A Comparative Study of Mechanised Cable Harvesting Systems in New Zealand

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ABSTRACT

Productivity and safety concerns of traditional cable harvesting systems have been the key drivers for increasing levels of mechanisation in New Zealand. The use of grapples in cable yarding could eliminate the need for motor-manual tree fallers and breaker-outs in most situations.

A comparative time study was carried out on two mechanised cable harvesting systems utilising grapple carriages in an attempt to better understand the benefits and limitations of each system in different harvest settings. These systems include the Mechanical system which involved a swing yarder operating a mechanical grapple carriage and the Motorised system, which used a tower yarder with a motorised grapple carriage.

The Mechanical system took less time to accumulate felled trees but took longer to unhook trees on the landing than the Motorised system. The Mechanical system had a shorter cycle time (2.07 minutes) than the Motorised system (2.32 minutes) and extracted 1.3 tonnes more than the Motorised system per cycle. The Motorised system had shorter cycle times when in horizontal haul distances of less than 90 metres, but had the longest times when the distance exceeded this. Utilisation rates were similar between the two systems, although the main difference in delays between the two systems was the use of surgepiles on the landing by the Motorised system.

Both systems were effective, although on average the Mechanical system was more productive, with a productivity of 45 t/SMH, compared to 40 t/SMH for the Motorised system. The Mechanical system was the most productive when extracting mechanically felled and pre-bunched or trees while the Motorised system was the most productive when extracting motor-manually felled trees. Pre-bunching with an excavator was a more cost effective method than handing stems directly to the grapple carriage. Further research of the Mechanical system under more adverse conditions would allow a better overall comparison.

<u>Key Words</u>: mechanised cable harvesting, grapple carriage, cable harvesting, motorised grapple carriage, live skyline, running skyline, surgepile.

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1. ACKNOWLEGEMENTS

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2. INTRODUCTION

The forestry industry is New Zealand's third largest export earner at $NZ4.5 billion, with 23 million cubic metres of wood being harvested by clearfell in 2012. Large-scale forest owners account for 63% of the 1.7 million ha of plantation forest in NZ (NZFOA, 2013), these companies are pursuing more cost effective harvesting operations in order to increase the financial feasibility of forestry. There is also a need for safer harvesting operations as forestry recorded an annual average of 18.4 serious accidents per 1000 full-time employees between 2003 and 2010; greater than six times the national average for all industry sectors (DOL, 2011).

Forest harvesting in New Zealand is increasingly occurring on steep terrain where ground based machines cannot operate safely, making cable harvesting the most effective method (Raymond, 2012). The majority of cable harvesting operations in New Zealand utilise traditional systems with strops and chokers that require breaker-outs to manually attach felled trees to the rigging (Harill & Visser, 2011). Breaker-outs had the second highest fatality rate in the forestry industry behind motor-manual tree fallers (McMahon, 2006).

Wood Contracting Limited and Moutere Logging Limited are two companies based in Nelson which utilise innovative technology in the form of a mechanical grapple carriage and motorised grapple carriage respectively; each has a remote camera attached to the underside. These grapples have replaced the need for breaker outs, spotters, and a pole man for the extraction phase. These operations further address safety and productivity issues by using a feller buncher where possible instead of motor-manual felling. Mechanical felling is designed to not only be safer than motor-manual tree felling, but also to increase the productivity of the extraction process for these grapple carriage systems as stems can presented to the grapple in a more organised way (R. J. Visser & Stampfer, 1998).

This study evaluates and compares the payloads, cycle times and delays which contribute to the productivity of these two systems under a range of different terrain, stand, and stem presentation conditions.

3. LITERATURE REVIEW

Mechanised systems have been shown to improve worker safety and operational efficiency when harvesting steep slopes (Evanson & Amishev, 2010; Murphy, 2003; R. Visser, 2008). Despite this, Harill and Visser (2011) founds that only 12 and 21% of logging crews in New Zealand had utilised mechanical and motorised grapple carriages from 2007 to 2012 respectively.

Cable yarder systems that utilise mechanical or motorised grapple carriages with a remote camera attached have no need for breaker-outs, ‘spotters’ down the slope to visualise logs, or a pole man to unhook logs on the landing. Generally, grapple carriages have been limited to use by swing yarders; although an innovative new motorised grapple carriage, the Forestry Falcon Claw (FFC) Series 1, has been developed by Moutere Logging Ltd to be compatible with a tower yarder. The FFC uses an internal combustion engine to power the hydraulic grapple which can rotate 360 degrees; this rotation and the remote camera allow for more manoeuvrability when grappling trees (McFadzean, 2012). Wood Contracting Ltd has developed a tether system whereby a self-levelling feller buncher is attached to a modified bulldozer which is positioned at the top of the slope. This can operate safely on slopes exceeding 80%, providing that there are suitable soil conditions and no large obstacles such as rocky outcrops impeding the tether. This machine can therefore reduce the need for motor-manual tree falling which would otherwise be the preferred felling method in steep slopes. Hence, a cable harvesting operation employing either a swing yarder with a mechanical grapple or a tower yarder with a motorised grapple carriage can now become fully mechanised.

Elemental time studies have been described as the most effective way of comparing the delay-free production times of harvesting systems (Olsen, Hossain, & Miller, 1998). By using data collected in a detailed elemental time study, regression equations can be developed using linear regression, which can be used to help explain the productivity of a system (Heinimann, Visser, & Stampfer, 1998). A limitation of elemental time studies is that often relatively narrow sample sizes are collected, which can often lead to delays and individual harvest areas being inadequately sampled (Olsen et al., 1998).

The challenges of maintaining productivity in mechanised harvesting operations has been described by Beaulieu (1989). He highlighted the need to maximise efficiency, and therefore the cost effectiveness, of expensive mechanised harvesting operations by maintaining a balance between the rates of tree extraction and processing. This is because slow extraction rates because the processor to become underutilised, in contrast, if processing is the yarder to become underutilised. He stated that the formation of a surgepile (or buffer) when the extraction rate exceeds the rate of processing, can reduce the risk of the processor becoming underutilised if mechanical or operational delays, or adverse extraction conditions reduce the rate of extraction. As one system in this study does use surgepiles and the other does not, this study will be suitable to analyse the impacts of using surgepiles on productivity.

An analysis of delays for traditional cable yarder systems which employ strops and chokers indicated that mechanical delays accounted 5% of scheduled machine hours, while operational delays accounted for 31% (Fitzgerald, 1996). A study of the motorised FFC carriage, found mechanical and operational delays of 15% each (McFadzean, 2012). This indicates that mechanical delays become more prominent for systems with higher levels of technology such as the FFC, as the mechanised yarder carriage and on-landing processing are more prone to breakdowns than traditional equipment. Despite this, mechanised systems tend to have less time spent in operational delays than traditional systems; possibly because improved technology requires a simpler work method and requires less human interaction.

Amishev and Evanson (2010) carried out an elemental time study on Wood Contracting Ltd which operated a swing yarder with a mechanical grapple that was complemented by mechanised felling and pre-bunching. The average productivity of this system was 63 tonnes per productive machine hour (t/PMH). They found that the number of stems yarded per cycle was significantly greater when mechanised felling and pre-bunching of stems occurred than when trees were motor-manually felled and pre-bunching did not occur. As the benefits of mechanised pre-bunching are more pronounced for smaller piece sizes (Heinimann, Visser, & Stampfer, 1998), and average piece size of this study site was relatively small, there is potential for further research to investigate the effect of larger piece sizes on the productivity benefits of pre-bunching for this system. Furthermore, this study did not include the formulation of a productivity function which could be used to predict the productivity of the system under different yarding conditions.

An elemental time study on Moutere Logging Ltd which operated a tower yarder employing a motorised grapple carriage (the FFC) was carried out by McFadzean (2012). In this study a linear regression model was developed which can be used to estimate the productivity of the system given terrain, stand and stem presentation information. It was found that productivity increased from 33 t/PMH when extracting motor-manually felled stems, to 63 t/PMH and 76 t/PMH when stems were bunched, or handed to the grapple, respectively. Operating the FFC instead of chokers was found to reduce productivity, although this was in situations where stems were motor-manually felled and not pre-bunched or handed by an excavator. However, this study was conducted when the FFC was in earlier stages of development, and hauler operators were relatively inexperienced in its operation. There has since been improvements to the design of the FFC to make it more efficient by decreasing mechanical delay times, and hauler operators have had more experience with using the FFC.

A comparative study would allow a more fairly judged understanding of the advantages and disadvantages of each system under given yarding conditions (Bell, 1985). Previous comparisons of swing yarder and tower yarder operations in New Zealand have found that swing yarder operations were on average 25% more productive than tower yarders; this may be due to the fact that swing yarders on average operated with lower extraction distance, easier terrain and larger piece sizes. It was found in the same study that all things being equal; tower yarder operations were more cost effective (R. Visser, 2011). A comparative study is required to make a more direct comparison between systems involving a swing yarder operating a mechanical grapple or a tower yarder operating a motorised grapple; both of which have significant potential for increased utilisation in New Zealand.

4. PROBLEM STATEMENT AND RESEARCH QUESTIONS

Concerns with the safety and productivity of traditional cable harvesting systems are looking to be addressed by the introduction of more mechanised harvesting systems. Cable harvesting systems which use grapple carriages and mechanised felling can increase the safety and productivity of cable harvesting. The capital cost of mechanised cable harvesting systems is significant and therefore there is a need to quantify the production benefits of these systems to ensure that it is economically viable.

