Dissertationes Forestales 82

Comparison of productivity, cost and environmental impacts of two harvesting methods in Northern Iran: short-log vs. long-log

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Academic dissertation

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ABSTRACT

An empirical time study was conducted, firstly, to evaluate the effect of log lengths on time consumption, productivity, and the cost of timber harvesting in Northern Iran and, secondly, to enable a search for better techniques and harvesting methods for the region. This study compared total harvested and damaged trees after logging operations that utilized two different methods: short-log and long-log. In the short-log method the maximum log length was 5.20 m and in the long-log method minimum log length was 7.80 m.

The performance of the Stihl chain saw, Timber jack 450 C skidder, front-end loader Volvo 4500 BM, and truck Benz 2624 and 2628 was studied for both the short- and long-log methods. Post harvesting assessment of damage to the residual stand was compared along skid trail by conducting the transect method while random sample plots were chosen for the assessment of damage along winching strips.

The average productivity of felling was 11.6 trees/effective hour while the average unit cost of felling was US$ 1.2/tree. The average productivity of processing in both the short- and long-log method was 32.5 and 39.4 m^3/effective hour, respectively. The average productivity of skidding was 10.8 and 11.11 m^3/effective hour in the short- and long-log method, respectively. The average loading productivity was 29.9 and 38.0 m^3/effective hour in the short- and long-log method, respectively. The average hauling productivity was 3.23 and 3.71 m^3/effective hour, while the average hauling unit cost was 9.6 and US$ 8.3/m^3 in the short- and long-log method, respectively. The average unloading productivity was 144.2 and 69.6 m^3/effective hour in the short- and long-log method, respectively.

Overall, productivity of the long-log method was higher than that of the short-log method, and consequently unit cost of the long-log method was lower than short-log method by US$ 1.2/m^3.

The results showed that along winching strips the percentage of damage to the residual stand was 32.2 and 37.7 %, while the damages along skid trails reached 25.7 and 34.9 % in the short- and long-log methods, respectively.

Based on the analysis made in this study of different work phases, the effect of log lengths on the time consumption and productivity in the skidding, loading, and long distance transportation were similar to the study performed in Iran. However, the effect of log lengths on the residual stand showed different results from the previous study done in Iran.

As a conclusion, the models and results provided in this study could, in general, help forest managers to better understand the influencing factors, especially log lengths, on the productivity and cost in different work phases. It can be used for reorganizing and planning of forest work in order to meet the economic and environmental concerns.

Keywords: short-log, long-log, time study, chain saw, felling, processing, skidding, skidder, loading, hauling, truck, unloading, loader, unit cost, damage, Iran.

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CONTENTS

SYMBOLS AND ABBREVIATIONS

Avg.	Average
cm	Centimeter
DBH	Diameter at breath height
Eq.	Equation
ha	Hectare
KJ	Kilo joule
km	Kilometer
m	Meter
mm	Millimeter
Max.	Maximum
Min.	Minimum
min	Minute
NSR	Nordic Forest Work Study Council
PMH	Productive Machine Hour
Sec.	Second
Std. dev.	Standard deviation
SMH	Scheduled Machine Hour
US$	USA dollar = 10000 Iranian Rials (IRR)

1 INTRODUCTION

1.1 Forests and forestry in Iran

Seven percent of Iran (12 million hectares of land) is covered by forest, of which only 1.8 million hectares or 15 % of the total forest area is considered as commercial forests (Mossadegh 1996, Naghdi 1996). The Hyrcanian forests, which are the only commercial forests in Iran, are located between the Caspian Sea and the Alborz Mountain Range. Large areas of these forests are located on steep to very steep slopes with an average altitude greater than 1000 m above sea level, with snow cover in the winter (Hosseini et al. 2000). The Hyrcanian forests are dominated by uneven aged broad-leaved tree species and comprise a significant part of the national property. It is rich in species including rare, threatened and endemic species (over 80 tree and 50 shrub species are recognized) (Marvi Mohajer 2006). These forests are also areas of natural beauty and aesthetic importance and offer different kind of services and advantages to people (Iranian cultural heritage…2007). Timber production in the area is very important because it provides both incomes for local inhabitants and employment on a national level (Rezaee 1995). The other forests in Iran are not considered as commercial because the volume per hectare is low; only reaching a high level in protected forest areas such as graveyards and respected holy areas (Mossadegh 1996). In order to protect the nation's forests, the Iranian government nationalized all forests and pastures in 1967 (Sobhany 1991).

