ECONOMIC FEASIBILITY OF GROUND-BASED STEEP SLOPE LOGGING USING WINCH-ASSIST TECHNOLOGIES

FACULTY OF NATURAL RESOURCES MANAGEMENT

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ABSTRACT

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Keywords: winch-assist, steep slope logging, sensitivity analysis, break-even analysis, forwarder, harvester, cable yarding, mechanized harvesting, British Columbia

This thesis examines the use of winch-assist technologies in logging operations in the interior of British Columbia. The data used for this thesis is from a contractor's (located in Central B.C.) professional judgment as well as from other studies that took place near this area. The objective of this thesis was to determine the economic feasibility of winch-assist logging systems and compare the cost ($\$/m^3$) to cable yarding systems. Comparisons between systems were made using a costing model that determined the total cost of wood to roadside for three different systems including; winch-assist, cable yarding with manual falling and cable yarding with mechanized felling. In addition, a sensitivity analysis was used to determine how sensitive cost was to a variety of variables. The analysis done is within the reasonable scope of the requirements of an undergraduate thesis.The results found that cost ($\$/m^3$) was most sensitive to productivity and machine utilization. A key finding of this thesis was cable yarding systems with mechanized felling had the lowest overall cost. The implications of the results and the applications of winch-assist logging systems are discussed further throughout the thesis.

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I would like to thank FPInnovations for providing me with many reports on winch-assist studies and answering many of the questions I had. These reports were a critical resource that I used in my literature review and for my costing model.

Lastly, I would like to thank the logging contractor in British Columbia for allowing me to tour their operation and providing estimates on production and costs as well as answering many questions I had along the way. This experience was not only important for my thesis but also for my future professional career.

1. INTRODUCTION

New technology in ground-based steep slope logging has sparked increasing interest in western Canada. Winch-assist logging equipment has been developed to increase the safe operating range of equipment on steep slopes (>35%) by increasing the traction between the drive wheels and the ground (Amishev 2016). The winch can either be attached to the chassis of the primary machine and secured to an anchor point or a secondary machine can be used to house and operate the winch (Visser and Stampfer 2015). There are currently 800 winch assist-units available worldwide and expected to be more on the way as interest grows (Dyson 2017). Mechanization of steep slope harvesting provides an attractive solution to reduce accidents to manual workers and adapt to new harvesting terrain. The introduction of winch-assist technology may also increase the amount of economically accessible timber on steep slopes. This is of particular importance for B.C. because of recent reductions in the annual allowable cut (AAC) for many timber supply areas (TSA).

Accessing fibre on steep terrain generally poses the problem of increased operating and capital costs. For the licensee, logging on steep slopes will result in higher fibre costs as well as harvesting different species mixtures (Stirling 2017). In addition, logging contractors may not be able to afford the high capital cost of new equipment and will be slow to start up due to the steep learning curve for operators. The problems presented all question the economic feasibility of ground-based steep slope logging in interior British Columbia.

The logging contractor providing input for this study is located in the interior of B.C. and is an integrated logging and road construction company. They annually deliver 900 000m^3 of fibre from stump to the mill. Recently, they updated their logging fleet to include winch-assist equipment in order to access timber on steep terrain. The key machines in the contractor's steep slope arsenal are a wheeled John Deer 1910E cut-to-length forwarder and a Tigercat 1185 wheeled harvester tethered to a T-winch. The steep-slope ground targeted for the operation ranges from 40-80%, however, the terrain in the region is inconsistent, containing steep pitches and flat sections.

The goals of this study are outlined in the objective section of the report and will be used to guide the direction of the research. Using the data collected, an assessment on the economic feasibility of the contractor's steep slope operation can be made. A break-even analysis is used to compare two cable yarding (grapple) systems to a ground-based winch-assist system. The analysis done is within a reasonable scope of an undergraduate thesis. A description of how data was collected and analyzed for this study are explained in detail in the materials and methods. This section also describes the costing model and sensitivity analysis used to determine the results. The literature review describes the current technology in ground-based steep slope logging and its development in western Canada. Additionally, a variety of logging systems and purpose-built machines for steep terrain are compared. In the results section, the sensitivity analysis shows how sensitive the cost ($\$/m^3$) is to changing various inputs. The findings of the break-even analysis are also presented. The discussion examines the implications of the sensitivity analysis and break-even analysis. From the findings of this study, recommendations are made on where winch-assist logging systems are best suited and the threshold for using ground-based logging technologies over cable yarding systems. In addition, recommendations are made on where research for future studies should focus to further improve the economic feasibility of winch-assist operations.

1.1. OBJECTIVE

The objective of this thesis is to determine the productivity and costs of a winch-assist steep slope logging operation and examine its economic feasibility. Using a break-even analysis with the input from an operation, a comparison can be made between a winch-assist system and a cable yarding (grapple) system with and without mechanized felling. The implications of using winch-assist technology in terms of productivity and cost are of particular interest in this study. The findings of this thesis will provide insight into the application of ground-based steep slope logging with the use of winch-assist technology in interior British Columbia.

1.2. LITERATURE REVIEW

Steep slope harvesting has been an ongoing challenge in forest operations due to high costs and safety implications. Conventional mechanized ground-based systems are constrained to terrain factors such as slope, soil strength and roughness (Visser and Stampfer 2015). Mechanized harvesting equipment is typically restricted to 35% slope for rubber-tired skidders and forwarders, 40% for tracked machines and 50% for any purpose-built equipment designed for steep slopes (Visser and Stampfer 2015). Steep slopes will be defined as greater than 35% for the duration of this report.

Accessing fibre on steep slopes has in the past been limited to harvesting systems such as helicopter logging, cable yarding and manual felling; however, these options have associated high costs and risks to workers relative to mechanized ground-based operations (Amishev 2016). Therefore, expensive steep slope logging operations are generally preferred for high-value, large diameter stems. Technology involving the use of a winch to assist machinery on steep slopes has provided a viable option to increase the mechanization of steep slope logging. The terms winch-assist, cable-assist, traction-assist and tethering all refer to technology that allows ground-based equipment to operate on steep slopes (Amishev 2016). Winch-assist technologies can be used on both tracked or wheeled machines and work by increasing the traction between the drive wheels or tracks and the ground (Dyson 2016). This technology may benefit the forest industry by increasing productivity, improving quality and environmental management and improving health and safety standards to workers (Amishev 2011; Strimbu and Boswell 2018). The use of winch-assist in forestry is gaining popularity with over 800 commercial units in use worldwide (Dyson 2017).

1.2.1. Types of winch-assist systems

There are a variety of winch assist technologies currently available for the forest industry. These systems have evolved and diversified with advancements in technology and feedback from users in the field. Winch-assist systems have been commercially available since the early nineties in Europe where they were primarily used on forwarders (Visser and Stampfer 2018). These systems are now highly versatile and can be used on most forestry equipment. There are two main types of winch-assist systems. These include integrated winch systems and anchor machine winch systems (Amishev 2016).

The most common winch-assist design is the integrated winch system, where the winch unit is mounted on the chassis of the primary machine (Visser and Stampfer 2015). The winch can be permanently attached to the machine or bolted on for easier removal and transfer of the winch between machines. The tether line is attached to a deadman, stump or mechanical anchor (Sessions et al. 2017). The cable used ranges from 14mm to 28mm in diameter, depending on the size of the equipment (Holzleitner et al. 2018). A radio input is required for the anchor monitoring device to ensure the anchor is stable (Amishev 2016). Typically, when using an integrated winch system, the winched machine starts at the top of the slope and works its way down. For a tethered harvester or feller buncher, cutting on the downslope prevents interference with the cable and facilitates trees for uphill extraction (Sessions et al. 2017). Once the cable is spooled and secured to an anchor point, the machine works its way down the felling corridor. Alternatively, when the top of the harvest block is inaccessible, the winched machine may work up from the base of the slope using intermediate anchor along the slope or a “strawline” could be used to rig the primary cable (Amishev 2016). Moving the cable between anchor points when moving across the harvesting profile can take between 10 and 15 minutes depending on the terrain and weather conditions (Amishev 2016). The integrated winch system can be advantageous because only one machine is required compared to the anchor machine winch system (described below). This results in lower capital costs, operating costs and transportation costs. However, adding the winch unit onto a machine increases the overall weight and power requirements (Visser and Stampfer 2015). Modification to the machine includes a monitoring system and a fairlead to ensure the cable doesn't move along the ground (Visser and Stampfer 2015). Manufactures of the integrated winch system includes all European winch-assist systems and the New Zealand made ClimbMAX (Amishev 2016). John Deere and Ponsse have teamed up with manufacturers Haas and Herzog respectively to develop integrated winch systems specifically designed for their machines (Amishev 2016).

Anchored machine winch-assist systems involve the use of a secondary machine to house and power the winch, which is tethered to the primary harvesting machine (Amishev 2016). The winch can be remotely powered, allowing the operator to work from the safety of his cab. This system is gaining interest as various new purpose-built machine are being designed specifically for the role of operating the winch as well as design options to mount winch units on existing equipment. In comparison to using machines with an integrated winch, this system can be advantageous because there are reduced weight and power requirements for the machine working on the slope (Visser and Stampfer 2015). This system provides flexibility as both the anchor machine and assisted machine can be detached and perform separate tasks when the winch is not required (Amishev 2016). The external winch system may also be used where there are no suitable anchor trees and the base machines ability to rotate and tilt may result in better alignment with the assisted machine (Boswell 2018). The type of anchor machine used can vary depending on factors such as the contractors budget, equipment available and type of assisted machines being used. The types of anchors primarily used include, bulldozers, excavators and purpose-built machines (Amishev 2016).

