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By Jaakko Salakka

IDENTIFYING APPROPRIATE SMALL SCALE HARVESTING TECHNOLOGIES FOR COMMERCIAL SCALE BAMBOO FUEL CHIP PRODUCTION IN LAO PDR

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Sirkkalantie 12 A
80100 JOENSUU
FINLAND
(013) 260 6900

Author(s)
Jaakko Salakka

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Abstract

The researches of mechanized bamboo felling do not exist and only available studies deal with manual felling. The objective of this thesis is to help identifying appropriate harvesting technologies for intended commercial scale bamboo fuel chip production, where raw material procurement is done in unmanaged stand. It does not provide final answer, but can be classified as the beginning of a larger whole.

The objective was achieved by conducting time and motion studies with several different supply chain elements in the pilot site area in northern Lao PDR. Obtained productivity figures were incorporated with machine cost calculations and thereafter unit costs per each element were determined.

The results presents that conventional manual harvesting method is inefficient in terms of productivity, but due to low labor cost, it is relatively competitive in terms of unit costs.

Due to low labor cost, the essential requirement for appropriate harvesting technology is high productivity rate. Felling with assistance of tractor winch was the most viable alternative in terms of by both, productivity and unit costs. The results were obtained with a workforce who had no work experience on mechanized forest work.

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1 Introduction

Forest, sustainable use of natural resources and renewable energy are all important priorities in Finland's development cooperation in Southeast Asia. In the Mekong region, which covers Lao PDR, Thailand, Cambodia and Vietnam, these objectives are promoted by EEP Mekong program. EEP Mekong provides funding inter alia projects in the field of environment and renewable energy.

Bamboo Fuel Chip Production for Renewable Energy is one ongoing project funded mainly under the EEP Mekong program, its scheduled duration is 2 years from 8/2013 onwards. It is carried out in the Bokeo province in northern Lao PDR. The underlying goal for the project is to establish the feasibility of a business model where local village communities can harvest bamboo in shifting cultivation areas and produce bamboo fuel chips for commercial purposes. This opens opportunities for higher seasonal incomes and poverty reduction in the pilot area. If successful, it will also bring significant environmental benefits in the area.

The essential key component of the project is a significant improvement of harvesting efficiency. So far, bamboo harvesting has been done with billhooks and forwarding by carrying culms manually, for commercial scale harvesting this kind of method is ergonomically too rudimentary and economically too inefficient. Therefore, upscaling of harvesting technology is inevitable. However, one challenge is that the word efficiency does not even exist in the Lao language and perception of the local people.

One essential component within the project is to perform time-motion studies with several different supply chain elements from felling to road transport of ready-made fuel chips. When these results are combined with machine cost calculations, the unit cost per supply chain element can be calculated and eventually, the total cost of bamboo fuel chip supply chain from forest to power station can be determined.

This thesis achieves to help identify the appropriate harvesting technology for commercial fuel chip production.

2 Context and the project introduction

2.1 Background

Forest fires, mainly from human actions, cause significant carbon emissions and forest degradation in Lao PDR. According to UN (UN-REDD programme 2009), deforestation and forest degradation, including forest fires, destructive loggings and agricultural expansion, cause nearly 20% of total greenhouse gas emissions around the globe, this is more than emissions from global transportation, and therefore it is crucial to decrease carbon emissions in the forest sector in order to slow down the global warming. The UN driven REDD program aims to reduce carbon emissions from deforestation and forest degradation. REDD+ is an extension of REDD and in addition, it takes into account sustainable forest management and increment of carbon stocks via establishing permanent forests. (UN-REDD programme, 2009)

These massive fires also cause severe haze pollution and deteriorate air quality. This is also a recognized problem on the ASEAN (Association of Southeast Asia Nations) level.

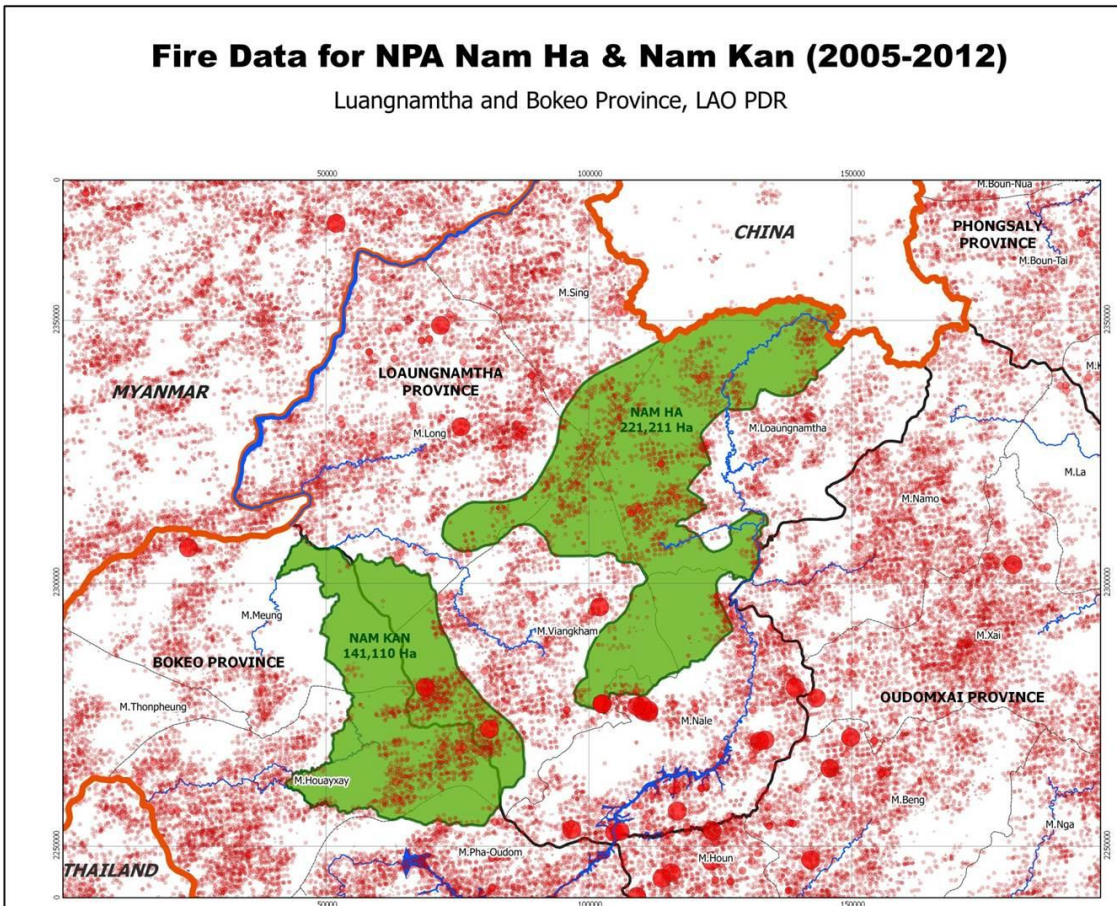
In 2002, ASEAN countries signed the ASEAN Agreement on Transboundary Haze Pollution agreement. The objective for this agreement is to prevent transboundary haze pollution caused by land or forest fire. (ASEAN Agreement, 2002) Agreements article 9 obligates each party to:

"…*undertake measures to prevent and control activities related to land and/or forest fires that may lead to transboundary haze pollution…"*

and

"Developing and implementing legislative and other regulatory measures, as well as programmes and strategies to promote zero burning policy to deal with land and/or forest fires resulting in transboundary haze pollution"

Despite of this, there are only very few concrete measures for forest fire control, and the fire map over the Bokeo and Luang Nam Tha provinces from 2005-2012 clearly indicates that fires are still a considerable problem in Lao PDR (Picture 1).



Picture 1. Fire data map over the Bokeo and Loaung Nam Tha provinces. Each red dot represents individual fire. Note rare fires in China due to a better land policies. (Mohns 2014, 7)

The current forest cover in Lao PDR is over 60% of the total surface area and this forest resource is exploited for purpose of shifting cultivation and industrial-scale logging and exporting harvested roundwood to neighboring countries. Felling has mainly been done by granting concession to foreign harvesting companies, which have imported own logging technology to Laos and excluded local people from the work. (Mohns 2006)

Shifting cultivation is still a commonly used cultivation method and also the major reason for forest fires and transboundary haze pollution, the Bokeo province in itself has more than 200 000 hectares of such areas. (Project proposal, 2). Clearing the land by fire for use of shifting cultivation or other agricultural purposes increases the risk of uncontrolled forest fires especially during the dry season.

Picture 2. Land clearing by fire for agricultural purposes (Mohns 2014, 5)

Industrial-scale loggings without forest regeneration combined with shifting cultivation has resulted into a situation where valuable timber has been harvested and bamboo among the other pioneer species has occupied these areas, suppressed the permanent tree species and formed secondary forests with low economic value (Mohns, 2006). Due to a neglect of silvicultural activities, these bamboo stands are full of dead biomass, which forms enormous fuel loads in the area. Figure1 presents total biomass accumulation after shifting cultivation and shows that bamboo biomass may reach the level of 40 tons/hectare during the first 20 years of succession and nearly 50% share of total biomass. In plantations, bamboo is mature for first harvesting at the age of 6-8 years (Kigomo 2007, 33). Considering this statement, it is easy to presume that at around the age of ten years in natural condition, dead biomass accumulation begins.

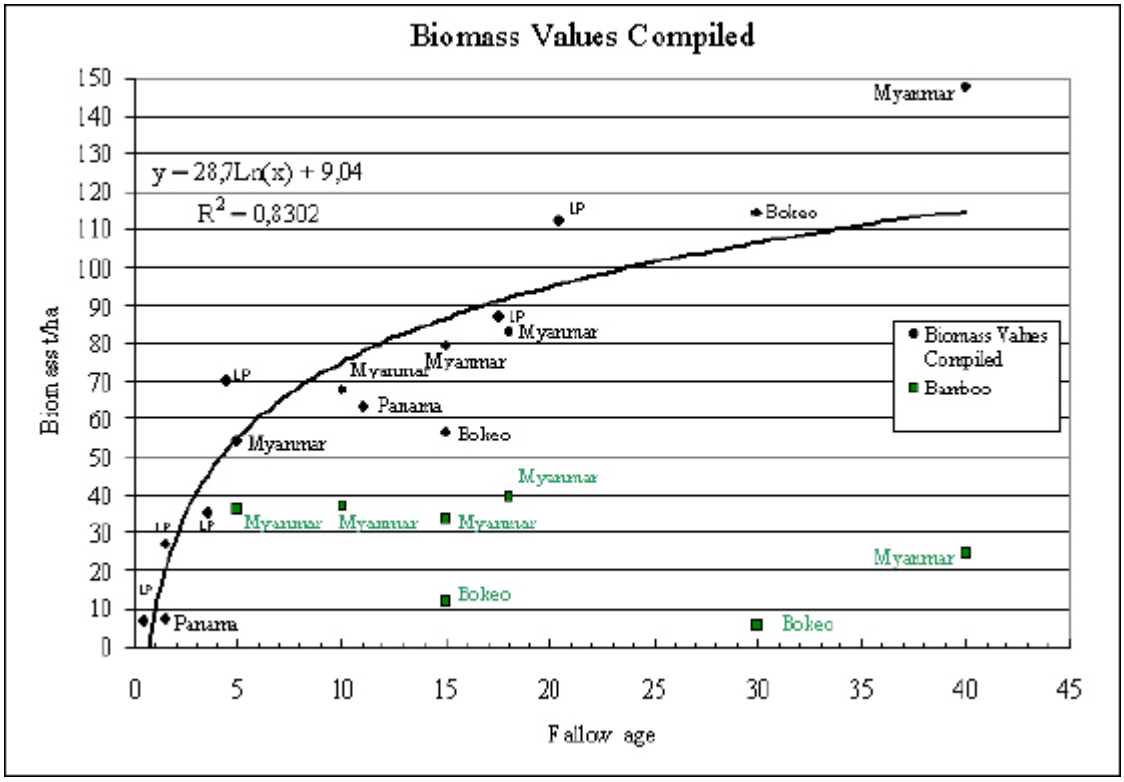
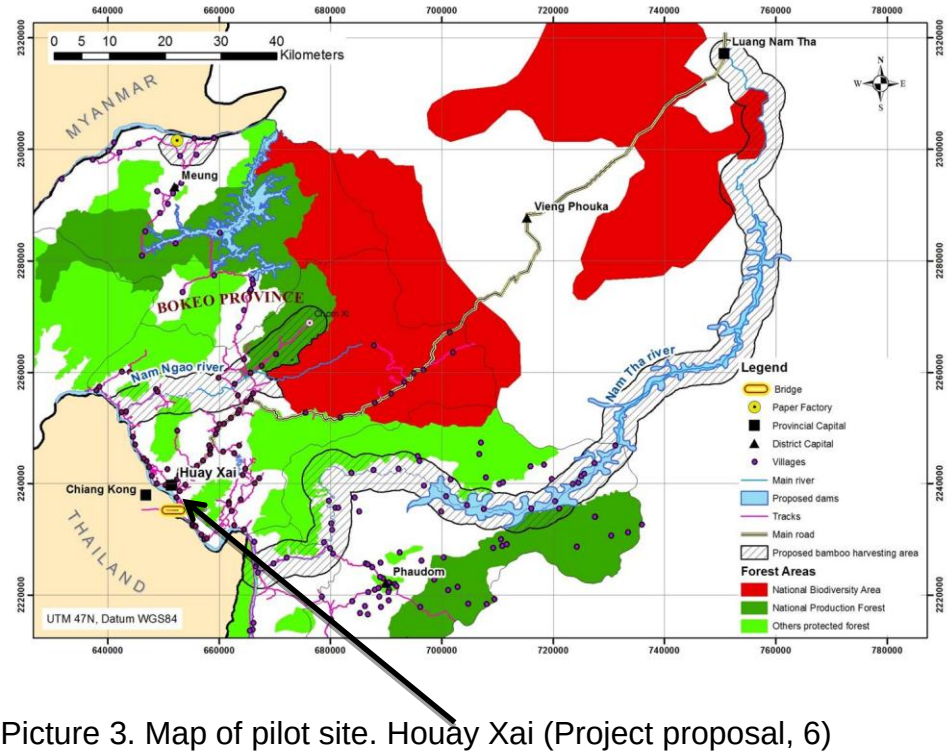


Figure 1. Accumulation of biomass after ending shifting cultivation (Mohns 2009, 7)

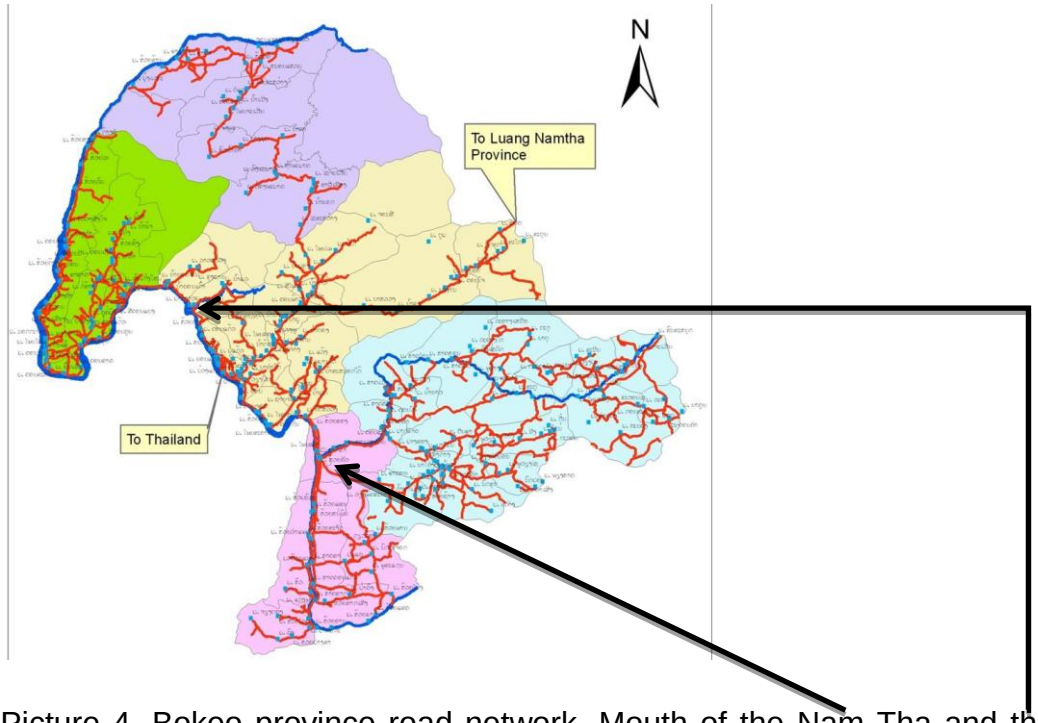
2.2 Pilot site location and end users

The project's field trials take place in the Bokeo province in the surroundings of the provincial capital Houay Xai. Bokeo is located in the northern part of the country and it is bordered with Myanmar in the west and with Thailand in the south/southwest, the Mekong river lies on the border of the countries. Possible main harvesting areas after the project are located along the Mekong tributaries Nam Tha and Nam Ngao (Picture3) (Project proposal, 5). Harvesting areas along the rivers form a corridor with the length of 40 kilometers in Nam Ngao and 180 kilometers in Nam Tha. This provides outstanding opportunities for cost-effective bamboo floating, and due to a limited road infrastructure along the rivers, rafting is the only option in some areas (Picture4).