Until recently various silvicultural methods were practiced in the Hyrcanian forests including clear cutting, strip cutting, and shelter wood cutting. Due to the destructive effect of these methods on the forest ecosystem, the forest planning and management system was reorganized towards a more sustainable approach – selective cutting. Selective logging, the removal of isolated mature trees on a sustained yield basis with the goal of improving the quality of future stand, is nowadays the most common method in used in Iranian forestry.

The working system in the western part of the Hyrcanian forest is based on ground skidding by skidder with all the equipment being oriented towards working with the ground skidding system. Although mainly cut-to-length method is practiced in this area, in some cases trees are extracted using tree length method (e.g. when the diameter of cut trees is low, they are delimbed and topped in the forest, and brought to the landing for more processing). Cut-to-length method is done in different log lengths which is classified as short-log (log length <5.2 m) and long-log (log length>7.8 m) method.

1.2 Timber harvesting and transportation in Iran

In the forestry system of Iran, the whole forest area is broken down into watersheds. Every watershed is subdivided into compartments and every compartment is divided into parcels. The average surface area of the watershed, compartments and parcels is 25000, 1000, and 50 ha, respectively (Rafat Nia 1997). Parcels are mainly used to organize and administer planning and operations. Natural barriers, such as streams, swamps, ridge tops or excessively steep slopes determine the shape and size of the parcel. Sometimes artificial barriers, such as roads, separate parcels from each other.

Harvesting performance in Iran consists of measuring the annual increment of forest stands and determination of removable volume from each parcel. A basic assumption is that the amount of timber harvested per year should be the equivalent or less than the annual volume increment (cutting budget). Trees selected for felling are marked before the felling operation. On the basis of volume and type of harvesting determined for each forestry plan in the related Action Plan (e.g. Action Plan 2000 for Nav II), the supervisor of the plan performs the tree marking. In tree marking, practices of other forestry disciplines such as ecology, silviculture, forest economy, pedology and prevention of soil erosion, including landslides, and protection of landscape are important issues to consider (Marvi Mohajer 2006, Nikoy Seyahkal 2007). Proper marking also aims to preserve the desired species composition. In addition, opening the canopy cover should be avoided in order to prevent the establishment of weeds. After tree marking, logging roads and skid trails are planned according to contour maps of the area and the density of the marked trees. Operational scale contour maps are a fundamental prerequisite for planning and locating skid trails in Iran. The scale of such maps varies from 1:5000 to 1:10000.

The planned locations of roads and skid trails are flagged or marked on existing trees after the felling operation. Successful skid trail planning should not be limited to the artificial administrative boundaries. Planning of the skid trails affects the wood extraction, and is one of the most important processes in logging. Before extraction begins, the skid trails are opened by a chain saw operator and constructed by bulldozer operator according to the route planned or marked. All trees within the skid trail with a diameter greater than 15 cm are cut by the chain saw operator before the bulldozer passes, uprooting the remainder of the trees.

The distance from a skid trail to the nearest landing normally should not exceed 1000 m. The skidding often starts from the nearest log to the landing. Sometimes the bulldozer carries out pre-skidding of logs from the felling sites to the skid trails. For winching and skidding operations the skidder (or tractor) is equipped with a winch with a length of 30-50 m and a diameter of 16-18 mm. During this process the tractor (or skidder) remains on the skid trail while the winch line is pulled out to the logs by a choker setter. The skidder cable is attached directly to logs which are subsequently winched to a concentration point on the skid trails. Skid trails should be as straight as possible and tight curves should be avoided. The average space between two skid trails is about 140 m.

