Development of a Small-Scale Harvester for Biomass Operations

by

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Abstract

The Oil Embargo of 1973-1974 that quadrupled the price of a barrel of oil in a matter of months sparked the discussions of alternative forms of energy; one of the topics that started to be addressed was renewable energies. Nowadays, biomass accounts for the most used form of renewable energy in the United States, with woody biomass specifically being third overall. However, although a promising source of energy, new investments in the United States on how to improve the biomass market have happened at a slow pace. Forest fragmentation, along with other factors, has caused the existence of a large share of timber supply on smaller tracts of timber. The timber found on these tracts generally cannot be profitably harvested because the high investment in machinery does not offset the low volume harvested. To make the harvest operations more economically feasible, a small-scale feller-buncher was designed for biomass harvesting. A mini excavator (IHI 80 VX) was the starting point for our studies. As this machine was not originally built to operate with a felling head and inside the woods, we modified the design of the boom for a better reach and added an auxiliary motor, hydraulic pump and hydraulic tank exclusively to run the felling head. We estimated the costs to run this machine to be around $5.70/ton at a production rate of 10.6tons/PMH, and considerably lower if higher productivity can be achieved. If productivity levels are met, this machine could help stimulate the harvesting of biomass when that market develops.

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Chapter 1. Introduction

1.1 Project Background

For many years our society has relied on the use of fossil fuels such as petroleum and natural gas to supply its energy demands. Although these fossil fuels have the benefit of being versatile, which allows them to be used in many forms, their use is limited by scarcity, the impossibility of production during a human lifespan, and their negative impacts on the environment (Höök and Tang, 2013). When utilization of fossil fuels as an energy source became possible in large scale, other sources of energy were simply not cost-competitive enough (Sørensen, 1991). After the Oil Embargo of 1973-1974, however, the adoption of renewable energy sources started to be discussed by governments as part of their energy planning and as a clean and continuous alternative to fossil fuels (Sørensen, 1991). The term "renewable energy" refers to sources of energy that are naturally replenishing, although limited in the amount of energy that is available per unit of time (EIA, 2020). Globally, there are many different types of renewable energies being studied and used, such as solar radiation, hydropower, and wind. None of these sources, however, come close to the use of biomass. Adequate sites for generation of wind energy are usually in remote locations and using these sites for energy generation might not be the most profitable opportunity (U.S. Department of Energy, n.d.). As for solar energy, the generation and productivity of this type of energy depends on the amount of sunlight that reaches the earth, which is not constant and varies based on location, time, seasons and weather (EIA,

2019a). Biomass, currently represents 13% of the energy consumption in the world, and 73% of all renewable sources (World Bioenergy Association, 2019).

Biomass as an energy source can come in the form of agricultural crops, waste material, animal manure and many more (EIA, 2018). One form of biomass that needs to receive special attention in the United States is woody biomass, especially because the country has an impressive 766 million acres covered by forest lands and a surplus in the growing stock of forests (FAO, 2019). Woody biomass is defined as a "*by-product of management, restoration, and hazardous fuel reduction treatments, as well as the product of natural disasters, including trees and woody plants (…)*" (USDA, 2020). Just like fossil fuels, woody biomass is also very versatile as it can be transformed using chemical or biological processes to create biofuels such as methyl esters, oils, and solid charcoal. When combustion processes are established, the heat generated from this feedstock may be used in the actual form of heat or even to generate electricity (Twidell and Weir, 2015). In comparison to other sources of renewable energy, woody biomass, if harvested sustainably, is advantageous because its generation does not cause visual intrusion, it does not interfere with TV and radio signal (wind), and it causes no direct impact on fish population and water flows (hydropower) (Laughton, 2003). The use of woody biomass is also promising because this feedstock presents CO_2 neutrality, meaning that the carbon that is released from the feedstock during its conversion processes is already part of the biogenic cycle of the Earth (IEA Bioenergy, 2020). Biomass derived from woody plants are also advantageous over biomass derived from agricultural because of a lack of conflict with the food sector (Searchinger and Heimlich, 2015).

Some different efforts have highlighted the relevance of biomass in the United States. The Billion Ton Report (Langholtz et al., 2016) demonstrates the biomass feedstock availability

and how this feedstock can be utilized in a sustainable manner. The "25 by 25" (25x'25, n.d.) is an alliance created to promote the use of renewable energies and its objective is to raise the participation of renewable sources in the energy supply of the United States to 25% by the year of 2025. However, an overlooked problem associated with the consumption of woody biomass is that only forest residues such as tree-tops, limbs, and waste from wood-related activities have been historically considered for bioenergy products (Durocher et al., 2019). As noted by Alavalapati et al. (2013), under increasing requirements of biomass for energy use, it is unlikely that harvesting residues and urban wood alone would be able to meet the energy demands. Timber harvested with the main purpose of being used for energy generation could easily become a desirable feedstock.

Forestry practices and timber consumption in the United States, along with land ownership patterns, governmental guidelines, procedures for prevention of wildfires, and numerous environmental and political circumstances have caused the existence of a large share of timber supply located in smaller tracts of timber (Paun and Jackson, 2000). The timber found in small tracts generally cannot be profitably harvested because the high investment on machinery does not offset the low volume harvested (Bardon, 2015). Studies conducted in the early 2000s showed that the biomass of small trees and shrubs was growing at an average rate of 237 ft³ per second (LeVan-Green and Livingston, 2003). More recent estimations show that by 2022 the potential of forestry resources alone to produce biomass will be underused by approximately 42% (Langholtz et al., 2016). According to Thiffault et al. (2016) the addition of non-commercial roundwood as feedstock for energy production from biomass could bring biomass importance to higher levels.

Unlike many other parts of the world, most of the forest land in the United States is privately-owned (Oswalt et al., 2018). The South itself is a very unique region with the highest percentage of privately-owned forests in the US, as much as 87% (MacDicken et al. 2016). There are approximately 11 million individuals and families who possess forest lands in the USA and from those, around 61% of the landowners own 10 or fewer acres (Butler 2014, MacDicken et al. 2016). While industrialization and the need for continuous growth keep pushing the boundaries for the development of higher-end machines and large-scale development, that portion of individuals and families who own small areas of forests is most of the time forgotten or not targeted. The smaller forest areas that are maintained for beauty, heritage or recreational reasons can become profitable (or add different sources of income) if the right tools are provided (Parron et al. 2015, Luederitz et al. 2015).

Small diameter wood is defined as stems that are too small to merchandise into traditional forest products. There are many reasons why utilization of small-scale diameter wood is limited. When efficient harvesting techniques are applied, however, small-scale material can contribute to economic returns for landowners (Bumgardner and Wiedenbeck, 2013). Out of the commonly utilized forest harvesting systems in the United States, whole-tree systems are the most widespread. This system is often fully mechanized and frequently comprised of large machinery (Conrad et al. 2018). Conventional whole-tree harvesting systems are comprised of rubber-tired or tracked feller-bunchers for felling and bunching the trees, and skidders are used to drag the stems to the loading deck (Wilkerson et al. 2008). These current harvesting systems were developed to fell and extract larger and more merchantable logs; when applied to harvest smaller and non-merchantable trees, these machines are usually not productive enough (Bolding, 2009). Furthermore, these systems can also be impactful for the environment and a lot of the time their

use is physically challenging. Therefore, the current logging systems are not completely adequate for the type of operations required for biomass harvesting.

Because there is an abundance of woody biomass in small tracts of forests, and/or in the trees with smaller DBH (diameter at breast height), in order for production of woody biomass to be efficient, there is a high need to invest in the development of small-scale machinery for the harvesting of the trees. Small-scale feller-bunchers are very promising when used to harvest trees with small diameter (Spinelli et al., 2007). These machines are considered an effective alternative because of their smaller size and lower purchase price when compared to conventional logging machinery.