Truck transportation is possible from the mouth of the Nam Tha and Nam Ngao and the distance to the Laos-Thailand border crossing point in Houay Xai is less than 40 kilometers.

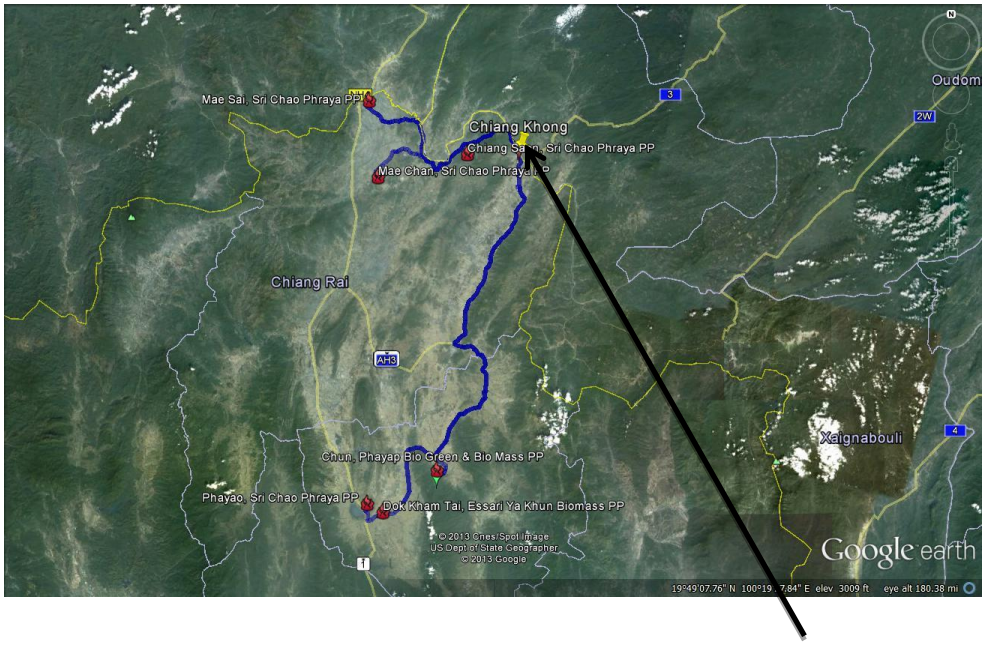


Picture 3. Map of pilot site. Houay Xai (Project proposal, 6)



Picture 4. Bokeo province road network. Mouth of the Nam Tha and the Nam Ngao (Mohns 2014, 14)

Potential fuel chip end users are located in Chiang Rai province in northern Thailand (Picture5), three of these power plants are located less than 100 kilometers and two less than 150 kilometers away from Houay Xai. Two of these power plants are also located by the Mekong, which enables boat transportation directly to mill. (Project proposal, 3-4)



Picture 5. Identified power plants in Chiang Rai. Houay Xai.

Identified power mills are currently using a rice husk for power generation, but each of them has reported seasonal rice husk shortage (Project proposal, 4) and Figure2 shows substantial increment of rice husk cost during this millennium, the price has risen from US$ 15.5 to US$ 62. Project proposal estimates that fuel chip price would be US$ 45/ton (dry), with 10% higher energy value in comparison with rice husk (Project proposal, 4). Extraction from forest to road side is predicted to cost US$ 10-15/ton (dry). (Project proposal, 19)

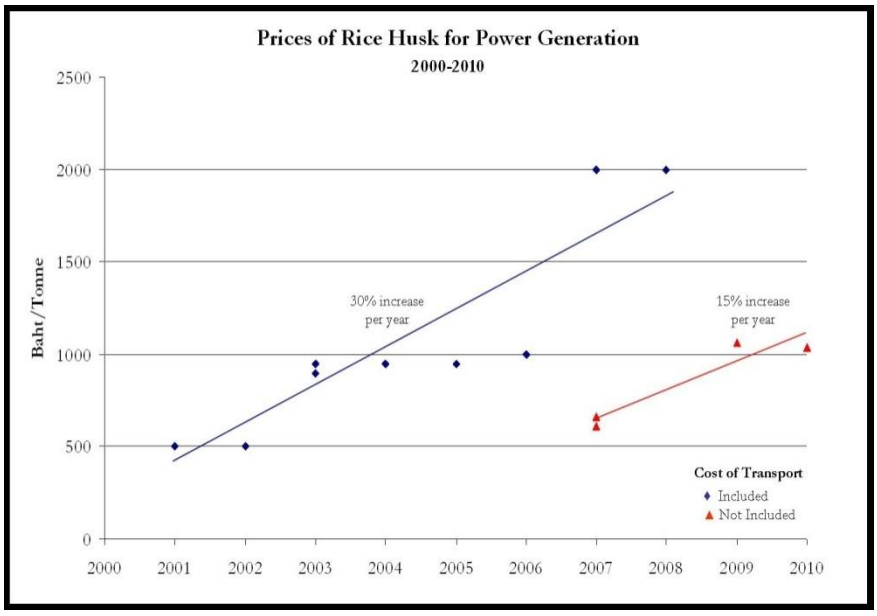


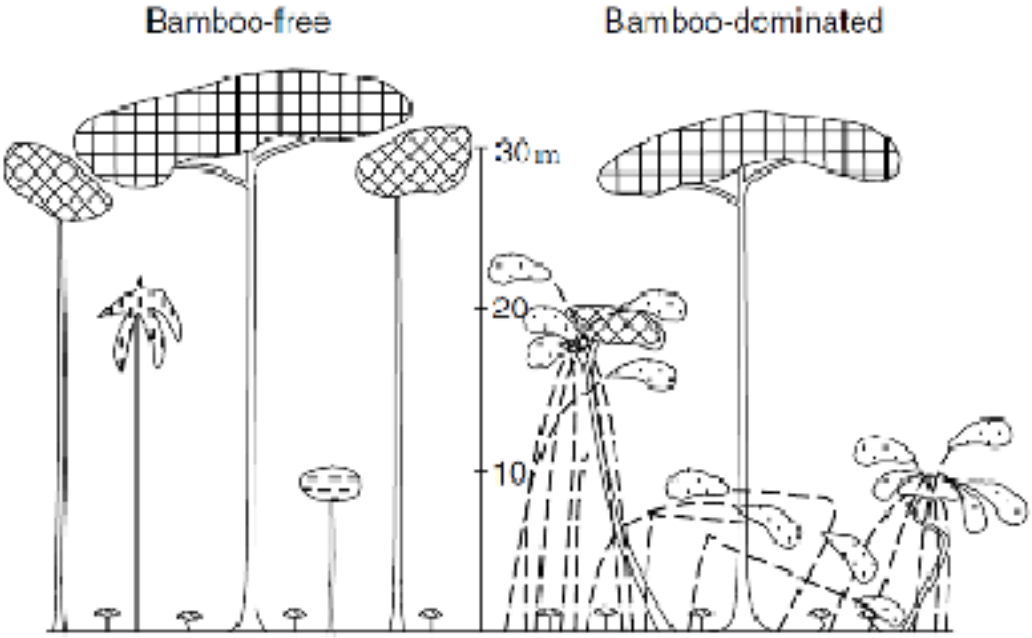
Figure 2. Rice husk price development in recent years

2.3 Purpose and objectives

The main objective of the project is to establish feasibility of a business model, where local village level communities can produce bamboo fuel chips for commercial purposes. This will create seasonal work, especially in felling and skidding phases with a targeted minimum daily wage of US$ 10/person. (Project proposal, 6)

Harvesting can be done in bamboo dominated shifting cultivation areas close to villages, roads and rivers. Environmental benefits will be realized through removal of dead bamboo biomass, removing this fire prone material will reduce uncontrolled forest fires, and the target is to decrease occurrence of fires by 20% before 2018, this will significantly reduce carbon emissions. The target is also to decrease CO_2 emissions at least by 400 000 tonnes by replacing fossil fuels in power generation with bamboo chips. (Project proposal, 6)

Extraction of excessive dead biomass enables permanent tree species to grow due to the fact that seedlings are free from bamboo suppression (Picture6) and later this will lead to rehabilitation from secondary to primary forest and increment of carbon stocks. (Project proposal, 1) If successful, the project promotes the objectives of REDD+ program and the ASEAN agreement of transboundary haze pollution.



Picture 6. Illustrative picture of bamboo-free and bamboo-dominated forest

Fuel chips from bamboo can be co-burned with rice husk, but this requires sufficiently small particle size in order to ensure trouble-free chip supply into fluid bed burner currently adjusted to work with rice husk. (Project proposal, 12)

The project purpose is in line with Renewable Energy Development Strategy in Lao PDR, which aims to develop new renewable energy resources which are not yet available in Lao PDR (Renewable Energy 2011, 4) as well as the bilateral research statement Renewable Energy Conservation Cooperation between Lao PDR and Thailand, which encourages to find out opportunities in biomass based transboundary supply chains for energy production (Project proposal, 4).

Conventional ways to harvest bamboo include felling with billhook and manual forwarding simply by carrying the culms. It is foreseen that for commercial scale fuel chip production, where raw material procurement is done in unmanaged stand with a target of at least 1 ton/person/day (dry), this method is too inefficient. This statement is based on the research from 2006 conducted in Bokeo, which shows results of 0.5 tons/person/day (fresh) (Mohns 2006). Therefore, it is essential to mechanize and identify appropriate small-scale

harvesting technologies. According to Mohns (2014), in this context, appropriate can be defined as:

- *"machinery should fit into the socioeconomic context of local communities: e.g can be financially recovered under local loan schemes*
- *can be operated safely and efficiently by local people*
- *can be maintained given the locally available workshops and spare parts*
- *should preferably also be used in agricultural operations during wet season in order to reduce fixed machine costs due to limited forest work in dry season"*

Despite of upscaled harvesting technology, productivity is still highly dependent on weight or volume/piece ratio. Figure3 presents this relationship very well. Time consumption per 1 m^3, when the skidding distance is 100 meters and log volume is 1 m^3, is around 20-25 minutes, while time consumption with 0.1 m^3 log volume is 50 minutes with the same skidding distance. Time consumption, therefore, is about 100% higher with a small size log, and on the contrary, the productivity rate is 50% smaller.

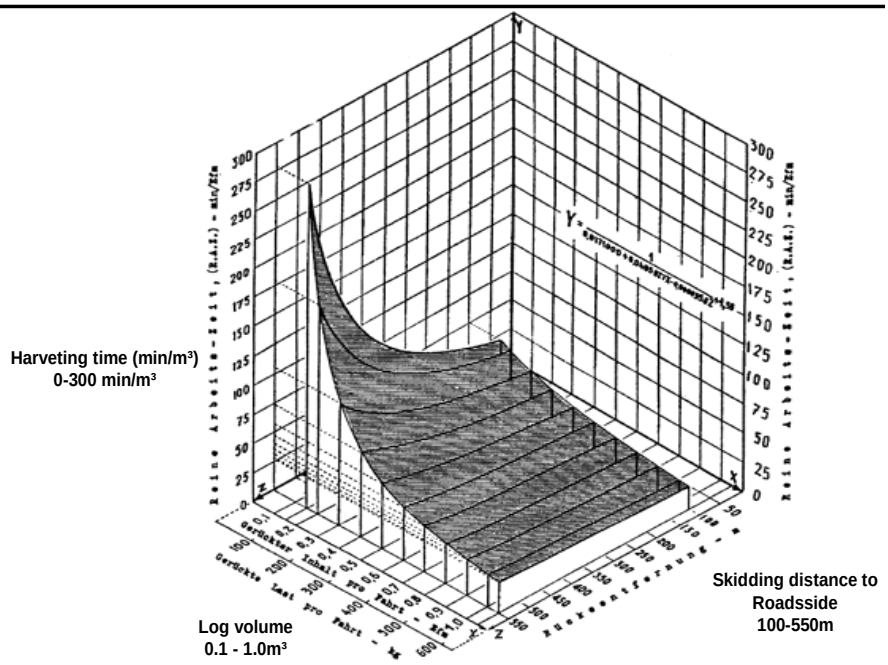
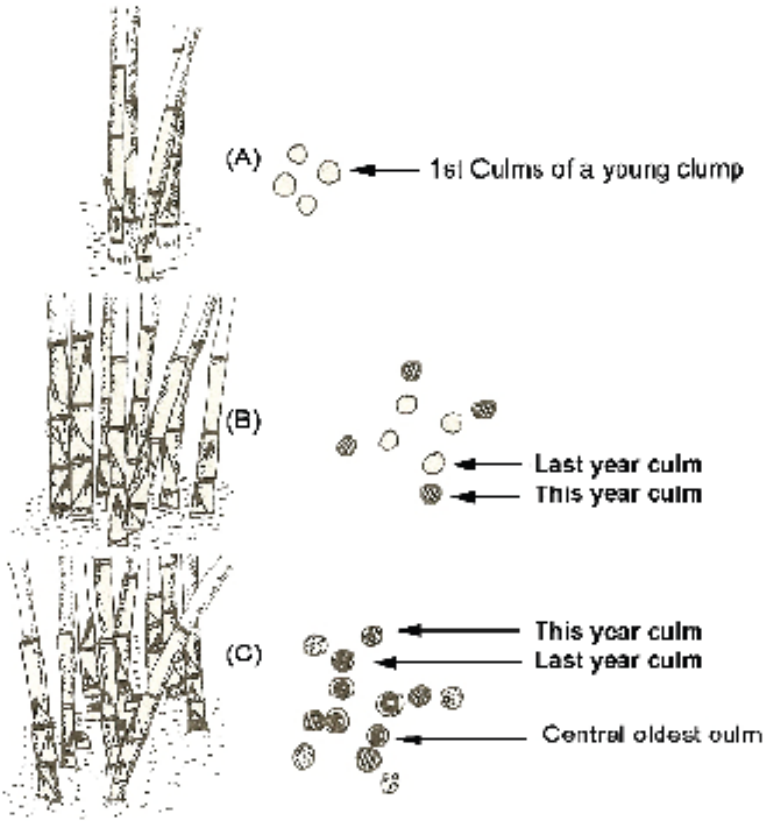


