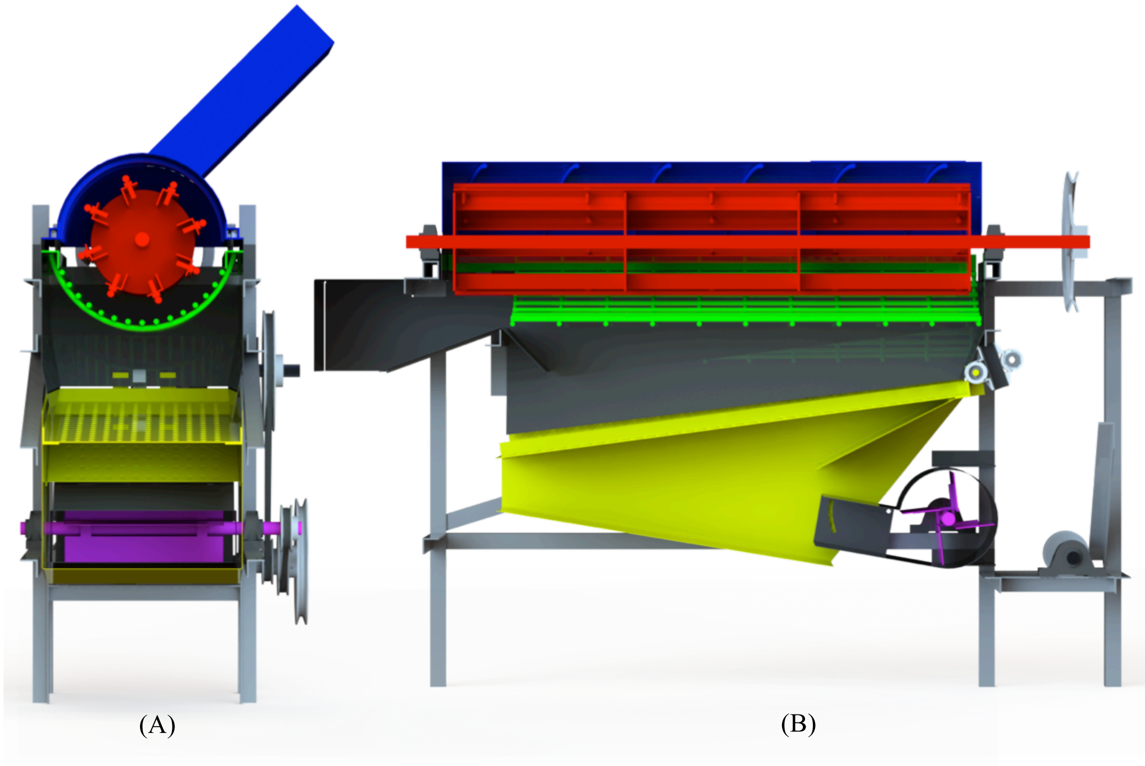

Figure 14 - A rendering of (A) a cross-sectional view from the end and (B) a cross-sectional view of the side of the final thresher design. Source: Author.

Figure 15 shows a summary of the process of threshing and cleaning grain in the thresher. Stalks of beans or ears of corn entered the threshing cylinder through the input chute on the upper concave. Once in the threshing cylinder, the crop material moved helically through the cylinder towards the back of the thresher where large pieces of MOG exited the thresher. Small MOG, grain, and chaff fell out of the threshing cylinder through the lower concave and onto the oscillating sieve. The shaking of the sieve helped move small MOG down the sieve and off the end. Grain and chaff fell through the sieve. Airflow from the fan blew the chaff out the back while the grain fell to the bottom and rolled down the slope of the pan and off the edge, just under the fan, into whatever container was in place for collecting the clean grain.

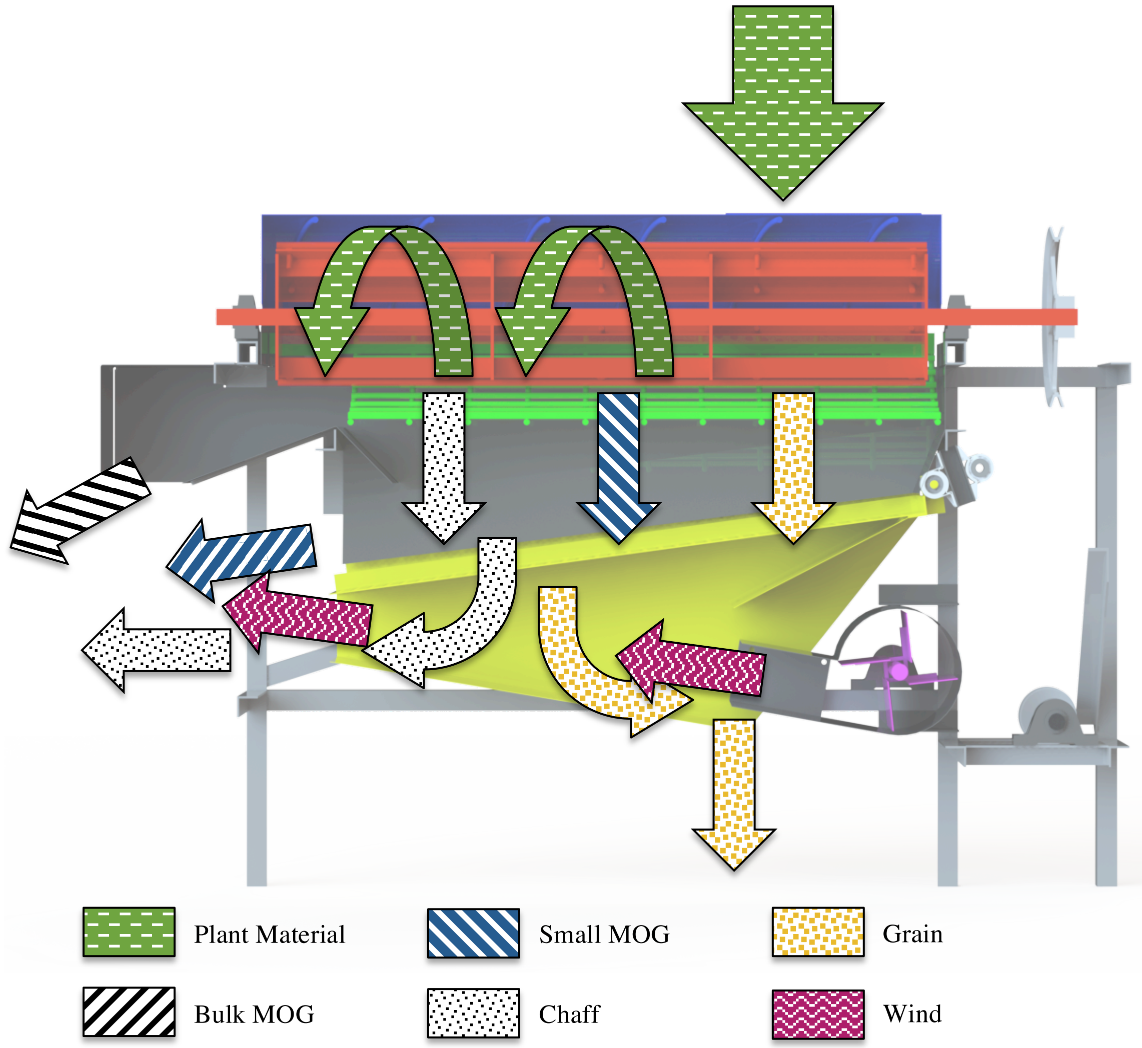

Figure 15 - A diagram showing the theoretical flow of plant material through the thresher. Source: Author.

3.2 Fabrication

The thresher was fabricated in the ADM shop over a period of about six weeks. The primary power tools used were band saws, welders, grinders, and drills. A shear was used to conveniently cut some pieces of sheet metal. Also, sheet metal roller equipment was used to shape the fan shroud and upper concave. Finally, a sheet metal brake was used to bend the sheet metal.