Bulldozers are used as anchor machines due to their low centre of gravity, hydrostatic drive and the large blade ensures a secure anchor point (ROB 2018). Using excavators as anchor machines can be beneficial because of their versatility. This allows them to be used for multiple tasks as well as increased maneuverability to pull themselves up steep slopes (Amishev 2016). Purpose-built machines are designed and operated specifically to house and power traction aid winches. Unmanned machines can be advantageous because there are reduced safety risks for operators and their relatively small size allows for easier transport and repositioning (Amishev 2016). There are currently two fully remote-controlled winch-assist anchor machines. These include the Austrian EcoForst T-Winch and the Canadian T-Mar Rhino (Amishev 2016).

1.2.2. Environmental considerations

The use of mechanized equipment on steep terrain has been until recent years relatively uncommon and thus there are gaps in knowledge on how this introduction will affect the environment. Using mechanized equipment in many cases has adverse effects on soil properties and these effects often become amplified as slope increases. Risk of damage to the soil is generally higher on steep terrain due to loss of traction and increased shallow soil disturbance (Thompson and Hunt 2016). The effects of harvesting upslope may have negative consequences for downslope areas such as alteration of drainage pathways and mass wasting events. The British Columbia Ministry of Forests have made soil conservation a priority in the province and are particularly concerned with disturbances linked to natural hydrology and soil productivity (Curran 1999). The forest practice code allows up to 5 or 10 percent net disturbance within a cut block, excluding permanent roads (Curran 1999). There is concern that the allowable soil disturbance levels may not be achievable with the increased mechanization of steep slope logging. Sologi and Najafi (2014) listed a variety of studies that showed increases in soil disturbance were positively related to increasing slopes. Logging on steep slopes increased the bulk density which in turn decreased the total porosity and moisture content (Sologi and Najafi 2014). Soil disturbance can be limited by using residual biomass on high traffic areas within a harvest block (Sessions et al. 2017; Dyson 2016). In addition, limiting the ground pressure of machines by using high floatation tires (Visser and Stampfer 2015) and a flexible suspension to spread the pressure distribution minimizes soil disturbance (Sessions et al. 2017).

Winch-assist systems are designed to minimize some of the negative impacts of steep slope harvesting by preventing the loss of traction and subsequent soil damage. Winch-assisted machines move straight up and down slopes with increased traction, fewer turns and better ground contact relative to untethered machines (Thompson and Hunt 2016). The use of winch-assist equipment can extend the harvesting season because of the greater ability to operate in adverse ground conditions with additional traction. Winch-assist systems can also reduce the required amount of haul road construction because of increased forwarding distance and the ability of feller bunchers to move trees short distances to avoid deflection obstacles (Thompson and Hunt 2016).

Visual quality management is a major management objective in B.C. that is primarily in place to ensure scenic quality expectations of the public and tourism industry are met (B.C. MFLNRO 2018). Harvest blocks on steep slopes are most confined by visual quality guidelines because they are most visible to the public. The B.C. ministry classifies harvest intensity into 5 categories (Preservation Retention, Partial Retention, Modification, and Maximum modification) (B.C. MFLNRO 2013). The sensitivity of the landscape being harvested is determined by the district manager based on consultation with stakeholder, First Nations and the public (B.C. MFLNRO 2018). A final determination of the amount of modification to the landscape is determined based on the results of the consultation. Restrictions on steep-slope harvesting can further increase costs and potentially lower profit margins.

There are two main types of soil disturbances from mechanized steep slope logging that may result in visual quality concerns. The first is exposed mineral soil from felling and skidding /forwarding activities which are expected to have a short-term visual quality impacts (Thompson and Hunt 2016). The second is disturbance from purpose-built skid trails which may restrict revegetation and have a longer visual quality impact (Thompson and Hunt 2016). In order for mechanized steep slope logging to operate in visually sensitive areas, management strategies must be in place to minimize ground disturbance and view of area harvested.

1.2.3. Safety factors

Steep slope logging is generally considered a high-risk activity due to the increased requirement of manual workers. WorkSafeBC's statistics from 2012 showed that injury rates are more than 10 times greater than mechanical felling operations (Gingras et al. 2015). Safety issues from conventional steep-slope logging arise from activities requiring the use of manual and motor manual workers, including hand felling and using choker setters in the extraction phase of cable yarding (Visser and Stampfer 2015). A large priority of increasing the mechanization of steep slope harvesting using winch-assist technology is to reduce the risk to manual workers. With advancements in winch assist technology, this goal is becoming increasingly achievable as the operability of machines is extended to steeper slopes. Operating logging equipment on steep slopes has a number of associated risks. The primary risk is a loss of machine stability and traction, resulting in a rollover. The basic principle when working on steep slopes is that the gravitational force pulling the machine down should not exceed the traction force the machine is able to generate on the ground (Visser and Stampfer 2015). Sessions et al. (2014), found that maximum gradeability was affected by tether tension, track slip, soil strength, grouser depth, hitch height, boom position, and grapple load. A risk assessment should be completed before operations on steep-slopes begin to evaluate the hazards and prescribe controls to minimize risks (BC Forest Safety 2015). In general, to avoid the risk of rollovers, machines should work straight up and down the hill and give extra caution when working in wet sites or broken terrain (Amishev and Hunt 2018). The owner's manual should be referenced for machine specific guidelines on slope limitations. If the maximum slope is not stated operators should follow Work Safe BC's regulations on slope limitations for rubber-tired skidders (35%), tracked machines (40%) and forestry equipment designed for steep slopes (50%) (Visser and Stampfer 2015). These regulations are in place to ensure the stability of equipment and safety of operators when working on steep terrain. Logging equipment may be operated beyond these slope limits if a qualified person conducts a risk assessment and written work safe practices are developed and implemented (Visser and Stampfer 2015).

Winch-assisted equipment mitigates the risk of rollovers by preventing a loss of traction when working on steep slopes. To ensure safety during operation, the overarching principle of winch-assist systems is that machines are not suspended from the cables and the assisted machine should be able to stop in full control without reliance on the cable (Amishev 2016; Fullerton 2016). There is an increased risk to workers when using winch-assisted equipment due to the risk of high tension cables snapping. To mitigate this risk, it is recommended that cable tension is limited to 33 percent of its breaking load at all times and the cable should be inspected for damage regularly (Visser and Stampfer 2015). In addition, operators and workers should establish a safe working zone when winch-assisted equipment is working (Amishev and Hunt 2018). To ensure the security of anchors, monitoring devices are also used to inform operators if the anchor moves. FP Innovations has recently produced a best practice manual for winch-assisted harvesters. This document provides many valuable recommendations and should be referenced by operators to ensure safe work practices when working on steep slopes (Amishev and Hunt 2018)

1.2.4. Impacts on productivity

The productivity of winch-assisted machines can vary greatly depending on a variety of factors. The contractor proving input for this study suggested snow, terrain, and slope all impacted productivity. These factors affecting productivity were also mentioned in other studies, for example, Dyson and Strimbru (2017), reported a decrease in productivity where slopes exceeded 60%, in deep snow (> 1.5m) and where exposed rock was prevalent. Operator skill level and comfort have a large impact on productivity, however, it is difficult to quantify its direct influence (Dyson and Mologni 2018). The productivity of winch-assisted harvesters and forwarders are negatively affected by decreasing average piece size and increasing number of log sorts (Dyson and Mologni

2018). Corridor length is another important factor that influences the productivity of winch-assist operations (Dyson and Mologni 2018). Short corridors result in more unproductive time spent on rigging and lower utilization.

1.2.5. Timber supply in B.C.

The annual allowable cut (AAC) is the maximum level of harvesting permitted in order to balance social, economic and environmental objectives. Areas regulated by government-set AAC's account for 90% of the total harvest in B.C. (B.C. MFLNRO 2018). Generally, the AAC for a given timber supply area (TSA) provides a sufficient amount of fibre for sawmills in the area. In the past 10 years, the average annual allowable cut was 83 million cubic metres per year and the average harvest was 67 million cubic metres (B.C. MFLNRO 2018). However, AAC's throughout the province have been decreased due to forecasted declines in timber supply as a result of wildfires and mountain pine beetle attacks. The provinces timber supply is expected to decrease from 70 million cubic metres per years to 58 million cubic metres per year (B.C. MFLNRO 2018). In 2017 the AAC in the Prince George TSA has been reduced by 33 percent from 12.5 million cubic metres set in 2011 to 8.3 million cubic metres in the first five years to 7.3 million cubic metres in the following five years (Maureen 2017). Reductions in AAC'S are likely to have negative effects for many sawmills. As supply is constrained, timber prices are likely to increase, and this will put more pressure on sawmill profit margins (Swantson 2017).

1.2.6. Break-even analysis

A break-even analysis is a valuable tool commonly used to aid in the decision-making process for any business. It is concerned with predicting costs, volume and profit as the level of activity changes (Hussey 1989). The break-even point is determined where total income generated is equal to the total expenses including fixed and variable costs (Tsorakidis 2014). This value is important when deciding to invest in new products or bid on a job because it indicates how sensitive the profit is to changes in production and costs (Tsorakidis 2014). The break-even point will provide financial managers with a minimum level of production required to make a profit based on total costs. A break-even analysis can be done by using the graphical method or algebraic method (Goyal 2012).