There are few investments being made on the development of equipment for harvesting of small-diameter trees. Based on this evidence, we proposed to design a small-scale feller-buncher following the criteria described by Wilhoit and Rummer (1999) for the effectiveness of small-scale harvesting systems.

Although we understand that for biomass operations to occur a whole harvesting system including chipping and transportation should be developed, we see the importance of starting this project with the felling function as the success of this phase is mandatory for the execution of other phases of the system.

1.2 Objectives

The objective of this study was to develop a cost-effective harvesting equipment to produce biomass feedstock for the bioenergy market.

The specific goals for this project are:

1. To develop a small-scale feller-buncher capable of harvesting small-diameter-trees with minimum capital costs and operational costs that is environmentally friendly and can operate with high fuel efficiency.

2. To analyze the costs of the modified small-scale feller-buncher in order to determine how feasible this machine could be.

Chapter 2. Literature Review

2.1 Advancements Involving Small-Scale Feller-Bunchers

According to Jernigan et al. (2016), not many studies involving investments in biomass harvesting productivity have been developed since the late 1980s, which would be a result of the reduced interest in woody biomass feedstocks. With the objectives to fill in that gap, those authors developed a research project in Monroeville, AL to understand the productivity of a harvesting system specifically designed for harvesting uniform small diameter trees. This study consisted of a Tigercat 845D feller-buncher with a specialized biomass shear head for felling, and a Tigercat 630D skidder equipped with an oversized grapple. The operation took place in a 10.87 acre stand where 600 was the minimum trees per acre; other characteristics of the site include minimum slope and age class of the stand varying between 10 and 15 years. The results of this study showed that productivity of the feller-buncher was of 47 green tonnes/productive machine hour (gt/PMH), while the productivity of the skidder was of 112 gt/PMH. Final production level of the system was 71,645 gt/yr. The authors concluded that productivity was hindered by crooked trees, operator inconsistency, and lack of experience, and they believed that a more experienced operator could bring productivity levels up to 96,446 gt/yr. In terms of costs, the felling operation was the most expensive part of the harvesting operation, costing $3.85/gt over a ten-year life span, which represents over 66% of the total cost of $5.80. The conclusions of that study were positive, the researches believed that the results indicated the improved

equipment was able to promote a highly productive system for harvesting young southern pine energy plantations (Jernigan et al., 2016).

Klepac (2013) also conducted a study analyzing the performance of the Tigercat 845D feller-buncher equipped with a shear felling head and the Tigercat 630D skidder for harvesting small-diameter trees. This study was conducted in a 15-year old Loblolly pine (*Pinus taeda*) plantation and in an 18-year old natural stand located at Covington County – AL and Butler County – AL respectively. Trees were felled both from plantations, and from the natural stand; in terms of diameter of the trees removed, the plantation had trees with diameter ranging from 2.6 to 10 inches, and the natural stands' trees ranged in diameter from 2.3 to 19.2 inches. The results showed that total cycle time was not significantly different between the two stands, but productivity was. In the plantation, mean productivity achieved was 77.9 gt/PMH, while on the natural stand productivity was 118.7 gt/PMH. According to Klepac (2013), those different levels of productivity were mainly caused by a greater mean tree size cut per cycle in the natural stand (1.88 gt/cycle *vs*. 1.51 gt/cycle in the plantation). The results of this study demonstrated this feller-buncher was "capable of operating productively in different stand types over a range of tree sizes" (Klepac, 2013). However, it was also pointed that at the production rate found in this study, if the system would be used in stands with 1000 to 1200 trees per acre where the trees would be smaller, potentially at least two feller-bunchers would be needed to achieve the required production.

Another study analyzing productivity in small scale stands for energy was developed by Spinelli et al. (2007) in Europe; in that study, the researchers used a Timberjack 870A energy harvester as the felling machine, and two models of shear head, TJ720 and TJ730, capable of harvesting a maximum diameter of 7.9in and 12in respectively. The study was conducted for

three years on three different sites: 1) a young forest of conifers in Finland; 2) a hornbeam coppice in France; and 3) a plantation of sycamore in Italy. All the sites chosen were fairly flat and even as to offer favorable conditions for the operation. The experienced operator who worked for Timberjack harvested all three sites. The machine was used both for thinning operations (in the forest of young conifers, and in the sycamore plantation) as well as for clearcut in the hornbeam coppice (Spinelli et al., 2007). The results of that studies varied a lot based on site characteristics and type of operation being conducted. Overall productivity ranged from 4 to 8 green tonnes per net working hour; the machine presented better results when removing single-row plantations, thinning coppice on the other hand was the most demanding work. Felling costs ranged from 12.1 €/gt to 22.7 €/gt (13.6 $/gt to 25.5 $/gt), the operation that took place in the young forest of conifers in Finland was the second least expensive, with felling costs of 15.1 €/gt (17 $/gt) (Spinelli et al., 2007).

Pan et al. (2008) conducted a study in Springerville and Black Mesa – AZ to measure productivity and cost of a mechanized whole-tree harvesting system used to harvest trees with less than 5 inches in diameter for energy use. The sites were subdivided into two subunits of 10-acres each, resulting in four harvested units that ranged in slope from 0% to 28%; the stand density ranged from 670 to 5889 stems/acre in the units, and nearly 100% of the trees were Ponderosa pine (*Pinus ponderosa*). The harvesting system was composed of a Valmet 603 three-wheel feller-buncher with a hot-saw, a CAT 525B skidder, a Prentice RT-100 log loader, and a Bandit Beast 3680 horizontal grinder, and chipping vans. The production rate of the feller-buncher (11.92 bone dry ton/PMH) fell in the middle of the five parts of the system, being more productive than the vans and grinder, and less productive than the skidder and loader in that order. The total cost of the system was found to be $55.27/BDT ($26.12/green ton) on average,

while the overall cost to run the feller-buncher was $6.37/BDT ($3.01/GT). In terms of

percentage, the overall cost of the feller-buncher represented 11.53% of the total costs. Pan et al.

(2008) discussed that even with market rate of $40/BDT ($18.9/GT) would not be enough to

break-even and realize profit when harvesting, for that reason other forms of valuing should be

considered. Reduced investments on site preparation, reducing fire risks, creating alternative

sources of energy are some of those other values that could increase the attractiveness of

harvesting for biomass supply.

Schweier et al. (2015) developed a study in Italy using different small-scale feller-

bunchers to study the productivity, cost-effectiveness and cut quality of a variety of machines in

coppice harvesting. Each of the feller-bunchers were modified small excavators that were

operated with three felling heads, each representing a different cutting mechanism, namely: a

single-action shear, double shear and disc saw. The feller-buncher models used in this study

were: Hitachi Zaxis 210 (164hp, 46,297lbs), CAT 317 (109hp, 38,149lbs), Hitachi EX 135

(125hp, 29,452lbs), and Hitach EX 165 (1,002hp, 35,715lbs). Five individual sites were chosen

to represent a type of coppice stand, the species harvested in each site, and the topological

conditions of the sites were also all different. Since there were many variables being analyzed,

the results found by Schweier et al. (2015) varied a lot depending on the combination of

excavator and felling head used, as well as the species and site. Overall, productivity ranged

from 3.6 dry t/PMH to 18.6 dry t/PMH, while felling costs ranged from 3.57 €/dry t (4.01 $/dry

t) to 20.57 €/dry t (23.13 $/dry t). According to Schweier et al. (2015), based on the numbers that

were found, using those feller-bunchers to coppice harvesting was not cost-effective when

comparing to manual harvesting; it was also further discussed that the resulting cut quality was

unsuitable, with the shear head producing poor cuts that were too high above the ground.