Hauling and unloading completes the cycle of timber from forest to mill. In order to haul logs from the forest, a certain amount of road construction is necessary. The road network consists of the main forest roads, which are at the core of the forest road network. They are permanent, functioning all year round and connect the logging sites to public roads. Branch roads and spur roads inter-connect different compartments and parcels. The issue of road density is related to the spacing of different kinds of roads in the forest. The objective is a density that results in the lowest combined cost of roading and skidding (Conway 1979). The basic considerations are terrain, volume per hectare and relative roading and skidding costs.

1.3 Harvesting systems and methods in Iran

A harvesting system refers to the tools, equipment and machines used to harvest an area (Pulkki 1997, Naghdi 2005), while harvesting method refers to the form in which wood is delivered to the logging access road, and depends on the amount of processing. Two harvesting systems are practiced in Iran: ground based skidding system and cable system (high-lead and teleferic) (Malakan Rad 1999). Except high-lead, the other approaches (ground based and cable system) are still applied. The main system for wood extraction in the Hyrcanian forests is based on ground skidding by skidder. Aerial logging system by helicopter was used only for a short period in the area under supervision of the headquarters of natural resources in Noshahr. Currently the aerial logging system is not practiced.

Throughout the world there are five harvesting methods employed: cut-to-length, tree length, full tree, whole tree method (completed tree) and chipping method (Pulkki 1997, Gerasimov 2006). The harvesting method in Iran refers mostly to the cut-to-length method and the tree length method, while the whole tree and chipping methods are not practiced in Iran. The full tree method in the western part of the Hyrcanian forest has been used (Feghhi 1989); however, this method is no longer applied.

Various researches have been conducted to show the weakness and merits, as well as the influencing factors, of each harvesting system in order to find the most appropriate system for a particular situation. Fegghi (1989) studied two ground based skidding systems and high-lead system and found the production rate of the high lead system and ground skidding was approximately similar to each other, while Pilevar (1996) found out the productivity of skidding by skidder was 18.2 % higher than the productivity of cable system (the productivity of cable system was 10.4 m^3/effective hour and the productivity of skidding by skidder was 12.3 m^3/effective hour). Hosseini et al. (2000) compared damage to residual stand by applying cable system and ground based skidding systems. The impact of skidder and high-lead system on forest soil and natural regeneration was compared under comparable conditions in a beech forest *Fagus sylvatica* in the environs of Brno, Czech Republic. The skidder was found to have caused greater damage to the consistency of the soil surface, as well as to soil properties and natural regeneration than the high-lead system operations (Odry and Ubeny 2003). However, no studies have been conducted comparing the productivity and cost of aerial logging and cable system or ground based system in Iran.

A few studies have reported about different aspects of various harvesting methods. For example, Feghhi (1989) studied the full tree method, by means of high-lead system, and tree length method using skidder. He found that in the tree length method the skidding costs were positively related to skidding distance and negatively related to load size and the number of trees. In the full tree method, by means of high-lead, time consumption of cable yarding had a direct relationship with the number of trees, volume skidded, yarding distance. Naghdi (2005) compared the production rate and cost, as well as damage, to the residual stand when using the cut-to-length and tree length method. The productivity of the tree length method was higher than that of the cut-to-length method. Damage to the residual stand in the cut-to-length method was higher than in the tree length method. Adebayo et al. (2007) studied productivity and cost of the whole tree method and cut-to-length methods. His results proved that the whole tree method was more productive than the cut-to-length method, and consequently the production cost was lower. Although comparison of cut-to-length method and tree length method provides important information about the effect of log length on the productivity and cost and also damage to the residual stand, it is not sufficiently detailed, because performing cut-to-length method involves large variations in log length that require more detailed studies. Therefore comparative studies on the short-log and long-log method are needed to determine various positive and negative aspects of both methods applied under similar conditions.