Wegner (1984) demonstrated how to algebraically calculate the break-even volume of producing seedlings in a nursery. The following equation was used to determine the level of production required to break-even on the operation. This equation is referred to as the contribution margin approach (Goyal 2012).

$$\text{Break} - \text{even volume} = \frac{\text{fixed costs}}{(\text{selling price per unit}) - (\text{variable cost per unit})}$$

The break-even point may also be calculated using the Margin of Safety ratio. The ratio is the proportion by which actual sales may fall before they become less than the break-even revenue (Goyal 2012). This is essentially the amount of buffer before losses will occur.

$$Margin\ of\ Safety = \frac{\text{Actual sales} - \text{B.E.P.}}{\text{Selling price per unit}}$$

A break-even analysis can be solved graphically by plotting the variable costs, fixed costs and revenue on a graph where the x-axis represents production and the y-axis represents revenue generated. The break-even point is found at the intersection of the total cost and total revenue line (Tsorakidis 2014). The angle between the total costs and total revenue lines is defined as the angle of incidence. The angle of incidence provides a measure of the degree of safety of the profit (Goyal 2012). A high angle of incidence represents high-profit increases while a low angle of incidence represents slow increases in profit after costs are recovered (Goyal 2012).

A break-even analysis may also be used when choosing between different alternatives on a total-cost basis when the revenue generated from each alternative is the same (Wegner 1984). Amishev (2011) used a break-even analysis to compare the costs of steep slope harvesting using a winch-assisted harvester and using manual felling. In the study, the harvester's required percentage to break even with the manual felling system was determined based on different capital costs and productivity ranges. Financial decision makers can determine if it is economically feasible to invest in new equipment based on the break-even productivity usage compared to their current equipment.

1.2.7. Cable yarding

Cable yarding involves the use of cables to transport wood from a cut-block onto a landing. Various types of cable yarding systems remain the mainstream way to access fibre on steep terrain (Visser and Stampfer 2015). The yarding cycle involves four phases: i.e. the outhaul, hooking, inhaul and unhooking (Conway 1982). The outhaul is when the carriage is sent to the location of the logs. Hooking involves securing the logs either with chokers or a grapple. The logs are pulled to the landing during the inhaul. Lastly, the logs are placed at the landing by chasers or the grapple releases the logs. A yarder is the central element of any yarding operation. They are generally diesel powered and have one to four drums that are used to store line and transfer power (Conway 1982). Spars, in addition to the natural terrain, are used to provide the vertical lift essential to cable yarding (Conway 1982). If a skyline system is being used the skyline will be suspended from the headspar (spar closest to the yarder) to the tailspar (spar furthest from the yarder) (Conway 1982). The distance between these spars is referred to as a span(s) (Conway 1982). In order for any skyline system to work, there must be deflection (Conway 1982). Deflection refers to the amount of sag in the line often expressed as a percentage for the span (WorkSafeBC 2006). Deflection is limited by the length of the span, line size, slope of ground and spar and support heights (Conway 1982).

There are 3 main types of cable yarding. These include; single drum and mainline system, high-lead system and skyline systems (WorkSafeBC 2006). For the purpose of this report, skyline systems will be the primary focus. There are 3 main types of skyline systems that are classified by their movement. These include; standing skyline, running skyline (scab) and a live skyline (Conway 1982). A standing skyline is secured and anchored at both ends, so the line cannot move (Conway 1982). A live skyline or “slackline” can be raised and lowered, generally with the use of a fourth drum (Conway 1982). In a running skyline system, the skyline runs through a block at the tailspar and back to the carriage, so that it acts effectively as both the haulback and the skyline (USDA Forest Service n.d.). This system works with three drums (mainline, skyline and slack pulling line) when operating a mechanical slack pulling carriage and two drums (skyline and mainline) with other carriages (USDA Forest Service n.d.).

To transport the logs, a carriage configuration holding either a series of chokers or a grapple can be used. Types of carriages include: motor-driven radio controlled self-clamping carriage, mechanical accumulator carriage, motor-driven self-propelled carriage, mechanical slack-pulling carriage, and north bend and south bend-rigged skyline carriage (WorkSafeBC 2006). Chokers are cables with a bell connector that are wrapped around a log and tighten as yarding is initiated. Grapple heads can be mechanical, hydraulic, remote controlled and stochastic (Conway 1982). A mechanical grapple can be used with the running skyline system and works best with shorter yarding distances along with larger timber (Conway 1982). The grapple rides on a carriage supported by the haulback line and is opened with the use of the slack pulling line (Conway 1982). The grapple yarder operator is guided by a spotter or the use of video cameras to aid in picking up bundles or individual trees (Visser and Harrill 2017).

1.2.8. Mechanical vs Manual felling in Cable yarding systems

With the introduction of winch-assist technologies, there are more opportunities to use mechanized felling in cable yarding systems. A variety of studies have compared the cost and productivity of cable yarding systems with mechanical and manual felling. Mechanized felling can be more productive and have a lower cost than hand felling, especially in stands with a lower average piece size (Amishev and Dyson 2016). When using a grapple yarder in second-growth stands with a smaller average piece size, yarding bunched stems can be advantageous because of an increase in the average number of stems per turn (Dyson 2016). Studies by Dyson (2016) and Chung and Garrelts (2019) both found a significant decrease in unit production cost ($\$/m^3$) when using mechanized felling compared to manual felling. The processing phase of the production phase may also be improved because bunched stems produce neat decks and well aligned (Dyson 2016). Wood and quality utilization may be high because of decreased stem breakage (Amishev and Dyson 2016; Dyson 2016)

2. MATERIALS AND METHODS

2.1. MACHINES STUDIED

On December 3, 2018 I flew to Prince George B.C. to tour a winch-assist steep slope logging operation. I observed two John Deere 1910E winch-assisted forwarders with Haas traction aid winches (Figure 1) working on steep terrain. The forwarder has 249 horsepower with a load rating of 19t and a maximum boom reach of 8.5m (John Deere 2019). The integrated Haas winch, shown in Figure 2, contains between 300 to 500m of 13 or 14mm in diameter steel cable and provides a tractive force of 225kN (John Deere 2019).

Figure 1. John Deere 1910E forwarder with Haas traction winch.

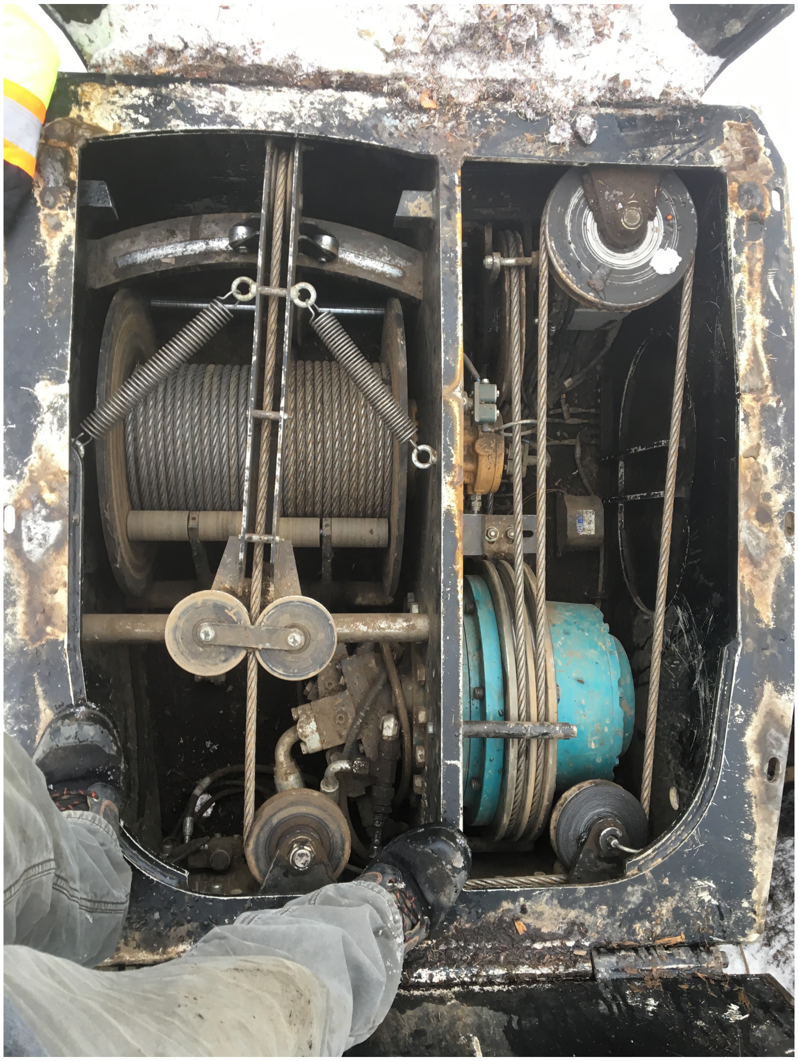

Figure 2. Inside housing of Haas traction winch

I also observed a Tigercat 1185 wheeled harvester (Figure 3) working on flat ground and an Ecoforst T-winch (Figure 4) that was not in operation. The 34t, eight-wheel drive harvester is designed for operating on steep terrain (Tigercat 2019). The contractor used the harvester, tethered to the t-winch. The Ecoforst T-winch 10.1 a is fully remote controlled, purpose-built machine designed to provide tractive assistance to machinery working on steep terrain. The t-winch weighs 6.9t and has one drum containing 500m of 18.5mm cable (Amishev 2011).