This study will validate and expand on the findings of past research and provide a more direct comparison of the motorised and mechanical grapple systems. In particular the effect of felling technique and stem presentation method, and terrain and stand variables on the payloads, cycle times, delays and the resulting productivity of the two systems will be analysed.

The following research questions aim to be answered by this study.

1. Does the system used have a significant effect on productivity
2. Does the felling and stem presentation method have a significant effect on productivity
3. Do terrain and stand variables have a significant effect on productivity

This information can then be used to develop functions which can be used to assess which steep terrain settings would suit either each of the harvesting systems which have been analysed in this study.

5. METHODS

An elemental time study focusing on two cable harvesting systems has been carried out for Hancock Forest Management during the 2013/14 summer. Below is a detailed explanation of the study methodology and description of the study conditions.

5.1. System Descriptions

Two different cable harvesting systems were analysed in this study and have been characterised by the type of grapple carriage which they use; the mechanical grapple (Figure 1) which will be referred to as the Mechanical system, and the motorised grapple (Figure 2) which will be referred to as the Motorised system. These systems have been described in regards to equipment and techniques used in Table 1.

Figure 1: The mechanical grapple.

Figure 2: The motorised grapple.

Table 1: Description of rigging configuration and equipment used for each system.

Component	System	
	Mechanical	Motorised
Hauler	Model: Pacific 1188 Swing Yarder Height: 18 m Power: 335 kW	Model: Madill 171 tower yarder Height: 21 m Power: 335 kW
Grapple	Description: Mechanical grapple with remote camera Weight: 1.3 tonne Opening width: 280 cm	Description: Motorised grapple with remote camera and 360 degree grapple rotation Weight: 2.3 tonne Opening width: 203 cm
Skyline system	Running	Live
Processing	Excavator with Waratah processing head	Excavator with Waratah processing head
Felling/Bunching	Mechanical: Tethered feller buncher Motor-manual: Chainsaw	Mechanical: Feller buncher Motor-manual: Chainsaw
Tail hold	Excavator with T-bar attachment (1-4 m elevation)	Tracked tractor (0.5 m elevation) or tail-spar (6 m elevation)

Both contracting crews have ground based capabilities which can be used to continue extraction in the case of extended mechanical delays. The Mechanical system uses the tethered self-levelling feller buncher to shovel trees to the landing while the Motorised system uses a pneumatic tyre skidder for ground based extraction.

One main difference between the techniques of these two systems was the presence of surgepiling (i.e. the creation of a production buffer). The Mechanical system did not create surgepiles; this meant the hauler operator would have to wait for the previous payload to be processed before moving the next payload onto the landing if extraction was faster than processing rate. The Motorised system, however, did make surgepiles so that the cable extraction could continue regardless of whether the processor had finished processing the previous payload, because payload was fleeted from the chute to the surgepile. The Motorised system created surgepiles because having a production buffer allowed the crew to continue production in the case ground based capabilities not being readily available when a mechanical delay occurred.

5.2. Study Sites

The data for this study was collected over 14 days at five different sites in the Hancock Forest Management estate in Nelson. Basic information of each site is shown in Table 2.

Table 2: Key site characteristics.

Site	System	Data capture	Piece size*	Horizontal haul distance*	Mid-span Deflection*	Hill slope*	Stem presentation		
							Motor-manual	Bunching	Handing
		(hrs)	(t)	(m)	(%)	(%)	(%)	(%)	(%)
HA1237	Mechanical	29.5	1.2	115	11	27	0.00	0.82	0.18
HA7361	Mechanical	5.8	1.0	172	10	40	0.27	0.37	0.36
HA2444	Motorised	8.0	1.4	185	21	76	1.00	0.00	0.00
HA2445	Motorised	24.8	1.4	156	10	36	0.04	0.44	0.52
HA2441	Motorised	19.5	1.5	102	16	41	0.39	0.61	0.00

*Average values.

5.3. Elemental Time Study

5.3.1. Cycle Components

An elemental time study was carried out by taking continuous time readings of four different components of the extraction cycle, as described below:

Carriage out: Begins when the carriage begins moving horizontally away from the landing after unhooking.

Accumulate: Begins when the carriage has stopped moving horizontally away from the landing and is at the position of the target payload.

Carriage in: Begins when the carriage begins to move horizontally towards the landing with the logs held in the grapple.

Unhook: Begins when the carriage has stopped moving horizontally once on the landing.

5.3.2. Delays

As well as the extraction time components, delays were also timed and categorised into operational, mechanical or personal delays. Operational delays are caused by an action that is necessary to continue extraction, but not caused by mechanical issues. While personal delays involve the crew taking necessary time off from extracting trees in order to rest. Operational delays are the most common and so have been further categorised below.

Processing:	Waratah processing trees into logs, or chute being cleared into a surgepile at a slower rate than that of extraction. This causes a delay before the unhook phase as the hauler operator must wait for machines to move away from the chute before landing the next payload onto the landing.
Handing:	The hauler operator must wait for the excavator to bunch felled trees before it hands them to the grapple.
Line shift:	The act of moving the tail-hold to a new cable corridor to extract a fresh line of felled trees.
Hauler shift:	Turning the hauler to access new terrain on the same setting or moving the hauler to allow trees to be extracted from a new setting.
Miscellaneous:	A relatively uncommon operational delay which does not fall within any of the above operational delay categories.

5.3.3. Block Factors

Several block factors were recorded in order to assess the effects of stem presentation, system type and tree recovery. The following variables were recorded as quantitative variables to make it possible to carry out statistical analyses.

System:	The system which was being utilised.	1 = Motorised, 0 = Mechanical
Motor-manual felling:	Trees felled using motor-manual felling. Subsequently no bunching or handing would occur.	1= Yes, 0 = No
Bunching:	Felled trees were sorted into bunches for improved extraction with the grapple carriage (Figure 1)	1 = Yes, 0 = No
Handing:	Felled trees were physically handed to the grapple carriage by an excavator or grapple skidder (Figure 1)	1 = Yes, 0 = No
Lost:	Trees were lost out of the grapple carriage on the carriage in component of the cycle	1 = Yes, 0 = No
Broken:	Trees were broken on the carriage in component of the cycle.	1 = Yes, 0 = No

Figure 1: Felled trees are bunched and/or handed to improve extraction efficiency.

5.4. Payload Estimation

Payloads were recorded by using average piece size (determined by pre-harvest inventory analysis by HFM Nelson) multiplied by the number of pieces yarded to the landing. It was assumed that 5% of the tree weight was lost when a tree was extracted in multiple pieces as the breakage often results in wood material being lost in the field. This is why the butt and top weights do not add up to 100%.

Full tree	=	1 * average piece size
Butt	=	0.8 * average piece size
Top	=	0.15 * average piece size

5.5. Terrain Variables

To support the time study information, terrain variables were analysed and collected as described below. The average position of the cable corridor was taken at each site on a hard copy map and later entered into ArcGIS. The cross section of this line position is then able to be analysed to calculate the mid-span deflection, hill slope and chord slope of the cable corridor using graphical methods (Liley, 1983).

Horizontal haul distance:	Horizontal distance between the hauler and the position of the felled trees which are being extracted.
Hill slope:	The average slope of the hill immediately under the cable corridor.
Chord slope:	The slope of a virtual straight line (chord) which travels from the top of the hauler to the tail hold.
Mid-span deflection:	The distance between the chord and the ground, divided by the horizontal length of the cable corridor.

5.6. Data Analysis

In preparation for the statistical analysis of this study, data was screened for outliers. This allowed the identification of incorrect data, such as the carriage being brought from a haul distance of 160 metres back to the landing in 0.1 minutes. This has to be an incorrect value as the carriage cannot possibly be moved this fast. It is more accurate to delete all the data from this cycle in this situation as the measurements for cycle components before and after the incorrect reading may be affected as well. This is one of the main limitations of an elemental time series using a continuous time recording method, as incorrectly recorded data can distort the measurement of the subsequent cycle component. Because of the large quantity of data which was collected (1428 cycles), 20 cycles with incorrect data were able to be removed without significantly affecting the sample size of the dataset, only one incorrect data point was replaced with an average value; a list of the data remediation actions is shown in Appendix 3.

Stepwise linear regression was carried out in order to produce functions, this is the best way to identify the most influential parameters which affect the dependent variable for harvesting situations (Heinimann et al., 1998). This statistical analysis was performed using IBM SPSS, a statistical software program. A statistical significance level of 90% was used for all analysis of variance (ANOVA) tests and function building, which is more lenient than the standard 95% significance level. This significance level was selected because harvesting operations are often highly variable as there are so many uncontrolled variables which determine extraction performance (Olsen et al., 1998). The error bars shown in several figures in this report also represent 90% confidence limits.

6. RESULTS AND DISCUSSION

Table 3 provides the averages and standard deviations of the parameters captured during the study of the two different systems.

Table 3: Key summary statistics for the two systems studied.

Variable	Mechanical		Motorised	
	Mean	Std. Dev.	Mean	Std. Dev.
Lost trees (%)	0.2	0.4	6.5	4.0
Broken trees (%)	5.1	3.0	1.5	1.0
Piece size (t)	1.2	0.1	1.4	0.1
Pieces per cycle	2.7	1.1	2.0	0.9
Cycle payload (t)	2.9	1.3	2.6	1.2
Delay free cycle time (centimins)	2.07	0.62	2.32	0.98
Total cycle time (centimins)	4.15	16.97	4.35	13.35
Delay free productivity (t/PMH)	89	48	76	42
Total productivity (t/SMH)	45	24	40	22

6.1. Payload Analysis

6.1.1. Overview

Table 3 indicates that the mechanical grapple system had a slightly greater average number of pieces extracted per cycle. This has resulted in a higher average cycle payload for the Mechanical system than the Motorised, despite on average working with slightly smaller piece sizes. This could be due to the Mechanical system extracting more bunched and handed trees than the Motorised system; bunched and handed trees increase average extraction payload considerably (Figure 4). It is also shown that the average payload when extracting handed trees is not noticeably greater than when extracting pre bunched trees for either of the systems.