2.2 Advantages of Small-Scale Harvesting

Motivations behind the adoption of small-scale harvesting systems may vary from case to case or can be the only feasible option for an area. Small-scale harvesting equipment is most beneficial when there is an intent to use the equipment primarily in timber tracts of smaller size, sites with high sensitivity to impacts, or in uneven-aged management activities (Updegraff and Blinn, 2000). Operators who choose to have smaller equipment along with their traditional sized equipment may also have an advantage over operators who do not possess smaller equipment, especially in the specialized market for thinnings (Updegraff and Blinn, 2000). The overall benefits of having smaller equipment can be described as both economical to environmental. In economic terms, small-scale harvesting equipment has lower capital investment and reduced operational costs. The purchasing price of a small-scale machine can be considerably lower than a conventional large-scale machine, and cost-effectiveness of harvesting is strongly related to the size of the tract (Wilhoit and Rummer, 1999). Moving costs of larger scale equipment result in increased average operational costs in smaller tract sizes. One of the reasons why moving costs of larger equipment may be higher might be related to the permits needed to haul these machines. Currently, the State of Alabama imposes many restrictions when it comes to the maximum allowed dimensions of vehicles, including the maximum total length of 85', width of 8'6", and height of 13'6"; for this reason, many larger machines need special oversize and heavy haul permits to allow them to be moved. Another reason includes the fact that only one large machine fits on the back of a tractor-trailer, while two small machines may fit on the same tractor-trailer; there is also the fact that a small machine may be able to be hauled using a dual axel trailer.

The environmental benefits of a smaller setup of harvesting equipment is potentially seen in the soil, seedling growth and residual stands (Updegraff and Blinn, 2000). Every soil when exposed to frequent external pressure is susceptible to compaction. Reisinger, et al. (1988) discussed that among many other factors, the weight of the machine and frequency of use have a great impact on the amount of soil disturbance. Reisinger, et al. (1988) also concluded that high compaction can lead to low site quality for the development of seedlings due to at least one of the adverse conditions: lower aeration and oxygen diffusion through the soil, altered moisture retention and increased soil strength. Therefore, the adoption of small-scale harvesting machines over conventional machines should contribute to lower environmental impacts due to better flexibility and adaptability, as well as considerably smaller size and lower weight (Updegraff and Blinn, 2000). Limbeck-Lilienau (2004) conducted a study in Austria comparing the impacts of different harvesting systems and combination of equipment. These authors demonstrated that there is a statistical difference in residual stands based on the equipment used. Although that study did not necessarily compare the results from small-scale equipment to large-scale equipment, the conclusion that smaller equipment could also present statistical differences in residual stands could be done anecdotally, given the smaller weight and lower ground pressure that some of these smaller machines have.

When compared to other less innovative harvesting techniques such as manual harvesting, the use of mechanized harvesting is safer and more ergonomic. A study conducted by Bell (2002) in West Virginia compiled data from 1995-2000 from 11 companies that had adopted feller-bunchers as their harvesting equipment. The injury rates were calculated on an average of 2.4 years of before feller-buncher data and 2.2 years of after feller-buncher data. The results demonstrated significant difference in injury claim rates (19.4 per 100 workers before feller-

buncher adoption vs. 5.2 per 100 workers after feller-buncher adoption); the number of "struck-by" injuries claimed was also relatively smaller after feller-buncher adoption (1.0 per 100 workers vs. 10.1 per 100 workers) (Bell, 2002). A similar study published in 2019 compared worker's compensation claim rate of nonmechanized and mechanized logging between the years of 2005 and 2015 in Washington state. The results of that study showed that the number of claims in the nonmechanized logging was 46.4 per 100 full-time employees (FTE), while for the mechanized logging the number of claims averaged on 6.7 per 100 FTE, an impressive 6.9 ratio (Bonauto et al., 2019); it was also noticed that a greater percentage of the claims of the nonmechanized logging was related to traumatic injuries (92.2% vs. 85.0% of mechanized logging claims) (Bonauto et al., 2019).

2.3 Reasons for Investing in Small-Scale Logging

One of the biggest challenges preventing small-scale operations from becoming widely used is its perceived limitations of productivity. Usually, traditional large-scale forest operators are not interested in investing in small-scale machines because these machines may not be able to match the average productivity of conventional larger equipment (Updegraff and Blinn, 2000). However, if taken into consideration that the investment and maintenance cost of small-scale forestry equipment are usually lower than those of large-scale equipment, contractors should take into consideration that the lower capital costs and investments that they would need to make would require less production numbers in order to make their payments (Parker, 2010).

Considering forest ownership patterns, the development of small-scale forestry is of utter importance especially in the southern United States. In a scenario where most private landowners have small holdings, forest operations cannot simply rely on current methodologies and

techniques that are designed for larger tracts. In situations where large-scale machinery is used in smaller tracts for thinning operations or under uneven-aged management, productivity tends to drop because of added maneuverability difficulties, which consequently results in higher operational costs (Updegraff and Blinn, 2000). Moreover, stands of uneven-aged, smaller diameters and multiple species are becoming more common (Parker, 2010). For a logging contractor, stand diversity can make equipment selection less efficient; there is not a one-size-fits-all piece of logging equipment, which reinforces the needs for development of small-scale machinery (Bowers and Belart, 2015).

The participation of non-industrial private landowners (NIPF) in the supply chain of woody biomass in the United States is fundamental to the long-term success of emerging biofuel industries nationally (Young et al., 2015). These NIPF landowners, who together come close to 11 million landowners, have been historically fundamental to the development of the forestry sector. Washburn et al. (1999) noticed that about 58% of the wood used by Weyerhaeuser Company was derived from NIPF landowners nationally, and 90% of the supply came from the South. While the amount of private woodlands has grown throughout the years, the amount of small parcels of woodlands have also increased (Sagor, 2006); therefore, there is a high importance in targeting this audience and creating adequate innovations so that the biomass sector can keep developing.

Another factor that can impact the importance of small-scale machines is the perception and interest of the landowners. Not all landowners want to be involved with timberland operations; many of the NIPF landowners do not have forest management as one of their main goals. These landowners may prefer to maintain their lands for beauty and scenery, wildlife and recreation purposes (Godar Chhetri et al., 2015). It is a lot more likely that these NIPF

landowners will be more prone to adopt small-scale management as they perceive small-scale equipment as being more environmentally friendly (Marui et al., 1995).

There are also policies that can serve as an incentive for those who want to invest in biomass harvesting. By facilitating the access to grants and loans, some policies such as the 2002 Farm Bill, 2005 Energy Policy Act, 2007 Energy Independence Security Act, and 2008 Farm Bill have encouraged the production of biofuels derived from wood (cellulosic biofuels). The requirement behind these encouragements was to establish renewable fuel standards of 15.5 billion gallons in 2012, and 36 billion gallons in 2022 of which 21 billion should be produced using cellulosic material as a source (Alavalapati et al., 2013). To meet these targets, along with the financial incentives, can be a great opportunity for investments on small-scale logging.