1.4 Introduction to time studies: What, why, and how

Time study is one of the most common practices of work measurements (Björheden 1991). It is used worldwide, in many types of production, to determine the input of time in the performance of a piece of work (Björheden 1991). Time study is defined as the analysis of the methods, material, tools and equipment used in the production process (Barnes 1968, González 2005) or as time measurement, classification and analysis of the data in order to increase the efficiency of work (IUFRO 1995). A detailed time study is comprised of the time consumption for each work element. This refers to determining the influencing factors, the time consumption, and the method of data collection (Samset 1990).

In a time study, all conditions hastening or hindering the progress of work should be recognized. The conditions of performing the time study should be as equal to the normal forest work. All the workers should be aware of reasons for the study as well as the methods. They should be experienced in the forest operation methods studied. The quality of production and the result should be clear and recorded because high quality work usually takes more time. All conditions of work such as weather, terrain conditions, type, shape and age of equipment should be well described (Sarikhani 2001).

The time study starts with work selection and all relevant data relating to conditions, methods and elements of the activity should be recorded, and then the recorded data should be examined to ensure that the most suitable method and technique are used. Choosing workers and training them for the time study, planning the measurement procedure and measurement technique should also be considered (Harstela 1991).

Time studies not only measure time and production, but also identify time categories according to the action. Total time recorded is subdivided into main time (productive) and general time (unproductive). Main time appears in the production process and also includes auxiliary times (e.g. fasten chain to log in skidding). General time that interrupts the productive process is divided into times for preparation and conclusion, maintenance, rest, technical and personal interruptions (FAO 2002b).

Time study is a basis for the establishment of a rating system. The results of time studies have been used to set the piece rate and rationalizing the production (Björheden 1991, Sarikhani 2001, Nurminen et al. 2006). Time study methods are used by public forest agencies in timber sale appraisal and by companies that employ operation research staff or consultants (Stenzel et al. 1985, Sarikhani 2001), as well as in determining the input – element of productivity, in studying the factors affecting productivity and in developing work methods by eliminating ineffective time (Harstela 1991). A time study can also be used for assessing the different harvesting methods for finding the most profitable one. According to González (2005) a time study is used for finding the most economical way of doing the work, standardizing the methods, materials, tools and equipment, as well as in assisting in training the workers to employ a new method.

Time study is an important tool used in studying the effects of management factors on productivity of logging systems. It had been used for many years for calculating the costs for logging practices (Gardner 1963), and is fundamental in the analysis of forest operations (McDonald 1999). The number of persons involved in a time study should be sufficient in order to cover all the harvesting activities. The problematic aspect of time studies is that several work elements are carried out at the same time (e.g. processing is done when the skidder is in skid trails or landing and therefore it is not possible to study both of them simultaneously). Forest operations are dispersed across a large area thereby requiring several people to perform the time study throughout the work site (González 2005). In order to minimize the risk and potential safety hazards as well as to reduce the cost of collection of data in the field, there have been attempts to implement an automated time study system for the skidder that was successful (McDonald 1999, González 2005).

In order to compare and apply the results of different studies, a time concept should be identified (Harstela 1993). According to the Nordic Forest Work Study Council recommendations, time concept includes total working time (moving time, change-over time, work place time, interruption time, and meal time) and unutilized time. The main portion of the total working time is work place time that is divided into effective time and delay times (Harstela 1993). Figure 1 shows a new time concept that was introduced by the International Union of Forest Research Organization (IUFRO 1995). In the concept, total time includes work place time and non-work place time. Non-workplace time is the portion of total time that is not used for the completion of a specific work task like traveling and resting away from the work place. Work place time is the portion of total time that a production system is engaged in a specific work task. Work place time is divided into productive work time and supportive work time. Productive work time is the portion of the work place time that a production system is directly or indirectly involved in completing a specific work task (IUFRO 1995). Work place time is divided into productive work time and supportive work time. Supportive work time is the portion of the work time that does not directly add to the completion of the work task, but is performed to support it, for example, preparation of work, service time for repairing the tools and refueling (IUFRO 1995).