Figure 3. Tigercat 1185 wheeled harvester

Source: Tigercat 2019

Figure 4. Ecoforst t-winch 10.1

2.2. DATA COLLECTION

I used a Nikon video camera to record the forwarder traveling, loaded (Figure 5) and unloaded in addition to loading and unloading the bunk. Further information on machine specifications, and operational challenges were gathered from talking with operators and supervisors from the winch-assisted logging operation visited. While at the logging site, the forwarders were not running at normal production levels due to wet ground conditions and high stumps left from harvesting; this prevented accurate data collection. The data used for my study is from a collection of literature and input from contractors and equipment dealers who specialize in winch-assist along with cable-yarding logging systems. The data from the contractor and equipment dealers is from professional judgment and not empirical data, therefore it should be used with caution.

Figure 5. John Deere 1910E forwarder traveling loaded down a slope.

2.3. EQUIPMENT COSTING MODEL

An equipment costing model was used to determine the cost per cubic metre ($/m^3) of each piece of equipment used in a harvesting system. The variables used are listed in (Table 1. Variables included in equipment costing model. with the corresponding values inputted for the John Deere 1910E forwarder and Tigercat 1185 harvester. The values used in the costing model were collected from the logging contractor providing input for the study, equipment dealers in B.C. and various pieces of literature on the subject.

Table 1. Variables included in equipment costing model.

Machine/system name:	Forwarder	Harvester	T-Winch
No. of working days/year:	210	210	210
No. of scheduled hour/shift (SMH/shift):	12	12	12
No. of shifts/day	1	1	1
No. of SMH/day	12	12	12
Machine utilization (%):	85	65	65
Productivity, m3/SMH	12.75	14.30	-
Installed or purchase price (P) ($):	840,000	1,020,000	250,000
Future salvage (% of P)	10.00	10.00	10.00
Future salvage value ($):	84,000	102,000	25,000
Expected economic life (years):	8	5	8
Interest rate (%):	5.00	5.00	5.00
Fuel consumption L/PMH):	18.50	30.00	20.00
Fuel cost ($/L):	1.00	1.00	1.00
Engine Oil Consumption (L/PMH)	0.10	0.10	N/A
Oil Cost ($/L)	7.00	7.00	N/A
Hydraulic oils and/or lubes (L/PMH)	0.96	1.20	N/A
Hydraulic oils and/or lubes cost ($/L)	2.50	2.50	N/A
Annual repair & maint. cost (% of P)	20.00	24.00	10.00
Operator wage ($/SMH):	30.00	30.00	-
Fringe benefits & employment expense (% of op. wage):	35.00	35.00	-
Number of operators required per shift:	1	1	-
Insurance cost per year (% of P):	3.00	3.00	3.00

Source: (Pers. Comm. March 4, 2019)
(Dyson 2016)

The values shown in Table 1 were combined and summarized into system costs, fixed costs, variable costs, labour costs, total cost and production. The cost per cubic metre ($\$/m^3$) was calculated by dividing the hourly operating cost (\$/SMH) by the hourly production (m^3/SMH).

2.4. SENSITIVITY ANALYSIS

A sensitivity analysis was formatted in Microsoft excel using the same costing model as described above. Various inputs from the model were increased and decreased by five, ten and twenty percent to assess the cost per cubic metre ($\$/m^3$) sensitivity to change. The input variables included; machine utilization (%), productivity (m^3/SMH), instilled or purchase price (\$), interest rate (\$), operator wage (\$/SMH) and number of scheduled hour/shift (SMH/shift). The resulting change in cost per cubic metre for each change in input variable was recorded to determine the sensitivity of each input variable. Table 2. Sensitivity analysis for machine utilization of Tigercat 1185 harvesterdisplays an example of how the sensitivity of machine utilization was calculated for the Tigercat 1185 harvester.

Table 2. Sensitivity analysis for machine utilization of Tigercat 1185 harvester

Percent change (%)	-20	-10	-5	0	5	10	20
Machine utilization (%)	52.00	58.50	61.75	65.00	68.25	71.50	78.00
cost/cubic metre (\$/m3)	22.30	19.99	19.02	18.14	17.35	16.63	15.37

Source: (Appendix II)

2.5. BREAK-EVEN ANALYSIS

A break-even analysis was used to compare three types of steep slope logging operations. These included winch-assist, cable yarding (grapple) with manual felling and cable yarding (grapple) with mechanical felling. The information for the machine costing models came from studies by Dyson (2016), Dyson and Boswell (2016), Strandgard et al. 2015, equipment dealers as well as from the logging contractor providing input for the study. The analysis assumed a 10% decrease in productivity for every 10% increase in slope for the forwarder, harvester, buncher and manual fallers. This estimate was based on personal communications with the logging contractor providing input for the study. The productivity for the cable yarder and roadside processor remained constant. An additional break-even analysis was made using the productivity for a winch-assist harvester and forwarder from a study by Dyson and Mologni (2018) to show the achievable range in production unit costs ($/m^3) using a winch-assist system.

3. RESULTS

3.1. SENSITIVITY ANALYSIS

The results for the forwarder and harvester showed a similar trend in terms of which variables were most sensitive to change. Table 3 and table 4 display the results from the sensitivity analysis for the harvester and forwarder respectively. The tables show the percent increase or decrease in production unit cost ($\$/m^3$) based on the percent change in input variable. Production unit cost ($\$/m^3$) cost was most sensitive to changing machine utilization (%) and productivity (m^3/SMH) for both the harvester and forwarder. Changing interest rates (%) and operator wages ($/SMH) had the smallest effect on production costs.

Table 3. Percent change in production unit cost ($\$/m^3$) of Tigercat 1185 harvester from sensitivity analysis.

Input variable	% Change of input Variable					
	-20	-10	-5	5	10	20
Machine Utilization (%):	22.9	10.2	4.8	-4.4	-8.3	-15.3
Productivity (m3/SMH):	25.0	11.1	5.3	-4.8	-9.1	-16.7
Instilled or Purchase Price (P) ($):	-15.2	-7.6	-3.8	3.8	7.6	15.2
Interest Rate (%):	-1.1	-0.6	-0.3	0.3	0.6	1.1
Operator Wage ($/SMH):	-3.1	-1.6	-0.8	0.8	1.6	3.1
No. of scheduled hour/shift (SMH/shift):	19.0	8.4	4.0	-3.6	-6.9	-12.7

Table 4. Percent change in production unit cost ($/m^3) of John Deere 1910E forwarder from sensitivity analysis.

Input variable	% Change of input Variable					
	-20	-10	-5	5	10	20
Machine Utilization (%):	22.5	10.0	4.7	-4.3	-8.2	-13.5
Productivity (m3/SMH):	25.0	11.1	5.3	-4.8	-9.1	-16.7
Instilled or Purchase Price (P) ($):	-13.6	-6.8	-3.4	3.4	6.8	13.6
Interest Rate (%):	-1.3	-0.6	-0.3	0.3	0.6	1.3
Operator Wage ($/SMH):	-4.4	-2.2	-1.1	1.1	2.2	4.4
No. of scheduled hour/shift (SMH/shift):	17.0	7.6	3.6	-3.2	-6.2	-11.4

The percent change of production unit cost based on a 10% increase and decrease for each input variable is illustrated in Figure 6 and Figure 7 for the harvester and forwarder respectively. The production cost increased by approximately 10% with a decrease in machine utilization and decreased by approximately 8% with an increase in machine utilization for both machines. The production costs were slightly more sensitive to productivity for both machines. The production cost increased by approximately 11% with a decrease in productivity and decreased by approximately 9% with an increase in productivity for both machines. Number of scheduled hours/shift and purchase price were slightly more sensitive for the harvester production cost and operator wage was more sensitive for the forwarder production cost. Interest rate had an identical effect on production costs for both machines.

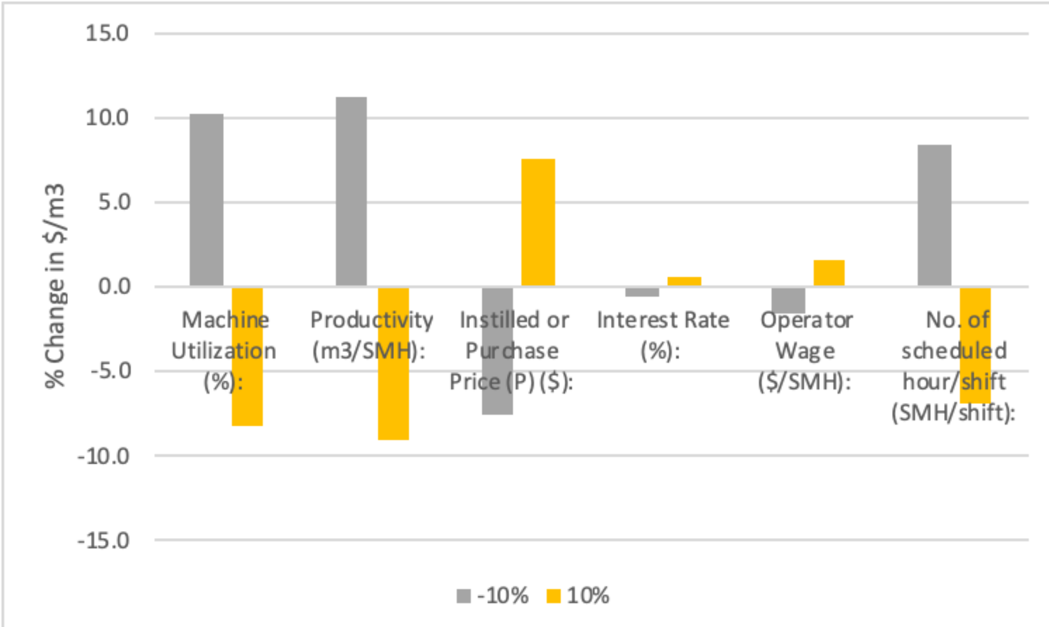

Figure 6. Percent change in production unit cost ($\$/m^3$) based on a 10% increase and decrease of the specified variable for the Tigercat 1185 harvester.