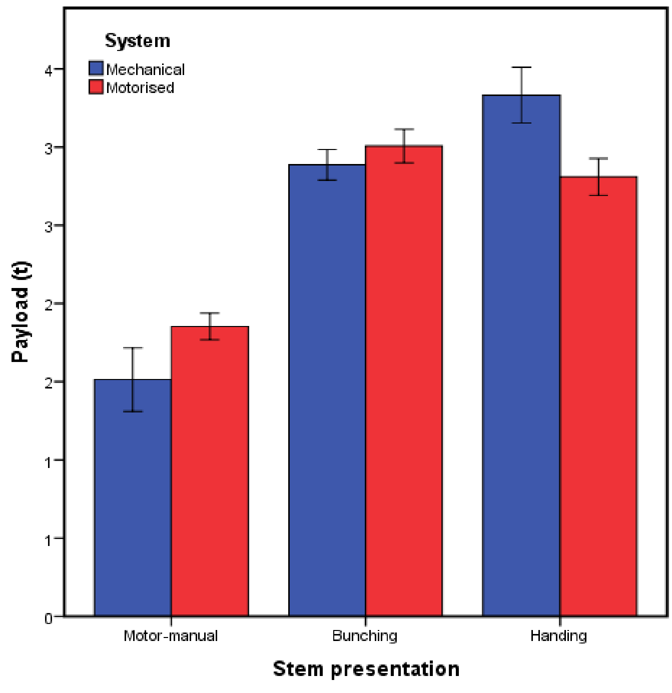

Figure 2: Average payload per cycle for each system by stem presentation.

6.1.2. Predicting Payload

The function shown in Equation 1 has an r square value of 0.153, indicating that payload is difficult to predict with the given variables. However, the function is still useful to get an understanding of the effect that certain variables have on payload.

Equation 1: Linear regression for estimating payload.

	Coefficient	Std. Error	Mean	Range	P-value	R^2
Constant	-1.878	0.823			0.023	0.169
Horizontal haul distance (m)	+0.002	0.001	130	10-450	<0.001	
Hill slope (%)	-0.012	0.004	37	23-76	0.005	
Chord slope (%)	+0.022	0.004	34	15-47	<0.001	
Piece size (t)	+3.753	0.62	1.0	1-1.5	<0.001	
System	-1.257	0.219			<0.001	
Motor-manual felling	-0.948	0.116			<0.001	

The most notable finding is that when all other variables are equal, the motorised grapple tends to extract smaller payloads. The two systems operate yarders with the same power rating, and deflection was found to have no influence on payload (see Appendix 1), so these two factors should not be affecting the payloads that were realised during the study. Operator accuracy has not been analysed in this studied in this report as this would have negatively affected the production of the crews, therefore we are assuming that there is no difference between the effectiveness of the operators of the two systems.

The difference in payload may be a result of the physical differences between the two grapples. The motorised grapple has a tare weight of 2.3 tonnes, compared to 1.3 tonnes for the mechanical grapple, giving the mechanical grapple an additional one tonne of potential payload per cycle. This issue has been addressed in the new model of the FFC (Series 2) which is 800 kg lighter, and has a maximum payload of approximately 4 tonnes. The reduced size of the carriage also gives it a narrower grapple opening width, meaning the maximum number of pieces accumulated will be reduced. Another possible reason for the mechanical grapple being able to hold more pieces is that the opening width of the grapple is 77 cm wider than that of the motorised grapple. This enabled the possible accumulation of at least one more stem per cycle.

Equation 1 can be utilised in two ways to predict the productivity of a system. The first is to calculate productivity as a function of predicted payload and predicted cycle time (covered in section 6.2.2). The second is to use predicted payload as an input variable into the corresponding productivity function (covered in section 6.4.2).

It was found that mid-span deflection was included in the equation with a negative coefficient value (see Appendix 1). This result shows evidence of confounding, as having increasing mid-span deflection is expected to increase payload. Mid-span deflection could be confounding results because payloads were not being limited due to the weight exceeding the theoretical maximum permissible weight. Mid-span deflection was shown to have a weak negative linear relationship with payload; indicating that mid-span deflection was not an appropriate variable for predicting productivity. Mid-span deflection has therefore been removed from the creation of functions in this study.

Variables such as the loss or breakage of stems, and individual sites were also excluded from the productivity function building process. This is because it is impractical to predict whether logs are going to be broken or lost in any situation; and therefore could not be inputted into the production function with sufficient accuracy. Individual sites have also been excluded from the productivity function; because using a site to predict the productivity of another site is inaccurate as no two sites are the identical.

6.2. Cycle Time Analysis

The Motorised system had a delay free total cycle time of 2.32 minutes, which was significantly greater than the 2.07 minutes for Mechanical system (P-value < 0.001).

6.2.1. Cycle Component Breakdown

Figure 6 shows the average time taken by the different components of the cycle for each system.

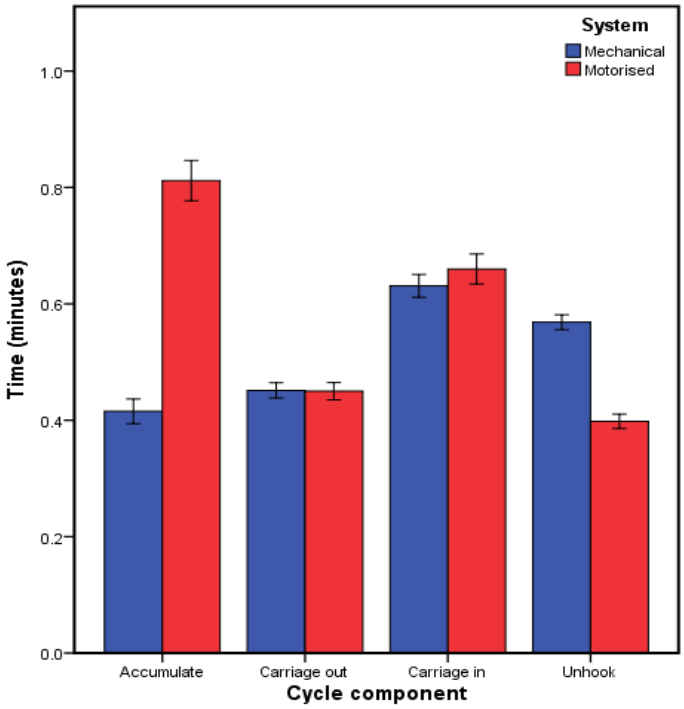

Figure 3: Average time taken per cycle for different cycle components.

Carriage Out

There was no significant difference between the carriage out time of the two systems (P-value = 0.921). Both the Mechanical and Motorised systems averaged 0.45 minutes. Carriage out time shows a large degree of heteroscedasticity, with further haul distances resulting in much more variable carriage out times than shorter haul distances. Of the 38 cycles in which the carriage out time exceeded one minute, 33 were at distances of more than 120 m horizontal haul distance. This is likely because beyond 120 m carriage speed was often observed to decrease when the hauler operator was relying solely on the remote camera to visualise target logs rather than a combination of vision from the hauler cab and the remote camera.

Accumulation

The linear regression model shown in Equation 2 has been developed to analyse the impacts of different variables on accumulation time for both of the systems. The model to predict accumulation times can be useful as the accumulation time was the largest point of difference between the cycles times of the two systems. The average accumulation time for the Mechanical system was 0.42 minutes while the Motorised system was 0.8 minutes (Figure 3). The following factors were found to have a significant effect on hook-up times:

- Lost stems: when stems were lost out of the grapple after they had been clamped the trees were often clamped again which resulted in longer accumulation times
- Terrain: further haul distances were found to have a positive influence on accumulation times as higher haul distances and hill slopes often resulted in decreased vision from the hauler cab.
- Stem presentation: having trees bunched or handed by an excavator was found to decrease the amount of time taken to accumulate trees compared to when they were motor-manually felled.
- System: the Motorised system took on average 92% longer to accumulate felled trees than the Mechanical system. This could be attributed to the motorised carriage needing to be more delicate when accumulating felled trees because it is less robust than the mechanical grapple.

Equation 2: Linear regression for estimating accumulation time.

	Coefficient	Std. Error	Mean	Range	P-value	R^2
Constant	-1.467	0.3521			<0.001	0.244
Horizontal haul distance (m)	0.002	0.0002	130	10-450	<0.001	
Hill slope (%)	0.010	0.0018	37	23-76	<0.001	
Chord slope (%)	-0.003	0.0018	34	15-47	0.099	
Piece size (t)	1.371	0.2600	1	1-1.5	<0.001	
System	-0.126	0.0910			0.167	
Bunching	-0.119	0.0492			0.016	
Handing	-0.234	0.0548			<0.001	

Carriage In

There was no significant difference between the carriage in times of the two systems (P-value = 0.163). Carriage in time tends to increase with increasing horizontal haul distance. The Mechanical system averaged 0.63 minutes and the Motorised system averaged 0.67 minutes. This finding is expected as the yarders both systems had the same power rating (335 kW).