First, the angle iron for the frame was cut and holes drilled in the pieces for mounting the eight bearings. The left and right sides of the frame were each tack welded together independently. This allowed for easy assembly since all of the pieces for each side lay in the same plane and could be assembled on a table. The whole frame was then put together by welding the horizontal cross-members between the two sides. After checking alignment and critical dimensions, full welds were made.

After the threshing drum had been assembled, it was balanced by adding and removing material until it seemed to have no bias when rotated by hand. Because of their high rotational speeds, the drum and fan may need balancing to reduce vibrations.

The lower concave required eleven curved pieces of rebar. Because these pieces would determine the concave clearance in the threshing cylinder, it was important that their radii be very close to the design radius. A simple method for bending the rebar used a twelve-inch pulley in a vice clamp. One end of the rebar was put in the gap between the vice and the pulley, while the other end was pulled around the pulley, as pictured in Figure 16. This method made good rounded pieces of rebar of more than 180 degrees. However, some material was wasted at both ends of the rebar. Slight adjustments to the curvature of the pieces were made by hand to make sure that they all had the same shape. Each piece was then cut to length.

Figure 16 - A series of photos showing how the rebar was bent into an arc. Source: Author.

The two long pieces of angle iron for the lower concave were spaced according to the design and clamped to a table. Then the curved pieces of rebar were tack welded perpendicular to the angle iron. However, full welds were made between the rebar and the angle iron after the clamps had been removed. This caused significant warpage where the ends of the angle iron pulled away from each other. To resolve this distortion, the angle iron was clamped both to a table and to straight pieces of square tubing, while the long, straight pieces of rebar were welded to the curved pieces and the original welds between the curved pieces and angle iron were reheated. This relieved the stresses enough that the concave came sufficiently close to the correct shape.

As mentioned earlier, the curved piece of sheet metal for the upper concave was bent using a large sheet metal rolling machine. The angle iron, rolled sheet metal, and end plates were all welded together. The helical rebar on the inside was made by first bending the rebar using the process described above for the lower concave. Then, six-inch sections were cut out of the bent rebar. These pieces fit tangentially inside the concave when placed at an angle. Pairs were placed together with ends butted up against each other and angled in opposite directions, approximately following a helical path (see Figure 17). Each end of each piece of rebar was welded solidly to the concave.

Figure 17 - The upper concave with pieces of rebar placed in a helical form. Left: the arrangement of the pieces. Right: the welds holding the pieces to the concave. Source: Author.

The input chute was made with two pieces of sheet metal. Angle iron was used to create a hinging mechanism at the top of the concave. When fully open, the chute sat vertically, an unstable position when the machine was running, making it difficult to run the machine with the chute open, exposing the rotating drum. The chute was latched closed with a bolt and nut.

The oscillating sieve used four bolts to hold the angle iron frame, perforated steel, and sheet metal enclosure together. Removing the bolts allowed for the perforated steel to be removed and replaced. With the bolts removed, the sieve frame still hung from the thresher frame, while the sheet metal enclosure came free. Four strips of B sized V-belts were used to support the sieve, but still allow it to move forwards and backwards (see Figure 18). Holes were drilled through both ends of the belt strips, and quarter-inch bolts with washers were used to clamp them to the thresher frame on one end and the oscillating sieve frame on the other end.

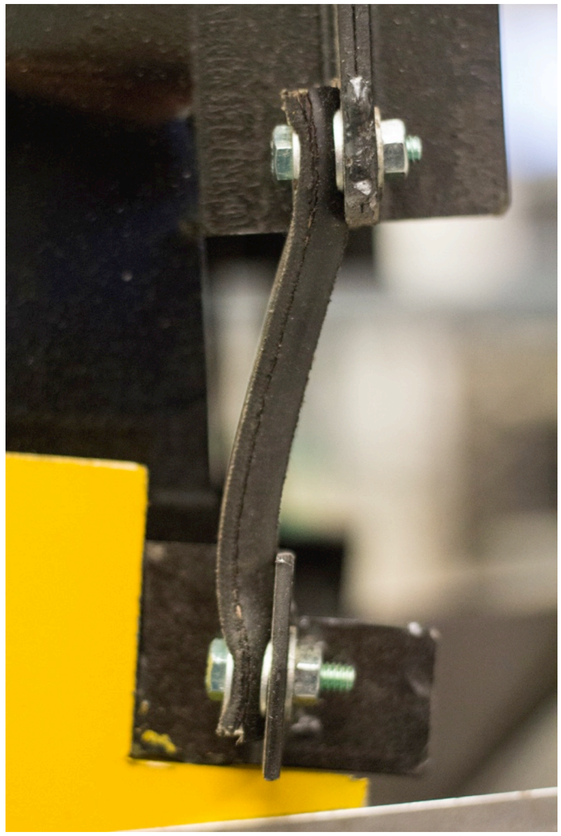

Figure 18 - One of the supports holding up the oscillating sieve. Source: Author.

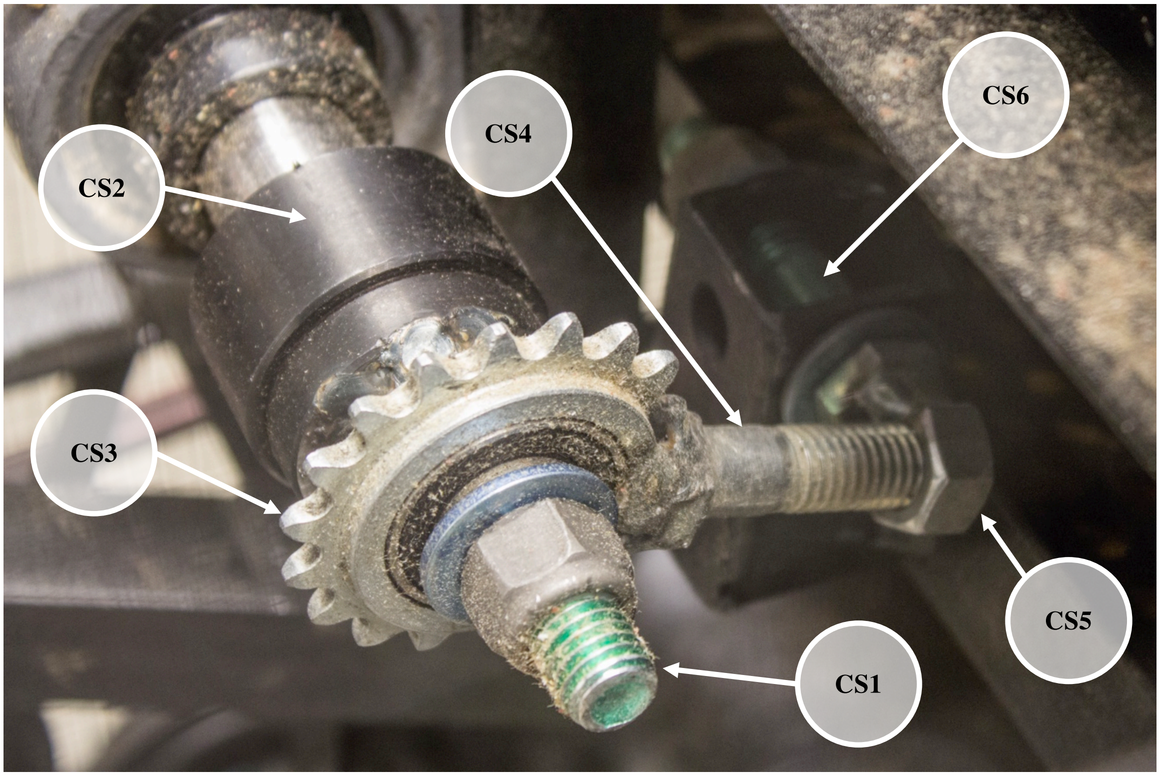

Figure 19 - The camshaft that drives the oscillations of the sieve. Source: Author.