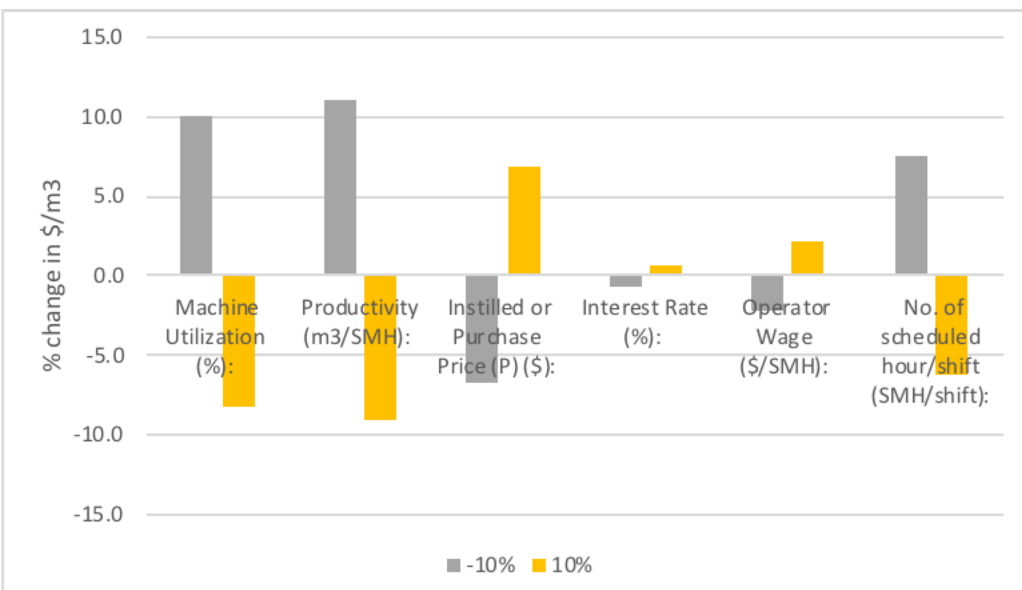

Figure 7. Percent change in production unit cost ($\$/m^3$) based on a 10% increase and decrease of the specified variable for the John Deere 1910E forwarder.

3.2. BREAK-EVEN ANALYSIS

The results from the break-even analysis using the data from the contractor providing input for this study resulted in no break-even point occurring. The winch-assist system was most costly, followed by the cable yarding system with manual felling and the cable yarding system with mechanized felling. The cost of the winch-assist system ranged from \$29.56/m^3 at a 30% slope to \$50.67/m^3 at an 80% slope. The cost of the cable yarding system with manual falling ranged from \$25.84/m^3 to \$28.52/m^3 and the cost of the cable yarding system with mechanized felling ranged from \$18.06/m^3 to \$22.67/m^3 at the same slopes as the winch-assist system. The winch-assist system had a higher increase in cost (\$/m^3) as slope increased while both cable yarding systems had a more gradual increase. These results are visually displayed in Figure 8.

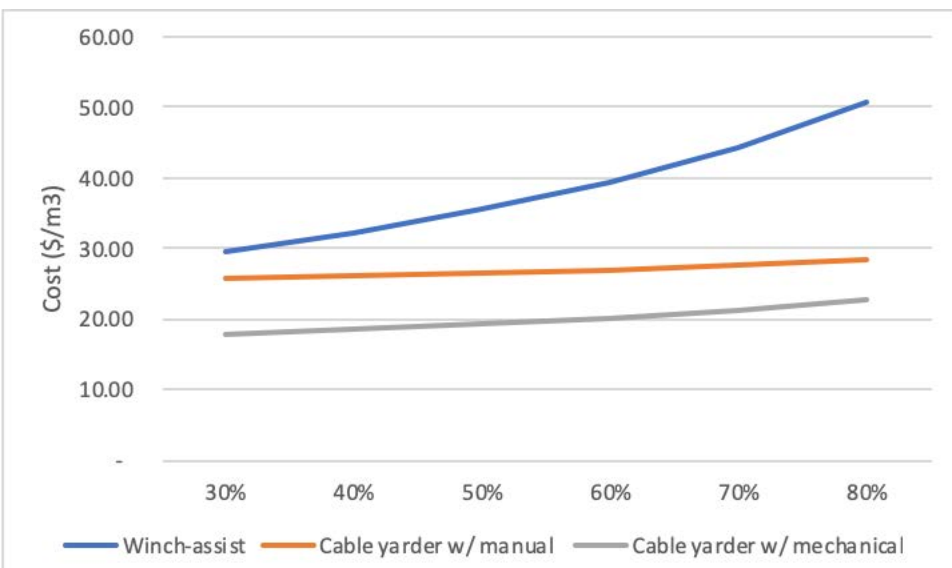

Figure 8. Break-even analysis comparing the cost (\$/m^3) between winch-assist, cable yarding with manual felling and cable yarding with mechanized felling operations.

The results from the alternate break-even analysis using the productivity data from Dyson and Mologni (2018) drastically reduced the cost ($\$/m^3$) of the winch-assist system. The winch-assist system had the lowest cost until approximately 50% slope, where it broke even with the cable yarding system with mechanized felling and it reached the break-even point with the cable yarding system with manual felling at approximately 80% slope. The cost of the winch-assist system ranged from $\$16.49/m^3$ at 30% slope to $\$28.27/m^3$ at 80% slope. The break-even points and cost of the logging systems based on slope is shown in Figure 9.

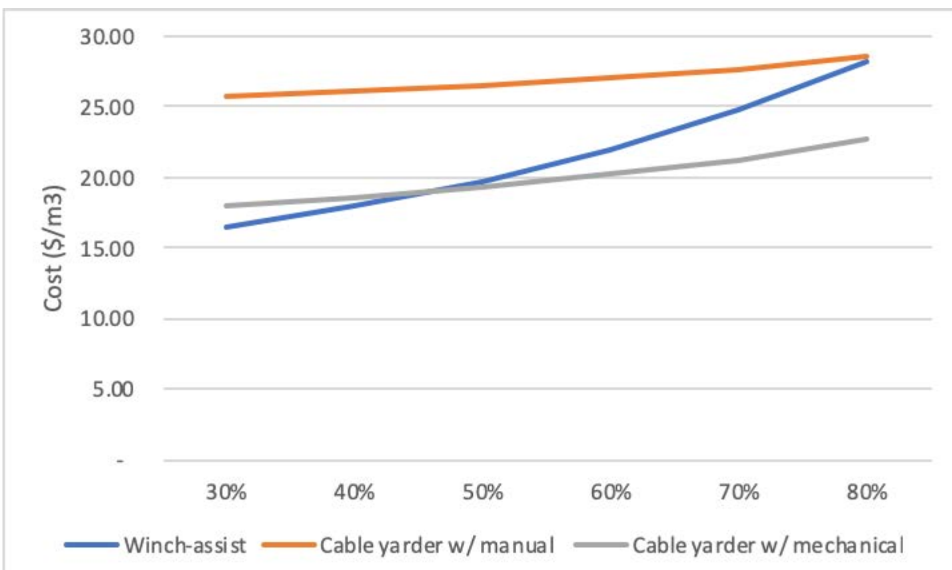

Figure 9. Alternate break-even analysis comparing the cost ($\$/m^3$) between winch-assist, cable yarding with manual felling and cable yarding with mechanized felling operations.

4. DISCUSSION

This study incorporated data from the literature, personal communications and the contractor providing direct input for the study. A new perspective on winch-assisted logging was formed from examining the results and reading literature on the topic. The results showed that the cost of the winch-assist logging system was comparable to traditional cable logging systems, i.e. grapple yarder with manual felling and costlier than a grapple yarder with mechanized felling (Figure 8). The sensitivity analysis yielded predictable results, as productivity and utilization had the greatest influence on overall cost ($\$/m^3$). These results have a variety of implications to both contractors and licensees who are involved in steep slope logging and already have or are looking into winch-assisted logging equipment.

The data collected for this thesis is based on the contractor's professional estimates of production and costs. The results should be viewed with caution. Field data collection was not possible due to the machines of interest not performing their usual tasks when visiting the logging sites. This is the reality of having a narrow window to collect data in an industry where a variety of variables can influence production on any given day. Nonetheless, the experience of visiting a winch-assisted logging operation and talking first hand with operational supervisors and operators was valuable for providing input into this thesis and for my future professional career.

This section will examine the implications of the results and how they may affect the parties involved. The future of winch-assisted logging in western Canada and the main drivers and constraints are discussed. Comparisons are made between winch-assist systems and cable yarding systems. Recommendations are made on where winch-assist logging systems are best suited, where yarding systems are best suited and where the two systems may be combined to optimize results. Lastly, recommendations are made on where future work should concentrate their efforts to further improve the economic and operational efficiency of winch-assist logging systems.