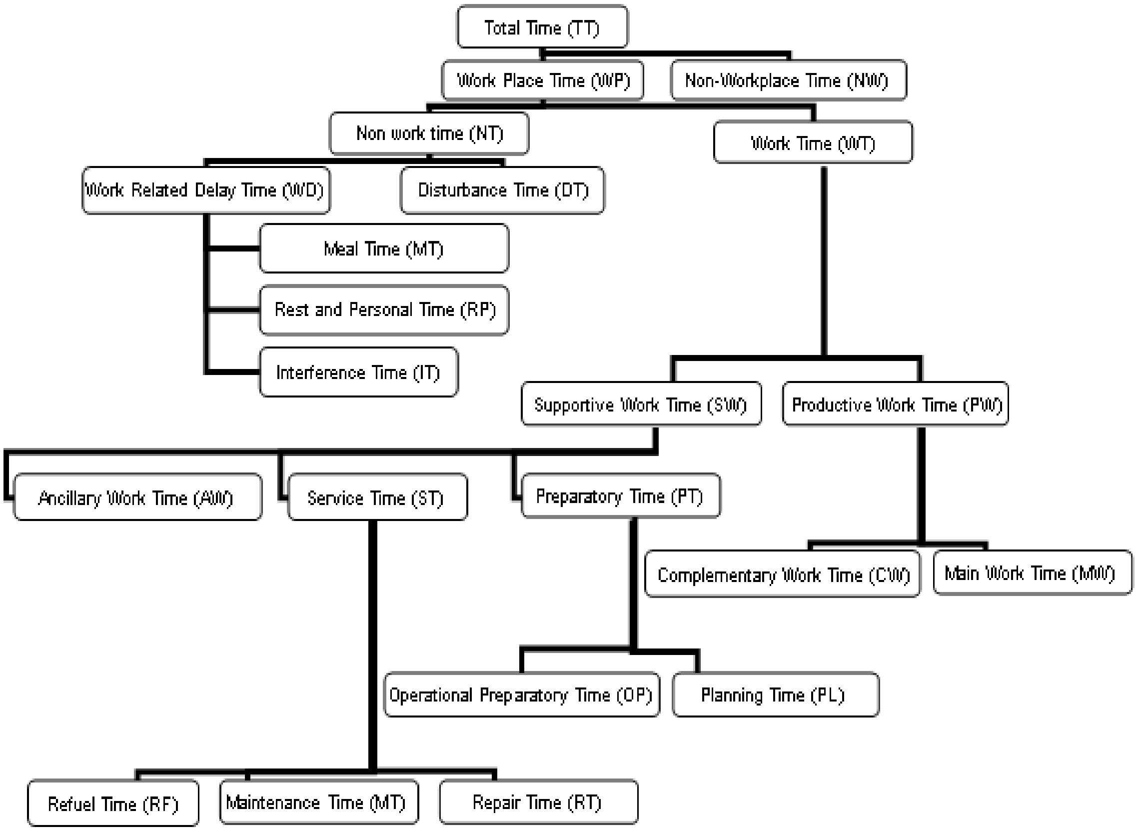


Figure 1. Time concepts, according to International Union of Forest Research Organization (IUFRO) recommendations (Source: IUFRO 1995).

Time measurements are done by using either direct or indirect methods depending on the required accuracy. In direct timing, the time for each work element is measured with a stopwatch or a handheld computer. Direct timing can be classified as continued timing and repetitive timing. In continued timing, the time is recorded continually and the elements are the differences between recorded times. In repetitive timing, the recording of very short elementary times is possible through applying snap back timing (Saarilahti and Isoaho 1992). The stop watch is snapped back to zero at the end of each time element (Saarilahti and Isoaho 1992). Repetitive timing is more suitable in the time study of harvesting especially manual felling and processing (Sarikhani 2001). Continued timing is a very time consuming process requiring many calculations, but it is more flexible if any mistakes happen during the time study. Indirect timing is used in forestry for predicting time consumption of different elements. It is used in the case when work has many elements which are repeated frequently. During work samplings the person conducting the study observes what the machine or worker is doing at specific points of time. These points are separated by either a random or a fixed time interval. The large advantages with work sampling are that elements of short duration can be studied; another advantage is the possibility to study more than one worker or machine at a time (González 2005). The sampling method is not an accurate method and it is used for the quick estimation of time consumption work phases. For scientific study, continuous timing method is the best and has been used in Iran in several studies in forestry (Feghhi 1989, Sobhany and Ghasem Zadeh 1989, Naghdi 1996, Naghdi 2005, Nikoy Seyahkal 2007).