Figure 3. Log volume and skidding distance relationship on time consumption (Efthymiou, P.N. 2002)

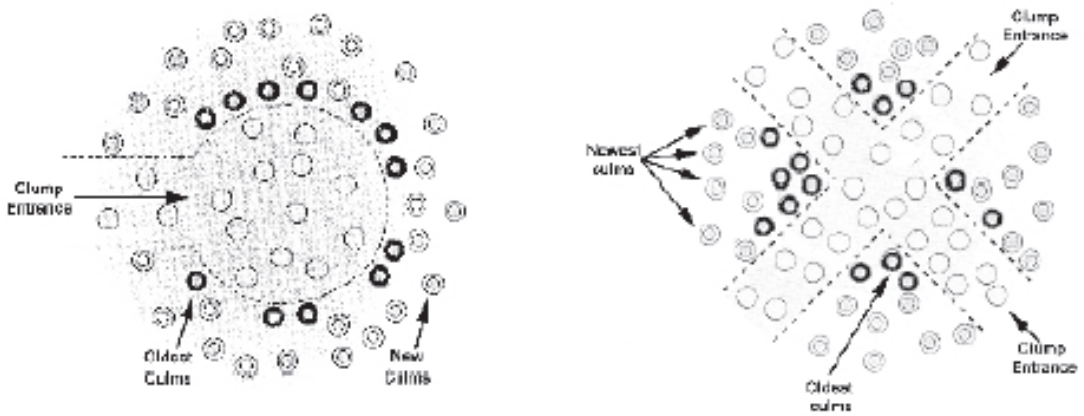
2.4 Recommended bamboo harvesting method

In a clumping type bamboo, new shoots are sprouted on periphery of the clump, according to Picture 7. After several years of growing, this will lead to a situation where older stems are at the central part of the clump and new culms are located on the outskirts of the clump. In plantations with proper management, first harvesting can be performed at the age of 6-8 years. Subsequently, harvesting in cycles of 4 years should be applied. (Kigomo 2007, 33-34)

Felling can be done under two separate methods, which are presented in Picture8. The result of both methods will be the removal of oldest stems in order to enable young individuals to grow. Left one in the picture is called the horse shoe clump harvesting method, which refers to a pattern which remains after excess culms are removed, and right one is called the cross tunnel harvesting method and also refers to the way how the work is done. (Kigomo 2007, 34)



Picture 7. Illustration of bamboo sprouting. New shoots grow on the periphery of the clump (Kigomo 2007, 34)



Picture 7. Recommended alternatives for bamboo harvesting. Purpose is to eliminate oldest stems. Later in this thesis, term U-shape felling refers to felling method presented in the left. (Kigomo 2007, 35)

Both methods facilitate old stem harvesting through providing easy access inside the clump where the major cutting should take place (Kigomo 2007, 34). In case of heavy entangling in the clump, the harvesting methods proposed above may be too challenging and in this situation clear-cut should be performed (Kigomo 2007, 35).

2.5 Supply chain elements

Within the project, the purpose is to conduct comprehensive time-motion studies with several different kind of supply chain elements. These elements can be classified as follows (machine model in italic text):

Cutting

- Pruning saw/knife
- Chain saw, *Stihl 192 T, displacement 30 cm^3, 1,3kW/1,8hp*

Winch extraction from the clump

- Portable winch, *Portable Winch Co. PCW 3000*
- Vineyard winch, *Werner Zieh-Max (year of manufacture: 1960)*
- Iron horse winch, *Jonsered, HI 2013 PW*
- Tractor mounted winch, *Kubota L3450*

Skidding to road side

- Manually
- Sulky, *locally manufactured*
- Mule
- Iron horse, *conversion of rice thresher (locally manufactured)*
- Iron horse, *Jonsered, HI 2013 PW*

Long distance transportation

- Truck
- Floating

Chipping

- Hand feed
- (Crane feed)

Transportation of chips

- Truck

2.6 Previous studies in context

Bamboo felling is a very marginally studied topic, and those few available researches deal with manual harvesting. No research has been conducted into mechanized bamboo felling, and therefore comparable results of the felling phase are manually performed.

In 2006, Mohns obtained the result where one person was able to harvest about 0.5 ton/day (6 h/day). Work was done with axes or straight-blade machetes in a team of at least two persons. The average piece weight was 14.4 kg with a diameter of 13.5 cm and length of 13.4 meters. The work cycle was divided into four elements; cutting, delivering on the ground, delimbing and stacking. The stacking distance was limited to 20 meters. The cycle time varied from 3.3 to 9.2 minutes, while the average was 4.7 minutes. With these parameters, time consumption per ton was 326 minutes or 5.4 hours for a team of two persons. In the other words, this means the productivity rate of 0.185 tons/hour for two

persons or 0.092 tons/hour for one person. Daily wage used on the research was US$ 2, so harvesting cost per ton was US$ 4.

In the same research, iron horse productivity was estimated in a slope below 30 %, the results were based on literature. Daily machine cost was estimated to be US$ 9.30 + operator US$ 2, equal to US$ 11.3/day.

Productivity with a distance of 100 meters was estimated to be 9 tons/day (6 h/day) which is equal with 1.5 tons/h and unit cost of US$ 1.25/ton. When the distance was extended to 250-500 meters, daily productivity was predicted to be 5.4-7.2 tons/day, which is equal to 0.9-1.2 ton/h. Then the unit cost would be US$ 1.4-2.1/tons.

Gallis (2004) studied mini skidder productivity with small-sized beech logs in terrain with average steepness of 17.25% and distance of 320 meters. Under these circumstances, productivity was 2.27 cord cubic meters per hour. The work was done in a team of two operators, and hourly cost was € 14.08, and therefore the unit cost was € 6.20 per cord cubic meter.

3 Thesis purpose and the objective

The purpose of this thesis is to help identify appropriate harvesting technologies for described conditions by providing unit cost calculations, and in addition it achieves to improve correct work method for mechanized bamboo felling. It does not provide final answer but assists to proceed to correct direction in the future of the project. The thesis provides unit costs for several supply chain elements, and through this it presents the most viable alternatives between different elements.

In practice, the unit costs are calculated by recoding time input data by conducting time studies with each element in supply chain and by measuring work output. The relationship between work output and time input is called productivity, and in this thesis is expressed as a tons/hour.

The next step is to calculate costs per hour for each machine used in a supply chain. When machine costs are determined, they can be combined with productivity rates, and this relationship is called the unit cost and is expressed in this thesis as a $/ton.

When unit cost for each supply chain element is calculated it is possible to define the most affordable way to produce bamboo fuel chips for commercial purposes.

4 Methodology

4.1 Site description and work method

Time-motion studies were conducted in Lao Louang village, located 30 km north of Houay Xai. The bamboo stand for felling trials was 15 years old and was located in uphill with steepness of ~35%, steepness was determined with clinometer. The site was completely in post cultivation condition and bordered with few years old tree plantation from extraction direction. Due to lack of management, extremely heavy entangling occurred within the clumps. Average bamboo clump included 50-100 culms with the height of 14-15 meter and with the average diameter of ~5 cm. Distance from the felling site to road side was 350 meter over the dry and flat paddy field, distance was determined with car odometer. The skidding trials were carried out over this same paddy field. The data was collected during the January 2014 - April 2014.

Contract with harvesting entitlement for 10 ton (dry) of bamboo were signed between Lao Louang village and Provincial Agriculture and Forestry Office (PAFO). One condition was that for every household has to be provided opportunity to participate in the work. This condition led to the result where new people were introduced to work on daily basis and competence of these people varied significantly. Because of dangerous nature of chainsaw work, it was agreed that chainsaw operators has to be same every day, and therefore group of four villagers were trained to work as a chainsaw operator.

Four people were involved to work every day in the way that two were capable to work with the chainsaw and rest of two were operating the winch and did other low risk work. However, maximum of two people were allowed to work simultaneously, while remaining two were allowed to rest.

Felling was done in two different ways; U-shape felling, which was described in chapter 2.5 and clear cutting. In U-shape felling it was decided to leave 10-12 vigorous culms to grow. In clear cutting each stem was removed. U-shape felling was preferred over the cross-tunnel alternative since it required only one extraction direction and therefore low time consumption.

All the felling work was done with the chain saw, except two days of manual felling/extracting trials, which were conducted in order to establish the baseline where other results can be compared. Due to heavy entangling in the naturally grown bamboo clump, it was necessary to use winches for extracting culms from the clump. Since the entangling, it was possible to cut several stems without them being collapsed on the ground. After the cutting of sufficient number of culms, they were bundled together with a winch rope and extracted from the clump. The number of extracted culms per one cycle was highly dependent on winch extraction power. Delimbing was done by both, a billhook and a chainsaw in order to compare their productivities. After delimbing, stems were collected on the stack. One work cycle included one winch extraction, and stacking was done in the way that stems from one extraction were delivered on their own pile. This was done in order to define extraction volumes per cycle.

At the end of the day, winch extraction volumes were calculated by measuring each stem with a balance, besides weight, also length and top/bottom diameters were measured, stem diameter was defined as an average of top and bottom diameters.

After measuring, culms were delivered to the beginning point of forwarding trials and were assorted according to diameter into different categories as follows:

- diameter < 5 cm, delimbed
- diameter > 5 cm, delimbed
- diameter < 5 cm, whole tree
- diameter > 5 cm, whole tree
- dead

This categorization was decided for two reasons, to get comprehensive productivity figures with several different skidding methods and for obtaining different raw materials for chipping trials. Skidding trials took place when enough raw material was harvested.

4.2 Time-motion studies

Initial plan was to conduct time studies without any major changes to work, but soon after trials began it was realized that the target productivity cannot be achieved without changes. This is the reason why it was, in addition to time studies, necessary to start improve work methods continuously, for example: billhook delimbing → chainsaw delimbing → rough delimbing or U-shape felling → clear cutting

Time studies were carried out with element level method. In this method, the observational unit is one work cycle, which is divided into elements/functional steps, and time consumption per each functional step is recorded and later added up together in order to define the cycle time. This method allows an opportunity to determine the most time consuming elements within the cycle and therefore enables a possibility to put effort for possible improvements. An essential aspect is also to describe or define the beginning and ending moment for each element, this has to be done in order to ensure repeatability for other researchers. (Magagnotti, L & Spinelli, R. 2012. 22-23) Time data was collected with stopwatch and time study templates.

During the trials, two different time recording techniques were applied; snap-back timing and continuous timing. Snap-back timing refers to a method where stopwatch is reset between every element, thereby time recording starts from zero every time when the element is changed. Continuous timing is a method where the clock is running without reset and each element time is calculated by subtracting the time when the element begins from the time when the element is completed. (Magagnotti, L & Spinelli, R. 2012. 25-26)

Trials were conducted in the way that U-shape felling with every winch type (excluding a tractor winch) was tested in the first phase and snap-back timing technique was applied. In the second phase, clear cutting method was performed and each winch type, including a tractor winch, was tested again, in the second phase continuous timing method was used.

Skidding trials over 350 meters were conducted when a sufficient amount of bamboo was harvested and the snap-back timing method was applied. Trials were conducted over 350 meters and 80 meters.

80 meters trials were decided to conduct since it was decided that the research baseline includes felling + forwarding over the 100 meters to roadside; however, this decision was made after majority of felling studies were completed and therefore, the results presented later are an incorporation of two separate researches done in different days; felling and forwarding.

During the U-shape felling trials, three winch types (portable winch, iron horse winch, vineyard winch) productivity rates, alongside with the chainsaw productivity, were tested. The tractor winch was excluded because it was foreseen that heavy entangling combined with high pulling power, and therefore, high extraction volume, will unintentionally lead to a result where also stems which are meant to be left will be broken.

During these trials, only one person was allowed to work, despite this command, employees occasionally helped each other, this was because of new people involved to work on a daily basis and had no understanding of the nature of the research, where the objective was to find out productivity per one person. Because of this distortion on productivity per one person, it was decided to subtract 15% from productivity rates in order to make it equal to one person work load. 15% is only an estimation, and therefore it can be even greater. The stacking distance was limited to 20 meters.

The standard template used during these trials is presented in Annex 1 and the work element definitions in Annex 3. However, the snap-back timing method and the above-mentioned template only allow observation of one operator and soon after the trials were started, it was realized that two operators were required in order to reach maximum efficiency level, one for a chainsaw and one for a winch. Despite this finding, it was decided to complete U-shape felling trials with the time recording method.

4.3 U-shape felling

4.3.1 Portable winch

Portable winch trials were conducted first. This winch type requires an anchoring point, which is a disadvantage and narrows a winch placement and in the worst-case scenario it defines the whole extraction direction. Working with

portable winch requires manual work, as it only assists the operator in extraction process and in cases with heavy loads, two operators are needed to pull the rope. In terms of work ergonomy, relatively heavy manual work can also be classified as a disadvantage compared to other alternatives. Extraction speed and volume are fairly low with portable winch. On the other hand, it is easy to carry and due to its structure, extraction distance is limited only by a rope length, however, because of low extraction speed it is foreseen that productivity rate will be relatively low over the greater distances.

As the hand winch trials were conducted first, the environment in terms of excessive logging residue and anchoring points was excellent and therefore, it was easy to work, and besides this, the location was in the edge of the stand. The extraction distance was 20 meters, measured with the loggers tape. Delimbing was done with a billhook. Soon after starting portable winch trials, it was clear that delimbing was the most time consuming work phase within the work cycle, and therefore, it was decided to test chainsaw delimbing after completing portable winch trials.

Picture 8. Working with the portable winch

Advantages	Disadvantages
Light weight	Anchoring point needed
Easy to remove	Requires manual work
Extraction distance limited only by the rope length	Slow extraction speed
	Low pulling power
	May require two operator (heavy loads)

4.3.2 Iron horse winch

Iron horse winching trials were conducted after portable winch. Because of high time consumption with a billhook delimbing, it was decided to test with a chainsaw. Iron horse winch was far more powerful in comparison with portable winch and did not require manual pulling, so it was preferred option among the employees. Entangling was so strong that despite the heavy weight of this machine, an anchoring point was still required in order to keep the iron horse still. Unlike the portable winch, iron horse was clumsy to move in steep uphill and over the logging residues. The winch rope was 23 meters and anchoring wire 5 meters long, this narrows the winch placement. Extraction distance was 15-25 meters, dependent on the winch placement.

Advantages	Disadvantages
Powerful	Clumsy to move
Convenient to use	Require anchoring point
	Short winch rope

Picture 9. Iron horse winching

4.3.3 Vineyard winch

Vineyard winch has three superior features compared to the iron horse and hand winch. First is wire with length of 100 meter, which enables considerably greater extraction distances, second is structure which does not require any anchoring point and third is cheap price. Due to a long wire, it was decided to test the productivity rate over two different distances.

In the first phase the distance was 30-40 meters and in the second phase 80-100 meters. Huge disadvantage is the heavy weight of this machine, so minimum of two people are required to carry the winch and basically only option is to work from road side due to moving it, at least manually, further in the forest is too time consuming. Winch manufacture year is 1960 and probably because of the age, machine breakdowns emerged frequently. Noticeable difficulties occurred also when employees were starting the machine and operating it. Winching required using of both hands in the way that the right hand controls the throttle and the left controls the clutch which engages the extraction motion on.

Considering that a new winch operator was introduced on daily basis, this operational complexity became a slight disadvantage, but can be overcome by gaining work experience.