4.1. IMPLICATIONS OF SENSITIVITY ANALYSIS

A sensitivity analysis is a valuable tool for a contractor or licensee to determine what variable have the greatest impact on overall cost. The variables chosen for the sensitivity analysis were used because they have a certain degree of flexibility to be lowered or increased by a logging contractor. A ten percent change in the variables used in the analysis was used because it is a realistic target that can be reached by a logging contractor through operational and financial improvements. The results from the sensitivity analysis of this study showed a similar trend for the harvester and forwarder. The total cost was most sensitive to changes in productivity (m^3/SMH) and changes in utilization. These results were expected because productivity and utilization directly influence the amount of volume that can be processed in a scheduled machine hour and help offset the cost of production. Productivity can be influenced by factors such as operator skill level, terrain, average slope and number of log sorts. Utilization can be influenced by factors such as anchor changeover time and block layout. Productivity and utilization generally improve over time due to improvements in technology, increased operator skill level and improved operational organization and efficiency. Logging contractors should strive to find ways to continually improve their production and utilization in order to lower their overall cost. The number of scheduled machine hours/shift and purchase price had the third and fourth most impact on cost respectively. The number of scheduled machine hours/shift can be increased in some situations. However, the contractor in this study does not run night shifts when using the winch-assist system because of safety concerns which limit the number of available hours to work per day. The purchase price may be influenced depending on the contractor's relationship with a dealership and if machinery is bought new or used. Used equipment are good options to be used for anchor machines because they have limited required use and function. The purchase price of winch-assisted equipment may also decrease with time as technology improves and new manufactures enter into the market. Leasing equipment is another potential option; however, it was not examined in this study. Operator wage had a relatively small impact on the overall cost. Operators of winch-assisted machines must be compensated fairly because of the high degree of skill level required and associated risk of operating on steep terrain. Interest rate had the lowest impact on overall cost and the rates set are largely dependent on the financial institute being used.

4.2. IMPLICATIONS OF THE BREAK-EVEN ANALYSIS

The findings of the break-even analysis showed that the winch-assist logging system had the highest cost for all slopes followed by cable yarding with manual felling and cable yarding with mechanizing felling. No break-even point occurred between any of the systems examined as each system remained either more or less expensive relative to each other. To find the range of production costs ($\$/m^3$) achievable using winch-assist logging systems, other studies were examined, and their results were used in another break-even analysis. Using the productivity values from a winch-assist harvester and forwarder in a study by Dyson and Mologni (2018) drastically reduced the cost of the winch-assist system and it became the cheapest system on slopes less than 50%. These results show that in optimal conditions winch-assist systems can be economically comparable to cable yarding systems.

The results from the break-even analysis show that cable yarding systems with mechanized felling provide the lowest cost for steep slope logging. Mechanized felling results in a large increase in yarder productivity and a subsequent lower cost per cubic metre. Despite the winch-assist system being the most expensive system, it still has many applications where it is preferred to cable yarding systems which will be discussed in detail in later sections of the discussion.

4.3. ECONOMIC FEASIBILITY OF WINCH-ASSSISTED LOGGING

One of the main findings of this thesis is that winch-assist logging systems are not the ultimate solution to drastically reduce the costs of steep slope logging. The total cost of the system examined in the study was slightly over $30/m^3. This cost is highly variable depending on the type of block being harvested, i.e. terrain, piece size, average slope, etc. and the season of harvest. New contractors will generally have a high cost due to the learning curve in both the tactical and operational stages of harvest development.

4.3.1. Investment cost

A factor that may discourage logging contractors from purchasing winch-assist logging equipment is the high upfront investment cost. The combined purchase price of the harvester, forwarder, and t-winch examined in this study was over 2 million dollars. This is a massive amount of money to spend especially for newer contractors entering the business. In order for contractors to invest in winch-assisted logging equipment, licensees must provide a contract guaranteeing a sufficient amount of annual wood to be harvested on steep ground. Lending institutions generally require such a contract in order to provide a loan.

4.3.2. Logging rates

Due to the higher cost of wood to roadside, logging rates should fairly compensate contractors. Since this type of logging system is relatively new, rates should be generated from previous studies on winch-assist systems on similar logging sites as well as information from contractors currently equipped with winch-assisted equipment. Rates may be adjusted accordingly depending on the specific circumstances of the contractor involved, number of log sorts, terrain, the season of harvest, etc. The higher degree of risk associated with steep slope logging and dealing with cables under high tension should also be incorporated into the logging rate. The appraisal manual in British Columbia currently appraises winch-assisted logging the same as cable yarding, which may help provide some additional savings on stumpage if lower margins are realized (B.C. MFLNRO 2018).

4.3.3. Costs from other studies

A variety of other studies have examined the cost and productivity of winch-assisted logging operations. Looking at the cost of other contractors using the same system is a valuable way to determine the potential range of cost reduction and ways to improve a logging system. A study by Dyson and Mologni (2018) found the productivity of a winch-assisted harvester to be 35.5 m^3/PMH and the productivity of a winch-assisted forwarder to be 32.0 m^3/PMH. These values were converted to m^3/SMH and entered into the machine costing model which reduced the total logging cost by approximately \$15/m^3. However, it was mentioned in the study that conditions were better than normal during the study period and on average lower productivity is expected. Nonetheless, this study shows there is potential for improvement in terms of lowering the roadside logging cost of winch-assist systems to increase their competitiveness compared to cable yarding systems. Another study by Dyson and Strimbu (2017), found very similar productivity results for a John Deere harvester and forwarder compared to the results in this study. This shows that the contractor in the study operates at a similar production compared to other winch-assist contractors in B.C.

4.4. WINCH-ASSIST SYSTEMS VS CABLE YARDING SYSTEMS

Cable yarding has been the dominant method of logging steep ground in western Canada, however, the introduction of winch-assist technology has been gaining traction. At the beginning of the study, I predicted that winch-assist systems would offer large cost savings over cable yarding systems. The results showed that there were little savings in harvesting costs from using a winch-assist system. However, it is important to note that winch-assist systems may offer savings from reduced set-up times and reduced road construction costs. Strimbu and Boswell (2018) stated that road construction efforts could be reduced by half compared to the road network required for conventional cable yarding systems, which is related to the increased flexibility in road locations because of the ability to move wood in areas with or without adequate deflection. These results began to make more sense after further reading into the literature and talking with the contractor providing input for the thesis. Winch-assist logging systems are best suited for areas with variable terrain containing smaller steep patches or areas with bad deflection (pers. comm., February 20, 2018). A cable yarding system should be used for large steep patches with good deflection because it will be the most cost-effective way to move large volumes of wood.

4.4.1. Combining cable yarding and winch-assist systems

The results from the cost analysis for this study showed that a cable yarding system, using a winch-assisted feller buncher and a roadside processor was the most cost-effective steep slope logging method (Figure 8). A variety of studies (Dyson 2016;

Amishev and Dyson 2018) have found that mechanized felling drastically reduces the cost of cable yarding systems because of increased yarder productivity when yarding bunched stems rather than individual stems. In this sense, the use of winch-assist technologies is likely to continue to increase in cable yarding systems and replace manual felling where terrain and piece size is suitable for machines. In addition to productivity advantages, increased mechanization reduces the need for manual workers and increases the overall safety of an operation.

4.4.2. Benefits of winch-assist systems

The versatility of winch-assist logging systems is one of its main advantages over cable yarding systems, especially in highly variable terrain. Machines that are equipped with cable-assist winches can easily change over to work on flat ground whereas cable yarding operations are restricted to steep areas with good deflection. Cable-assist winches are compatible with almost all forestry equipment, including grapple skidders, feller bunchers, processors and hoe chucker in addition to harvesters and forwarders. This versatility allows a variety of harvesting systems to utilize winch-assist technologies in their operation without completely overhauling their current equipment which helps minimize costs and training on new equipment. Contractors who work in variable terrain are able to obtain greater utilization from their capital investment in equipment (Fullerton 2016). Winch-assist logging operations have lower mobilization and demobilization costs (pers. comm., February 20, 2018), which make operations better suited for smaller blocks where moving may occur more frequently. Gingras et al. (2015), estimated a potential savings of 90 million per year to the forest industry in B.C. through increased profit margins as a result of integrating winch-assist technologies into steep slope logging operations. A cut-to-length system with a harvester and forwarder provides several other advantages including; no landings required for decking and processing, no harvesting debris at landings and only two pieces of equipment are required (Dyson and Strimbru 2017). Lastly, cable-assist winches help reduce wear on machines, reduce fuel consumption and reduce stress on operators (Fullerton 2016).

4.4.3. Disadvantages of winch-assist systems

Winch-assist systems have some disadvantages compared to cable yarding operations which are partially related to the fact that winch-assist logging systems are relatively new to western Canada and learning is continually taking place on the tactical and operational scales. Operating mechanized equipment on steep terrain requires highly skilled operators and longer periods of additional training is likely required. Compared to flat-ground operations there are added risks including the risk of rollover and chance of cables breaking. Winch-assist operations are impractical and inefficient when operating in deep snow (>1.5m) and in stands with heavy brush or understory (Dyson and Strimbru 2017). The contractor providing input for this study limits their winch-assist equipment to slopes under 50% in the winter due to deep snow conditions. This limitation will put added pressure on contractors during summer months to harvest slope profiles over 50% that will be inaccessible during the winter. Another possible disadvantage of using a cut-to-length system is a forwarder is only able to forward short logs (<8m) (Dyson and Strimbru 2017), whereas a grapple skidder or grapple yarder can skid full trees if desired. Compared to manual felling, mechanized equipment will increase the level of soil disturbance on harvest blocks, however, the additional traction assist provided from winches reduces the amount of track slippage and spinning and helps minimize rutting.