A camshaft, pictured in Figure 19, was used to drive the shaking of the oscillating sieve. To make the camshaft, a half-inch bolt (CS1) was welded to a hub (CS2) on the end of the shaft. Instead of welding the bolt concentrically to the hub, it was offset by 3/8-inch (9.5 mm), but still parallel to the axis of the hub. An idler sprocket (CS3) was used on the bolt because it had a half-inch inside diameter and because the sprocket was weldable. The sprocket was slid onto the bolt on the hub and held in place by a nylon lock nut. Another bolt (CS4) was welded by the head to the sprocket, perpendicular to the axis of rotation. A nut (CS5) was welded to the head of a third bolt (CS5), which was placed through holes in the oscillating sieve frame, parallel to the axis of rotation of the shaft.

With the pieces removed, the bolt on the sprocket (CS4) was screwed into the nut (CS5), allowing adjustment of the offset of the sieve from the camshaft.

The fan shroud was formed using a sheet metal roller. A pulley of the same outside diameter as the shroud was used to help keep and form the shape of the shroud. While the shroud was bolted in place to the frame, a pulley and disk with spacers were used to hold it concentric with the fan shaft.

The shield around the cylinder exit chute was attached with bolts, as were the two pieces of sheet metal between the concave supports. All of the other sheet metal shields were welded to the frame. Removable safety shields were added to the thresher around the moving components. Finally, a base with two rigid and two pivoting pneumatic caster wheels was made to easily move the thresher. The final product is shown in Figure 20.

Figure 20 - The final thresher before testing. Wheels were added to assist movement. Source: John Lumkes.

CHAPTER 4. RESEARCH RESULTS

4.1 Cost

Table 2 summarizes the cost of parts and materials that were used to make the thresher prototype.

Table 2 - List of parts, quantities, and costs for the thresher.

Item	**Unit**	**Qty.**	**$/unit**	**Cost**
Paint	Can	10	$0.99	$9.90
Idler Pulley		2	$11.76	$23.52
6.5 hp Engine		1	$99.99	$99.99
2.5" Pulley		1	$5.25	$5.25
3" Pulley		1	$7.75	$7.75
3.5" Pulley		1	$9.40	$9.40
4" Pulley		1	$11.40	$11.40
6" Pulley		1	$16.25	$16.25
7" Pulley		2	$19.50	$39.00
9" Pulley		1	$25.95	$25.95
Pillow block bearing		8	$9.60	$76.80
Nuts and Bolts	lb	6	$4.00	$24.00
V-Belts		4	$7.00	$28.00
Wire mesh	roll	1	$12.99	$12.99
Angle Iron	ft	161.4	$1.00	$161.40
3/16" Plate	sq. ft.	1.8	$4.44	$7.90
Perforated Steel	sq. ft.	3.5	$15.85	$54.96
Rebar	ft	95.7	$0.40	$38.28
20 ga. Sheet Metal	sq. ft.	38.0	$1.50	$57.06
14 ga. Sheet Metal	sq. ft.	6.7	$1.95	$13.08
1" Steel Shaft	ft	8.6	$3.92	$33.68
Total				**$756.54**

Costs for some parts, like nuts and bolts, were estimated. Sheet metal, plate steel, and shaft prices were based on quotes from Purdue’s Research Machining Services. Bearing and pulley prices came from Surplus Center (www.surpluscenter.com, 12/08/2015). It should be noted that total cost is based on these prices, not costs of parts in developing countries or when purchased in higher quantities. Including both of these factors could bring the total cost down significantly.

4.2 Threshing Tests

The thresher was first run with both corn and soybeans to check if all of the parts were functioning and how well it was threshing and cleaning. These initial trials showed that the machine was threshing well (breaking kernels away from the pod or cob), but it was not separating and cleaning well, since most of the grain was landing on the ground. It was observed that a few minor changes might make a noticeable improvement. At that point, it was decided to run an initial quantitative test, then make iterative changes between informal tests, and finally run another quantitative test to demonstrate the improvement based on the modifications. The raw test data as measured can be found in the Appendix.

4.2.1 Methods

Two pairs of quantitative tests were run with the thresher, one set with the original design and a second after modifications had been made. Each set of tests had one batch of twenty-five pounds of corn and one batch of ten pounds of soybeans. Crops were taken from fields at Purdue University's Throckmorton farm on October 20th, 2015. Whole ears of field corn (dent) with the husks were pulled off of dried stocks. All ears of any size were taken from every stalk along a short row. The corncobs were put in the thresher with the husk. Whole, dried soybean stalks were collected from the last standing row in a field. The stalks were broken at the base by hand and bunched together. The stalks were fed into the thresher whole, as they had been collected. After threshing, the moisture content of the grain was measured. For corn, it was 14.2%, and for soybeans, it was 8.7%. Tests were conducted on a large tarp in a flat area behind the ADM shop on campus. To assist in sample collections, the thresher was placed on a smaller tarp on top of the larger tarp. A plastic bin was put in place under the thresher to catch the grain from the cleaning pan. A trash bag was placed over the exit chute from the cylinder. Before a test began, the crop to be threshed was measured using a low profile platform scale. The scale did not display the correct weight values, but a calibration curve was made using five-pound weights. The measured values were adjusted accordingly. The lower concave of the thresher was also adjusted appropriately for the crop being threshed: about 3 cm (1.2 in) for corn and about 2 cm (0.8 in) for soybeans. Then, the thresher was started and the engine set to the appropriate speed. The test time began when the first material hit the threshing drum and stopped shortly after the last material entered the threshing cylinder, when it was estimated that the crop had had time to be threshed and exit. During the test, one person fed the crops into the thresher as fast as they could, while another person kept time, monitored the engine speed, and generally watched the machine's performance. After each test, four separate samples were collected, as shown in Figure 21. The first sample (1), referred to as "grain bin" or just "bin," was cleaned grain in the plastic bin. Second (2), the bag over the cylinder exit chute was removed. Any material sitting on the chute, but not yet in the bag, was also collected with this sample. This sample will be referred to as "exit chute" or "chute." Third (3), the thresher was rolled off of the tarps and all the material on the tarps was collected. This sample will be referred to as "ground" and represents everything that was blown or shaken out of the cleaning shoe. Fourth (4), the thresher was cleaned out reasonably well and all of the removed material was collected as the "in thresher" sample. Neglecting some minor losses (within ±5%), these four samples accounted for the total crop material that was initially weighed for the test.