Picture 10. Winching with the vineyard winch

Advantages	**Disadvantages**
Enables longer extraction distances	Heavy weight
Anchoring point not required	Machine breakdowns
Cheap price	Complex to use

4.3.4 Manual harvesting

Manual harvesting was done in order to get comparative baseline for other results. Cutting was done with a pruning saw or with a billhook and delimbing with a billhook. Extraction was done manually, by pulling the culms away from the clump. After trials were conducted, it was decided that forwarding distance of 100 meters had to be accommodated in to baseline. Because of this, manual forwarding trials were conducted and have to include with manual harvesting result.

Picture 11. Manual harvesting with a billhook

4.4 Clear cutting

As the name indicates, in this method every culm is removed. During the clear cutting trials each winch type mentioned earlier were tested again. In addition, the tractor winch was included to the trials since there was no same issue with entangling that was in U-shape felling. The clear cutting trials were made in the way that delimbing was performed with the portable winch trials and omitted with the iron horse and vineyard winch trials. This decision was based on the finding that delimbing had become the production bottleneck, even if it was carried out with a chainsaw. The purpose of this decision was to increase productivity rate.

When delimbing was omitted, time consumption for stacking was greatly increased since the extracted bundle still had heavy entangling. Due to this, overall productivity had no considerable enhancement, and for this reason a new delimbing method was introduced. The new delimbing method was called rough delimbing and was performed with a chainsaw. This means cutting off only the excessive branches in order to reduce entangling and facilitate the stacking process. This delimbing method was applied during the tractor trials.

When clear cutting trials began, it was decided to change the way of working in the way that two people were allowed to work simultaneously. The decision was that one person could operate a chainsaw while another could operate a winch and they were allowed to fully collaborate. Despite this saw/winch division, both operators were allowed to involve all the work elements presented in Annex 3, except that the winch operator was not allowed to do chainsaw work due to it required sufficient safety equipment. For example, in case that the winch operator was stacking the culms and the chainsaw operator had cut sufficient number of culms, the chainsaw operator were allowed to winch them out from the clump. This kind of way of working required a new recording method and therefore, continuous method was applied. The template used for this method is presented in Annex 2. Idea of this template was that time was running continuously and when new element began, time and corresponding work code was marked.

Clear cutting trials were decided to conduct in order to get new productivity figures, it was expected that productivity may be higher as well as extraction volume since there was no need to worry about the remaining culms. Also, topography was slightly easier in the way that slope steepness during the iron horse, vineyard winch and tractor winch trials was fairly flat.

4.4.1 Portable winch

As mentioned earlier, two people were allowed to work simultaneously during the clear cutting trials. Compared to U-shape felling, the extraction distance had to be extended by 10-20 meters, since there were no appropriate anchoring points and therefore, the average distance was ~35 meters. The purpose was also to find maximum extraction volume. The felling environment had become more challenging due to an excessive amount of logging residues. Delimbing was done again with a billhook in order to get more data. One finding over the portable winch trials was that compared to U-shape felling, culms were more likely to collapse on the ground due to each stem being cut. This may slow down the overall work since culms are spreading inconsistently in every direction and because of this, difficult to winch.

4.4.2 Iron horse

In order to improve daily productivity, it was decided to omit delimbing from iron horse trials onwards. As the extraction distance was ~35 meters with hand winch, it was decided to maintain the same distance with the iron horse. The iron horse rope is only 23 meters long and lack of anchoring points defines winch placement. Due to these reasons, it was necessary to move the iron horse relatively much during the harvesting/extraction operation. The extraction process required an average of 2 re-placements, and it was done in the way that the winch rope was not opened around the bundle and the operator drove the machine to the appropriate anchoring point where the next winching took place.

4.4.3 Vineyard winch

Vineyard winch trials were conducted in the same way as with iron horse winch. Delimbing was omitted and the extraction distance was ~35 meters.

4.4.4 Tractor winch

During the tractor winch trials, the work method was slightly rearranged. Bundling was made before the chainsaw work in order to prevent culms from collapsing inconsistently all around. In addition, it was noticed that if delimbing is omitted, stacking productivity collapses significantly and overall productivity remains on a poor level. Therefore, rough delimbing was introduced. The extraction distance was extended all the way to 100 meters, since harvesting with extraction distance of 20-40 meters will soon lead to over-exploitation of bamboo resources and also greater distance naturally provides the greater harvesting area, in case that costs remain viable level. The winch wire was 60 meters long, so it was necessary to move the tractor 1-2 times and re-winch. Besides re-winching, forwarding was tested in the way that after winching, bundles were removed by dragging them behind the tractor while driving, but due to the heavy weight of bundle, front wheels rose up from the ground. This method would be faster, but it will require an additional weight pack on the front of the tractor.

During the tractor winch trials, the snap-back timing method with template in Annex 1 was applied. Only the winch operator was observed and few new elements were added to template; the trip without the load, opening the wire and waiting. Rough delimbing and stacking was studied later due to the long distance between felling and delimbing sites. Because winching and delimbing operations were impossible to record simultaneously, the winch operator had too much empty/waiting time while he was waiting for the chainsaw operator to perform felling work. The described work method is too inefficient due to high waiting time and should not been applied in real work. Both operators should been involved to work in the way that one is in charge of chainsaw and winch while the other one is in charge of delimbing and stacking.

Picture 12. Winching with the tractor

4.5 Skidding

The skidding trials were conducted over the flat rice paddy and therefore the terrain condition was relatively favorable. The distance from felling site to road side was 350 meters and work was done in a team of two persons. The cargo clamping belts were used for tie-up the load. During the skidding trials, typical problem especially with locally manufactured iron horse was load slipping off from the machine. This problem occurred due to a culms were dragged behind the machine and the bundle had contact with soil, this caused heavy friction and also the machine's loading structure was relatively rudimentary which does not allow sufficiently tight binding, though the machine is prototype and therefore loading structure can be improved with sharp teeth loading benches and moveable side arms.

Time spent for re-loading, belt opening and other actions, which had to be done due to a load slip off, were recorded under the element of "re-loading during the trip". This element was added to the standard forwarding template.

The snap-back timing was applied and the template used for the trials is presented in the Annex 4 and definitions in Annex 5. Following methods were tested over 350 meters:

- Iron horse, Jonserd
- Iron horse, locally manufactured
- Sulky, locally manufactured

Each of these forwarding methods was tested with five different bamboo categories mentioned in chapter the 3.1. Load weight was determined by calculating number of stems and multiplying that by piece weight.

Picture 13. Skidding with the Jonsered iron horse

Picture 14. Skidding with the locally manufactured iron horse

Picture 15. Locally manufactured sulky

4.6 Sample sizes

Sample sizes over the U-shape felling were as follows:

- Portable winch: 15 cycles
- Iron horse: 21 cycles
- Wine yard winch 30-40 meter: 18 cycles
- Wine yard winch 80-100 meter: 14 cycles
- Manual felling: 8 cycles

Over the clear cutting trials:

- Portable winch: 9 cycles
- Iron horse: 7 cycles
- Wine yard winch: 7 cycles
- Tractor: 9 cycles

In the skidding trials, each of the five raw material classes was forwarded twice with each machine. Amount of bamboo determined this sample size.

Sample sizes were determined with assistance of the following equation:

$$t^2 * \frac{V}{\left(E * \frac{Mean}{100}\right)^2}$$

where:

- t = student's t-value (95% → 1.96)
- V = expected variance of work cycle time
- E = level of precision required (e.g 5%)
- Mean = expected mean of work cycle time

This equation can be found in Good Practice Guidelines for Biomass Production Studies booklet, and helps to define sufficient sample sizes with desired confidence level (Magagnotti, N.& Spinelli, R 2012, 14). The initial plan was to test every method with confidence level of 95%, however this required too large sample sizes and therefore was impossible within the given time frame. Above listed sample sizes reaches the confidence level of 90%.

For the equation, V and Mean values were calculated after trials and in case that sample size was incomplete, more trials were conducted. V value was calculated by subtracting the fastest cycle time from the slowest. With confidence level of 90 %, t-value is 1.645 and E is 10 %.

The example with portable winch U-shape felling:

Confidence level of 95%

- t = 1.96
- V = 41.75
- E = 5
- Mean = 31.2

$$1.96^2 * \frac{41.75}{\left(5 * \frac{31.2}{100}\right)^2}$$

= 66

Confidence level of 90%

- t = 1.645
- V = 41.75
- E = 10
- Mean = 31.2

$$1.645^2 * \frac{41.75}{\left(10 * \frac{31.2}{100}\right)^2}$$

= 11

5 Results and analysis

5.1 Table of culm parameters

Culm parameters	Weight, kg	Diameter, cm	Length,m
Delimbed culm			
< 5 cm	7.1	4.0	6.9
> 5 cm	14.8	5.9	8.8
Dead	6.4	6.5	3.1
Rough delimbed culm			
< 5 cm	8.5	4.0	10.8
> 5 cm	17.7	5.9	14.4
Dead	6.4	6.5	3.1
Whole tree			
< 5 cm	9.4	4.0	10.8
> 5 cm	21.1	5.9	14.4
Dead	6.4	6.5	3.1

Table 1. Measured culm parameters

5.2 Felling productivities

5.2.1 Manual felling –baseline of research

The manual felling trials were conducted in order to establish the baseline in terms of productivity. Manual harvesting gave result of 0.071 t/h/person, this includes 20 meters of forwarding (stacking distance). The result is in line with Mohns (2006) result of 0.092 t/h/person, if stem weight variation is considered; 14.4 kg in 2006 → 11.0 kg in 2014.

As mentioned earlier, the baseline includes 100 meters of forwarding and therefore 80 meter forwarding result has to be combined with the felling result mentioned above. One round trip over the flat paddy field, with distance of 80 meters required 02:26 minutes, while forwarded load was 2 x 11 kg stems. This gives the productivity figure of 0.508 t/h/person.

The baseline productivity therefore is 7h x 0.071 equals 0.497 t/day/person, in addition this requires one hour of forwarding. The conclusion is that one person is able to harvest and forward 0.5 t/day to road side. Due to easy circumstances

on forwarding, it is expected that this productivity can be achieved only in the best-case scenario. All the productivity figures are presented as a green tons.

5.2.2 Chainsaw felling/portable winch extraction

During the U-shape felling trials average cycle time was 31.3 minutes, while extraction volume was 60.6 kilograms. The overall productivity for one person was 0.099 t/h, with the extraction distance of 20 meters.

Unlike expected, productivity over the clear cutting trials were considerably lower in comparison with U-shape felling. Average cycle time was 50.7 minutes while average extraction volume was 112.2 kilograms. The overall productivity remained in 0.069 t/h/person.

Table1 presents the machine productivities and delimbing productivity done with the billhook and stacking productivity.

Productivities	U-shape	Clear cutting	
Chainsaw	**0.592**	**0.393**	**t/h**
Winch	**0.640**	**0.426**	**t/h**
Delimbing, billhook	**0.258**	**0.181**	**t/h**
Stacking	**1.827**	**1.494**	**t/h**

Table 2. Machines, delimbing and stacking productivity rates

As Table1 indicates, the productivity rates during the clear cutting trials were considerably lower compared to U-shape felling. One target during the clear cutting trials, were to test the maximum extraction limit of the winch, due to there was no risk of breaking the remaining culms. Despite that the average extraction volume was increased from 60.6 → 112.2 kilograms, the overall productivity declined, since the bunch with this weight was too heavy for the hand winch and therefore extraction became more time consuming. Table3 shows that the extraction time was increased from 2.7 minutes to 10.1 minutes. Extended extraction distance 20 → ~35 meters also has impact for the result. Same table also reveals that during the clear cutting trials, the chainsaw

operator spent almost 10 minutes more time per cycle on removing undesired material. The variation between operator's work skills may be the explanatory factor for the chainsaw productivity result. Larger bundle size had also negative impact on delimbing especially when the billhook was used. In addition to larger bundle size, also work environment was more challenging in terms of excess logging residues. Stacking of delimbed stem has high productivity rate due to it is easy to handle, 1.8 ton productivity was achieved when stacking distance was less than 10 meters and logging waste did not slow down the work.

	U-shape	**Clear cutting**	
Element		**Chainsaw**	**Winch**
Preparatory work	1.7	2.2	1.3
Clearing area around the clump	0.7	0.0	0.0
Removing undesired material	3.8	13.2	0.0
Chainsaw cutting	2.3	3.9	0.0
Bundling the culms	2.9	2.8	4
Extraction with the winch	2.7	1.6	10.1
Delimbing	14.1	12.5	24.8
Stacking	2.0	0.0	4.5
Delays	1.0	3.9	1.8
Waiting	-	8.6	6.2
Overall time, min	**31.2**	**50.7**	**50.7**

Table 3. Element times within the cycle

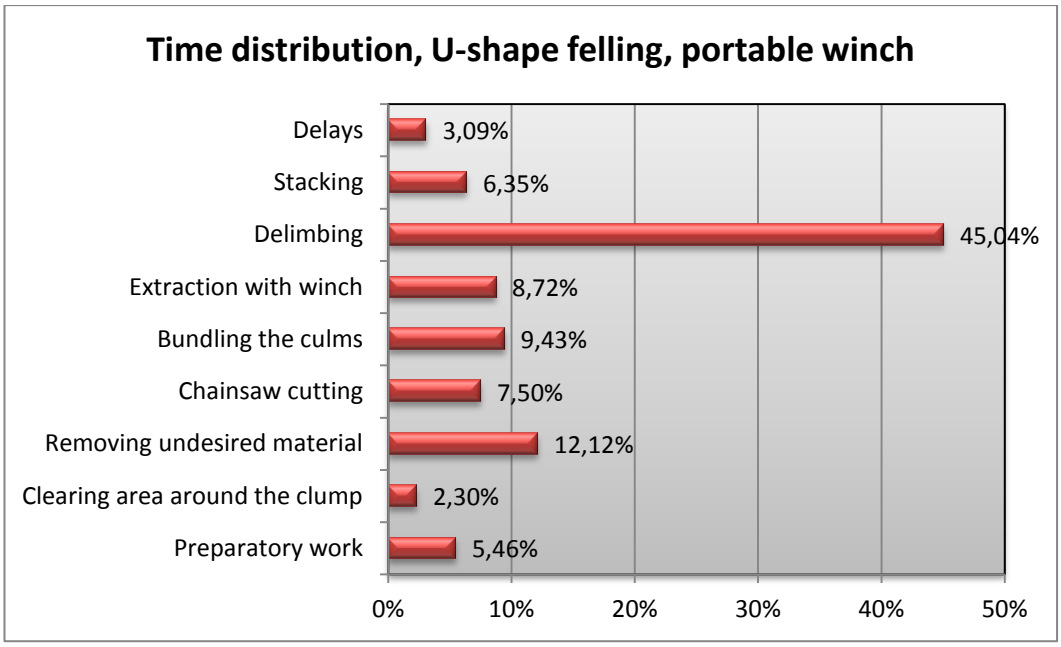


Figure 4. Time distribution between different elements during the U-shape felling trials. Delimbing required 45.04% of total time, while other elements required less than 13% of total time. Only one operator was allowed to involve to work.