4.4.4. Safety

An important factor that is often cited as an incentive to use winch-assist technologies in steep slope logging operations is to improve safety standards (Visser and Stampfer 2015; Amishev 2016; Hudson 2017; Girvan 2017). Cable-assist winches allow for the increase in the mechanization of logging operations on steep slopes and reduce the need for manual workers to perform dangerous tasks associated with the felling and extraction phases of harvesting. Gingras et al. (2015), estimated the increased mechanization of steep slope logging can reduce the number of injuries by 50%. The highest risk associated with using winch-assist systems is the chance of a cable breaking, resulting in machine rollovers. As mentioned previously in the literature review, the underlying rule to ensure safety, is the assisted machine should be stable at all times with or without a cable attached. The highest risk occurs when operators work on slopes too steep where they would rollover if the cable was not attached. Winch-assist contractors and licensees should become familiar with the following publication by FPInnovations, “Winch-assist harvester: Best Practice Manual”. This manual is a valuable resource that provides many recommendations to ensure the safe working conditions of winch-assist operations. The improved safety of steep slope logging operations with winch-assist systems is likely to be an important driver for the continued use of the system in the future.

4.5. TIMBER SUPPLY CONSTRAINTS

Timber supply constraints resulting in AAC reductions are expected to be an important area of concern for may licensees in B.C. As a result of AAC reductions, sawmills must find new and innovative ways to access available fibre. The economic viability and robustness of the forest industry will depend on being able to harvest the complete terrain profile in order to sustain the AAC (Gingras et al. 2015). A possible solution is to increases harvesting on steep slopes. Steep slopes (>35%) make up 24 percent of the total AAC in B.C., this makes up 56% of the costal AAC and 14% of the interior AAC (Hunt 2016). The introduction of winch-assist technologies may increase the amount of economically available fibre on steep terrain, providing relief during supply constraints. Gingras et al (2015), estimated that harvesting on steep slopes using innovated harvesting technology has the potential to generate an additional 2 million m^3 of fibre per year. The versatility of winch-assist logging systems will help increase the variety of terrain that is accessible and extend the logging season. Constraints in timber supply may be a large driver for licensees to incentivize contractors into upgrading their equipment fleet with winch-assist technologies in order to increase the range of timber accessible. This point will be especially applicable to licensees with TSA’s that contain a high content of variable terrain with inconsistent slope profiles.

4.6. FUTURE WORK

In the future, as winch-assist logging systems continue to develop there are likely to be further studies done to examine ways to lower costs and increase productivity. Ultimately to verify the results of this thesis, there is a need for real data generated from multiple site visits with varying conditions. From examining the literature on the subject, I found a lack of quantitative data on the impact slope had on productivity. An operator from a study by Dyson and Strimbu (2017) felt that productivity was not affected on slopes between 30% and 60% and on slopes greater than 80% a different system should be used. The contractor providing input for this study felt slope significantly influenced productivity and estimated a 20% decrease in productivity from a 40% to 60% slope. Further research should focus on quantifying the impact slope has on productivity, so contractors are better able to predict costs and determine the economic feasibility of harvesting a specific block. In addition, licensees would be able to have a more accurate estimate on fair logging rates.

As discussed previously, winch-assist logging systems work best in variable terrain that may contain both flat and steep patches. They work better than cable yarding systems in smaller steep patches because of lower mobilization and demobilization costs. In large steep patches with good deflection, cable yarding systems will generally be more productive than winch-assist systems and have a lower overall cost. In the future, break-even analyses can be used to determine the amount of volume required in one steep patch to use either a cable yarding system or winch-assist system. This type of analysis may apply to an individual harvest block or to a specified area with multiple steep slope blocks. This type of analysis would be important for contractors who are looking into determining which type of system would be better to use based on the harvesting profile and the subsequent type of equipment that makes the most economic sense to purchase.

5. CONCLUSION

The finding of this thesis showed that winch-assist logging systems with a harvester and forwarder may be costlier than cable yarding systems with mechanized felling. Cable yarding systems should be the preferred logging systems when large volumes of timber are available on relatively consistent steep slopes with good deflection. Winch-assist technologies are valuable in cable yarding systems to increase mechanization resulting in both productivity and safety improvements.

Winch-assist logging systems are best suited in areas with variable terrain containing a mixture of flat and steep sections. They are advantageous over cable yarding systems because of their versatility, lower set up costs and mobilization and demobilization costs. The main drivers that will increase the abundance of winch-assist logging systems in B.C. include; reduce the need for high-cost grapple yarding, improve safe working conditions and increase the economic availability of timber. I believe that winch-assist technologies are a valuable way to improve logging operations in B.C. and will continue to increase in abundance in the future.

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APPENDICES

APPENDIX I: MACHINE COSTING MODELS

EQUIPMENT COSTING MODEL	Cable-Assist System		
Machine/system name:	Forwarder	Harvester	T-Winch
No. of working days/year:	210.00	210.00	210.00
No. of scheduled hour/shift (SMH/shift):	12.00	12.00	12.00
No. of shifts/day	1.00	1.00	1.00
No. of SMH/day	12.00	12.00	12.00
Machine utilization (%):	85.00	65.00	65.00
Productivity, m3/SMH	12.75	14.30	-
Installed or purchase price (P) ($):	840,000	1,020,000	250,000
Future salvage (% of P)	10.00	10.00	10.00
Future salvage value ($):	84,000	102,000	25,000
Expected economic life (years):	8.00	5.00	8.00
Interest rate (%):	5.00	5.00	5.00
Fuel consumption L/PMH):	18.50	30.00	20.00
Fuel cost ($/L):	1.00	1.00	1.00
Engine Oil Consumption (L/PMH)	0.10	0.10	N/A
Oil Cost ($/L)	7.00	7.00	N/A
Hydraulic oils and/or lubes (L/PMH)	0.96	1.20	N/A
Hydraulic oils and/or lubes cost ($/L)	2.500	2.500	N/A
Annual repair & maint. cost (% of P)	20.00	24.00	10.00
Operator wage ($/SMH):	30.00	30.00	-
Fringe benefits & employment expense (% of op. wage):	35.00	35.00	-
Number of operators required per shift:	1.00	1.00	-
Insurance cost per year (% of P):	3.00	3.00	3.00
Wire rope ($/SMH)	N/A	N/A	N/A
Rigging & radio ($/SMH)	N/A	N/A	N/A
Lube & oil ($/SMH)	N/A	N/A	N/A
Track & undercarriage ($/SMH)	N/A	N/A	N/A
Operating supplies ($/SMH)	N/A	N/A	N/A
Repair & maintenance ($/SMH)	N/A	N/A	N/A
System Cost Summary			
Interest rate (decimal)	0.05	0.05	1.05
PV of salvage value ($):	56,854.51	79,919.67	16,920.98
Scheduled machine hours per year (SMH/a)	2,520.00	2,520.00	2,520.00
Productive machine hours per year (PMH/a)	2,142.00	1,638.00	1,638.00
Fixed Costs			
Annual capital cost ($/a)	124,012.42	221,130.85	36,908.46
Capital cost ($/SMH)	49.21	87.75	14.65
License and insurance cost ($/a)	25,200.00	30,600.00	7,500.00
Variable Costs			
Energy, oil and lube cost ($/PMH)	21.60	33.70	20.00
Repair and maintenance cost ($/a)	168,000.00	244,800.00	25,000.00
Labour Costs			
Operator Cost ($/SMH)	40.50	40.50	-
Total Cost			
Annual operating cost ($/a)	465,539.62	653,791.45	102,168.46
Hourly operating cost ($/SMH)	184.74	259.44	40.54
Sum of Hourly operating cost ($/SMH)		299.98	
Production			
Annual Production (m3/a)	32,130.00	36,036.00	-
m3 produced per SMH (m3/SMH)	12.75	14.30	-
m3 produced per PMH (m3/PMH)	15.00	22.00	-
Cost per m3 ($/m3)	**14.49**	**20.98**	
Total cost	**35.47**		

Source: (Pers. Comm. March 4, 2019)
(Dyson 2016)