2.4 Global Trends in Woody Biomass Consumption

The use of woody biomass as a source of energy dates as early as the discovery of fire, although initially the consumption happened in inefficient forms (Klass, 1998). One of the biggest advantages of woody biomass over other sources of renewable energy is related to this feedstock's versatility. While commonly used for heat and electricity, woody biomass, especially that rich in lignocelluloses, can be converted into second generation biofuels or transportation fuels (Gonçalves and Sousa, 2018). However, despite bioenergy being the largest contributor to the mix of renewable energy sources globally, and forestry biomass accounting for over 85% of the all the bioenergy generated in the world, the participation of woody biomass in the global energy supply is still limited. The majority of the use of forestry-derived products for energy generation is in the form of residues from pulp and paper industries and sawmill industries (WBA, 2019). In 2017, the domestic supply of biomass globally was 55.6EJ, which was 1.5%

less than the previous year; that decrease was primarily caused by a 2% reduction in supply of solid biofuels (wood, wood chips, wood pellets, and fuelwood) (WBA, 2019).

In terms of participation of biomass in the supply of renewable energies of the continents, Africa leads with 96% of biomass of all its renewable supply; in Asia, Europe and the Americas the share of biomass in renewable energies is 65%, 59% and 59% respectively (WBA, 2019). The biomass usage patterns also vary drastically worldwide. The most common application of solid biofuels is to produce electricity and heat for domestic uses such as cooking and heating (known as "traditional use"). This usage is mainly driven by continents like Asia and Africa. In those two continents alone production of woodfuel in 2019 was of 1.418 million m³, which accounted for 73.5% of global production of woodfuels (FAOSTAT, 2019). The use of biomass in the Americas and Europe tend to be more industrial. The United States and Brazil for example are responsible for over 70% of the global biofuels supply, while Europe is responsible for more than 50% of the global supply of biogas. About 2% of all the energy consumed in the United States in 2018 was derived from wood and wood residues such as bark, sawdust, wood chips, and paper mill residues (EIA, 2019b).

When it comes to the electricity sector specifically the situation is slightly more promising. Two of the benefits of the adoption of biomass for electricity generation are that biomass can be easily stored and easily dispatched. In 2017, biomass was responsible for providing 596TWh of energy for electric power; solid biofuels (including wood chips and wood pellets) were the biggest contributor to that energy generated, with a total of 389TWh (65.2%). In comparison to the previous year, supply of electricity from solid biofuels globally increased by 5.1% (World Bioenergy Association, 2019). In terms of electricity generated by solid biofuels, Asia is responsible for the greatest share of generation, followed by the Americas and

Europe with 164TWh, 125TWh and 95.3TWh generated respectively. Oceania and Africa are way behind the global generation of electricity from solid biofuels, with a percentage share of only 0.67% and 0.45% respectively (World Bioenergy Association, 2019). In 2018 in the United States, wood solids (residues from forestry, lumber production and manufacturing, and paper mills) accounted for 21.4 million MWh or 30% of total biomass and waste electricity generation (EIA, 2019c).

There is a growing interest in products derived from woody biomass such as pellets. Pellets are a solid biomass form of fuel that results from the compression of small fractions of biomass (usually woody residues, but it can be agricultural residues) to form a product with high density, high energy content, and easy to store and transport (Braga, 2012). Pellets have great heating properties and therefore are used with that purpose in residences and industries. 35.4 million tonnes of wood pellets were produced in 2018, a 6.5% increase compared to the previous year, and a 48.9% increase in comparison to 2012. When it comes to location, 19.4 million tonnes of pellets were produced by Europe, while 11.2 million tonnes were produced by the Americas. While the production of pellets in Africa and Oceania is relatively minimal in comparison to the other continents, these continents increased their production of pellets 15.1 and 8.3 times between 2012 and 2018 (FAOSTAT, 2019).

Charcoal is another product of biomass used for heating that is mainly derived from woody biomass, and it can also be formed from agricultural residues. Differing from pellets, charcoal is most commonly used in developing countries from Asia, Africa and South America. In 2017, global production of charcoal hit 51.6 million tonnes, 1.6 times higher than pellets production. In Africa alone 33.5 million tonnes of charcoal were produced, followed by Asia (9.05 million tonnes) and the Americas (8.31 million tonnes) (FAOSTAT, 2019).

Chapter 3. Methods

This thesis is a continuation of a previous study developed by O'Neal and Gallagher (2007). In their original study, they analyzed a small-scale harvesting system for biomass operations. O'Neal and Gallagher designed and tested a small-scale feller-buncher along with a skidder and chipper. The results of their studies showed the harvesting system was not economically viable, mainly because the productivity of the feller-buncher was not high enough. In that study, the authors discussed some improvements that would need to be made to better improve the productivity, including some mechanical modification. The modifications and design elements presented here are aligned with their findings.

We understand that a complete harvesting system for biomass harvesting includes operations from cutting of the trees to chipping and processing, and delivering the final product. This project, however, focused on the felling part of a harvesting system. This way we could evaluate economic and mechanical feasibility individually before extending investments to other areas.

3.1 Base Model and Equipment Design

The design of the feller-buncher was projected around the idea of modifying parts of existing equipment, which can reduce the initial capital investments of the machine. Based on that, a mini excavator (Figure 1), model IHI 80 VX, was used as the base for our studies. The excavator chosen operates with a 56hp, water cooled diesel engine, and it weighs approximately

9 tons. This machine has two travel speeds (1.6mph and 2.6mph), its original ground pressure before modifications is 5.2psi, and its slewing speed is 9.2 rpm/min. The machine also has rubber tracks that together with the aforementioned specs should provide less soil compaction, potentially leading to reduced impact on the environment in comparison to conventional felling machines. Another benefit of having tracks over wheels is that when there are excessive machine passes and/or excessive turnings, wheels tend to disturb more the soil than tracks would. To address the impacts of the machine on the soil, we weighed and calculated its ground pressure in psi and compared to its original ground pressure before modifications.

For this study, we proposed two main modifications to improve productivity levels: 1) straightening of the boom, and 2) addition of an auxiliary hydraulic pump. Other modifications such as the addition of a protective cage for safety purposes were also part of the project.

Figure 1. IHI 80VX small excavator before modifications.

3.2 Auxiliary Motor and Felling Head

Because the original machine was a small excavator, we wanted to improve its power by adding an auxiliary motor (Briggs and Stratton #613477-2141, 35hp at 3600 rpm) and a hydraulic pump. With this new setup, the original motor that was used to run the mini excavator will continue to be used for that purpose, while our new auxiliary motor will be used exclusively to run the shear. To achieve a satisfactory severing time, we wanted to increase the machine's hydraulic capacity. The hydraulic component of the head was modified in a way that would allow greater pump flow, which consequently should result in faster opening and closing of the shear head. Additionally, a new hydraulic tank was also designed and installed to work in conjunction with the auxiliary motor running the harvesting head.

Since the machine is proposed to be used for harvesting stands with small diameters, a Fecon shear head (model FBS1400EXC) was chosen to be used as the felling head (Figure 2). This model has a single action knife, weighs about 2,000lb, and has a maximum cutting capacity diameter of 14", which should be more than enough for biomass purposes and thinnings. The original valves on the machine that were previously used to run the bucket were adapted to be used for the felling head. On the modified feller-buncher, these valves will be responsible for the opening and closing of the arms. To run the actual shear on the felling head, a new separate valve was installed.

Figure 2. Fecon shear head.

3.3 Additional Modifications

Knowing that this machine was not designed to handle forest operations, we wanted to

increase operator safety by building a metal cage around the main cab. The cage was built in a

crossed pattern to have minimum impact on the visibility and should protect both the operator

and the new features implemented (auxiliary motor and hydraulic pump) from falling objects.

This cage was not necessarily engineered following standards for the design of cages; the

thought process behind having a metal cage was that, in comparison to having no protection

equipment, this cage should give the operator some level of protection. If standards were to be

followed in the designing of this cage, we most likely would have followed the standard

J1119_201307 provided by SAE International, a global association that develops standards for

engineering industries. This specific standard refers to choosing and utilizing materials in

protective structures (SAE International, 2013).