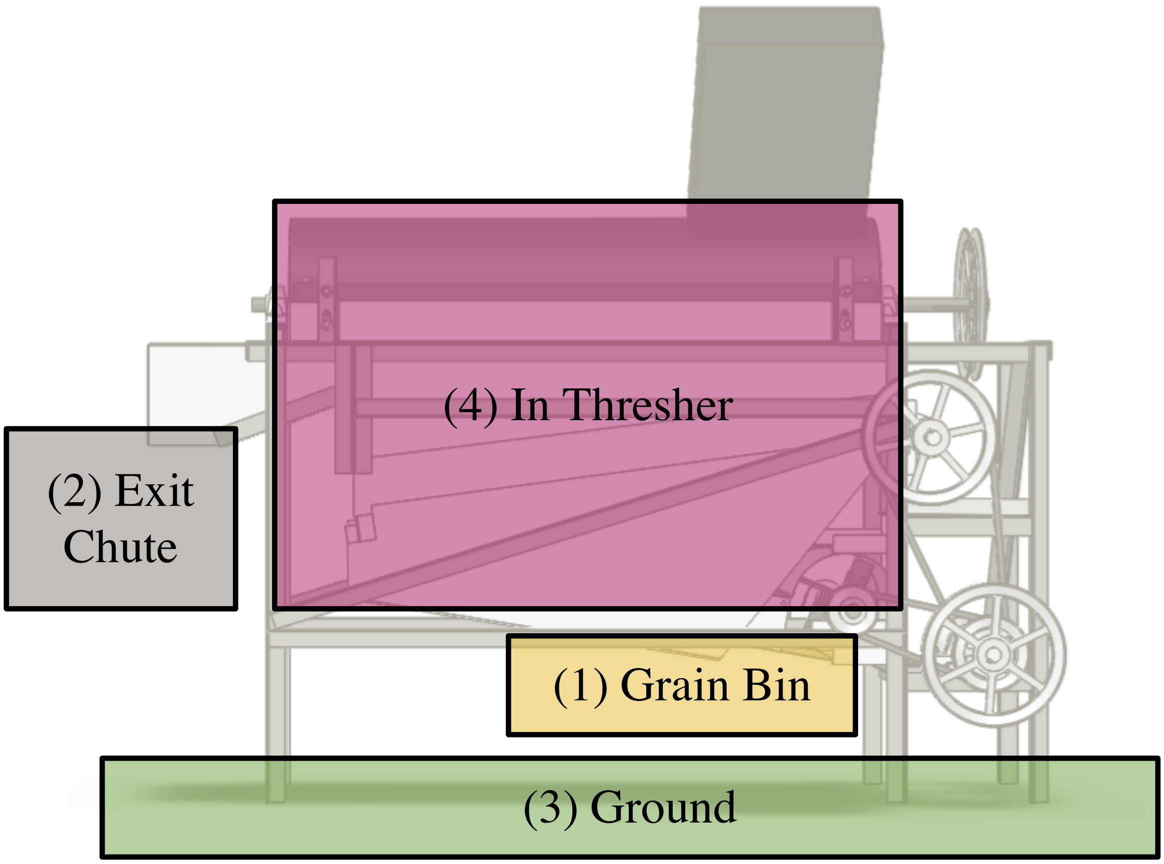

Figure 21 - A diagram showing the divisions of where the test samples were taken. Source: Author.

After all of the samples were collected, each sample was weighed and then divided into three parts: threshed grain, un-threshed grain, and MOG. However, the first soybean test samples did not have the un-threshed pods separated from the MOG. Also, for the second soybean test, the un-threshed and threshed grains were combined for the thresher, chute, and ground samples. When separating samples, first the MOG and un-threshed material was separated from the grain and then the un-threshed pods or cobs were threshed by rubbing by hand. A series of sieves assisted the manual process of separating the grain from the MOG. This process left only some light chaff with the grain samples. When observed, foreign material (rocks or grain from the other crop) was removed altogether. After separation, each sample part was weighed.

4.2.2 Initial Test Results

4.2.2.1 Corn

The cobs did not always enter the cylinder-concave gap quickly. Also, when lightly loaded, cobs would not move helically around the drum, but rather rotated around the drum at the same point axially where they entered. The corn was nearly completely shelled, leaving only 0.2% un-threshed. The threshing drum had a peripheral speed of about 28 ft/s (8.5 m/s), the sieve oscillated at 4.2 Hz, and the fan ran at 900 rpm. The test took 1.7 minutes giving an approximate feed rate of 350 kg/h (770 lb/h). As seen in Figure 22, a majority of the grain entered the bin, but 32.2% was still lost, mostly on the ground. Much of grain loss was observed happening by corn bouncing off the sieve. Many of the kernels did not fit in the 3/8-inch (9.5 mm) holes of the sieve, possibly because the corn was a newer and larger variety than the corn used to size the holes. Some kernels also flew out of the input chute upon initial impact with the threshing drum. Any that came out in this way were included in the losses on the ground, but to minimize these losses, a piece of flat cardboard was held over the chute in-between dropping cobs into it. Also, some of the corn kernels were falling into the fan shroud.

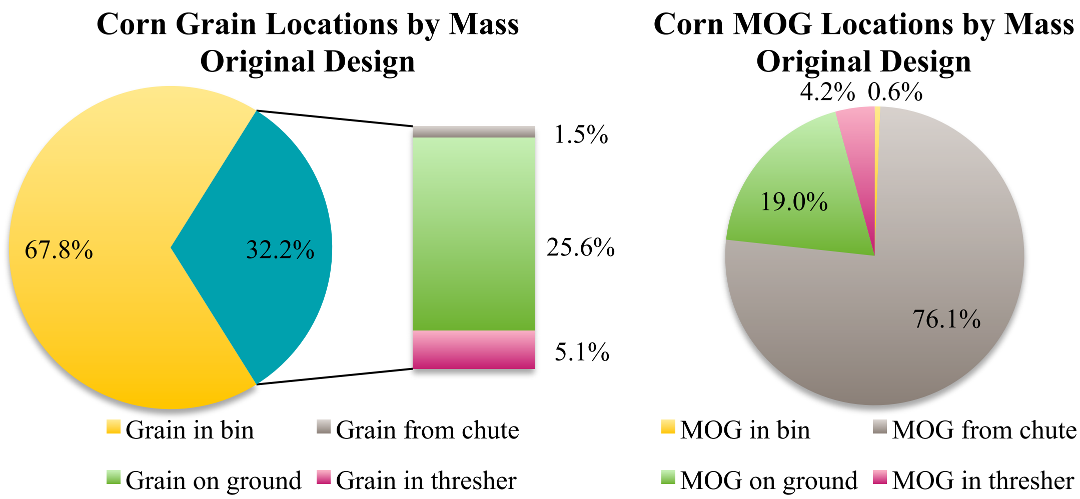

Figure 22 - Charts showing where the grain and MOG was after the initial test with corn. Source: Author.

MOG location is very descriptive of how the thresher is performing. The MOG for corn is mainly cobs and husks. In this test, most of the MOG came out of the exit chute. This is because most of the cobs and husks wouldn't easily fall through the lower concave. Only 0.6% of the total MOG landed in the grain bin. Grain dockage, defined as the percentage of MOG in the grain bin, was 0.2%.

4.2.2.2 Soybeans

The soybean stalks were difficult to feed into the threshing cylinder for several reasons. First, the narrow chute opening (12 in by 4 in, 30 mm by 10 mm) made fitting bunches of beanstalks into the chute difficult. Second, the rotor did not easily pull material into it, and a piece of wood was used to assist in pushing stalks into the cylinder-concave gap. Like the corncobs, the soybean stalks didn't always move axially down the threshing drum. The threshing drum had a peripheral speed of about 33 ft/s (10 m/s), the sieve oscillated at 4.9 Hz, and the fan ran at 1050 rpm. The test took 13.9 minutes giving an approximate feed rate of 12 kg/h (26 lb/h). By observation, the soybeans seemed to also be threshed fairly well, but only in this test were the un-threshed beans measured together with the MOG and not separated out. There were very clear problems with the cleaning process. Significant amounts of the stalks fell through the concave and overloaded the oscillating sieve. Instead of moving down and out, the MOG piled up. The majority of the grain was lodged in the mat of MOG as well. A photograph of the sieve after the test shows the problem (Figure 23) and the measurements verified it (Figure 24).

Figure 23 - Picture of the overloaded sieve after the initial soybean test. Source: Author.

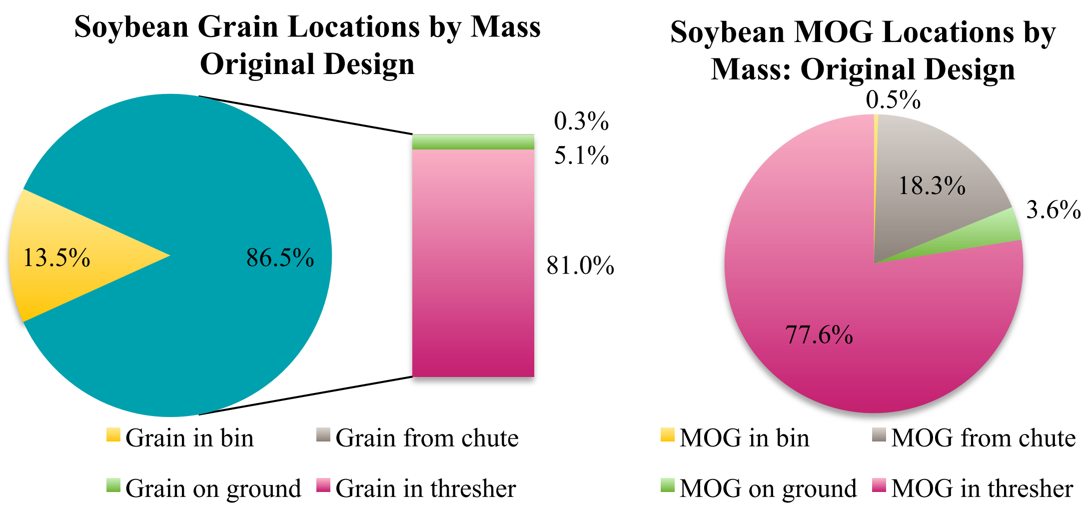

Figure 24 - Charts showing where the grain and MOG was after the initial test with soybeans. Source: Author.