Methodologically, there are two different types of time studies: correlation studies and comparative studies. Correlation studies are done to establish relationships between the time consumption for the work task and the factors influencing the work. Samset (1990) found that correlation studies emphasize how time consumption varies with the difference of influencing factors. In order to determine the variation of factors two research areas, one with small dimension and the other one with large dimensions (e.g. with easy and difficult conditions) may be considered. The objective of the correlation study is to describe the relationship between performance and the factors influencing the work (Bergstrand 1991, Nurminen et al. 2006). Comparative studies compare the time consumption or productivity for different equipment or work methods used to perform the same work task. They are usually done to evaluate the performance of new equipment or work methods compared to the prevalent way of doing work. According to Samset (1990), in order to compare two methods or machines, not only all conditions in the research unit (e.g. stands) but also other factors including tree shape, dimension, stand density and terrain should be similar. However, the normality around the average should also be considered as an important factor. Harstela (1991) found that the objective of comparative study is the assessment of the impact of different conditions on productivity, when the other influencing factors (e.g. workers) are almost fixed. The basic statement in comparative time studies is that the relative time consumption by using different working methods and conditions is constant and independent of the worker. In a comparative time study, the same workers are employed in both work methods being compared or in varying work conditions if the aim is to study the influence of condition factors on time consumption (Harstela 1993).

In a time study it is necessary to eliminate the influence of the worker's performance especially when the different methods are carried out in different places by different workers (Samset 1990). Therefore, normal (average) workers should be evaluated. Two relevant issues related to workers are training and motivation. Vocational training is very important in the progress of work. According to Harstela (1993), a proportion of variance of more than 50 % between productivities can only be partly explained by work condition~~s~~ factors. The main part of it is most probably explained by the skills and motivation of the operators (Harstela 1993). In order to evaluate the worker the time consumption for performing an operation should be compared with the standard time. Standard time is the time required to do the work by an average, qualified worker. Standard time is a sum of basic time, relaxation allowance and contingency allowance, including unavoidable delays (Harstela 1993). Basic time is observed time multiple rating. Rating means the subjective estimation of a performance in relation to standard performance that depends on the quality of the worker (Harstela 1993). For instance, if the work rate of a worker is estimated to be 20 % higher than that of an average worker, the performance rating is 1.2 (Harstela 1993). If the rate is higher than the average, it may show the workers are trying hard to get paid more or the tariff is not accurate and this level of work may be harmful to the worker's health in the long term (Sarikhani 2001). If the worker spends more time to perform an action than the average worker, it means that they need more training to reach the required level or the tariff may not be accurate (Sarikhani 2001). In general, rating is a difficult task. In this way, economic speed has been defined to illustrate the aim of rating and to determine an effective speed (Harstela 1993). Overall, statistics and testing can be used to choose the average worker (Lehtonen 1975, Harstela 1991).

One of the main problems of work studies is how to produce results which can be generalized (Harstela 1996). Due to practical and economical limitations to study the whole phenomenon, a sample is used as a representative of the whole population. The sample should be sufficiently representative with the measurements being reliable as possible. In a small sample it may not be possible to generalize the results. If the results can not be generalized they will have little scientific value (Pallant 2001). Samset (1990) found that the number of observations required depends on the variation of influencing factors. He felt that at least 10 observations should be collected for each of the influencing factors when the variation is large. The issue of the generalization of results refers to different working conditions, equipment and tools, as well as workers. Harstela (1996) defined internal and external reliability as two important concepts in generalization. Internal reliability emphasizes data collection, tools, techniques, and meticulousness, in addition to validity of the model. On the other hand, external reliability focuses mostly on the results. It determines how much the results are representative of the whole population. According to Harstela (1996), techniques, including choosing the standard time study and performance rating (normal worker), comparative time studies, and large amount of statistics, are possible solutions for generalization (Harstela 1996).