After the modifications were completed, the resulting equipment was comparable to a

small-scale feller-buncher that we believe could minimize soil disturbance and maximize

productivity.

3.4 Economic Feasibility

The methods used to determine economic feasibility were similar to those used by

O'Neal and Gallagher (2007) in their original project. We used the machine costs calculations

described by Tufts and Mills (1982) in the form of a spreadsheet. Their methodology compiles

the cost to own and operate a machine over the desired economic life of a machine, which in our

case would be 4 years, and the output of their spreadsheet is the cost ($)/ton on an after-tax basis.

Besides determining a depreciation schedule, these calculations include costs for both

fixed and variable costs. Fixed costs or ownership costs are the costs that are going to exist even

if the machine is not being operated, which means that these costs do not depend on the rate of

the work completed. Fixed costs commonly include depreciation, insurance, interest and taxes.

Variable costs are the costs that varies based on the amount of work that is completed; some of

these costs include fuel and lubricants, and maintenance and repairs.

Many of the variables and prices we used came straight from O'Neal and Gallagher's

study, with the exception that, whenever needed, we adjusted the prices to better reflect the used

state of the machine and/or today's cost estimates. To analyze our numbers, we compared our

costs to the costs found in 2007 by O'Neal and Gallagher at their productivity level

(10.6tons/PMH); we also conducted a sensitivity analysis on costs when productivity levels

increased from 10tons/PMH to 16tons/PMH in increments of 1 ton.

Chapter 4. Results and Discussion

4.1 Boom Modification

The first major modification we proposed was the boom modification (Figure 3). When we chose our base model, we purposefully chose a boom machine because this model would reach to individual trees and reduce the travel between cuts which should help minimizing environmental impacts to the residual stand. We believed, however, that the boom on this machine was designed in a way that could hinder the productivity. The original boom was configured for digging and would stick out from the machine during normal operation. This reach, which can be helpful in many cases, was not necessarily for small-scale operations where trees are too small or close together. Also, keeping the original reach of the boom could prevent the operator from rotating the cab in the woods. By straightening the boom (Figure 4), we believed that the operator would gain more flexibility with their movements, being able to bring the boom closer to the cabin, which would result in even fewer trips and consequently greater productivity.

Figure 3. Original design of the boom.

Figure 4. Straightened boom.

We removed the curvature of the boom and welded the remaining parts back together, which resulted in a slightly shorter and straight boom. After this modification, the minimum reach at which the boom can operate (with the felling head close to the ground) is 11'6" (Figure 5), while the maximum operational reach is 21' (Figure 6). At the maximum operational reach, the boom should be able to lift about 500lb. The minimum swing radius when the boom is retracted is 9' (Figure 6). This modification did not change the original minimum and maximum reach of the boom very much, but in normal operating conditions the boom is in a better location

to facilitate the swing of the machine and reduce machine movement before laying bunches down on the ground.

Figure 5. Minimum operational reach of modified boom.

Figure 6. Fully extended boom after modification.

Figure 7. Minimum swing radius of the boom.

A commercially available attachment is used to connect the felling head to the boom

(Construction Attachments, model 1EXSSADPT, Figure 8, Figure 9, and Figure 10).

Figure 8. Excavator to skid steer universal adapter being installed.

Figure 9. Detailed view of the attachment used to mount the felling head on the boom.

Figure 10. Shear head attached to new boom.

With the new boom configuration, it was decided to modify the back part of the felling head. We removed part of a cross bar that was on the top of the felling head so that the bucket cylinder can go through it; by doing that, the operator is going to be able to bring the felling head even closer to the machine (Figure 11, Figure 12) and facilitate swing.

Figure 11. Top view of the modified felling head.

Figure 12. Felling head modification.

To open and close the shears on the felling head, an actuator was placed close to the operator's hand near the right joystick (Figure 13). This way the operator can easily switch between the controlling joystick and the actuator. The hydraulic hoses connecting the actuator and the felling head were placed outside the cabin to protect the operator and minimize interference (Figure 14).

Figure 13. Proximity of the joystick and the actuator used to operate the shear.

Figure 14. Hydraulic hoses connected to the actuator responsible for opening and closing of the shear.

The mechanism responsible for the opening and closing of the gathering arm is controlled by a toggle switch, which was placed near the left joystick, between the second joystick and the arm rest (Figure 15). The accumulating arm will open and close using a foot pedal.

Figure 15. Toggle switch responsible for opening and closing of the gathering arm on the felling head.

4.2 Auxiliary Motor, Gas Tank and Hydraulic Pump

The new auxiliary motor (Figure 16a) was placed in the front part of the machine, slightly below the cabin. We placed the gas tank on top of the motor on a supporting platform in a way that would not affect the visibility of the operator (Figure 16b). In order to achieve a greater hydraulic flow, we added a hydraulic pump that was connected to the motor (Geartek, model C85-2B5); this new hydraulic pump has a maximum pressure of 3500psi, and maximum speed of 3400rpm (Figure 16c).
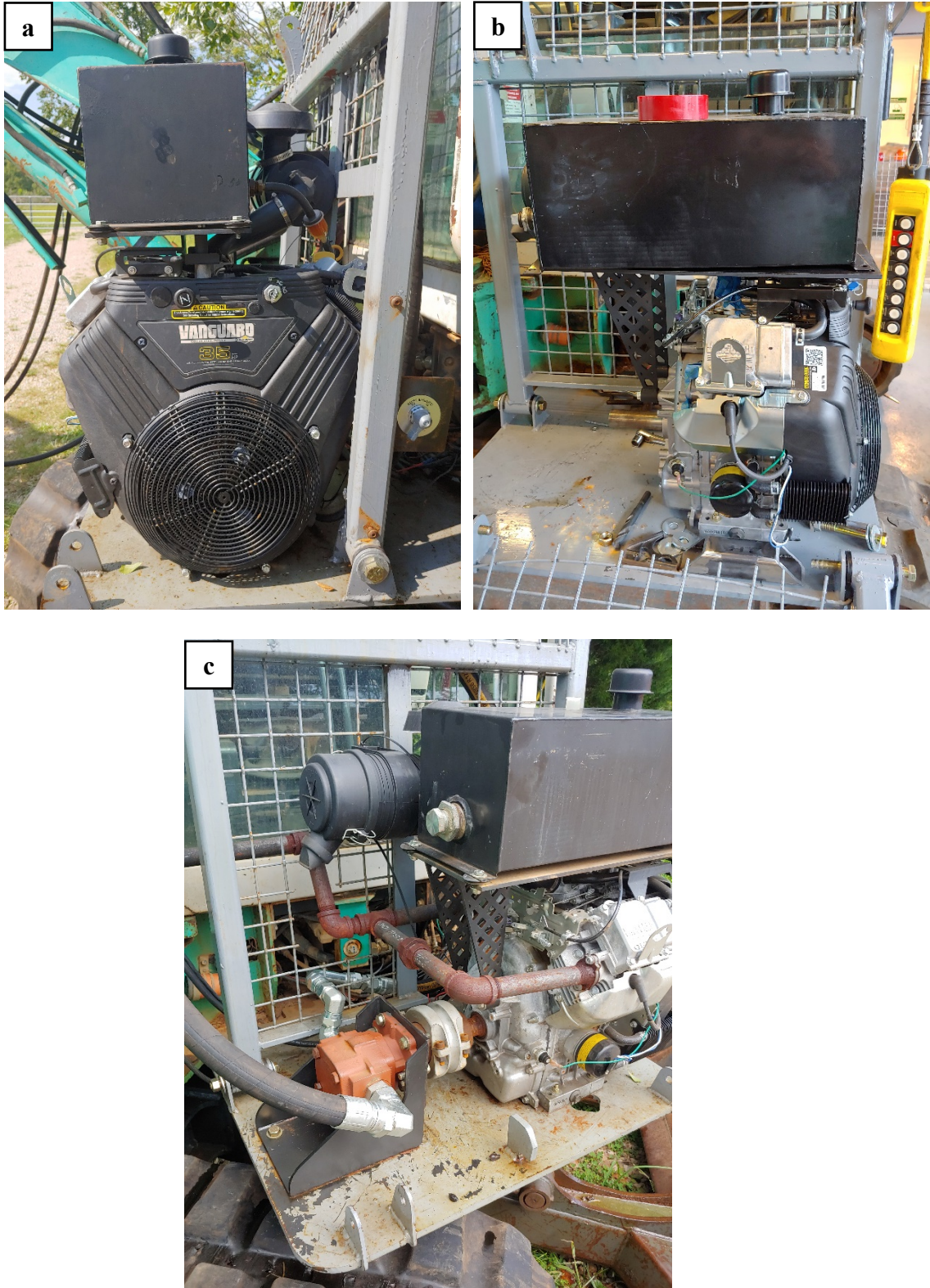
Figure 16. Briggs and Stratton 35hp motor on supporting platform (a). Front view of new gas tank for the auxiliary motor (b). Hydraulic pump connected to auxiliary motor (c).