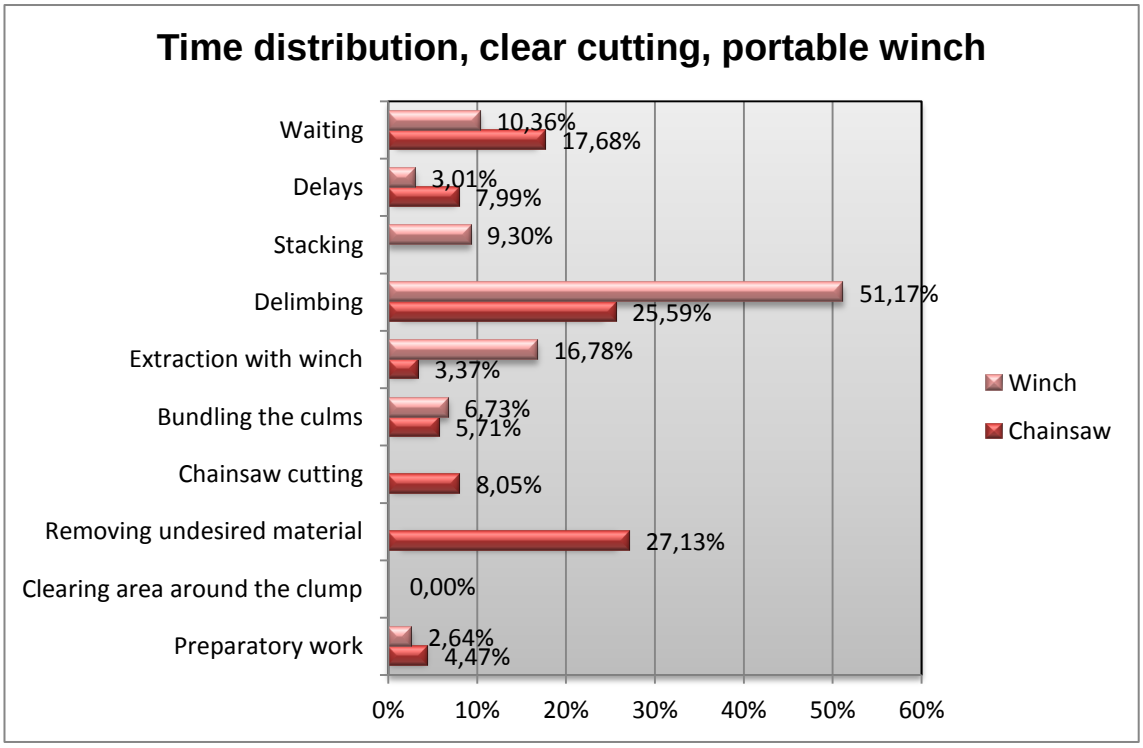


Figure 5. Time distribution between different elements during the clear cutting trials. Two operators were allowed to work simultaneously.

5.2.3 Chainsaw felling/Iron horse winch extraction

The average cycle time during the U-shape felling trials were 66.1 minutes and average extraction volume was 147.5 kilograms. Overall productivity was 0.114 t/h/person. Extraction distance was 20 meters.

The clear cutting trials were carried out in the way that delimbing was omitted, due to high time consumption and for desire of reaching higher productivity rate. The average cycle time was 37.5 minutes and the average extraction volume was 159 kilograms. The overall productivity reached the level of 0.128 t/h/person. The extraction distance was ~35 meters and required winch replacement due to the short winch rope on the iron horse as explained in the chapter 3.4.2.

More detailed productivities are presented in Table4. Chainsaw productivity was increased from 0.665 to 1.021 t/h when delimbing was omitted. Excluding delimbing naturally raises the stem weight, which leads to higher productivity rate. Despite higher piece weight, the winch productivity was collapsed due to time consuming extraction process where new the anchoring point had to be located and the iron horse was removed by driving. Figure7 shows, that this kind of extraction process required 28.33% of total time of winch operator, while extraction time was 5.06% (Figure6) of total time when winch removal was not necessary (U-shape felling).

Bringing the winch back from the delivering point, to the place where first winching can be performed, was recorder under the preparatory work category. Preparatory work required 21.46% of total time of winch operator. These numbers illustrates very well how time consuming this process was and therefore this approach is too inefficient and should not be performed anymore.

Noticeable figure is also collapsed stacking productivity when delimbing is not performed. Heavy entangling within the extracted bundle is explanatory factor for this downfall. Stacking required 33.73% of total time of the winch operator and 9.38% of the chainsaw operator, even distance was 10 meter with no logging residues.

Productivities	U-shape	Clear cutting	
Chainsaw	**0.665**	**1.021**	**t/h**
Winch	**1.428**	**0.526**	**t/h**
Delimbing, chainsaw	**0.306**	**Omitted**	**t/h**
Stacking	**1.099**	**0.592**	**t/h**

Table 4. Productivities during the iron horse winching trial

	U-shape	Clear cutting	
Element		**Chainsaw**	**Winch**
Preparatory work	6.6	3.4	8.0
Clearing area around the clump	0.3	2.1	0.0
Removing undesired material	8.2	5.6	0.0
Chainsaw cutting	5.0	3.8	0.0
Bundling the culms	2.9	2.1	3.0
Extraction with winch	3.3	2.5	10.6
Delimbing	28.9	0.0	0.0
Stacking	8.1	3.5	12.6
Delays	2.8	2.3	0.8
Waiting	-	12.3	2.4
Overall time, min	**66.1**	**37.5**	**37.5**

Table 5. Element times within the cycle

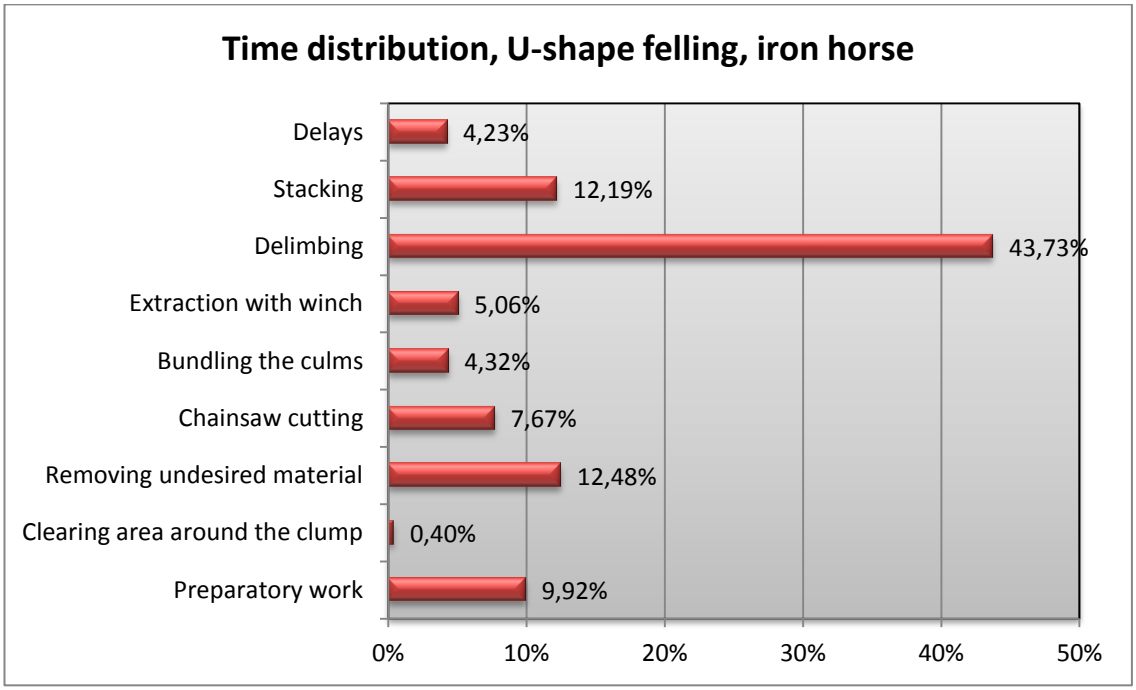


Figure 6. Time distribution between different elements. One operator was allowed to work

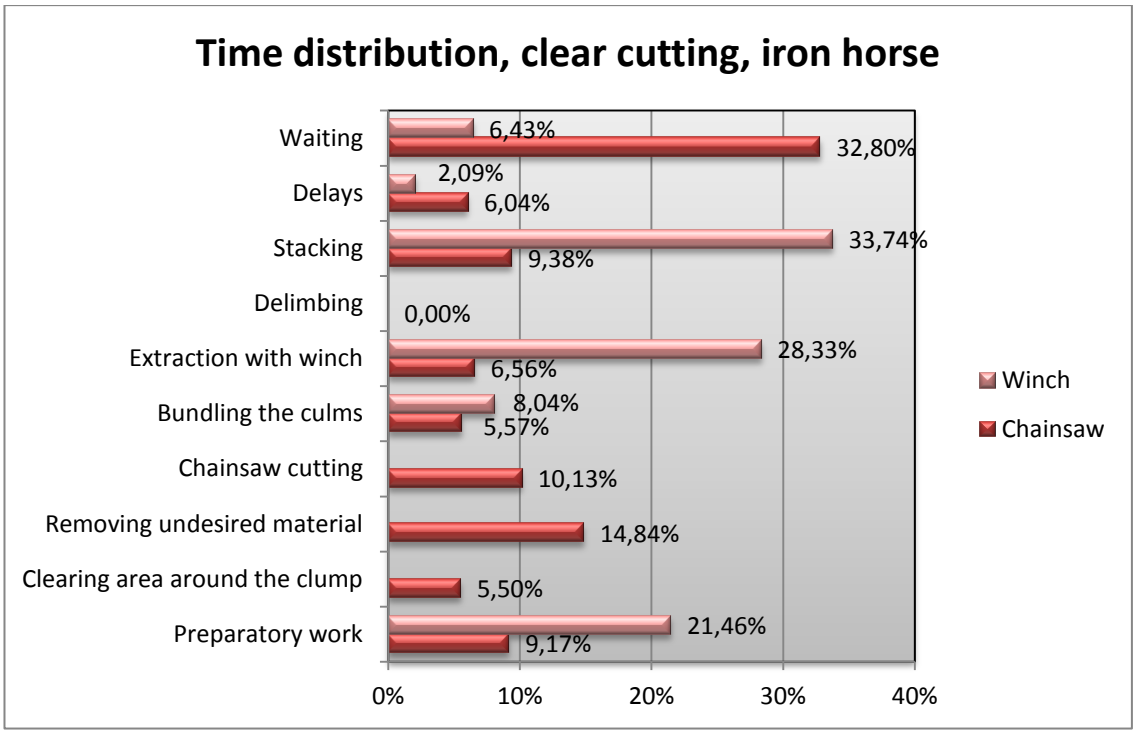


Figure 7. Time distribution between different elements. Two operators were allowed to work simultaneously

5.2.4 Chainsaw felling/vineyard winch extraction

During the U-shape felling trials vineyard winch was tested with extraction distances of 30-40 and 80-100 meters. The overall productivity with 30-40 meters extraction distance was 0.094 t/h/person. The average extraction volume was 98 kilograms, while the cycle time was 53.4 minutes.

When the distance was extended to 80-100 meters, the overall productivity remained in the same level as it was 0.092 t/h/person. The average volume was 96 kilograms and the cycle time 53.3 minutes.

Clear cutting trials showed better performance rate as the productivity was 0.125 t/h/person. The average extraction volume was 168 kg, while the extraction distance was ~35 meters. Delimbing was not carried out.

Table6 shows more detailed productivity numbers during the vineyard winch trials. The winch productivity drop down from 0.564 t/h to 0.403 t/h when the extraction distance was extended from ~35 to 80-100 meters. Stacking phase had relatively low productivity rate despite delimbed culms. However, this result

reveals what is impact when stacking distance is 20 meters and the ground is full of logging residues, this in contrast with stacking productivity during the portable winch trials when distance was less than 10 meters and no logging waste interrupted the work (1.8 t/h).

Chainsaw productivity was increased from 0.550 t/h to 1.3 t/h over the clear cutting trials. Explanation is omitted delimbing which caused the heavier stems because of any biomass was not reduced. Excluding delimbing, however, caused poor stacking productivity, which was 0.347 t/h and required 52.63% of total time of the winch operator and 19.78% from the chain saw operator. The winch performance was increased from 0.564 t/h to 0.630 t/h.

	U-Shape		**Clear cutting**	
Productivities	**30-40 meters**	**80-100 meters**	**30-40 meters**	
Chainsaw	**0.534**	**0.566**	**1.322**	**t/h**
Winch	**0.564**	**0.403**	**0.630**	**t/h**
Delimbing, chainsaw	**0.305**	**0.365**	**Omitted**	**t/h**
Stacking	**0.855**	**1.004**	**0.347**	**t/h**

Table 6. Productivities during the vineyard winch trials

	U-shape		**Clear cutting**	
Element	*30-40*	*80-100*	*Chainsaw*	*Winch*
Preparatory work	3.0	3.2	3.2	3.0
Clearing area around the clump	2.3	2.6	0.0	0.0
Removing undesired material	8.0	7.5	5.0	0.0
Chainsaw cutting	3.0	2.7	2.6	0.0
Bundling the culms	4.4	4.9	5.0	3.0
Extraction with winch	6.0	9.4	0.7	7.4
Delimbing	19.3	15.8	0.0	0.0
Stacking	6.9	5.8	8.0	21.2
Delays	0.5	1.4	2.5	2.3
Waiting	-	-	13.3	3.5
Overall time, min	**53.4**	**53.3**	**40.3**	**40.3**

Table 7. Element times within the cycle

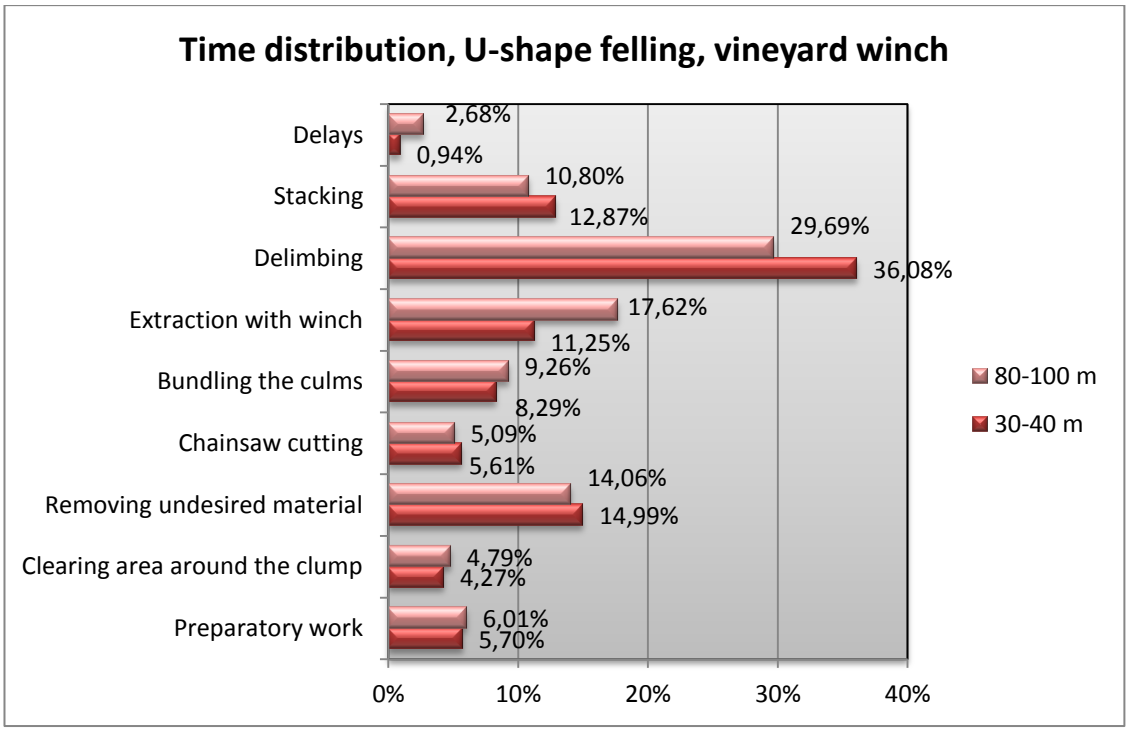


Figure 8. Time distribution between different elements with two different extraction distances