The fact that these averages are higher than carriage out time is expected; as a carriage loaded with stems is much heavier, increasing skyline tension which causes slower drum winding speeds. Terrain roughness was not measured due to time and measurement technique constraints, although it may have had a significant effect on carriage in times as rugged terrain can impede the path of the carriage.

Unhook

The Mechanical system had significantly (P-value < 0.001) greater unhook time of 0.57 minutes than the Motorised system, which averaged 0.40 minutes. The results of a linear regression analysis indicate that the type of system was the main influencer on un-hook times. This was likely because the tower yarder in the Motorised system only requires one movement of the skyline to lower and unhook the trees, while the swing yarder in the Mechanical system needed to swing the boom past the unhooking area and then lower the skyline. Another reason may be that the mechanical grapple requires several ropes to be adjusted to open the grapple and release the logs, while the hauler operator in the Motorised system can simply press a button to release the trees from the grapple.

6.2.2. Predicting Delay Free Total Cycle Time

The delay free total cycle time functions shown in Equation 3 and Equation 4 indicate that increasing horizontal haul distance increases cycle time for both of the systems. Differences between the functions are that in the Mechanical cycle time function, motor-manually felled trees increase cycle time, while in the Motorised function increasing hill slope increases cycle time and mechanically handed trees decreases cycle time. The r squared of the Mechanical and Motorised cycle time functions are 0.333 and 0.497 respectively, which is sufficiently accurate for cable harvesting extraction time functions.

Equation 3: Delay free total cycle time linear regression for the Mechanical system.

	Coefficient	Std. Error	Mean	Range	P-value	R^2
Constant	1.165	1.0108			<0.001	0.317
Horizontal haul distance (m)	+0.006	0.0004	125	12 - 300	<0.001	
Chord slope (%)	+0.003	0.0019	26	15-41	0.076	
Motor-manual felling	+0.281	0.1010			0.005	

Equation 4: Delay free total cycle time linear regression for the Motorised system.

	Coefficient	Std. Error	Mean	Range	P-value	R^2
Constant	-1.592	1.2320			0.211	0.495
Horizontal haul distance (m)	+0.009	0.0005	134	10-450	<0.001	
Hill slope (%)	+0.024	0.0022	43	34-76	<0.001	
Chord slope (%)	-0.011	0.0048	40	21-47	0.027	
Piece size (t)	+1.365	0.7532	1.4	1.4-1.5	0.07	

The r square of the Motorised function is higher than the r square value of 0.42 found in the study of the Motorised system by McFadzean (2012). The only similarity of the equations in these two studies is the inclusion of haul distance, although McFadzean (2012) used true haul distance, rather than horizontal haul distance, as was the case in this study.

Figure 13 and Figure 14 (Appendix 2) indicate that there was a slightly biased prediction of cycle times for both systems. The amount of underestimation which was being displayed at actual cycle times of more than 2.7 minutes is concerning, and must be taken into account when utilising these functions. It may be caused by payloads taking longer to accumulate in adverse conditions than expected, as the stems were either not visible or were presented to the grapple in an ineffective position.

It is shown in Figure 6 that increasing horizontal haul distance has a larger effect on cycle time of the Motorised system than the Mechanical system. The Motorised system had on average faster cycle times than the Mechanical system when extracting from horizontal haul distances of less than 90 m. This is due to the shotgun configuration in the Motorised system allowing the carriage to travel out at much higher speeds (due to gravity) than that of the Mechanical system, which relies on the tail line drum to pull the carriage down the hill. However, at a horizontal haul distance of between 90 and 300 m (the range of distances sampled for the Mechanical system), the Mechanical system was the fastest, which is mainly attributable to the fast accumulation times.

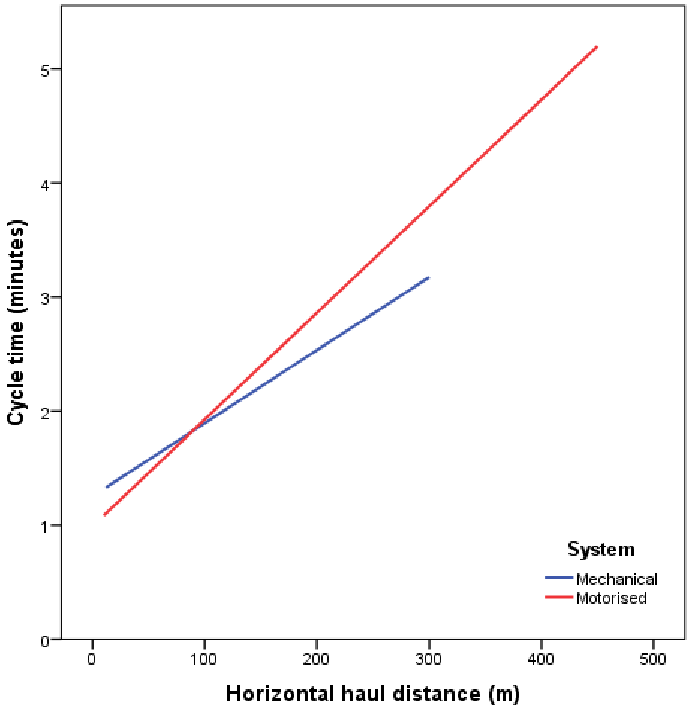

Figure 4: Cycle time as predicted by the separate functions (Equations 3 & 4) for each system, given haul distance, when all other variables are constant.

6.3. Delay Analysis

6.3.1. Overview

The Mechanical and Motorised systems displayed similar duration of mechanical and operational delays (Figure 5). The significant range of the confidence interval bars in Figure 5 for the mechanical delays is due to there being few, but large delays, whereas the operational delay time has more narrow error bars as operational delays occurred more often. The difference between the personal delays of the two systems was due to the Mechanical system being more productive in general so there was less pressure for the crew to have a shorter break in order to continue production.

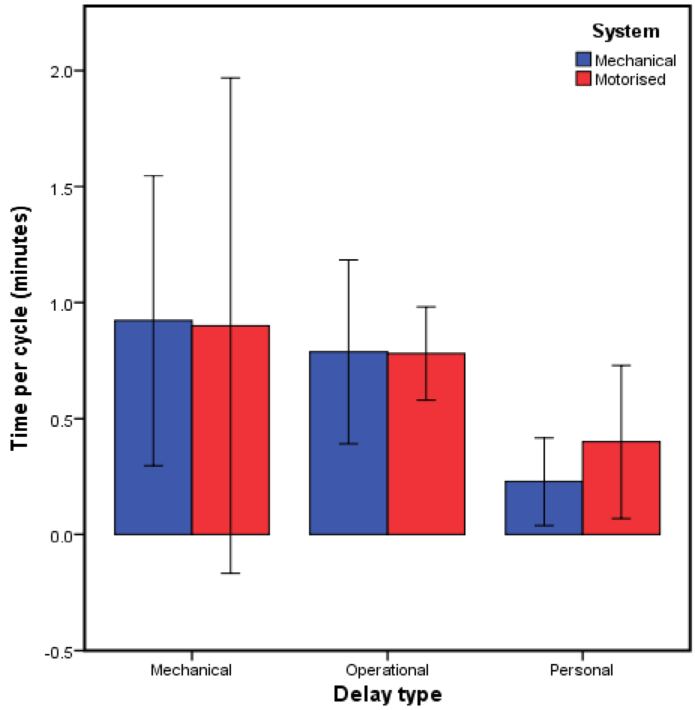

Figure 5: Average delay time by type for each system studied.

The average total cycle time with delays was 4.15 minutes for the Mechanical system with 2.07 minutes of this being delay-free, resulting in a 50% utilisation rate. The study by Amishev and Evanson (2010) found the total cycle time to be 3.0 minutes, of which, 2.48 minutes was productive time (81% utilisation rate). That study also indicated an operational delay rate of 17% and a mechanical delay rate of 1%; whereas, this study found operational and mechanical delay rates of 19 and 22%, respectively. The disparity between these findings could be due to varying sample sizes. The sample size for the Mechanical system in this study was 612 cycles which was collected over seven days, whereas the study by Amishev and Evanson (2010) sampled 193 cycles over two days. The sample size within this study is significantly larger than the study mentioned above and therefore has a higher probability of being more representative of the actual system delay breakdown.

The Motorised system had a slightly higher average total cycle time of 4.35 minutes, with 2.3 minutes of this being productive time. This resulted in a utilisation rate of 53% which is very similar to that found by McFadzean (2012) who found a utilisation rate of 56%, with a delay-free cycle time of 4.21 minutes when motor-manually felled stems, 2.63 minutes with bunched stems and 2.12 minutes with handed stems. That study also found 15% mechanical and 15% operational delays, which is similar to those found in this study where 21% was mechanical delays and 18% was operational delays. The McFadzean (2012) study measured 598 cycles, which is comparable to the 816 cycles measured in this study.

6.3.2. Operational Delays

The differences between the operational delays of the two systems are shown in Figure 8. The handing delays experienced by the Motorised system were due to the hauler operator having to wait for the feller buncher to accumulate and hand the stems to the grapple, this occurred at site HA2445.