On the back of the machine, we placed a new hydraulic tank that is going to be used for cooling and filtering the hydraulic fluids (figure 17).

Figure 17. New hydraulic tank for the auxiliary motor.

The motor and hydraulic pump were mounted on a metal platform on the front of the machine. This allows them to be clearly visible to the operator. (Figure 18a and 18b).
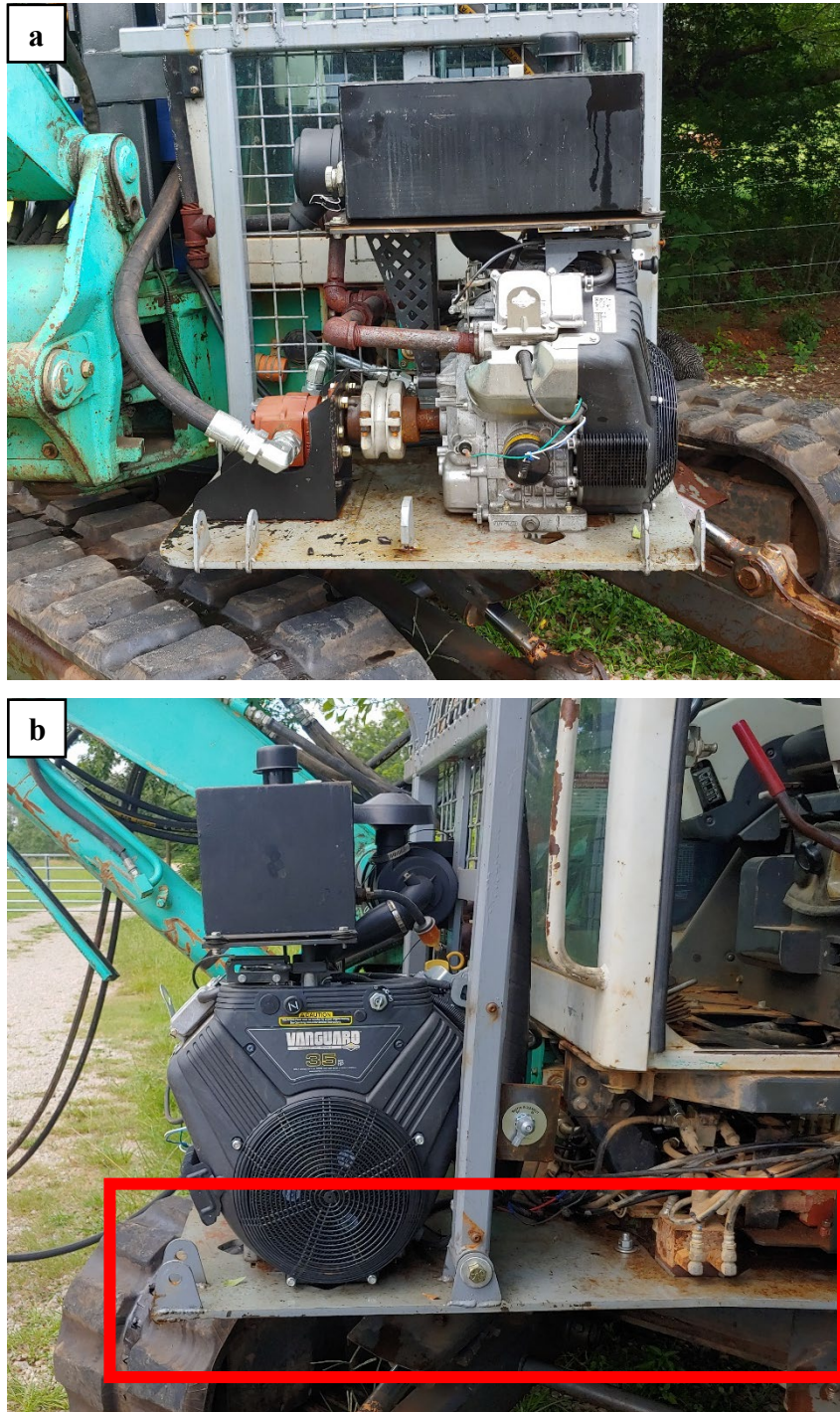

Figure 18. Front view of supporting platform (a). Side view of supporting platform (b).

4.3 Protective Cage

The protective cage was placed around both the cabin for operator safety as well as around the new features (Figure 19a). The part of the cage that protects the auxiliary motor, hydraulic pump and hydraulic tank comes off, allowing easy access to these parts of the machine when maintenance needs to be completed (Figure 19b).
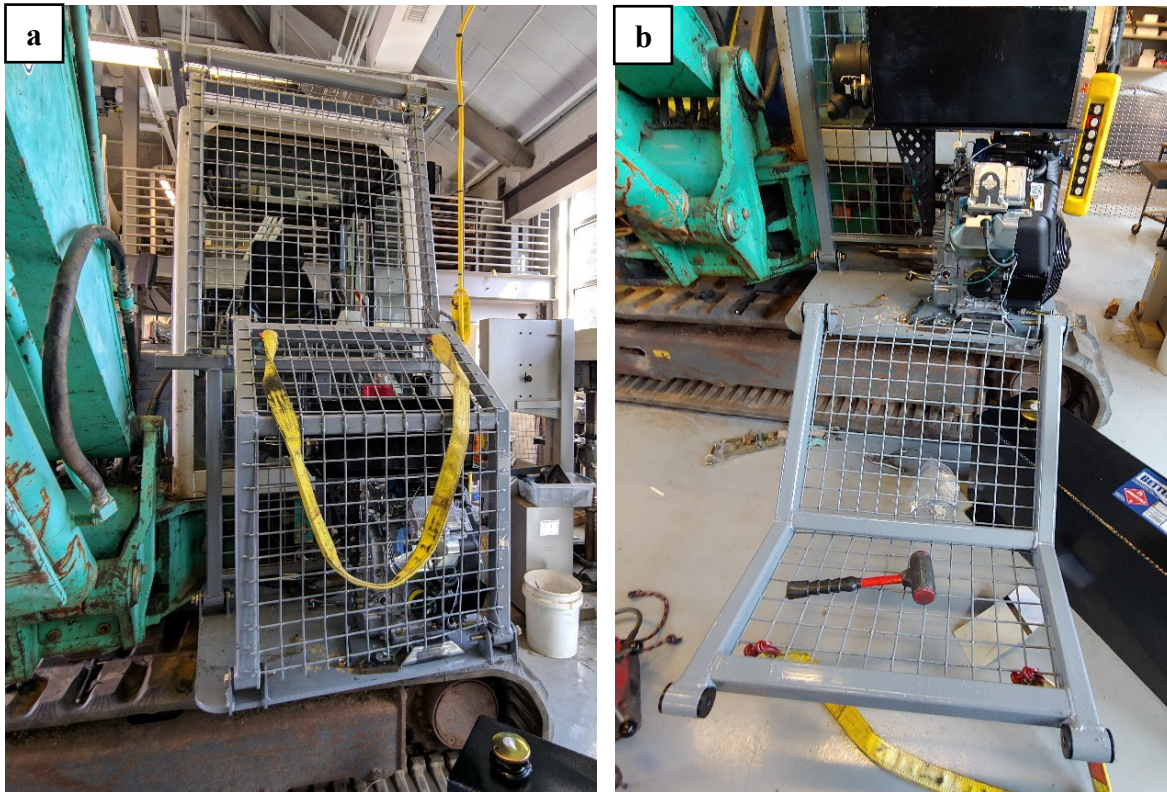