The main application of a time study is in the calculation of the productivity. According to Harstela (1993), productivity is the ratio between output (volume of wood) and input (time consumption or fund). One of the most important issues in appraisal of productivity is how to bring factors like weather conditions and operator motivation into the calculation. One way is to assume all the factors to be fixed, repeating the study or making use of a simulation model (Bergstrand 1987). Simulation models help us to know how productivity and cost change in different conditions, different machines and different methods (Seppälä 1971).

1.5 Harvesting work phases and factors affecting their productivity

1.5.1 Felling

Felling is the process whereby a standing tree is severed from its stump, so that subsequent logging operations may be undertaken. The severing point is made at a point on the trunk (stump) above the root collar. This activity is identified as felling and is carried out by a felling crew (Pearce and Stenzel 1972).

Felling is one of the most important processes in forest harvesting. Felling is the first step to change the tree to monetary value. With felling value is added to standing trees in the forest. From an economical point of view, standing trees in the forest have no value, although from the ecological and environmental point of view, a forest is highly appreciated as an ecosystem. The trees should be cut and brought to the market to turn the value into money (Rezaee 1994).

The chain saw is the most common tool for felling and cutting trees in Iran. Its relatively low purchase price, low weight and ability to be carried by one person have made it a commonly used tool for working the forest (Schmincke 1995). Manual felling, using a chain saw, is one of the logging components that are directly related to human labor performance. In spite of the introduction of new machineries in forestry, which have decreased the reliance on human power, labor still plays an important role in manual felling. In felling trees with a chain saw, stumps should be as close to the ground as possible because the most valuable part of tree is its butt, additionally it should be cut at an angle to minimize hang-ups (Pavel 1999, Han and Renzie 2005). Felling needs to be carried out at a certain period of time (mainly in winter time to avoid fungi attack).

In felling, finding a clear path eliminates lodged trees, throwback and damage to the tree being felled as well as the other trees (Conway 1979). All technical, environmental and safety issues should be considered for finding a clear path. Conway (1979) found that about 40 % of the value loss occurs in timber felling alone. Felling the tree in a desired direction is called directed felling. The objective of directed felling is to save time and unnecessary work by directing the tree according to the log transport route. The required felling direction is determined by the foreman and trained workers. This decision should be based on the safety of the feller, the field situation, tree position, log skidding, timber breakage, residual stand, transport route, natural obstacles, and working methods. Skilful felling is the first stage of transport, bringing the logs closer to their intended destination (Kantola and Virtanen 1986).

Planning, terrains, undergrowth, stand composition, lean of the timber, stand density, climate, type of cutting, subsequent operation and topography are the most important factors affecting the felling operation (Pearce and Stenzel 1972, Conway 1979). Planning time is the most valuable time spent; illustrating good management (Conway 1979). The general terrain features are a very important variable in the felling operation, because slope has the greatest effect on timber breakage. Heavy brush decreases productivity as it encumbers walking between trees and decreases the productivity per hour (Pearce and Stenzel 1972, Conway 1979). The lean of the trees determines how the fellers will lead the tree when felling it. Stand composition is a variable that, in combination with type of cut, can affect the breakage. Stand density affects the felling operation. In low–density stands the cuts are scattered and walking distances are increased, where cutting is performed by the worker or machine. Weather conditions may interfere with the efficiency of the worker and machines, for example, heavy snow fall, or an extended rainy season. In partial cutting, hanging-up is common, while in clear-cutting it is not a problem. Steep topography provides conditions which tend to produce excessive breakage particularly when timber is felled downhill instead of along the counter (Pearce and Stenzel 1972, Conway 1979).