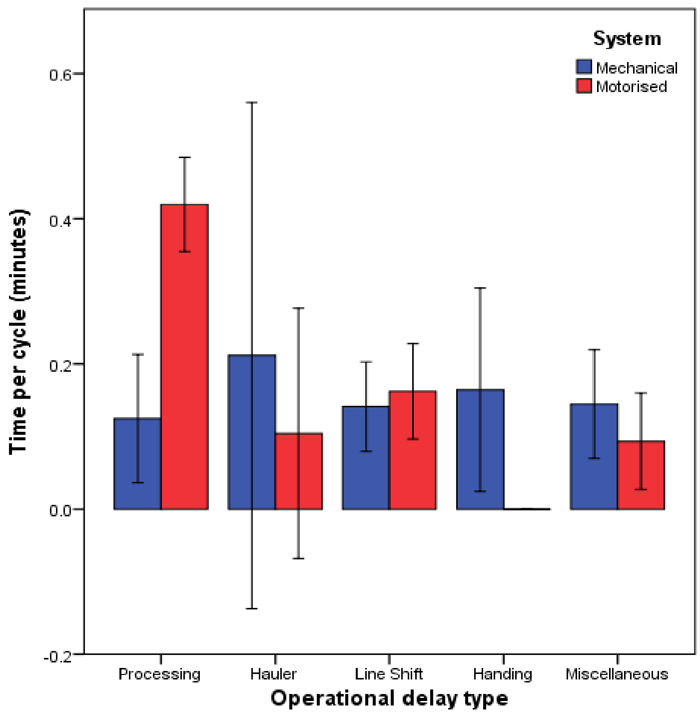

Figure 6: Breakdown of operational delays as average time per cycle.

Both of the systems had one hauler shift each. The hauler shift took approximately one hour for the Mechanical system and three hours for the Motorised system. This was due to the swing yarder in the Mechanical system having a mobile guy line hold (Figure 9), making hauler shifts faster. While the tower yarder was less mobile because it had eight guy lines (the swing yarder had three) which were required to be individually dug into the ground.

Figure 7: The Motorised system (left) and Mechanical system (right) guy line configurations.

The Mechanical system had more processing delay time than the Motorised system. This is attributable to the different techniques employed by the different crews. The crews which operated the Motorised system created surgepiles near the hauler using a Bell loader, the Waratah processing head then processes stems from this pile. This method therefore ensures the stems in the chute are cleared quickly. Creating surgepiles results in less processing delays and creates a 'buffer' in case of a mechanical issue with the extraction process. Although having a surgepile results in congestion on the landing, double-handling of stems, and increased pressure on the processor operator. The crews operating the Mechanical system generally did not create surgepiles; instead, the stems would be processed straight from the chute, which meant that the hauler had to wait if the processor had not finished the previously extracted payload. This meant that in more favourable extraction conditions processing delays were more prominent for the Mechanical system.

Both of the Mechanical and Motorised systems had 14% of their operational delays attributable to line shifts, which involve moving the tail hold to shift the cable corridor. The Mechanical system carried out 33 line shifts and the Motorised system carried out 30, resulting in the Mechanical system averaging a line shift every 18 cycles, while the Motorised system averaged a line shift every 27 cycles. The average line shift delay time of the Mechanical system was 3.0 minutes while the Motorised system was 3.8 minutes per line shift, respectively. This is likely due to the excavator tailhold for the Mechanical system being more manoeuvrable and positioned in easier terrain than the bulldozer for the Motorised system, making line shifts faster.

6.4. Productivity Analysis

6.4.1. Overview

The Mechanical system had significantly greater productivity than the Motorised system (P-value < 0.001). On average, the Mechanical system achieved an average productivity of 89 t/PMH, while the Motorised system achieved 76 t/PMH. The Motorised system was often exposed to more difficult sites with longer haul distances and steeper slopes, and extracted motor-manually felled trees much more often than the Mechanical system (Table 3).

When taking into account the utilisation rate of the two systems, it was found that the Mechanical system had an average productivity of 45 tonnes per scheduled machine hour (t/SMH), and the Motorised system averaged 40 t/SMH.

The average productivity of the Mechanical system (89 t/PMH) was considerably more than the 63 t/PMH found in the study by Amishev and Evanson (2010) . This may be partly due to the Amishev and Evanson study having a longer average haul distance (163 m), smaller average piece size (0.85 t) and a lower proportion of cycles grappling bunched/handed trees (58%).

The Motorised system had substantially higher productivity than those found by McFadzean (2012), having higher productivity when extracting handed, bunched and motor-manually felled trees. In the McFadzean study, operating chokers produced a productivity of 42 t/PMH when extracting motor-manually felled trees, which is lower than the motorised grapple in this study of 59 t/PMH when extracting motor-manually felled trees (Figure 8). This indicates that using the Motorised system can be both safer and more productive than using chokers in motor-manually felled trees.

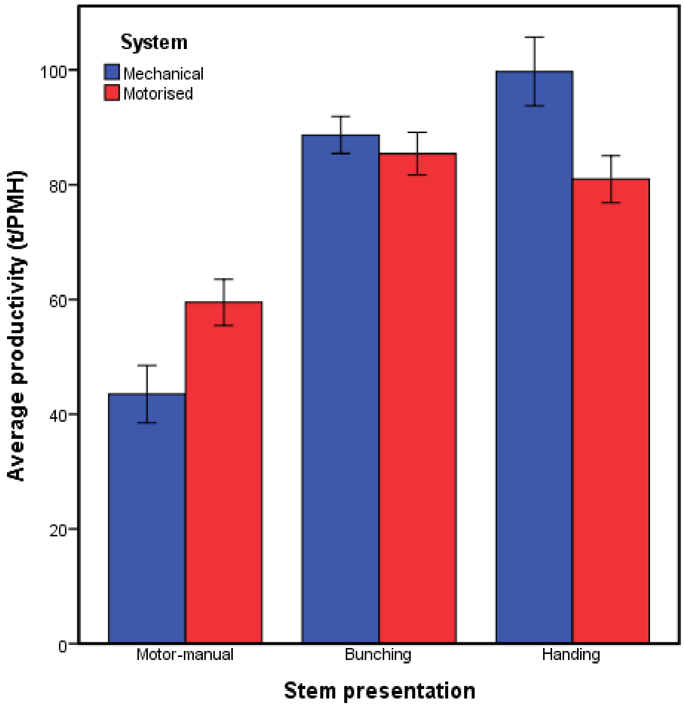

Figure 8: the effect of stem presentation on productivity by system.

The Mechanical system achieved greatest productivity when extracting handed trees (Figure 8). While the Motorised system was the most productive when extracting motor-manually felled trees, as the motorised grapple was able to rotate its grapple when accumulating unorganised motor-manually felled trees. There was no notable difference between the bunched and handed productivity levels for the Motorise system, while the productivity of the Mechanical system was higher when handing occurred than bunching.

The implications of these findings for crew scheduling are that preference should be given to crews operating the Mechanical system if there is mechanically felled trees with bunching or handing present, and the Motorised system should be preferred in sites with more segments of motor-manual felling. Also, that bunching is likely to be a more cost effective method than handing for both systems, as it achieves relatively similar productivity levels but does not require an excavator to remain down the hill during extraction.

It was found in a study by Heinimann et al. (1998) that the effects of pre-bunching and handing are less pronounced for smaller piece sizes. This could cause bunching and handing to become less effective for both systems in harvest settings where the average piece size is much larger, such as in some North Island regions.

Table 3 shows that the Mechanical system was found to break more stems (one breakage every 67 cycles) than the Motorised system (one breakage every 20 cycles). Broken stems result in a loss of value as the broken piece that is lost is often not recovered, and because the breakage section of the tree becomes waste when processing occurs.

The Motorised system was found to lose more stems out of the grapple during the carriage in phase than the Mechanical system, having a loss in 15 cycles compared to the one loss in the 613 cycles sampled for the Mechanical system. Losing stems is especially detrimental for the Motorised system because it operates a tower yarder which has no lateral yarding capabilities. So when trees were lost and went to the wrong side of the corridor, the lost trees could not be recovered. If the stems were picked up once being lost, this resulted in substantially increased accumulation times.

6.4.2. Predicting Productivity

A productivity function was developed with the purpose of predicting the productivity for each of the two systems, as shown in Equation 5 and Equation 6. It is shown that increasing cycle payload positively impacts productivity, which can be estimated for a setting using Equation 1, while increasing horizontal haul distance decreases productivity for both systems.

Equation 5: Productivity linear regression for the Mechanical system.

	Coefficient	Std. Error	Mean	Range	P-value	R^2
Constant	56.081	2.79			<0.001	0.736
Horizontal haul distance (m)	-0.279	0.628	125	12-300	<0.001	
Payload (t)	+23.824	0.017	2.9	0.2-7.2	<0.001	
Motor-manual felling	-23.325	4.302			<0.001	

Equation 6: Linear regression for the productivity of the Motorised system.

	Coefficient	Std. Error	Mean	Range	P-value	R^2
Constant	35.119	5.997			<0.001	0.674
Horizontal haul distance (m)	-0.199	0.013	134	10-450	<0.001	
Payload (t)	26.165	0.789	2.6	0.2-7.2	<0.001	
Hill slope (%)	-0.243	0.075	43	34-76	0.001	
Chord slope (%)	0.262	0.124	40	21-47	0.034	

The productivity functions developed for each system are potentially very useful when matching systems to different harvesting settings, as the total cycle time and payload equations can be used to check the results given. The fact that the payload value is a prediction in itself, rather than a known value, means that the high r square values being indicated by these functions are irrelevant.

The productivity functions will be most useful when attempting to predict the productivity of both systems in sites with variables inside of the range given. Figure 13 and Figure 14 (Appendix 2) show that both of the productivity functions tend to under predict the productivity of cycles which have actual productivities of above 160 t/PMH, with several points being under predicted by more than 100 t/PMH.