Figure 19. Protective cage (a). Part of the cage that comes off for easy access purposes (b).

Another major question when determining the style of the protective cage was visibility. We selected a cage with a cross pattern that would have minimum interference on the operator's visibility, while still serving as a protection device (Figure 20).

Figure 20. Operator's view from inside of the cab.

4.4 Environmental Impacts

There can be many environmental impacts resulting from forest operations, but damages to the soil such as rutting and compaction are among the most concerning ones. To have an understanding of how impactful our machine could be for the environment and especially the soil, the ground pressure was estimated and compared to a conventionally sized track feller-buncher and a rubber-tired feller-buncher.

After the modifications and additions of new parts to the machine, we estimated its new weight to be around 22,000lb. The tracks were measured and their length and width were 8ft and

18in respectively. We then applied the following formula to find the ground pressure in pounds

per square inch (psi):

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

Where:

P: Pressure
F: Force
A: Area

The result of the above formula was divided by two since the pressure is divided between

the two tracks. The ground pressure of our feller-buncher was found to be approxiately 6.37psi.

This ground pressure was slightly higher than the original ground pressure of the machine

(5.2psi), which was expected because of the modifications we made. On the other hand, the

higher ground pressure of our feller-buncher is still considerably lower than those found in other

commonly used track feller-bunchers for thinnings. In comparison to a John Deere 753J that has

a ground pressure of 7.20psi, for example, the ground pressure of the John Deere 753J is about

13% higher than ours. We also compared the ground pressure on our machine to a wheeled

feller-buncher. For this comparison we used the John Deere 643L. This model has a ground

pressure of 10.6psi, which represents an increase of 66.4% in comparison to our feller-buncher.

4.5 Machine Costs

As this project was a continuation of O'Neal and Gallagher (2007), we incorporated some

of the numbers they used into the financial analysis, adjusting them to today's cost estimates

whenever that was necessary (Table 1).

Table 1. Machine Cost Inputs

Costs	Values
Machine price ($) (NEW)	120,000
Machine modifications ($)	20,000
Economic life (years)	4
Scheduled Machine Hours (SMH/year)	2000
Utilization (%)	80
Loan life (months)	48
Interest rate (%)	6.0
Indirect cost rate (%)	33
Marginal tax rate (%)	28
Discount rate (%)	5.0
Fuel and lube ($/hour)	5.60
Inflate F&L (%)	5.0
Maintenance and repair ($/hour)	8.00
Inflate M&R (%)	15
Labor rate ($/hour)	15.00
Inflate labor (%)	3.0
Fringe benefit (%)	30
Insurance and taxes (%)	4.0
Residual value end of life (%)	20

The majority of the numbers used on our estimations came from the original study; the costs that needed to be adjusted were the purchase price of the machine from $95,000 to $120,000 (price to purchase a new machine), the costs of fuel and lube from $8.75/h to $5.60/h (off road diesel: 1.8 gal/h @ $2.00/gal + $2 for lubes), and the labor rate from $12/h to $15/h. We also included $20,000 for the modifications, which will boost up the price of the machine by 16.7%. In the modifications costs we included the prices to acquire a new motor; hydraulic pump and hoses; felling head and felling head attachment; boom modifications; the safety

modifications and the labor cost. It is important to point out, however, that some of these costs, may vary from location to location, and could be considerably higher.

In their original study, O'Neal and Gallagher found that with an average production of 10.6 tons/PMH, the costs to operate the feller-buncher would be around $4.88/ton. After we input our numbers into Tufts and Mills spreadsheet (1982), we found that by keeping their original production of 10.6 tons/PMH, the updated cost of the machine today would be about $5.41/ton.

We ran the numbers again, this time including the extra $20,000 for the modifications but keeping the production levels the same 10.6 tons/PMH; given all the variables included, the final cost to operate our small-scale feller-buncher after modifications would be around $5.70/ton. Comparing the costs to operate the machine before and after modifications, we found that the cost to run the modified machine is only $0.29 higher than the costs to operate the machine without the modifications, which represents an increase of 5.4% (Table 2).

Table 2. Costs/ton to operate the feller-buncher at a production rate of 10.6 tons/PMH.

Machine	Cost/ton
O'Neal and Gallagher (2007)	$4.88
O'Neal and Gallagher (2020)-rev.	$5.41
New machine after modifications	$5.70

Although the cost to operate the modified feller-buncher would currently be higher than what it was when O'Neal and Gallagher first developed their project, the $5.70/ton is still lower than the $6.87/ton (€5.83/ton) operating costs of a medium-sized chainsaw used by Spinelli and Magagnotti (2010); if we take into consideration that Spinelli and Magagnotti's study was

developed 10 years ago, their costs to operate a medium-sized chainsaw nowadays would most likely be even higher.