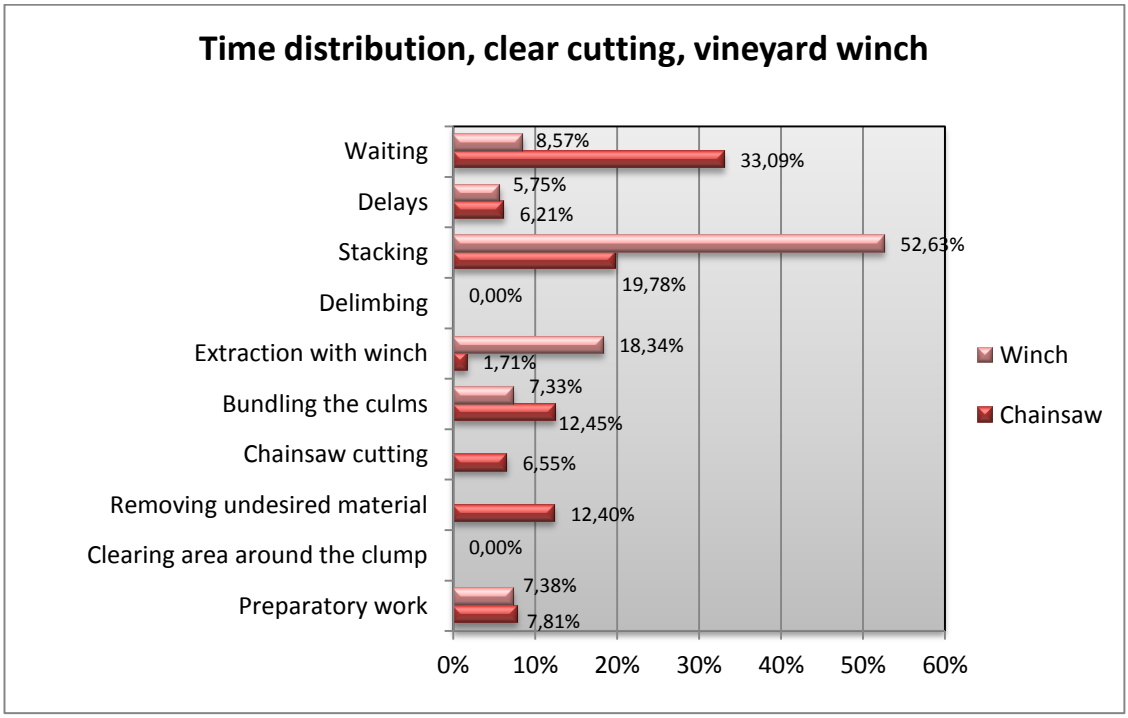


Figure 9. Time distribution between different elements when two operators were allowed to work simultaneously

5.2.5 Chainsaw felling/tractor winch extraction

During the tractor winch trials only the winch operator was observed, despite this the chainsaw operator was also working. Winching and delimbing phases were studied separately due to the long distance (100 meters) between felling and delimbing sites. Productivity was 0.490 t/h (before delimbing/stacking), when bundle was extracted 100 meters, productivity for one person therefore was 0.245 t/h. Average cycle time was 43.5 minutes and from this, 52.15% was spent for waiting, basically this is the time chainsaw operator used for felling work. Extraction volume was 355 kilograms. The winch productivity over the 100 meters, in case that waiting time is subtracted was 1 024 t/h. Productivity can be increased when the operator gains confidence with a tractor. During the studies a tractor was driven with gear 1 while engine was idling, therefore speed was extremely low. Work organization described above is inefficient due to a high waiting time for winch operator and should not be applied in real work.

Productivity with rough delimbing was 1 772 t/h and on the next phase, the stacking reached the performance level of 0.890 t/h. The average cycle time was 40.6 minutes. Combining productivities of rough delimbing and stacking leads to overall productivity rate of 0.590 t/h.

In case that two operator would work simultaneously, total productivity could be improved if one person would be in charge of both, chainsaw and winch work, while another would be in charge of delimbing and stacking. Presuming that 52.15% waiting time for winch operator can be eliminated by adding chainsaw work to him and improving extraction speed by gaining the tractor driving speed, these changes would improve one person’s productivity significantly. Total productivity per person could be ~0.450 t/h. This productivity rate repeated 8 hours would give the result of 3.6 t/day. If overall productivity of rough delimbing and stacking can be sustained in the level of 0.590 t/h, it would approximately require ~6 hour to delimb and stack 3.6 tons. This result is equal with 1.8 t/day/person or 0.225 t/h/person.

However, paragraph above is speculation based on measured results, in order to verify this estimation real time studies should be conducted in the way that chaisaw-winch/delimbing-stacking -division is applied.

Productivities		
Rough delimbing	**1 772**	**ton/h**
Stacking	**0.890**	**ton/h**
Winch	**1.024**	**ton/h**

Table 8. Productivities during the tractor trials

Element	
Trip without the load	4.7
Bundling the culms	4.3
Waiting	22.7
Extraction with winch	10.7
Opening the wire	1.1
Delays	0.0
Overall time, min	**43.5**

Rough delimbing	13.6
Stacking	27.0
Overall time, min	**40.6**

Table 9. Element times during the tractor winch trials

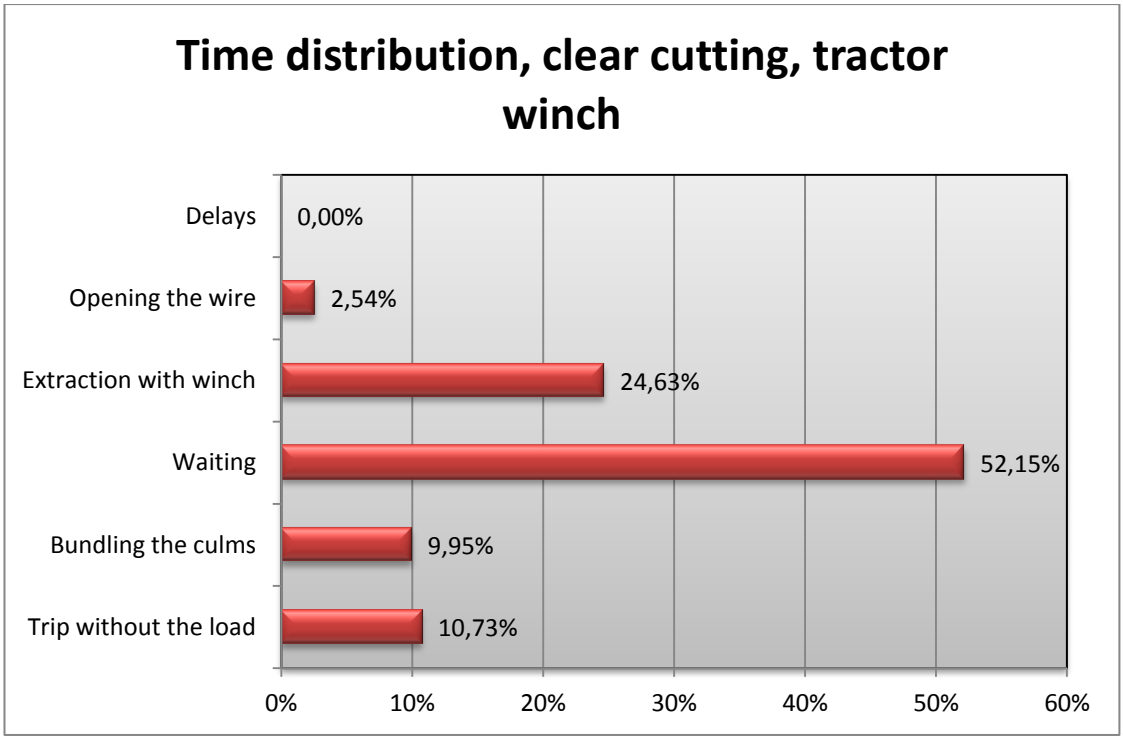


Figure 10. Tractor winch operator time distribution

5.3 Skidding trials

5.3.1 Iron horse, Jonsered

Iron horse skidding productivities with several different raw material classes are presented in Table10. Productivity varies from 0.472 t/h (dead) to 0.783 t/h (over 5 cm delimbed). The average cycle time is around 45 minutes, however average cycle time with over 5 cm delimbed stem was 54.5 minutes, Table11 shows that trip with the load, opening the belts and unloading has required slightly more time compared to other classes. This probably is the operator related distortion and can be overcome in the way that cycle time will be reduced to ~45 minutes. Despite longer cycle time, productivity is the highest due to a high piece weight. Other noticeable class is whole tree over 5 cm. Cycle time has been 61.9 minutes and Table11 shows that loading and unloading has required 40 minutes of total cycle time or in the other word 65% of total time (Figure11). Time consumption has been so high in this category due to a heavy stems and large quantity of thick branches, these features makes culms difficult to handle manually and therefore probably operator does not have significant effect on the result.

	Productivity, t/h	Average load, kg	Average cycle time, min
Dead	0.472	366	46.6
Below 5 cm delimbed	0.731	556	45.6
Over 5 cm delimbed	0.783	710	54.5
Below 5 cm whole tree	0.463	343	44.5
Over 5 cm whole tree	0.532	549	61.9

Table 10. Iron horse productivities and the average load and cycle times with different categories with the distance of 350 meter

Element	Dead	< 5 cm delimbed	> 5 cm delimbed	< 5 cm whole tree	> 5 cm whole tree
Trip without the load	7.2	7.7	6.5	6.2	5.9
Loading	14.7	13.0	13.9	15.0	21.6
Tie-up the belts	5.7	6.7	6.9	3.9	4.5
Trip with the load	9.0	8.3	10.3	5.7	9.4
Opening the belts	2.4	2.1	3.7	0.9	1.5
Unloading	7.7	7.8	10.7	8.9	19.1
Delays	0.0	0.0	2.5	3.9	0.0
Overall time, min	**46.6**	**45.6**	**54.5**	**44.5**	**61.9**

Table 11. Element times during the iron horse forwarding trials

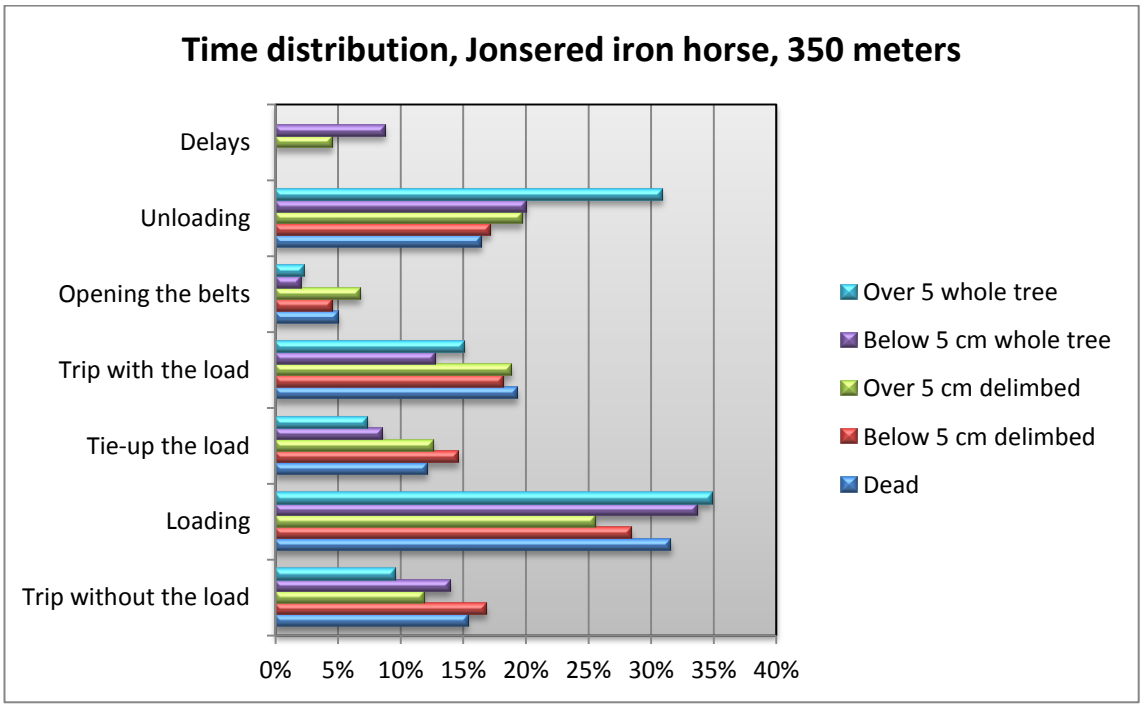


Figure 11. Time distribution between different elements with different bamboo categories

5.3.2 Iron horse, local

Productivity varies from 0.241 t/h (dead) to 0.401 t/h (over 5 cm whole tree). The average cycle time of all categories is 63.9 minutes (compare to Jonsered iron horse ~45 min). Noticeable fact in Table12, which also decreases the

productivity, is row Re-loading during the trip, this is the time spent for re-loading the culms which slipped off from the loading bench during the skidding operation. In worst case-scenario it has required ~30% of total time within the cycle (Figure12). Comparison with the Jonserd iron horse reveals also that driving speed has been much slower with the local iron horse. Trip without the load required average of 12.5 minutes with local iron horse, where Jonsered iron horse spent only 6.7 minutes to travel same trip. With the load, numbers are 13.1 for the local and 8.5 minutes for the Jonsered iron horse. Slow driving speed issue with the local iron horse can be solved by adjusting gearbox ratio. Both of the above-mentioned weaknesses leave room for significant productivity enhancement by improving the machine prototype.