7. LIMITATIONS

The productivity functions for both systems tend to underestimate the productivity of extremely favourable extraction conditions where productivity rates of up to 160 t/PMH were being realised. Regarding cycle time predictions, it was found that cycle times were being under predicted in extremely adverse extraction conditions, where actual cycle times of up to 4.2 minutes were being recorded. Therefore predictions of productivity in harvest settings should be accounted for accordingly.

The estimation of payload was limiting, as it was based on average piece sizes, and assumptions of what proportion of a tree top or butt would be, rather than the direct measurement of the realised payload of each cycle. Also, the payload function has a very low r square value of 0.153, therefore productivity calculations including a prediction made from this function could be highly inaccurate and therefore the main limiting factor.

The elemental time study was carried out using a continuous time scale, which meant that any mistakes in the recording of a cycle component would adversely affect the measurement of the subsequent component. The screening of errors in the dataset removed the outstanding errors; less obvious errors would not have been picked up and would have been included in the data analysis. Despite this, the effect of these errors would be relatively minor due to the large size of the dataset.

The Mechanical system has been measured generally on more favourable sites with lower haul distances, hill slopes and more mechanically felled trees. Therefore the productivity function for the Mechanical system would be limited in more adverse sites.

During the study, both of the systems only employed one rigging configuration each, therefore the use of productivity predictions will become limited when other configurations are used that were not sampled in this study.

The measurement of horizontal haul distance had an accuracy of ± 10 metres. Horizontal haul distance could be measured more accurately with a laser range finder or specialised GPS unit attached to the carriage.

8. CONCLUSIONS

The Mechanical and Motorised systems were found to be effective mechanised cable harvesting systems, with observed average productivity levels of 40 and 45 t/SMH, respectively.

Although on average the Mechanical systems only extracted 0.3 t more payload per cycle, it was found to extract 1.3 t more payload per cycle than the Motorised system when all other variables were equal. This may be due to the mechanical grapple being one tonne lighter and has 28% larger opening width than the FFC, so it can carry heavier payloads and/or more stems.

On average the Mechanical system had the shortest delay free cycle time, with 2.07 minutes compared to 2.32 minutes for the Motorised system. The main points of difference between the cycles of the two systems were the accumulation and unhooking of felled trees. The Mechanical system was almost twice as fast at accumulating stems as the Motorised system, which may be attributable to the mechanical grapple being more robust so it can be more forceful when grappling trees. However, the Motorised system was significantly faster at unhooking stems than the Mechanical system, as fewer lines needed to be adjusted to lower the payload and release the stems from the grapple. The Motorised system was found to have shorter cycle times than the Mechanical system at shorter haul distances, which was not expected as swing yarders are often assumed to have faster cycle times in shorter haul distances.

The utilisation rates of the Mechanical and Motorised system were 50 and 53%, respectively. A breakdown of operational delays indicated that the use of surgepiles is a key factor in determining how many processing related delays occur. Only the Motorised system used surgepiles which resulted in less than a third of the time spent in processing delays than the Mechanical system. However, this technique could cause congestion on the landing, increased production pressure on the processor operator, and double handling of trees.

The Motorised system took approximately three times longer carry out a hauler shift than the Mechanical system, which is due to the more manoeuvrable nature of the swing yarder than that of the tower yarder (i.e. guyline setup). Both systems spent similar amounts of time making line shifts, although the Mechanical system carried out line shifts more often and each one was faster on average. This is because the excavator tailhold for the

Mechanical system was faster and in easier terrain than the bulldozer in the Motorised system.

The payload, cycle time, and productivity functions created in this study indicated that terrain variables, stand variables, and the stem presentation method significantly affected the productivity of the two systems. Productivity can be predicted by system for a given harvest setting as a product of predicted payload and cycle time, or by using predictions of payload as an input into the productivity functions.

It is recommended that both methods be used as a way to moderate the predictions. These predictions can be used as preliminary tools for the selection of optimal systems for given harvest settings, although an understanding of the limitations of the functions is required.

The average productivity of the Mechanical system was significantly higher than the Motorised system, with the Mechanical system utilising handed trees the best, and the Motorised system utilising motor-manually felled trees the best. Extraction of bunched stems was found to be more productive than the extraction of motor-manually felled trees, although neither system was more effective at extracting bunched trees than the other. The benefits of bunching and handing for both systems may be less pronounced in harvest settings with significantly larger pieces.

Both systems in this study realised productivity levels when extracting motor-manually felled trees greater than those of strops and chokers as found by McFadzean (2012). Therefore, providing the increased productivity levels found in this study would outweigh the extra cost of introduction, there are economic benefits for contractors and forest owners who utilise these systems.

9. FURTHER RESEARCH

Future research of the Mechanical and Motorised harvesting systems could aim to reduce some of the limitations associated with the predictions of productivity in this study, as well as capturing benefits of subsequent innovative technology relating to these two systems. This includes sampling:

- The Mechanical system in more adverse extraction conditions;
- Both systems when utilising alternative rigging configurations;
- Both systems in settings with significantly larger average piece sizes such as those found in some North Island regions;
- Using a laser range finder or GPS unit attached to the carriage;
- Using a discontinuous timing method;
- More accurate measurements of cycle payload, by collecting diameters of extracted stems;
- The FFC Series 2.

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APPENDIX 1: Relevant figures

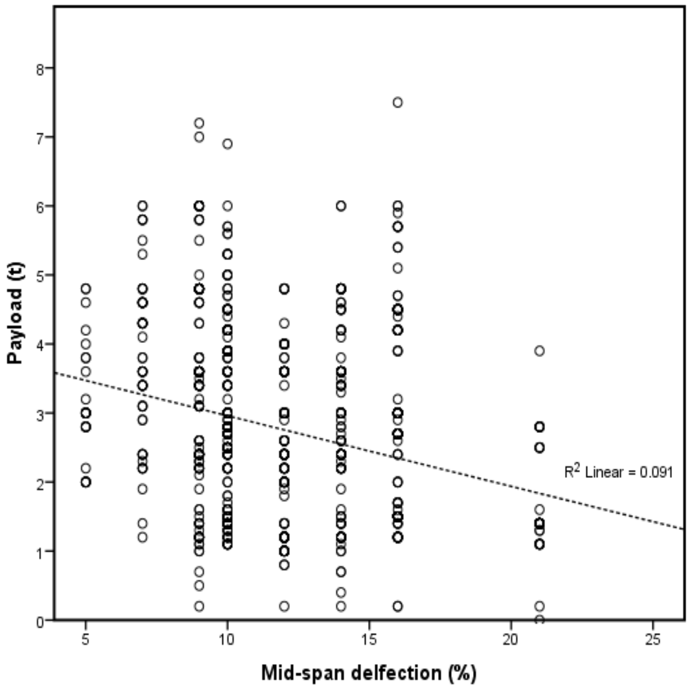

Figure 9: The effect of mid-span deflection on payload for both systems

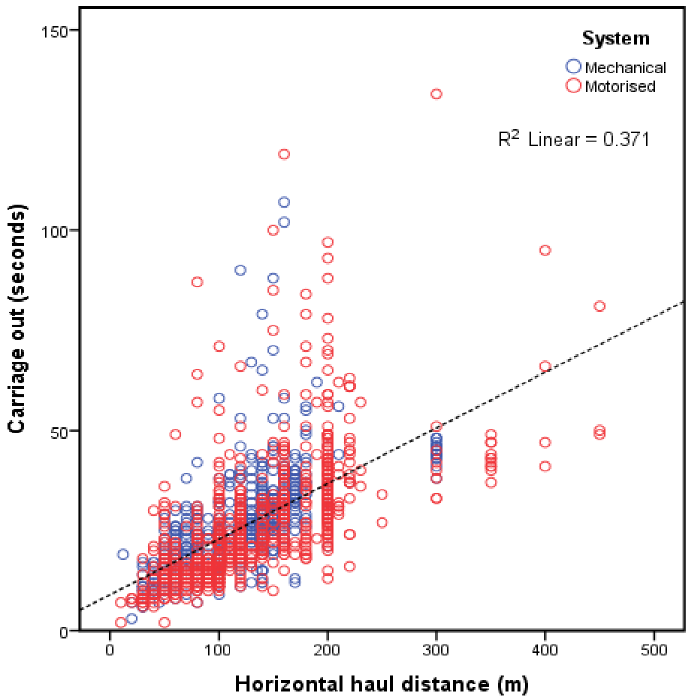

Figure 10: Effect of horizontal haul distance on carriage out time by system.