Only 13.5% of the grain made it to the grain bin while most (81%) remained in the thresher, mostly on the sieve. However, very little MOG (0.5% of total MOG) entered the grain bin. The grain dockage was 2.4%. As with the corn, some of the soybeans were falling into the fan shroud.

4.2.3 Modifications

Based on the initial tests, it was clear that changes to the thresher needed to be made. First, a sequence of changes to the speed ratios was made. Then, some additional shields were added to control the grain better. Finally, a lip was added to the end of the sieve to catch grain coming off of the end.

4.2.3.1 Speed Ratios

The first change made was increasing the oscillation frequency of the sieve. This made a very noticeable difference in moving the material along the sieve. The ratio between the engine and the intermediate shaft was then decreased, thereby slightly speeding up all of the components. The fan speed was increased several times, as was the sieve. The sequence of ratio changes is summarized in Table 3.

Table 3 - Summary of the sequence of ratio changes to the thresher.

	Original	Change #1	Change #2	Change #3	Final
Engine/IS	3.1	3.1	2.8	2.8	2.8
IS/drum	2.3	2.3	2.3	2.3	2.3
IS/sieve	2.9	2.0	2.0	1.7	1.7
IS/Fan	0.8	0.8	0.5	0.5	0.4

4.2.3.2 Shielding

Because grain was observed bouncing off of the sieve and out the back, a shield extension was added as pictured in Figure 25. To be effective, the shield had to come down closer to the sieve, but it couldn't be placed too close or else the MOG on the sieve would be blocked from moving out.

Figure 25 - Additional shield near the end of the thresher, above the sieve.

Another short shield was added as an extension to the shelf under the perforated steel and over the fan. The purpose of this extension was to prevent grain from entering the fan, as it was doing in the first test.

4.2.3.3 Sieve Exit Lip

Even with the added shields, there was still a considerable amount of grain falling onto the ground off of the back of the sieve. Another modification made to help prevent this was the addition of a lip or catchment at the exit of the oscillating sieve, pictured in Figure 26. The purpose of this lip was to catch any grain that hadn't fallen through the holes in the sieve. Any MOG that came off of the perforated steel would be blown out because of its lower density.

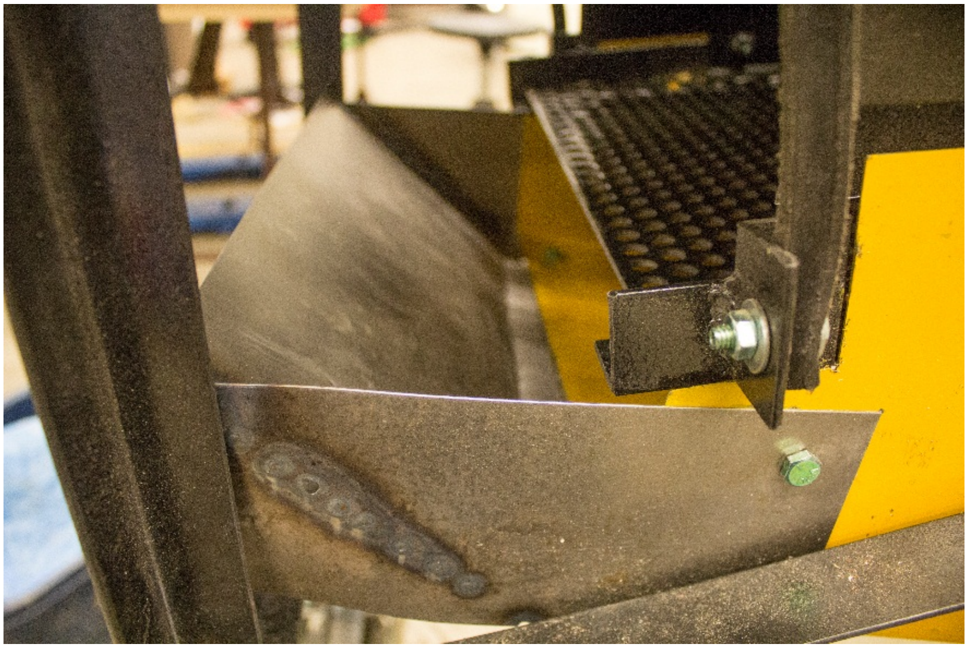

Figure 26 - A lip to catch grain coming off of the sieve.

4.2.4 Final Test Results

A second set of quantitative tests was done after all of the modifications to the thresher were made.

4.2.4.1 Corn

The threshing drum had a peripheral speed of about 31 ft/s (9.4 m/s), the sieve oscillated at 7.8 Hz, and the fan ran at 1900 rpm. The test took 2.8 minutes giving an approximate feed rate of 220 kg/h (490 lb/h). Threshing efficiency was 100%, as there was no measurable amount of unshelled corn. Grain dockage was 1.3%. Ninety-six percent of the grain made it to the grain bin with the 4% of losses divided between the chute, ground and thresher. Most of the MOG came out of the discharge chute. These results are shown in Figure 27.

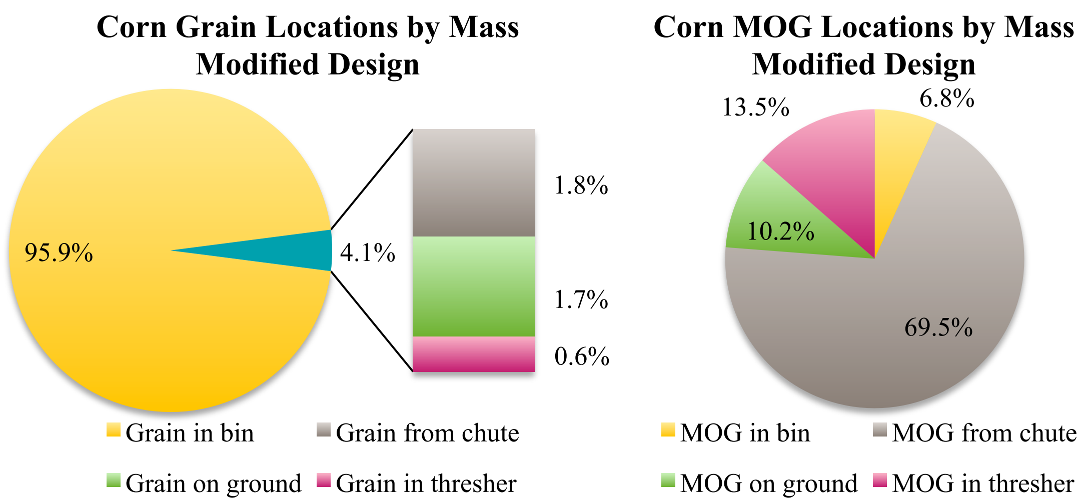

Figure 27 - Charts showing where the grain and MOG was after the final test with corn. Source: Author.

4.2.4.2 Soybeans

The threshing drum had a peripheral speed of about 36 ft/s (11 m/s), the sieve oscillated at 9.0 Hz, and the fan ran at 2170 rpm. The test took 7.1 minutes giving an approximate feed rate of 23 kg/h (51 lb/h). Un-threshed grain (only measured in the grain bin) was 4.3% of the total grain. Any other un-threshed grain (in the thresher, from the chute, or on the ground) was threshed out, but counted with the threshed grain from each location. Of the grain, 94% went to the bin, and 5% was lost on the ground. Only 1% remained in the thresher or came out of the chute. Two-thirds of the MOG landed on the ground, 19% came out of the chute, but over 9% went to the grain bin, leaving only 5% in the thresher. These results are summarized in Figure 28.