Element	Dead	< 5 cm delimbed	> 5 cm delimbed	< 5 cm whole tree	> 5 cm whole tree
Trip without the load	12.5	12.5	12.5	12.6	12.6
Loading	4.9	7.8	8.2	16.8	11.0
Tie-up the belts	4.9	6.7	7.4	12.4	8.5
Trip with the load	15.2	12.4	13.8	10.7	13.6
Opening the belts	1.1	1.9	2.4	5.9	2.8
Unloading	2.9	6.0	8.2	6.6	11.6
Re-loading during the trip	14.9	9.2	22.9	0.0	6.0
Delays	0.0	0.0	0.0	0.0	0.0
Overall time, min	**56.4**	**56.5**	**75.4**	**65.0**	**66.1**

Table 12. Time consumption between different elements

	Productivity, t/h	Average load, kg	Average cycle time, min
Dead	0.241	226	56.4
Below 5 cm delimbed	0.362	340	56.4
Over 5 cm delimbed	0.348	437	75.3
Below 5 cm whole tree	0.356	385	65.0
Over 5 cm whole tree	0.401	443	66.3

Table 13. Productivity, the average load size and the average cycle time of locally manufactured iron horse

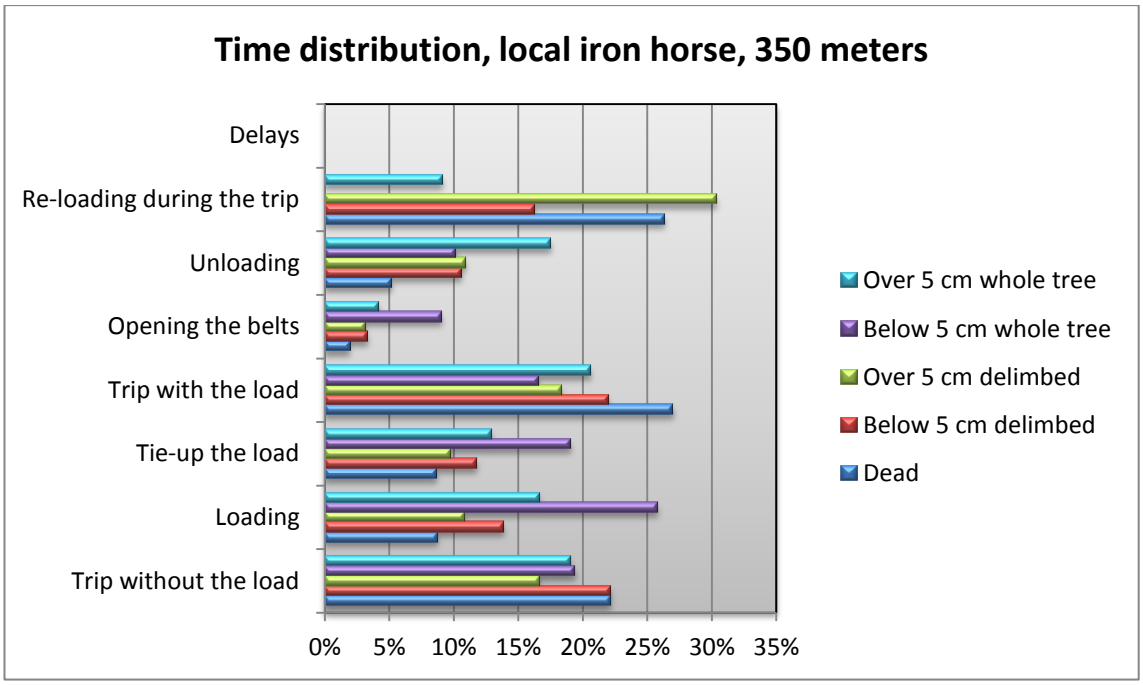


Figure 12. Time distribution between different elements with several different bamboo categories

5.3.3 Sulky

Variation in productivity results is quite large, as Table13 presents. The lowest recorded rate was 0.200 t/h (over 5 cm whole tree) and highest 0.467 t/h (over 5 cm delimbed).

Sulky is designed to carry loads over 200 kilograms, but based on employee's opinion, load size of 120 kilogram was ergonomically suitable when two operators were pulling the sulky, the forwarding distance was 350 meters and topography was flat. Two productivity figures stand out in Table13, both whole tree categories, below and over 5 cm. Load size has been 85 kilogram and therefore productivity has been remained in a poor level. Despite this relatively light load, Table14 and Figure13 shows that trip with the load has required 9.0 and 13.6 minutes or ~40% and ~55% of total cycle time. In the other categories time consumption has been maximum of 30 % of total time, while load size has been considerably heavier. These poor productivity figures are operator related, and reflects the reality during the trials, but higher rates can be expected with other operators.

Sulky has potential to relatively high productivity rates, but due to its manual work requiring characteristic, productivity is highly dependent on the operators work skills.

	Productivity, t/h	Average load, kg	Average cycle time, min
Dead	0,283	134	28,4
Below 5 cm delimbed	0,302	106	21,1
Over 5 cm delimbed	0,467	155	20
Below 5 cm whole tree	0,236	85	21,5
Over 5 cm whole tree	0,200	84	25,3

Table 13. Productivity, average load and cycle time during the sulky forwarding trials

Element	Dead	< 5 cm delimbed	> 5 cm delimbed	< 5 cm whole tree	> 5 cm whole tree
Trip without the load	5,1	4,5	4,4	4,6	4,7
Loading	4,6	3,4	3,2	2,9	3,2
Tie-up the load	2,2	5,3	4,5	2,5	0,7
Trip with the load	8,5	4,9	5,6	9,0	13,6
Opening the belts	1	1,7	0,8	1,1	0,7
Unloading	1,8	1,3	1,6	1,5	2,4
Delays	5,2	0	0,0	0,0	0,0
Overall time, min	**28,4**	**21,1**	**20**	**21,5**	**25,3**

Table 14. Element times during the sulky forwarding trials

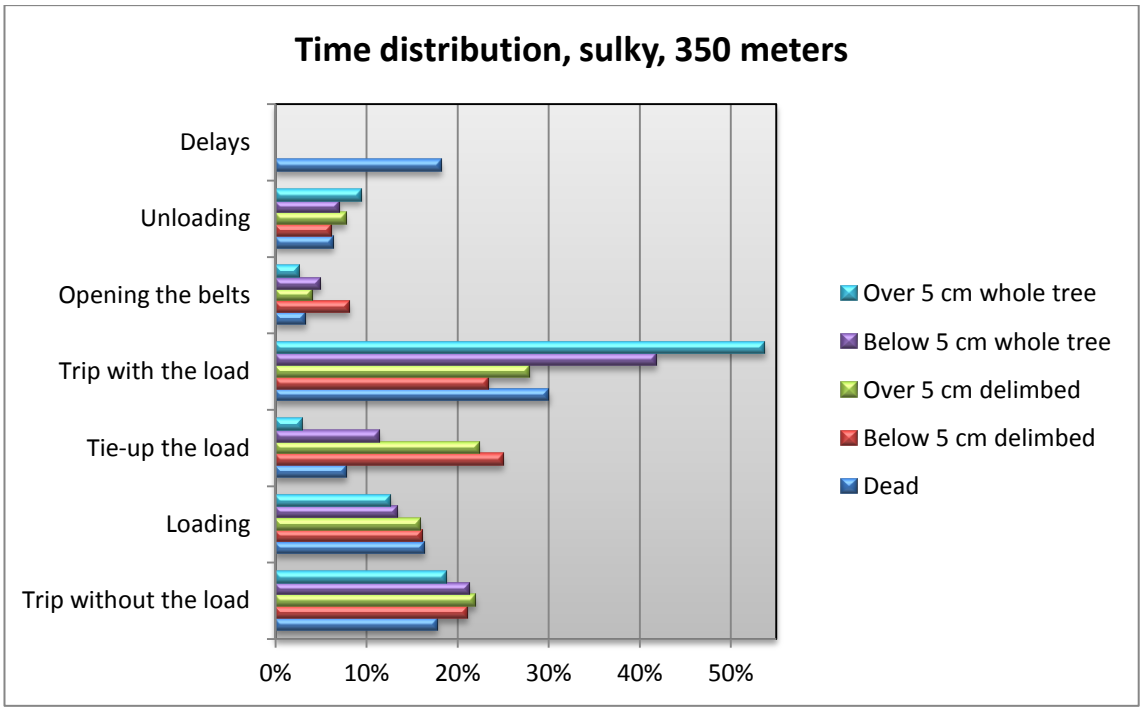


Figure 13. Time distribution between different elements during the sulky trials

5.4 Machine cost calculations

Machine costs are presented in Table15. Purchase prize, spare parts/maintenance cost and machine life time in years, are based on information received from Bamboo Fuel Chip Production for Renewable Energy project manager.

Annual depreciation is calculated by dividing purchase price with lifetime in years. It is expected that there is no salvage value for any machine.

Annual interest is calculated with formula:

AI = (i/100) * [(P*S)/2]

where,

- AI = annual interest, $
- i = interest rate, % (10 %)
- P = purchase prize, $
- S = salvage value, $

Annual operation time is calculated with assumption that the chainsaw, portable winch, vineyard winch and tractor mounted winch are used only for forest harvesting during the dry season, in other words 150 days per year. Daily utilization rate is based on the performed time studies.

The tractor and the iron horses are expected to use for other agricultural purposes and therefore extra hours has been added, amount of extra hours are based on information received from project manager. Annual hours of sulky is also based on same information.

Machine	Hours used/day	Days/year	Hours/year
Chainsaw, felling	1.6	150	240
Hand winch	1.45	150	218
Wineyard winch	1.56	150	234
Tractor	3.83	150	974
Tractor winch	3.83	150	574

Table 14. Principles of how annual utilization rate was calculated

Machine + maintenance cost were calculated by adding up all the costs (annual depreciation, annual interest, spare part/maintenance cost) and dividing this by annual operation hours.

Fuel and oil cost is based on current prices in Lao PDR and 1.25 $ salary is calculated by dividing 10 $ (target salary) with 8 hours. Total cost is calculated by adding up these costs.

Machine type	Purchase prize (Incl delivery)	Lifetime, years	Annual depreciation	Annual interest	Spare parts / maintenance cost	Cost	Oparation time, hours/year	Machine + Maintenance cost	Fuel+oil cost	Salary	Total cost	
Chainsaw	350	7,5	47	17,5	Chains	120	240	0,77	1,09	1,25	**3,11**	**$/hour**
Hand held winch	1500	10	150	75	Rope service	150	220	1,70	0,52	1,25	**3,47**	**$/hour**
Wineyard winch	400	10	40	20	Rope service	200	235	1,11	2,8	1,25	**5,16**	**$/hour**
Tractor	10000	11	909	500	Repairs	300	975	1,75	3,33	1,25	**6,33**	**$/hour**
Tractor winch	1500	10	150	75	Rope service	150	575	0,65		1,25	**1,90**	**$/hour**
Manual Logging Sulky	200	10	20	10	Repairs	50	600	0,13		2,50	**2,63**	**$/hour**
Iron Horse, Winching	12000	8	1500	600	Spare parts	600	800	3,38	2,42	1,25	**7,05**	**$/hour**
Iron Horse, Forward	12000	8	1500	600	Spare parts	600	800	3,38	2,42	2,50	**8,30**	**$/hour**
Iron horse, local	3000	6	500	150	Spare parts	400	800	1,31	1,79	2,50	**5,60**	**$/hour**

Table 15. Machine costs for each machine used on trials. All the monetary figures are presented in US $ and time figures in hours.

5.5 Productivity summary tables

Harvesting operations (ton/h)	U-Shape	Clear cutting
Chain saw	0.589	1 172
Hand winch	0.640	0.26
Wine yard:		
30-40 meter	0.564	0.630
80-100 meter	0.403	
Iron horse	1 428	0.526
Tractor		1 024
Knife delimbing	0.215	
Chain saw delimbing	0.336	
Rough delimbing	1 772	
Stacking delimbed stem	1 256	
Stacking rough delimbed stem	0.890	
Stacking non delimbed stem	0.470	

Table 16. Summary of all harvesting operations. Figures are calculated averages of measured results.

The major explanation in difference between chainsaw productivities is because of delimbing is omitted in clear cutting figures, which results to heavier stem and therefore higher productivity.

	Iron horse, Jonsered	Iron horse, local	Sulky	
Over 5 delimbed	0.783	0.348	0.467	t/h
Below 5 delimbed	0.731	0.362	0.302	t/h
Over 5 whole tree	0.532	0.401	0.200	t/h
Below 5 whole tree	0.463	0.356	0.236	t/h
Dead	0.472	0.241	0.283	t/h

Table 17. Summary of skidding productivities with the distance of 350 meters

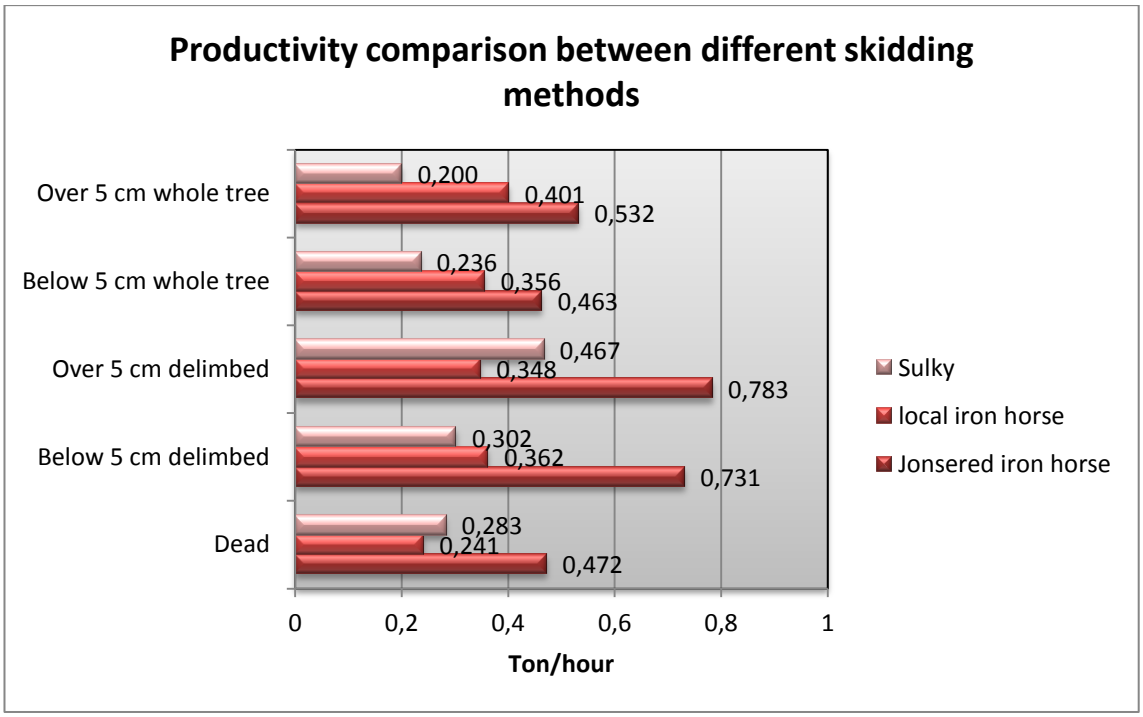


Figure 14. Summary of skidding productivities with different methods. 350 meters

5.6 Unit cost tables and analysis

Manual harvesting productivity with the extraction distance of 100 meters in best-case scenario is 0.5 ton/person/day. Daily wage of US$ 10 will give a unit cost of US$ 20/ton.

The unit costs are presented as a cost per green ton. Productivity figures are presented as a green ton/hour, however Preparatory work, Waiting and Clearing surroundings are work elements which do not have this kind of productivity, but they still have a cost. That cost is determined as follows:

1. Calculating time consumption/ton with respective felling method, e.g. chainsaw felling/portable winch extraction → 10.14 hour
2. Defining time consumption in percentages for “Preparatory work (5.46 %)” and “Clearing area around the clump (2.30 %)” from corresponding time distribution figure. In cases of two operators, both of their time consumption was calculated from total time.
3. Calculating % share from time consumption/ton → 10.14 x 0.0546 = 0.55

Cost per hour in this case is the operator pay.

Summary of the unit costs for the chainsaw and winch extraction operation are presented in Table18, more detailed costs are presented in Annexes 6-9. Tables 19-21 presents the unit costs for the skidding operations with different bamboo categories.

Table18 shows that only vineyard winch in clear cutting operation and tractor winch were able to overcome manual harvesting unit costs, although the extraction distance was ~35 meters during the vineyard winch trials. However, it is good to remember that during the manual harvesting trial, delimbing was performed, unlike during the tractor and vineyard winch trials.

The results shows, that due to low hourly cost, the sulky is the most inexpensive choice in terms of unit cost and the locally manufactured iron horse is currently the most expensive. The skidding trials will be conducted also with the mule, since it may be very competitive alternative.