APPENDIX 2: Residual analyses

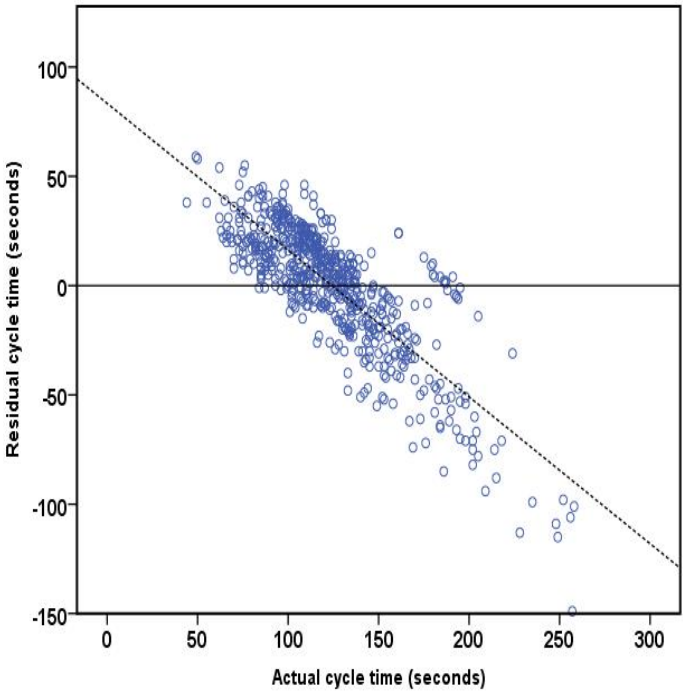

Figure 11: Spread of residuals when using Equation 3 to predict total cycle time for the Mechanical system

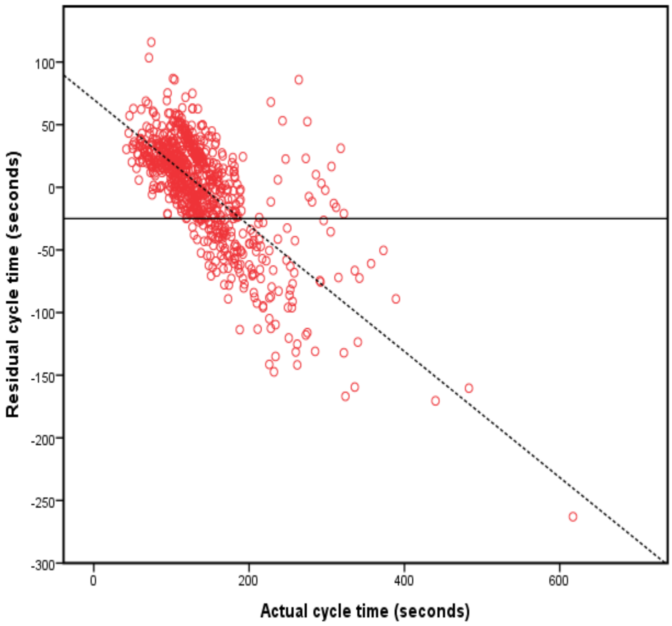

Figure 12: Spread of residuals when using Equation 4 to predict total cycle time for the Motorised system

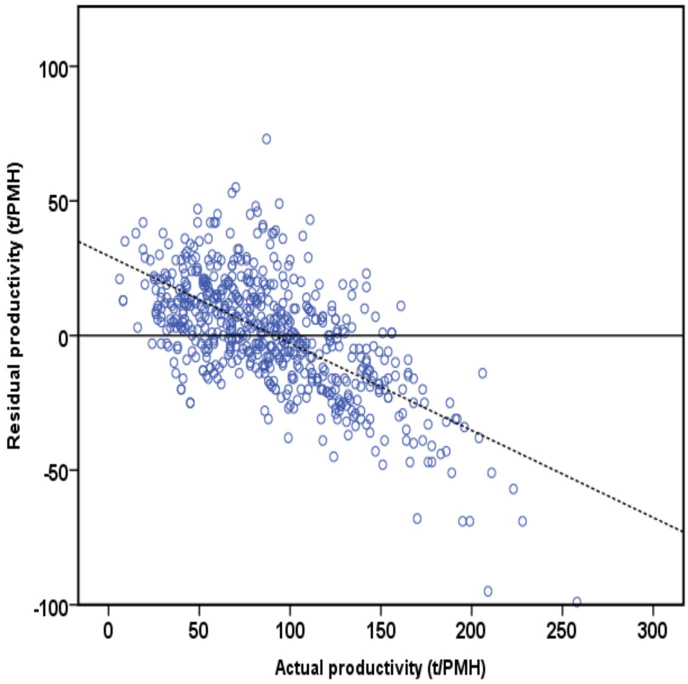

Figure 13: Spread of residuals when using Equation 5 to predict productivity for the Mechanical system

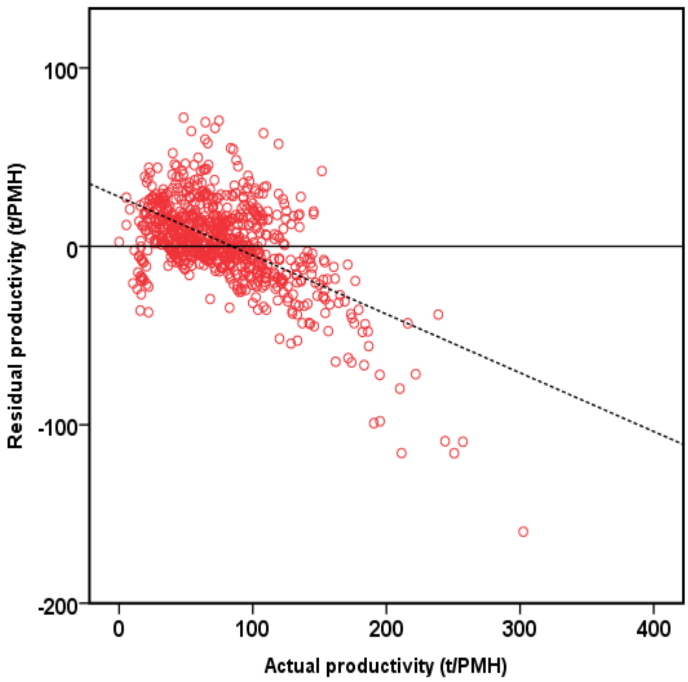

Figure 14: Spread of residuals when using Equation 6 to predict productivity for the Motorised system

APPENDIX 3: Edited data

Table 4: Identification and reason for cycles to be incorrect and therefore removed or altered

Cycle number	Incorrect component	Reason
921	Carriage-in	227 seconds at 120m haul distance
1325	Carriage-in	213 seconds at 140m haul distance
27	Carriage-out	2 seconds at 140m haul distance
700	Carriage-out	97 seconds at 50m haul distance
714	Carriage-out	4 seconds at 300m haul distance
794	Carriage-out	141 seconds at 160m haul distance
795	Carriage-out	0 seconds at 150m haul distance
805	Carriage-out	6 seconds at 160m haul distance
993	Carriage-out	150 seconds at 200m haul distance
629	Accumulation	663 seconds
630	Accumulation	627 seconds
635	Accumulation	511 seconds
1095	Accumulation	237 seconds (bunched)
1339	Accumulation	186 seconds
1342	Accumulation	270 seconds (bunched)
1352	Accumulation	314 seconds (bunched)
20	Un-hook	125 seconds
541	Un-hook	158 seconds
714	Un-hook	123 seconds (replaced with average)
1338	Whole cycle	Mechanical issue
1340	Whole cycle	Mechanical issue

APPENDIX 4: Miscellaneous and mechanical delay descriptions

Table 5: Description and duration of miscellaneous delays for the Mechanical system

Delay number	**Description**	**Duration (minutes)**
1	Unknown	15.0
2	Al left hauler	2.7
3	Felling head used to clear slash/salvage wood in the gulley	2.2
4	Swap blocks on tail hold	3.9
5	Fuel tankers filling up machines	16.5
6	Unknown	6.9
7	Raimondo's GPS fell off carriage	5.1
8	Clearing slash from chute	0.6
9	Unknown	4.4

Table 6: Description and duration of mechanical delays for the Mechanical system

Delay number	**Description**	**Duration (minutes)**
1	broken I-beam in hauler	330.6
2	Broken rope - sent away for fix	220.1

Table 7: Description and duration of miscellaneous delays for the Motorised system

Delay number	Description	Duration (minutes)
1	Unknown	13.0
3	Unknown	0.8
4	Unknown	5.0
5	Unknown	3.5
6	Unknown	3.6
7	Check hydraulic level of hauler, let fleeting and felling machines catch up	24.6
8	Unknown	3.5
9	Unknown	12.5
10	Unknown	5.3
11	Unknown	3.7
12	Unknown	8.4
13	Unknown	1.4
14	Unknown	3.3
15	Manually taking root ball off stem	6.0
16	Hauler operator checking carriage	2.7
17	Hauler operator checking carriage	2.1
18	Move hauler	3.5
19	Unknown	14.9
20	Attached chainsaw to carriage and sent down to feller	0.6

Table 8: Description and duration of mechanical delays for the Motorised system

Delay number	Description	Duration (minutes)
1	Unknown	6.8
2	Replace aerial on carriage	14.4
3	Unknown	1.1
4	Fix broken screw on Waratah	46.8
5	Waratah maintenance	18.3
6	Waratah broken + clearing chute + hauler hydraulic leak	193.8
7	Hauler stopped working	21.2
8	Broken fitting on Waratah	109.6
9	Carriage camera problem	39.8
10	Carriage camera problem	20.0
11	Grapple - rest of drags slow after this	10.9
12	Grapple	3.8
13	Grapple	64.1
14	Grapple	8.0
15	Waratah breakdown	193.5

APPENDIX 5: Site terrain profiles

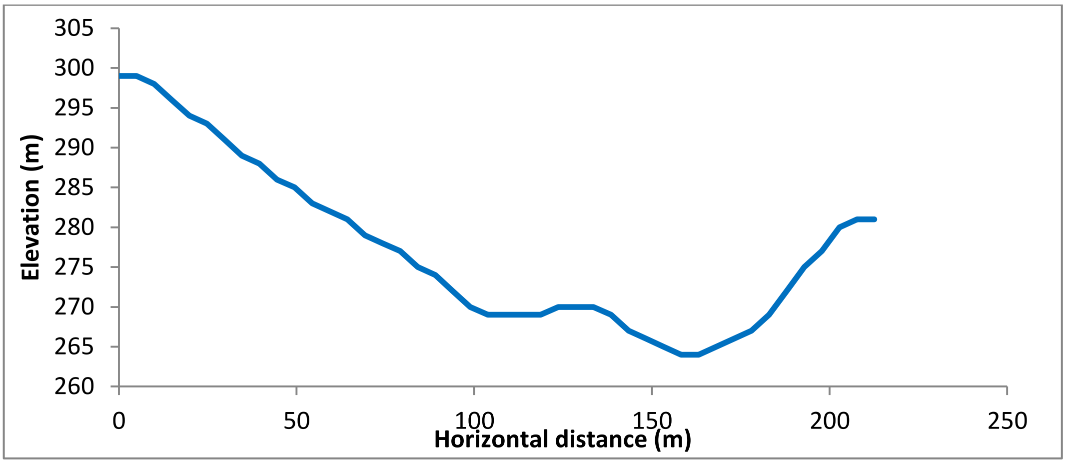

Figure 15: Cable corridor terrain profile for the Mechanical system in site HA1237.