EQUIPMENT COSTING MODEL	Cable yarding system w/manual felling			
Machine/system name:	Cable yarder	Back spar	Manual faller	Processor
No. of working days/year:	210.00	210.00	210.00	210.00
No. of scheduled hour/shift (SMH/shift):	8.00	8.00	6.00	8.00
No. of shifts/day	1.00	1.00	1.00	1.00
No. of SMH/day	8.00	8.00	6.00	8.00
Machine utilization (%):	80.00	80.00	-	83.00
Productivity, m3/SMH	17.00	-	15.00	40.00
Installed or purchase price (P) ($):	1,300,000	80,000	-	600,000
Future salvage (% of P)	30.00	10.00	-	15.00
Future salvage value ($):	390,000	8,000	-	90,000
Expected economic life (years):	12.00	5.00	-	7.00
Interest rate (%):	5.00	5.00	-	5.00
Fuel consumption L/PMH):	36.00	2.00	-	25.00
Fuel cost ($/L):	1.00	1.00	-	1.00
Engine Oil Consumption (L/PMH)	N/A	N/A	-	N/A
Oil Cost ($/L)	N/A	N/A	-	N/A
Hydraulic oils and/or lubes (L/PMH)	N/A	N/A	-	N/A
Hydraulic oils and/or lubes cost ($/L)	N/A	N/A	-	N/A
Annual repair & maint. cost (% of P)	N/A	N/A	-	N/A
Operator wage ($/SMH):	33.00	N/A	50.00	30.00
Fringe benefits & employment expense (% of op. wage):	35.00	N/A	35.00	35.00
Number of operators required per shift:	2.00	N/A	1	1.00
Insurance cost per year (% of P):	3.00	3.00	-	3.10
Wire rope ($/SMH)	29.16	N/A	-	-
Rigging & radio ($/SMH)	11.11	N/A	-	-
Lube & oil ($/SMH)	3.60	0.2	-	1.88
Track & undercarriage ($/SMH)	6.88	N/A	-	-
Operating supplies ($/SMH)	5.75	0.3	-	-
Repair & maintenance ($/SMH)	57.5	7.5	-	32.33
System Cost Summary				
Interest rate (decimal)	0.05	0.05	-	0.05
PV of salvage value ($):	217,166.59	6,268.21	-	63,961.32
Scheduled machine hours per year (SMH/a)	1,680.00	1,680.00	1,260.00	1,680.00
Productive machine hours per year (PMH/a)	1,344.00	1344.00	-	1,394.40
Fixed Costs				
Annual capital cost ($/a)	133,029.45	17,343.60	-	95836.17
Capital cost ($/SMH)	79.18	10.32	-	57.05
License and insurance cost ($/a)	39,000.00	2,400.00	-	18,600.00
Variable Costs				
Energy, oil and lube cost ($/PMH)	39.60	2.20	-	26.88
Repair and maintenance cost ($/a)	96,600.00	12,600.00	-	54,314.40
Labour Costs				
Operator Cost ($/SMH)	92.70	N/A	67.50	42.38
Total Cost				
Annual operating cost ($/a)	477,587.85	35,300.40	85,050.00	277,430.45
Hourly operating cost ($/SMH)	284.28	21.01	67.50	165.14
Sum of Hourly operating cost ($/SMH)	305.29		N/A	N/A
Production				
Annual Production (m3/a)	28,560.00	-	18,900.00	67,200.00
m3 produced per SMH (m3/SMH)	17.00	-	15.00	40.00
m3 produced per PMH (m3/PMH)	21.25	-	-	48.19
Cost per m3 ($/m3)	**17.96**		**4.50**	**4.13**
Total cost	**26.59**			

Source: (Dyson 2016)
(Pers. Comm. Jan 29, 2019)
(Strandgard et al. 2015)

EQUIPMENT COSTING MODEL	Cable Yarding system w/ buncher				
Machine/system name:	Cable yarder	Back spar	Feller buncher	Anchor machine	Processor
No. of working days/year:	210.00	210.00	210.00	210.00	210.00
No. of scheduled hour/shift (SMH/shift):	8.00	8.00	8.00	8.00	8.00
No. of shifts/day	1.00	1.00	1.00	1.00	1.00
No. of SMH/day	8.00	8.00	8.00	8.00	8.00
Machine utilization (%):	80.00	80.00	65.00	65.00	83.00
Productivity, m3/SMH	41.60	-	45.00	-	40.00
Installed or purchase price (P) ($):	1,300,000	80,000	700,000	465,000	600,000
Future salvage (% of P)	10.00	10.00	30.00	10.00	15.00
Future salvage value ($):	130,000	8,000	210,000	46,500	90,000
Expected economic life (years):	12.00	5.00	5.00	8.00	7.00
Interest rate (%):	5.00	5.00	5.00	5.00	5.00
Fuel consumption L/PMH):	36.00	2.00	38.00	10.00	25.00
Fuel cost ($/L):	1.00	1.00	1.00	1.00	1.00
Engine Oil Consumption (L/PMH)	N/A	N/A	N/A	N/A	N/A
Oil Cost ($/L)	N/A	N/A	N/A	N/A	N/A
Hydraulic oils and/or lubes (L/PMH)	N/A	N/A	N/A	N/A	N/A
Hydraulic oils and/or lubes cost ($/L)	N/A	N/A	N/A	N/A	N/A
Annual repair & maint. cost (% of P)	N/A	N/A	N/A	N/A	N/A
Operator wage ($/SMH):	33.00	N/A	30.00	25.00	30.00
Fringe benefits & employment expense (% of op. wage):	35.00	N/A	35.00	35.00	35.00
Number of operators required per shift:	2.00	N/A	1.00	1.00	1.00
Insurance cost per year (% of P):	3.00	3.00	3.00	3.00	3.10
Wire rope ($/SMH)	29.16	N/A	-	3.56	-
Rigging & radio ($/SMH)	11.11	N/A	-	-	-
Lube & oil ($/SMH)	3.60	0.2	3.80	1.00	1.88
Track & undercarriage ($/SMH)	6.88	N/A	8.00	0.89	-
Operating supplies ($/SMH)	5.75	0.3	0.30	0.25	-
Repair & maintenance ($/SMH)	57.5	7.5	67.50	32.50	32.33
System Cost Summary					
Interest rate (decimal)	0.05	0.05	0.05	1.05	0.05
PV of salvage value ($):	72,388.86	6,268.21	164,540.49	31,473.03	63,961.32
Scheduled machine hours per year (SMH/a)	1,680.00	1,680.00	1,680.00	1,680.00	1,680.00
Productive machine hours per year (PMH/a)	1,344.00	1344.00	1,092.00	1,092.00	1,394.40
Fixed Costs					
Annual capital cost ($/a)	142,125.17	17,343.60	131,904.68	68,649.73	95836.17
Capital cost ($/SMH)	84.60	10.32	78.51	40.86	57.05
License and insurance cost ($/a)	39,000.00	2,400.00	21,000.00	13,950.00	18,600.00
Variable Costs					
Energy, oil and lube cost ($/PMH)	39.60	2.20	41.80	11.00	26.88
Repair and maintenance cost ($/a)	96,600.00	12,600.00	113,400.00	54,600.00	54,314.40
Labour Costs					
Operator Cost ($/SMH)	92.70	N/A	40.5	33.75	42.38
Total Cost					
Annual operating cost ($/a)	486,683.57	35,300.40	379,990.28	205,911.73	277,430.45
Hourly operating cost ($/SMH)	289.69	21.01	226.18	122.57	165.14
Sum of Hourly operating cost ($/SMH)	310.70		348.75		N/A
Production					
Annual Production (m3/a)	69,888.00		75,600.00		67,200.00
m3 produced per SMH (m3/SMH)	41.60		45.00		40.00
m3 produced per PMH (m3/PMH)	52.00		69.23		48.19
Cost per m3 ($/m3)	**7.47**		**7.75**		**4.13**
Total cost	**19.35**				

Source: (Dyson 2016)
(Dyson and Boswell 2016)
(Pers. Comm. March 4, 2019)
(Strandgard et al. 2015)

APPENDIX II: SENSITIVITY ANALYSIS

Tigercat 1185 Harvester cost ($/m3) with % change of input variable

Input Variable	% Change of input Variable						
	-20	-10	-5	0	5	10	20
Machine Utilization (%):	22.30	19.99	19.02	18.14	17.35	16.63	15.37
Productivity (m3/SMH):	22.68	20.16	19.10	18.14	17.28	16.49	15.12
Instilled or Purchase Price (P) ($):	15.39	16.76	17.45	18.14	18.83	19.52	20.90
Interest Rate (%):	17.93	18.04	18.09	18.14	18.19	18.25	18.35
Operator Wage ($/SMH):	17.58	17.86	18.00	18.14	18.28	18.43	18.71
No. of scheduled hour/shift (SMH/shift):	21.59	19.67	18.87	18.14	17.49	16.89	15.85

John Deere 1910E forwarder cost ($/m3) with % change of input variable

Input Variable	% Change of input Variable						
	-20	-10	-5	0	5	10	20
Machine Utilization (%):	17.75	15.94	15.18	14.49	13.87	13.30	12.53
Productivity (m3/SMH):	18.11	16.10	15.25	14.49	13.80	13.17	12.07
Instilled or Purchase Price (P) ($):	12.51	13.50	14.00	14.49	14.98	15.48	16.46
Interest Rate (%):	14.31	14.40	14.44	14.49	14.54	14.58	14.67
Operator Wage ($/SMH):	13.85	14.17	14.33	14.49	14.65	14.81	15.12
No. of scheduled hour/shift (SMH/shift):	16.96	15.59	15.01	14.49	14.02	13.59	12.84

APPENDIX II: BREAK-EVEN ANALYSIS

Logging costs used in break-even analysis based on 10% decrease in productivity per 10% increase in slope.

Cost ($/m3)	Slope					
	30%	40%	50%	60%	70%	80%
Cable assist	29.56	32.24	35.47	39.41	44.33	50.67
Cable yarder w/ manual	25.84	26.18	26.59	27.09	27.71	28.52
Cable yarder w/ mechanical	18.06	18.64	19.35	20.21	21.28	22.67

Logging cost ($/m3) used in break-even analysis based on adjusted productivity values from (Dyson and Mologni 2018).

Cost ($/m3)	Slope					
	30%	40%	50%	60%	70%	80%
Cable assist	16.49	17.99	19.79	21.99	24.74	28.27
Cable yarder w/ manual	25.84	26.18	26.59	27.09	27.71	28.52
Cable yarder w/ mechanical	18.06	18.64	19.35	20.21	21.28	22.67