Unit cost summary, US$/green ton		
	U-shape	**Clear cutting**
Portable winch	20.03	30.42
Iron horse winch	27.74	22.63
Vineyard winch	27.87 (~35m)/29.62 (80-100m)	***17.55***
Tractor winch	-	***16.51***

Table 18. The unit cost summary table for the chainsaw work and winch extraction operation

Iron horse, Jonsered	Productivity, t/h	Time consumption/ton	Cost/hour	**Unit cost, US$/ton**
Over 5 cm delimbed	0.783	1.28	8.3	**10.60**
Below 5 cm delimbed	0.731	1.37	8.3	**11.35**
Over 5 cm whole tree	0.532	1.88	8.3	**15.60**
Below 5 cm whole tree	0.463	2.16	8.3	**17.93**
Dead	0.472	2.12	8.3	**17.58**

Table 19. Unit costs for the Jonsered iron horse, skidding distance 350 meters

Iron horse, local	Productivity, t/h	Time consumption/ton	Cost/hour	**Unit cost, US$/ton**
Over 5 cm delimbed	0.348	2.87	5.6	**16.09**
Below 5 cm delimbed	0.362	2.76	5.6	**15.47**
Over 5 cm whole tree	0.401	2.49	5.6	**13.97**
Below 5 cm whole tree	0.356	2.81	5.6	**15.73**
Dead	0.241	4.15	5.6	**23.24**

Table 20. Unit costs for the locallly manufactured iron horse, skidding distance 350 meters

Sulky	Productivity, t/h	Time consumption/ton	Cost/hour	**Unit cost, US$/ton**
Over 5 cm delimbed	0.467	2.14	2.63	**5,63**
Below 5 cm delimbed	0.302	3.31	2.63	**8,71**
Over 5 cm whole tree	0.200	5.00	2.63	**13,15**
Below 5 cm whole tree	0.236	4.24	2.63	**11,14**
Dead	0.283	3.53	2.63	**9,29**

Table 21. Unit cost for the locally manufactured sulky, skidding distance 350 meters

6 Conclusions

This thesis presents unit costs for felling and skidding phase with several different elements within the supply chain for fuel chip production. However, this is just a beginning phase in a bigger context and more research has to be conducted until ready-made chip price can be determined. Unit costs which were calculated based on the recorded productivity figures are still too high, this means that more focus has to put on especially improvement of felling work operation.

In addition to unit cost calculation, important priority was also to develop efficient work method in collaboration with the local people. However this correct and the most efficient way of working is still imperfect concept and has to be developed further, this also requires higher professional skills of the employees. Daily rotation of the work force ensured that the employees did not gain high expertise on the work and therefore work efficiency remained in poor level. Lack of expertise caused uncertainty to work, which was especially obvious during the clear cutting trials when two operators were allowed and encouraged to work simultaneously. As explained earlier, four people were involved to field work on daily basis, but maximum two of them (winch-chainsaw operator division) were allowed to work at the same time, considering that and daily rotation of the work force, result was that uncertainty occurred about when it is allowed to work. Because of this uncertainty, labor was too dependent on supervisor's instructions. Overcoming this uncertainty will lead better and more confident labor performance

Besides to paragraph above, higher felling work productivity can be tried to achieve by upgrading the chainsaws. According to Stihl, the chainsaws used in the trials are recommended for arborist instead of forest work.

The results of different felling methods are slightly difficult to compare directly to each other since the nature of the work, where important priority, in addition to unit cost calculation, was to develop correct work method which enables highest daily productivity rate. This is the reason why small changes to work were done continuously during the research process. Decision of extend baseline's forwarding distance to 100 meters in middle of the research may also distort the

results. Stacking distance was limited to 20 meters on the trials, but this is too high and does not make sense, in case if purpose is anyway deliver them over to 100 meters.

Delimbing and stacking of whole tree became unforeseen issue which has to be solved somehow. Currently it looks like that target productivity cannot be achieved if delimbing is performed. The most promising result in terms of productivity and unit cost was obtained with tractor winch + rough delimbing combination. Only this combination, along with vineyard winch in clear cutting process, beat the unit cost of manual harvesting, this of course is because the labor cost is extremely low in Lao PDR and therefore machine productivities has to be high. It is also necessary to emphasize that the employees are highly accustomed to work with conventional harvesting methods and entirely unaccustomed with mechanized felling operation. Daily rotation of the work force had certainly negative impact on any anticipated productivity increment. Currently it looks like rough delimbing could be the correct approach for the problem caused by delimbing and staking of the whole tree.

Despite superior productivity of tractor winch and relatively low machine cost, there are few other interesting alternatives. First one is vineyard winch. Machine used during the trials were over 50 years old and according to instruction manual, gasoline consumption is 1 liter/hour, however consumption measured over the trials were 2 liters/hour. This raised total machine cost relatively much. Due to its simple structure this kind of machine can be built locally and with new engine with higher efficiency rate, machine cost is possible to significantly reduce. Second interesting alternative is the locally manufactured iron horse. Current version is the prototype and can be significantly upgraded. In addition of enhancing the driving speed by adjusting a gearbox ratio and improving a loading bench in order to prevent a load sliding away on the machine, these upgrades would increase the productivity and therefore decrease the unis costs. In addition, it is possible to build a winch to the machine as it is in Jonsered iron horse. Winch would make this machine more versatile and therefore annual utilization rate can be increased higher than it is with the current machine. Due to simplicity of the locally manufactured iron horse and vineyard winch, in comparison with a tractor, those alternatives for village communities are much

easier to maintain, repair and purchase spare parts, and these are important facts to take into account in a region where workshops are remote and spare parts may be difficult to find.

In a next step, chipping trials have to be conducted. Initial plan was manual feeding of the delimbed stems to a chipper, but considering low harvesting productivity rate when delimbing is performed, feeding probably will have to be done with a whole tree/rough delimbed stems. Manual feeding of a whole tree/rough delimbed stem in chipping operation may decrease productivity, due to this raw material is difficult to handle. Therefore, feeding with tractor mounted crane should be considered in the future of the project.

Lots of potential harvesting areas are located along the Nam Tha and the Nam Ngao rivers, where road infrastructure is limited. This provides great opportunities for bamboo floating but building a raft requires delimbed stems. In case that delimbing issue cannot be solved, it will narrow potential harvesting areas relatively much.

U-shape felling did not work on mechanized felling as planned. Due to heavy entangling, too many culms went broken during the winch extraction operation. Even in cases when desired 10-12 culms were successfully able to left grow, some of these stems went broken within a few days after harvesting, this happened for a two reasons. First, because of the extraction operation had negative affect on remained culms, often these stems bend little bit even they did not get broken. Secondly, because the stand was in natural condition and therefore stems had become tall and thin. When most of the supportive culms were removed around, these remained, often slightly bended culms were extremely sensitive for any external disturbances, such as wind. Heavy rainfall and wind in the upcoming rain season probably will break all of the culms. However, this method works well when felling is done manually and culm individuals are brought down one by one.

The next challenge is continuously raising salaries. Currently, typical wage is US$ 12/day. This is paid by for example Chinese, who are also doing considerably investments in the province, and through this, creating employment. Typical investments are for example banana and rubber tree

plantations, where food and raw material for Chinese industry are produced. It is expected that in the near future wages will be raised and because of in bamboo harvesting salary is earned under the concept of piecework pay, this requires high productivity of the machines which enable harvest even more than current target is.

After the project, if fuel chip production under the described concept is feasible, one option is that local smallholder communities will establish some kind of cooperative or bamboo harvesting association, which owns the machines and can run this business model. However, this requires identifying of appropriate persons who can be in charge and manage the whole process, and this, may be surprisingly difficult task.

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Annex 1 Template for the snap-back timing method

Cycle number		1		2		3		4		5		6		7		8		9		10
TOTAL TIME																				

Code Legend

1 Preparatory work
2 Clearing area around the clump
3 Removing undesired material
4 Chainsaw cutting
5 Bundling the culms
6 Extraction with winch
7 Delimbing
8 Stacking
9 Delays

Annex 2 Template for the continuous time method

Time	Saw	Winch	Time	Saw	Winch	Time	Saw	Winch	Time	Saw	Winch	Time	Saw	Winch	Time	Saw	Winch

Code legend:

1. Preparatory work
2. Clearing area around the clump
3. Removing undesired material
4. Chainsaw cutting
5. Bundling the culms
6. Extraction with winch
7. Delimbing
8. Stacking
9. Delays
10. Waiting

Annex 3 Element definitions for felling and the winch extraction operation

Definitions	
Preparatory work	Work which does not fall in other categories; planning remain culms, clearing winch line etc.
Clearing area around the clump	Clearing non wood vegetation around the clump. Done with knife. Does not occur on every cycle. ***Begins when operator take the knife - Ends when operator take chainsaw***
Removing undesired material	Chainsaw cutting of dead culms and excessive brances in order to reach desired culm. ***Begins when operator first time pull the starter rope-Ends when operator start to cut fresh culm or stop the chainsaw***
Chainsaw cutting	Chainsaw cutting of alive culms. ***Begins when operator start to cut fresh culm-Ends when operator start to cut dead culm, excess brances or stop the saw***
Bundling the culms	Bundling the culms with winch rope, which are cut in previous phase. ***Begins when operator stop the chainsaw-Ends when operator make first action in order to start winch***
Extraction with winch	Extracting culms from clump on the ground. ***Begins when operator do first action in order to start winch-Ends when winch rope is open***
Delimbing	***Begins when winch rope is open-Ends when knife/chainsaw in on the ground***
Stacking	***Begins when knife/chainsaw is on the ground-Ends when last culm is placed on the pile.*** Without delimbing begining moment is when winch rope is open.
Delays	Delays less than 15 minute was recorded. Social breaks, machine breakdown, machine refuels etc.
Waiting	Category which was added for continuous method. Due to a two operator sometimes another one has no productive work to do.

Annex 4 Template for the skidding trials

Code	1	2	3	4	5	6	7	8	9	10
TOTAL TIME										

Code Legend

1 Trip without the load
2 Loading
3 Tie-up the load
4 Trip with the load
5 Opening the belts
6 Unloading
7 Delays
8
9
10

Annex 5 Element definitions for the skidding trials

Definitions	
Trip without the load	Begins when operator does the first action to start the machine-Ends when machine is parked next to bamboo stack
Loading	Begins when machine is parked-Ends when operator takes the cargo strap
Tie-up the load	Begins when operator take the cargo strap-Ends when machine starts to move toward unloading site
Trip with the load	Begins when machine starts to move toward unloading site-Ends when machine motion stops.
Opening the belts	Begins when machine motion stops-Ends when operator take the first culm
Unloading	Begins when operator take the first culm-Ends when last culm is placed on the pile
Delays	All the other actions which does not fall in mentioned categories

Annex 6 The unit costs for the chainsaw felling/portable winch extraction

	Productivity/hour	Time consumption/ton	Cost/hour	**Unit cost, US$/ton**
Preparatory work		0.55	1.25	**0.69**
Clearing surroundings		0.23	1.25	**0.29**
Chainsaw work	0.592	1.69	3.11	**5.25**
Winch work	0.640	1.56	3.47	**5.42**
Billhook delimbing	0.258	3.88	1.25	**4.84**
Stacking	1 827	0.55	1.25	**0.68**
Forwarding 80 meter, manually	0.508	1.97	1.25	**2.46**
Delays		0.31	1.25	**0.39**
			TOTAL COST	**20.03**

	Productivity/hour	Time consumption / ton	Cost/hour	**Unit cost, US$/ton**
Preparatory work		0.51	1.25	**0.64**
Clearing surroundings		0.00	1.25	**0,00**
Chainsaw work	0.393	2.54	3.11	**7.91**
Winch work	0.426	2.35	3.47	**8.15**
Billhook delimbing	0.181	5.52	1.25	**6.91**
Stacking	1 494	0.67	1.25	**0.84**
Forwarding 80 meter, manually	0.508	1.97	1.25	**2.46**
Delays		0.79	1.25	**0.99**
Waiting		2.02	1.25	**2.53**
			TOTAL COST	**30.42**

Unit costs portable winch, clear cutting, the extraction distance 35+80=115 meters

Annex 7 The unit costs for the chainsaw felling/iron horse winch extraction

	Productivity/hour	Time consumption/ton	Cost/hour	**Unit cost, US$/ton**
Preparatory work		0.87	1.25	**1.09**
Clearing surroundings		0.35	1.25	**0.44**
Chainsaw work	0.665	1.50	3.11	**4.68**
Winch work	1 428	0.70	7.05	**4.94**
Chainsaw delimbing	0.306	3.27	3.11	**10.16**
Stacking	1.099	0.91	1.25	**1.14**
Forwarding 80 meter, iron horse	1.661	0.60	8.03	**4.83**
Delays		0.37	1.25	**0.46**
			TOTAL COST	**27.74**

Unit cost iron horse winch, U-shape felling, the extraction distance 20+80=100 meters

	Productivity/hour	Time consumption / ton	Cost/hour	**Unit cost, US$/ton**
Waiting		1.53	1.25	**1.91**
Preparatory work		1.19	1.25	**1.49**
Clearing surroundings		0.22	1.25	**0.27**
Chainsaw work	1 021	0.98	3.11	**3.05**
Winch work	0.526	1.90	7.05	**13.40**
~~Delimbing~~	0.000	0.00	0.00	**0.00**
Stacking	0.592	1.69	1.25	**2.11**
Delays		0.32	1.25	**0.40**
			TOTAL COST	**22.63**

Unit cost iron horse winch, clear cutting, the extraction distance 40 meters

Annex 8 The unit costs for the chainsaw felling/vineyard winch extraction

	Productivity/hour	Time consumption / ton	Cost/hour	**Unit cost, US$/ton**
Preparatory work		0.52	1.25	**0.65**
Clearing surroundings		0.39	1.25	**0.48**
Chainsaw work	0.534	1.87	3.11	**5.82**
Winch work	0.564	1.77	5.16	**9.15**
Chainsaw delimbing	0.305	3.28	3.11	**10.20**
Stacking	0.855	1.17	1.25	**1.46**
Delays		0.09	1.25	**0.11**
			TOTAL COST	**27.87**

Unit costs vineyard winch, U-shape felling, the extraction distance 30-40 meters

	Productivity/hour	Time consumption / ton	Cost/hour	**Unit cost, US$/ton**
Preparatory work		0.55	1.25	**0.69**
Clearing surroundings		0.44	1.25	**0.55**
Chainsaw work	0.566	1.77	3.11	**5.49**
Winch work	0.403	2.48	5.16	**12.80**
Chainsaw delimbing	0.365	2.74	3.11	**8.52**
Stacking	1 004	1.00	1.25	**1.25**
Delays		0.25	1.25	**0.31**
			TOTAL COST	**29.62**

Unit costs vineyard winch, U-shape felling, the extraction distance 80-100 meters

Annex 9 The unit costs for the chainsaw felling/vineyard winch (top) and tractor winch (bottom) extraction

	Productivity/hour	Time consumption / ton	Cost/hour	**Unit cost, US$/ton**
Waiting		1.66	1.25	**2.07**
Preparatory work		0.60	1.25	**0.76**
Clearing surroundings		0.00	1.25	**0.00**
Chainsaw work	1 332	0.75	3.11	**2.33**
Winch work	0.630	1.59	5.16	**8.19**
~~Delimbing~~	0.000	0.00	0.00	**0.00**
Stacking	0.347	2.88	1.25	**3.60**
Delays		0.48	1.25	**0.60**
			TOTAL COST	**17,55**

Unit costs vineyard winch, clear cutting, the extraction distance ~35 meters

	Productivity/hour	Time consumption / ton	Cost/hour	**Unit cost, US$/ton**
Waiting		2.13	1.25	**2.66**
Preparatory work		0.00	1.25	**0.00**
Clearing surroundings		0.00	1.25	**0.00**
Chainsaw work	1 172	0.85	3.11	**2.65**
Winch work	1 024	0.98	8.23	**8.04**
Rough delimbing	1 772	0.56	3.11	**1.76**
Stacking	0.890	1.12	1.25	**1.40**
Delays		0.00	1.25	**0.00**
			TOTAL COST	**16.51**

Unit costs tractor winch, clear cutting, the extraction distance 100 meters