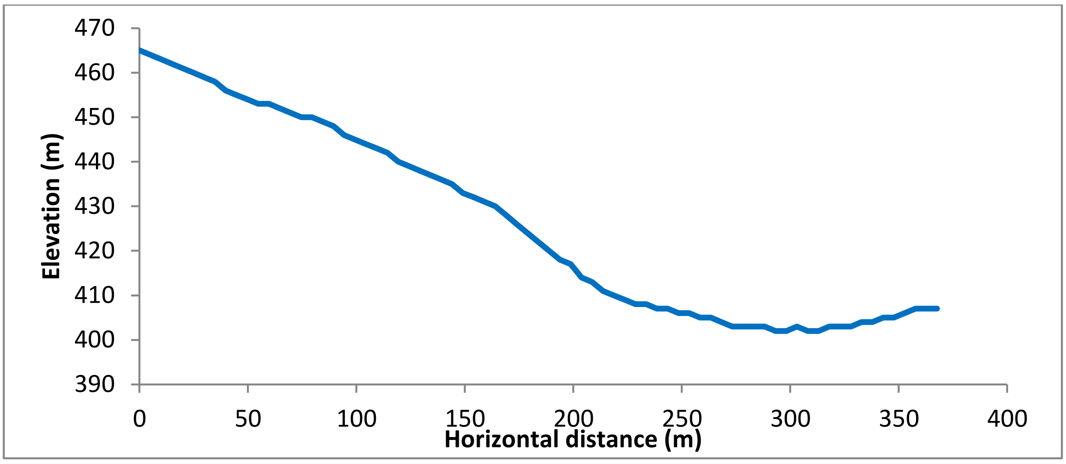

Figure 16: Cable corridor terrain profile for the Mechanical system in site HA7361.

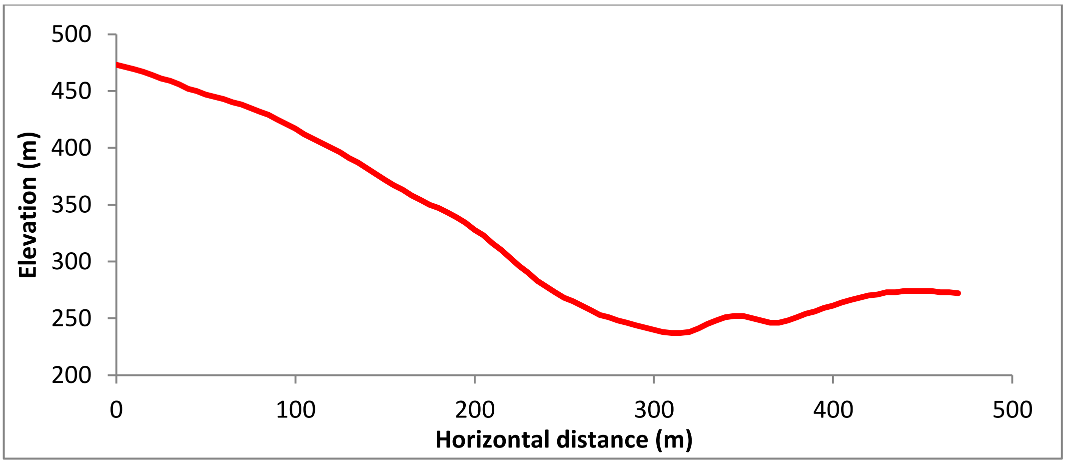

Figure 17: Cable corridor terrain profile for the Motorised system in site HA2444.

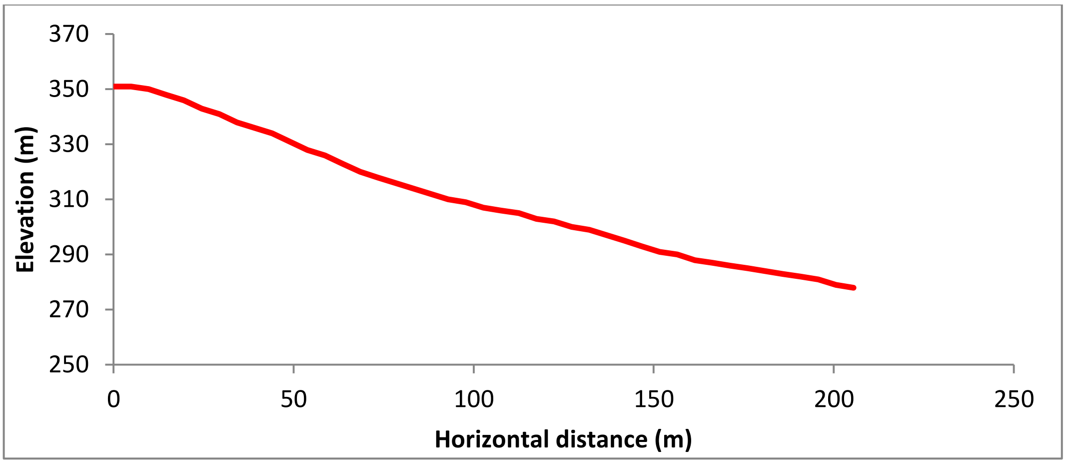

Figure 18: Cable corridor terrain profile for the Motorised system in site HA2445.

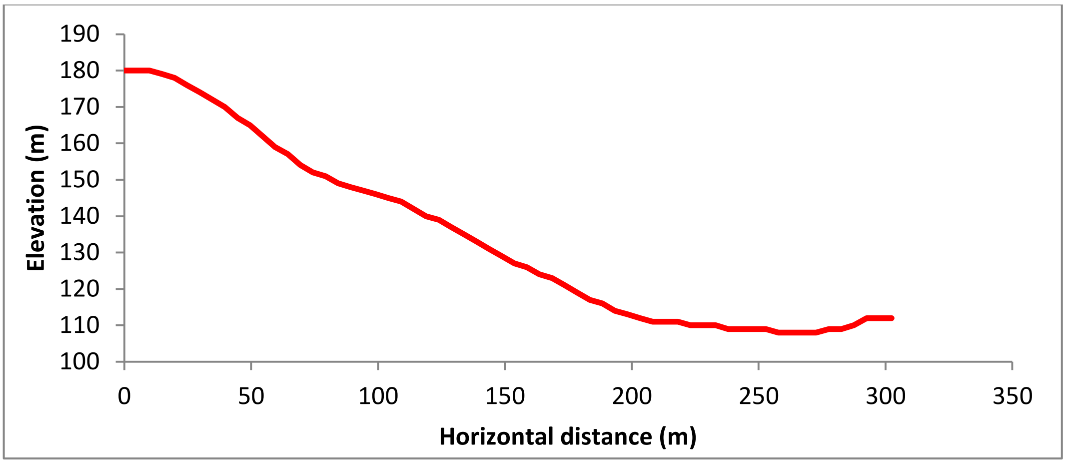

Figure 19: Cable corridor terrain profile for the Motorised system in site HA2441 for the first setting.

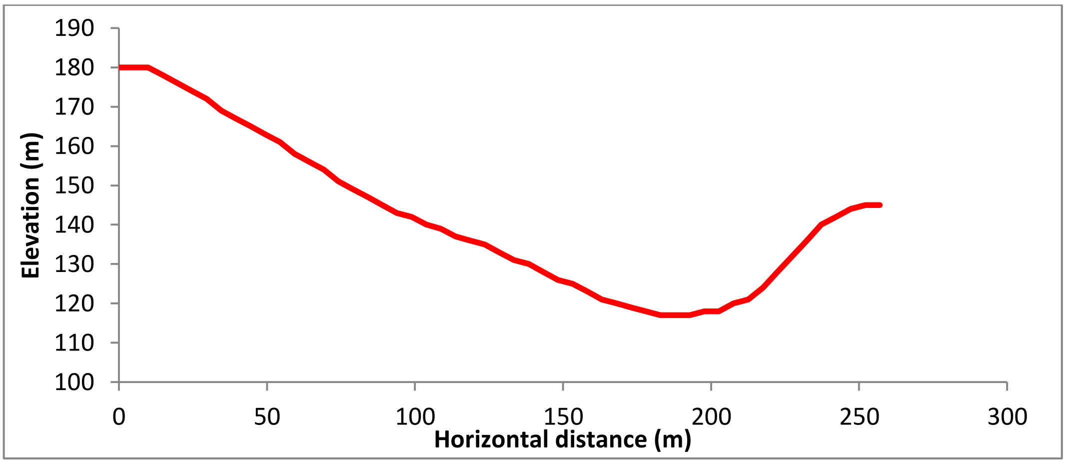

Figure 20: Cable corridor terrain profile for the Motorised system in site HA2441 for the second setting.