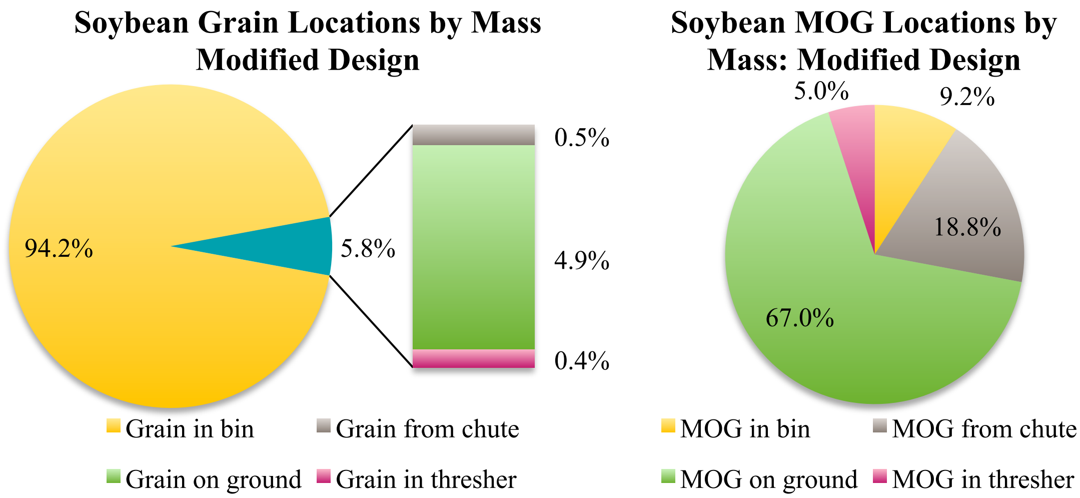

Figure 28 - Charts showing where the grain and MOG was after the final test with soybeans. Source: Author.

4.2.5 Air Speed

After the above tests were done, air speed measurements were taken. The belt driving the oscillating sieve was removed for these measurements. Measurements were taken at positions A and B, shown in Figure 29. Both positions were approximately centered in the width of the sieve. Position A was just below the end of the perforated steel. Position B was 10 inches in front of the end of the fan outlet and approximately centered vertically with the outlet.

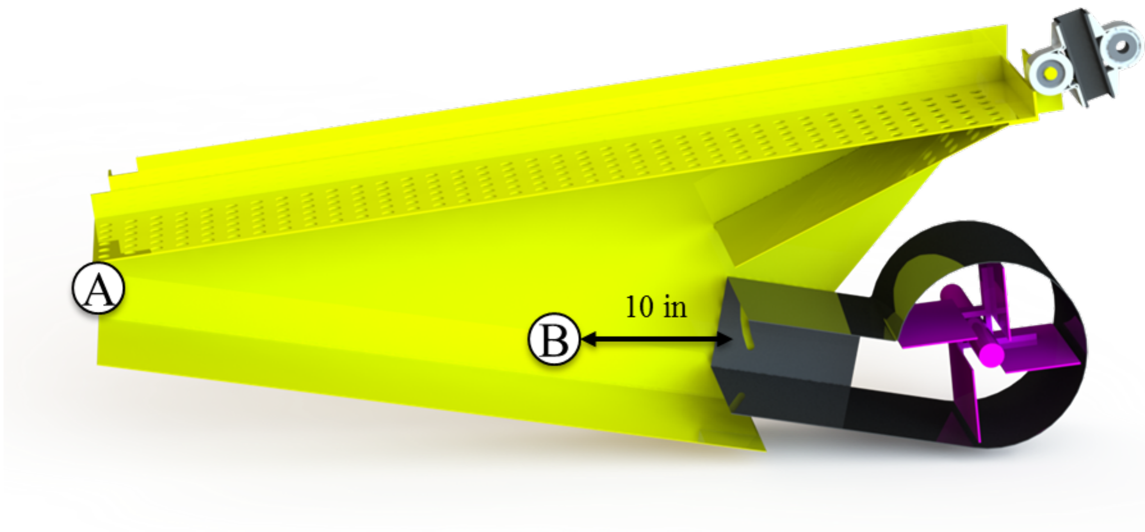

Figure 29 – Anemometer positions in the cleaning shoe.

For each position, measurements were taken at various fan speeds from 1400 rpm to 2800 rpm. Air speeds were between 2.7 and 5.4 m/s (8.9 and 18 ft/s) at the exit of the sieve and between 4.4 and 8.4 m/s (14 and 28 ft/s) in front of the fan outlet. A plot of the measurements along with corresponding linear regression lines is shown in Figure 30.

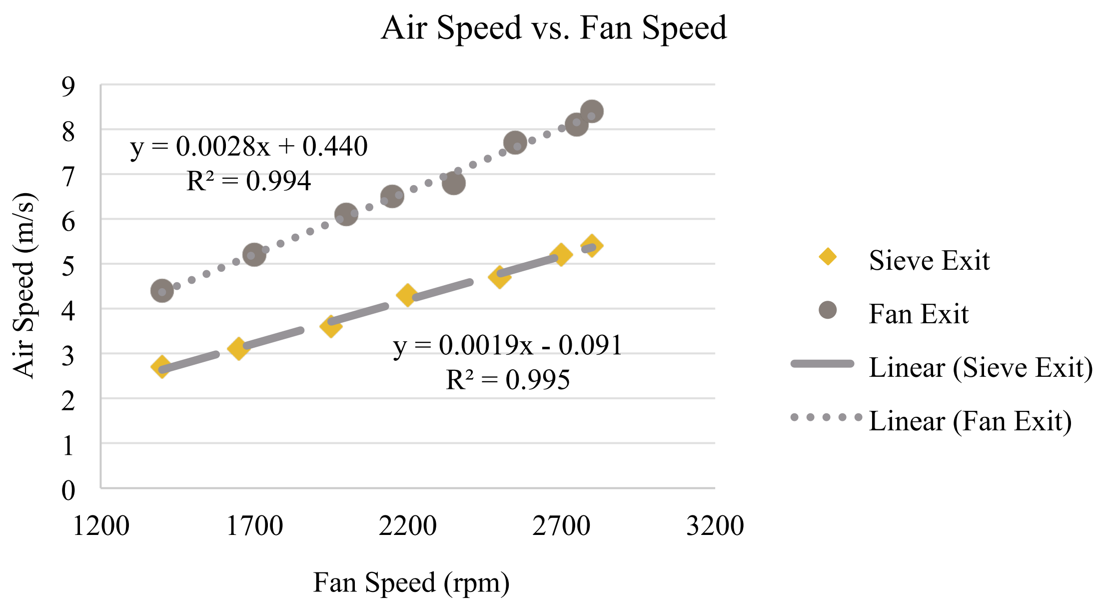

Figure 30 – A plot of air speed over fan speed and corresponding trendlines for two positions in the cleaning shoe.

4.2.6 Corn Cobs in the Cylinder

Several cobs were shelled individually in order to measure the time a single cob spent in the threshing cylinder. An action camera, recording at 60 frames per second, was placed at the end of the threshing drum. Three corn cobs were shelled and the video footage was used to determine the length of time one cob was in the cylinder. The second cob broke while in the threshing drum and part of it exited at 11 seconds, while the rest of the cob exited at 16 seconds. The longer time was used in the calculations. The first cob was in the cylinder for 20 seconds, the second cob for 16 seconds, and the third cob for 11 seconds. The average time that these three cobs were in the threshing cylinder was 16 seconds. The engine was running at 2460 rpm, giving an approximate drum speed of 390 rpm.