Besides comparing our numbers to those found by O'Neal and Gallagher, we wanted conduct a sensitivity analysis to estimate what the costs would look like if different production levels were achieved. It was already expected that the costs per ton would decrease as the production increased, but we found out that there is a very strong correlation of -0.9909 between production and cost, meaning that the decrease in costs is almost perfectly inversely proportional to the increase in production (Figure 21). This negative correlation is mainly caused by average of the ownership costs (fixed costs) and the variable costs; given that variable costs tend to grow based on the amount of work that is done, the correlation between variable costs and production would not necessarily be inversely proportional.
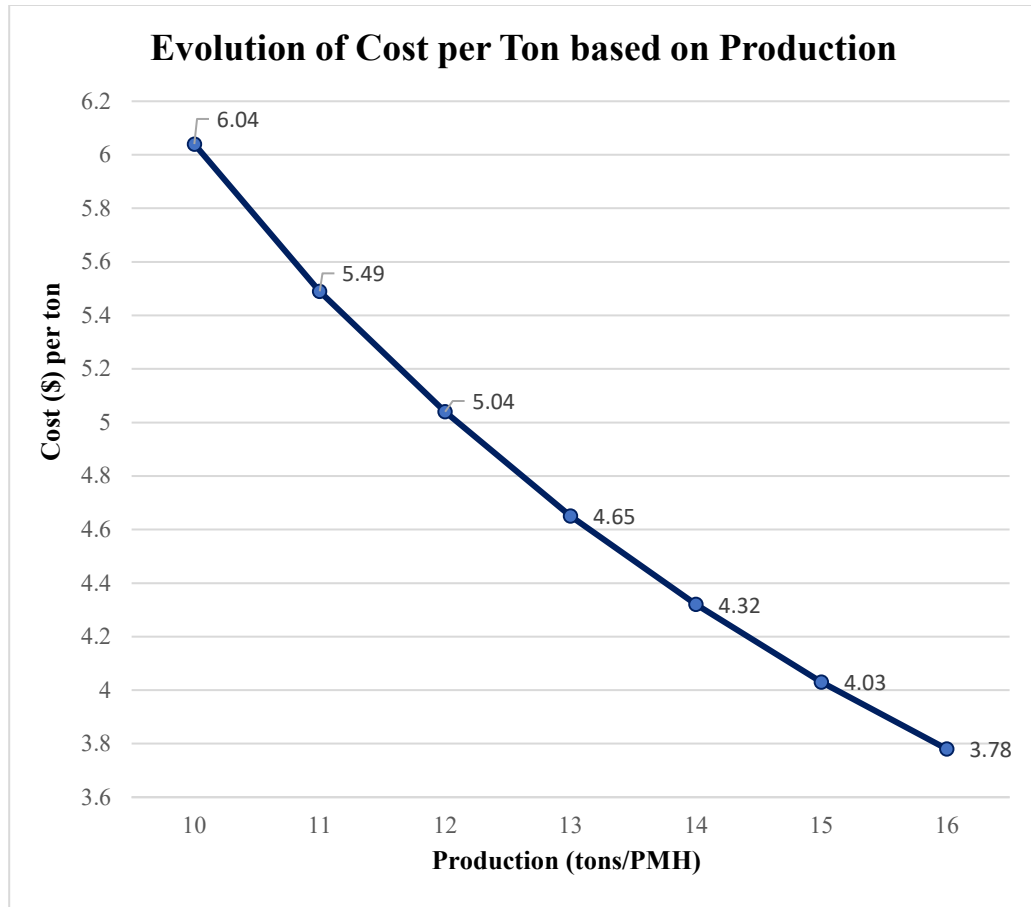
Figure 21. Evolution of cost when production is increased.

As it can be seen on Figure 21 above, costs per ton drops considerably from $6.04/tons when production is 10tons/PMH to $3.78/tons at a production level of 16tons/PMH. At the level production rate of 15.6tons/PMH desired by O'Neal and Gallagher (2007), the operating costs of the machine will be $3.87/ton.

4.6 Machine with All the Modifications

After all modifications were completed, the final machine should be able to be operated as a small-scale swing boom feller-buncher for thinning operations (Figure 22, Figure 23, and Figure 24).

Figure 22. Side view of feller-buncher.

Figure 23. Front view of feller-buncher.

Figure 24. Back view of feller-buncher.

Chapter 5. Conclusion

Although large-sized feller-bunchers tend to be more productive in many case scenarios, investing in these machines might not always be the best option from an economic and environmental standpoint. The capital costs of these machines are usually high, and when used to harvest small-scale forests, their size can hinder productivity and cause a lot of residual stand damage. Developing a small-scale feller-buncher using an excavator can be very promising given the reduced costs, and especially for areas like in the southern United States where there is a high abundance of trees on small tracts.

We estimated that the capital investments to modify our machine would be $20,000, which would result in a final purchasing price of $140,000. This number represents a 16.7% increase in cost when compared to the machine before modifications, however, the cost/ton to operate our machine is only 5.4% higher than the cost/ton to operate the machine before modifications (given a production level of 10.6tons/PMH).

As expected, the relation between costs and production is inversely proportional, as the production goes up, the operating costs decrease. If the newly modified machine is able to achieve the exact same productivity as before, operating costs will be around $5.70; if productivity can be raised to the theoretical rate of 15.6tons/PMH proposed by O'Neal and Gallagher, the costs to operate the machine will drop to $3.87/ton.

This project focused primarily on applying the design changes O'Neal and Gallagher proposed in 2007 and the productivity and costs described here were based on the actual and

hypothetical productivity adopted by those researchers. In order to fully evaluate the impacts and efficacy of these modifications on productivity, additional research including field tests should be completed. For information on how to proceed with the data collection and productivity study for this feller-buncher, see Appendix A.

Furthermore, if this project were to be replicated in the future, we would suggest some minor modifications that could make cutting cycles shorter and eventually aid in better productivity. For instance, instead of using a toggle switch to open the arm on the felling head, future modifications of this machine could have a rocker switch for easier operation. Also, the placement of this switch could be on top of the joysticks; this way the operator would not need to move their hands frequently in order to turn the switch on and off, which would not only be more efficient but also more ergonomic. An engine that runs on diesel instead of gas would also reduce the amount of modifications needed in the area of the auxiliary motor.

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Appendix A

Prior to the data collection

It is of major importance to know the characteristics of the site where harvesting operations is going to take place. Some features that must be known are location; tract size; site slope; soil characteristics; stand characteristics; and many others. A preliminary cruise should give an idea of the stand composition. In this cruise, trees have to have their diameter at breast height (DBH) and height measured, besides measuring the spacing between the trees and the trees per acre.

Based on that information, the research team should choose the design of their study and how the harvesting activities are going to be conducted. If it is a thinning operation where the intent is to remove every third row, for example, the research team should go out and measure the DBH and height of every single tree in each of the rows that are going to be cut. Each tree should be marked and numbered (possibly with paint and on more than one side of the tree) with a unique number for easy identification.

By measuring each tree individually, the research team should be able to get accurate estimations of volume per stem and green weight of harvested trees.

Study Design

The felling operator should be given the opportunity to run the machine in the forest stand to become familiarized with the equipment, the site, and the expected silvicultural regime.

This phase serves as a way of minimizing the human variability on the results of the feller-buncher productivity. To minimize this variability even further, the operator chosen should be preferably experienced in the use of forestry machinery, and using boom type machines. The experience of the operator may be a determining factor affecting productivity, thus the importance of having an experienced operator. After the period of familiarization, the operator should be ready to start the field tests. The silvicultural regime chosen will depend on the characteristics of the site, especially the density of the trees.

Data Collection and Productivity Study

To analyze a project like this, an elemental time studies will be completed. This time study method to analyze productivity tends to be more detailed and considers different sources of variability.

Small HD video recorders are the main piece of equipment for this data collection. These cameras can be attached to the exterior of the excavator cabin at an angle that best captures how the machine operates, or they can be held on a tripod at a safe distance from the feller-buncher. If held on a tripod, as the feller-buncher cuts the trees, someone should be calling the identifying numbers of those trees, so when the videos are reviewed, the research team can easily associate each tree that was cut to the DBH and height of the trees.

After the videos are shot on the field, the files need to be reviewed in the office. While watching the videos, the research team should look for how long it took for each process to be completed. The processes or elements that are relevant for the analyses are driving to first tree; cutting; intermediate travel to the next tree; driving to dump; dumping; and various types of delays (mechanical, operational, and others). Considering that density and spacing of the trees is

a major factor affecting productivity, the research team can paint the tracks on the feller-buncher and use that to estimate distance traveled between cycles. By painting the tracks, the research team should be able to tell when the machine makes a partial or full revolution, and therefore that can be related to distance.

After all that data has been collected and analyzed, different outcomes can be achieved. The research team should be able to create a graph relating time to harvest the trees and diameter class; this graph would most likely show that harvesting trees with a higher DBH takes more time. The research team should also be able to relate the productivity in tons/hour to the diameter classes, and get a statistical analysis resulting in a regression equation for production. This graph should most likely show that the larger the volume/tree, the more productive the machine can be. Another positive outcome of this analysis would be checking what elements of the harvesting cycle may need some more efforts to increase efficiency