The video footage was also used to calculate the rotational speed of the cobs in the threshing drum. Using the video frame rates, the time for each cob to complete 11 rotations was determined. The average time per rotation was 0.40 seconds, giving a rotational speed of 150 rpm. Figure 31 shows example frames from the video footage, where a cob is moving across the lower concave, near the exit.

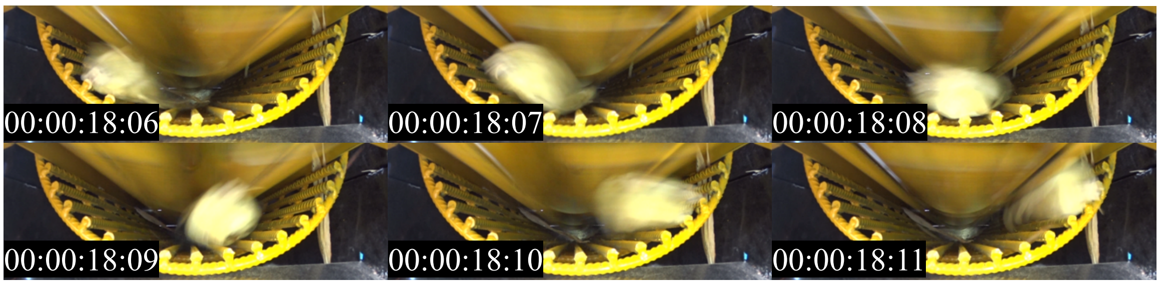

Figure 31 - Six frames from video footage of a cob moving around the threshing cylinder.

Using the drum speed, cob speed, length of time in the threshing cylinder, and the number of rasp bars, the number of rasp bar impacts seen by a single cob was determined to be approximately 500.

Although the three cobs used to do these calculations moved relatively well through the threshing cylinder, some cobs in other trials jammed in the thresher. These cobs stayed in the thresher for over two minutes or until removed, after the thresher was shut off.

4.2.7 Summary

The threshing machine remained functional during all tests. No component broke or failed at any point. However, the machine was only run for several hours in total, which is not sufficient time for parts to wear or fatigue. The thresher was never observed to be nearing a power-limited state. Based on observations from the initial tests, speed ratios were modified and small sheet metal additions were made, which resulted in improved overall performance of the thresher.

CHAPTER 5. CONCLUSION

5.1 Discussion

5.1.1 Cost

The total estimated cost of parts and materials for the thresher was just over $750. This is 50% more than the original target price given in Chapter 2. However, as noted in the previous chapter, the cost will drop when more economical parts are bought (e.g. stamped, not cast pulleys), especially in larger quantities. Additionally, prices for basic parts are often lower in SSA. If another power source is available, the price would drop by another $100, by excluding the engine. When these factors are taken into account, the target of $500 is within reach for this design.

5.1.2 Threshing and Cleaning

As mentioned earlier, the thresher threshed and shelled well and showed promise of good mechanical reliability. The threshing efficiency of 100% for the corn is excellent. The threshing efficiency for the soybeans was 96%, if not less. This efficiency could improve if the concave clearance is reduced even more for soybeans and if the cylinder speed increased. Although initial tests had disappointing results for cleaning and separating, especially for soybeans, simple modifications improved the thresher's performance significantly. Modifications focused on improving the separation and cleaning of the grains from the MOG, by moving MOG down the sieve quicker and by adding guards and catchments for the grain. During the qualitative tests, it was observed that the largest improvements came from increasing the oscillation frequency of the sieve and from adding the catchment lip to the end of the sieve. Much of the corn would not fit through the 3/8-in (9.5 mm) holes of the sieve, but the corn observed in Ghana was smaller, rounder white corn, unlike the yellow field corn used to test here. Grain loss, measured as the sum of the grain from the ground and chute over the total grain (excluding grain in the thresher), decreased from 28.6% to 3.5% for corn and from 28.8% to 5.4% for soybeans. This is close to the acceptable maximum losses (Kutzbach & Quick, 1999). However, it should be clearly stated that the tests performed for this research are only approximations. A more accurate method of determining losses, efficiencies, and rates, would be to take samples while the machine is running at steady state. The results of these measurements would reflect more accurately the actual losses, efficiencies, and rates. However, for the purpose of initial approximation and quantifying improvements, the methods used were sufficient. Figure 32 shows the results of all four tests for final grain and MOG locations.

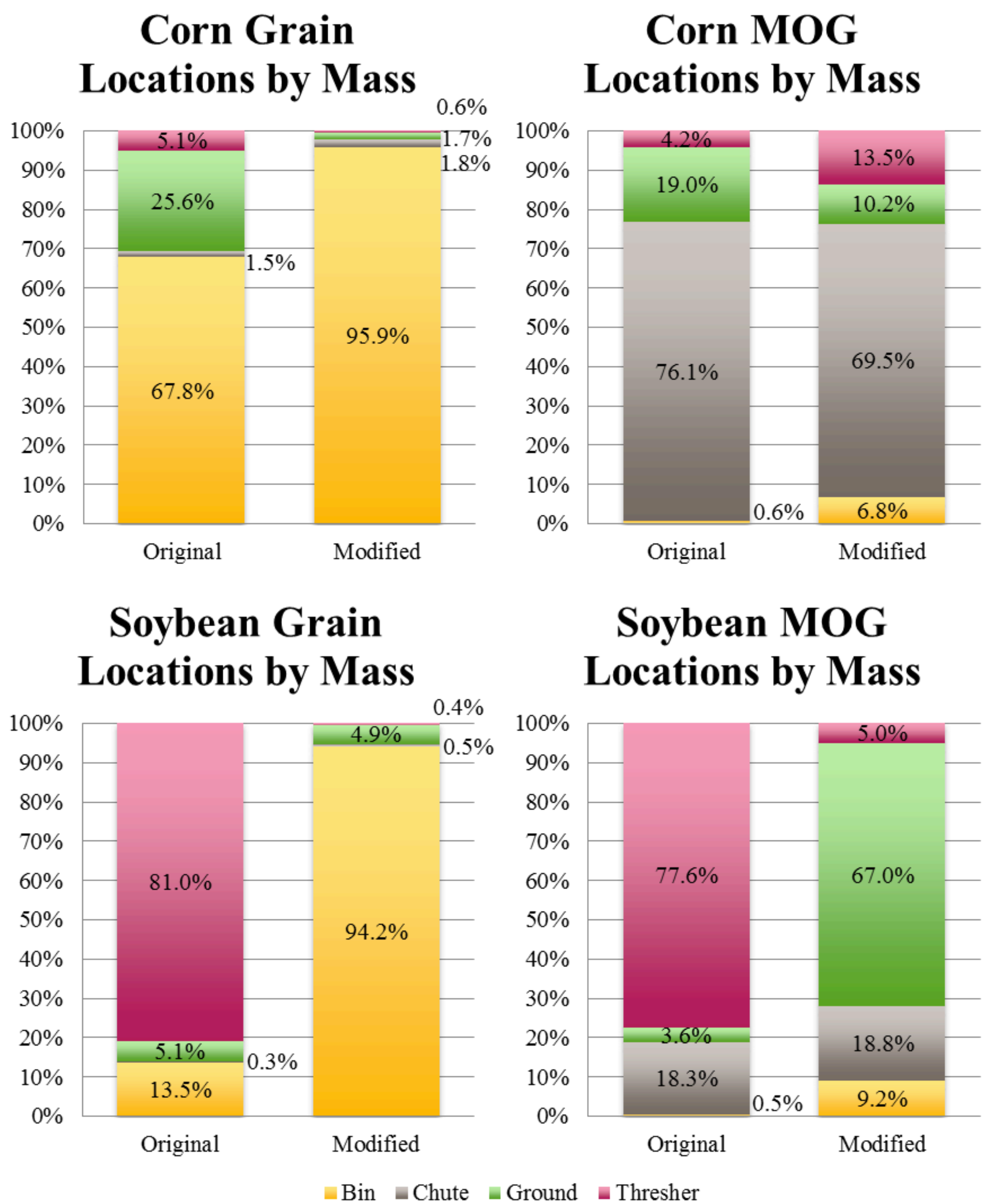

Figure 32 - Charts summarizing where the grain and MOG went during the tests.

Most notable in these figures is the increase of grain saved. However, this came at the expense of more trash in the grain bin. For corn, the grain dockage increased from 0.2%

to 1.3% and for soybeans it increased from 2.4% to 6.6%. This increase of MOG with the grain came from dense MOG that fell onto the sieve. The lip that was added to the end of the sieve to catch grain also caught the dense MOG coming off of the sieve.

Interestingly, the feed rate for corn decreased (350 to 217 kg/h, 770 to 480 lb/h), while the feed rate for soybeans increased (12 to 23 kg/h, 26 to 51 lb/h). As noted above, these measurements only give rough approximations. This is especially true for the timing of the tests because the end time was not clearly defined and feed rates should be measured at continuous flow. In addition, difficulties with feeding the material into the chute varied the feed rate considerably. This aside, the rates for corn shelling are far above those for the manual methods given in Chapter 2 and comparable to the first thresher observed in Ghana. The soybean rates would need to be improved significantly to make this machine an attractive alternative. There is ample opportunity to do this based on the facts that feeding material into the machine was limiting the process, not engine power.

The air speed in the cleaning shoe was calculated using the engine speeds for each test, the speed reduction for the fan, and the curves developed in section 4.2.5. During the corn test, the fan ran at 1900 rpm, giving an air speed of 3.6 m/s (12 ft/s) at the sieve exit and 5.8 m/s (19 ft/s) in front of the fan outlet. The highest air speed is 2.1 m/s (6.9 ft/s) below the minimum terminal velocity of corn. During the soybean test, the fan ran at 2170 rpm, giving an air speed of 4.1 m/s (13 ft/s) at the sieve exit and 6.5 m/s (21 ft/s) in front of the fan outlet. The highest air speed is 2.6 m/s (8.5 ft/s) below the minimum terminal velocity of soybeans. Clearly, the fan speed can be increased for better cleaning of the grain without risk of losing significant amounts of grain.

5.2 Recommendations for Future Work

Although the research, design, and tests discussed in this thesis are a good foundation, more work should be done. This section is divided into two parts. The first section will discuss further work that can be done on this specific thresher design, and the second section will give broader recommendations for future work and areas to explore.

5.2.1 Thresher-Specific Recommendations

- Modify the input chute to have a wider mouth so that plant material, especially beanstalks, can easily be fed in.
- Explore options for making it more difficult for a worker's hand to come into contact with or be pulled into the threshing drum.
- Modify the chute, concave, and/or threshing drum for positive feed or easier acceptance of material into the cylinder-concave gap.
- Consider putting stronger material on the upper concave at the entrance of the threshing cylinder, because more material wear is expected at that point.
- Modify the cylinder and/or concave to more aggressively drive the axial movement of the plant material. One easy modification to try is to double the helical pieces of rebar in the upper concave so that they are twice as tall. Another possibility is to add some angled pieces to the rotor.
- Narrow the gaps in the lower concave, at least in the first section, so that un-threshed pods are less likely to fall through.
- Modify the sieve to have ridges like a straw walker or teeth like a chaffer sieve. These would restrict movement of MOG to only move down the sieve. This might

increase the flow rate of material down the sieve allowing the oscillating frequency to decrease, thus reducing power consumption and machine wear.

- To reduce the grain dockage caused by large MOG, a screen (0.5 in or larger) should be added over the catchment at the end of the sieve.
- Use wire mesh instead of perforated steel for the sieve. This might allow all of the grain to fall through and not bounce out, removing the need for the catchment at the end of the sieve. The mesh might need supports to maintain a flat surface.
- Add wind-boards to act as nozzle controls at the outlet of the fan and at the end of the sieve. These would allow air speeds to be changed without having to change engine speed or pulley ratios. The wind-board at the sieve exit would also control how much air passes through the perforated steel.
- Once the above issues have been addressed, run complete and more thorough tests with the thresher. This should include:
    - Multiple tests with all the same settings for redundancy. The variation and average of the results can be analyzed.
    - Samples taken when the thresher is running at steady state.
    - Sweeps of tests at different concave clearances, cylinder speeds, and feed rates.
    - Tests with more crop varieties like millet, cowpeas, and sorghum.
- After the modifications, calculate the expected cost of parts and materials.

5.2.2 General Recommendations

- Modify the way the perforated steel is attached to the sieve for easier removal.

- Look into ways that material can be reduced in order to reduce costs and decrease weight, especially at the cylinder, because the thresher is top-heavy.
- Future designs should take component attachment and removal into more consideration. Currently, it is difficult to assemble all of the parts because of how they overlap or block each other (e.g. putting the sieve or fan into the frame).
- Explore the use of a 55 or 30 gallon steel drum for use as the upper concave.
- Explore options for manufacturing the fan shroud and upper concave that do not require a sheet metal roller.
- Explore using different helix pitch angles for the rebar on the inside of the upper concave and/or a shorter threshing cylinder.
- Explore possibilities of an even smaller machine that reduces the costs more and is easier to transport.
- Calculate the expected hours of labor required to fabricate a thresher in a micro-factory.

5.3 Summary

Based on the literature review and experiences in SSA, a threshing machine has been designed and tested that used only parts and materials easily obtained in SSA. Results show that the thresher can shell and clean corn significantly faster than any traditional method and shows high potential for the same with soybeans and similar crops. Grain losses were reduced significantly with a few modifications and further efforts could bring them down even more. The cost of the thresher is expected to be lower than currently available threshers in Ghana. Although the design targeted smallholder farmers in SSA, the thresher could be appropriate for many other regions. The thresher's smaller size and lower cost has the potential to bring mechanized threshing to smallholder farmers, thus reducing the time and drudgery of processing their harvest. This can also ultimately help to increase their production, decrease their losses, and increase their income, consequently establishing food security for their household and putting quality food on the marker for others.

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APPENDIX

APPENDIX

Table 4 - Test data

		Unit	Original Test 1 (c1)	Modified Test 3 (c2)	Original Test 2 (s1)	Modified Test 4 (s2)
	Crop		Corn	Corn	Soybeans	Soybeans
	Speed	rpm	2250	2250	2600	2600
	Time	min	1.7	2.8	13.9	7.1
	Prethreshed weight	lb	25.8	25.8	10.4	10.4
Chute	Total (measured)	lb	3.10	3.31	0.79	0.86
	Grain	lb	0.29	0.41	0.02	0.03
	Unthreshed Grain	lb	0.04	0	0	0
	MOG	lb	2.76	2.89	0.77	0.82
Ground	Total (measured)	lb	6.20	0.82	0.47	3.25
	Grain	lb	5.49	0.38	0.31	0.30
	Unthreshed Grain	lb	0	0	0	0
	MOG	lb	0.69	0.43	0.15	2.93
Thresher	Total (measured)	lb	1.24	0.71	7.84	0.26
	Grain	lb	1.08	0.13	4.81	0.03
	Unthreshed Grain	lb	0	0	0	0
	MOG	lb	0.15	0.56	3.26	0.22
Bin	Total (measured)	lb	14.6	21.9	0.84	6.11
	Grain	lb	14.6	21.7	0.80	5.44
	Unthreshed Grain	lb	0	0	0	0.26
	MOG	lb	0.02	0.28	0.02	0.40

Table 5 – Air speed data at sieve exit

Engine Speed (rpm)	Fan Speed (rpm)	Air Speed (m/s)
1680	1400	2.7
1980	1650	3.1
2340	1950	3.6
2640	2200	4.3
3000	2500	4.7
3240	2700	5.2
3360	2800	5.4

Table 6 – Air speed data in front of fan outlet

Engine Speed (rpm)	Fan Speed (rpm)	Air speed (m/s)
1680	1400	4.4
2040	1700	5.2
2400	2000	6.1
2580	2150	6.5
2820	2350	6.8
3060	2550	7.7
3300	2750	8.1
3360	2800	8.4

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