Time consumption of felling and productivity depends on several variables, such as harvesting intensity, DBH (or stump diameter) and inter-tree distance (Ashe 1916, Lynford 1934, Mann and Mifflin 1979, Koger 1983, Kluender and Stokes 1996). Time studies of felling in different areas showed that felling, delimbing, bucking, and finding the tree are the most time consuming elements (Schmincke 1995). The highest felling productivity was found under high intensity harvests of large trees, while the lowest was found under low intensity harvests of small trees. Productivity is more related to stem diameter than harvest intensity (Lortz et al. 1997). Felling productivity is also affected by environmental conditions. Mitchell (2000) showed that in colder climates, felling efficiency decreased, because when the wood is frozen it is harder. This issue was also raised by Renzie (2006). A study by Barreto (1998) revealed that the productivity is affected by the number of workers in each group. The productivity was higher for a group with two persons rather than group with three persons.

Where manual felling is required, the primary concern must be the safety of the feller (Moore 1991, Parker 2002) because felling is the most risky job (Dykstra and Heinrich 1996). The feller must take into account the kick back potential of the chain saw, falling or broken tree branches, and make an escape route in case the tree does not fall as planned.

1.5.2 Processing

Processing is a procedure whereby a felled tree is debranched and cut into logs in preparation for the skidding or yarding phase of logging. In addition to knowing how to cut the logs the chain saw operator must be familiar with the log description by grade or log type, the range of acceptable lengths, and the required trim allowance (Conway 1979). Manual processing is done by means of chain saw by an experienced worker when the felling season finishes (in winter), while in the mechanized harvesting system, with a harvester, felling and processing is done simultaneously. Similarly to felling, processing is tedious and hard work and is related to labor. Labor performance is mostly affected by age, gender, race, individual variation, social background, and diet (Strehlke 1987).

After a tree is felled, the operator assistant measures the tree before cross-cutting. While measuring the logs, the operator (bucker) should carefully examine the logs for changes in the surface characteristics such as knot size and rotting (Conway 1979). The measuring device used by the bucker is a stick (in Iran the measuring stick is 1.3 m in length). Measuring should begin at the butt of the tree and proceed to the top because the maximum of value is in the butt. If maximum value is the objective, the entire tree should be examined and measured before the bucking operation. Another consideration is safety. If the tree is in an unsafe location, it should be pulled by skidder or bulldozer blade to a safe position for processing (Conway 1979).

Delimbing is one of the most dangerous parts of tree processing and involves many safety aspects because when the tree is lying on the ground, branches may be storing enormous potential energy. This energy can be released suddenly when a branch is cut. Delimbing and topping is done prior to cross-cutting and it starts from the side with the fewest branches (Kantola and Harstela 1988). Bucking is technically one of the most important elements of processing because a cut tree should be bucked in a length that maximizes profit. Sickler (2004) found that bucking has direct impact on logging profitability. Bucking optimization requires simultaneous consideration of species, tree stem quality, tree stem dimensions, log lengths, current market demand and prices, in addition to other factors (Pearce and Stenzel 1972, Conway 1979, Sessions 1988, Wang et al. 2007). Poor bucking practices may result in 20 % loss of value in comparison to what is considered good practice (Faaland and Briggs 1984, Wang et al. 2007). Practically, bucking a tree with different types of bind (top bind, bottom bind, and side bind) is risky and needs more attention from the bucker. In order to buck a tree with top bind on a steep hillside, the bucker stands on the upper side, cutting the far side first, then the top and finally the bottom. If the bucker attempts to cut straight through the tree from the top the saw will become pinched and hung up (Conway 1979). The actual depth of the various cuts depends on the amount of bind, the size, and the tree species. Bottom bind occurs when the tree is lying over some solid object or when one end or the other is hanging unsupported. With bottom bind the tree is under tension on the top side, while the bottom is under compression (Conway 1979). A side bind is the condition when the stem of a felled tree is constrained to one side or another, therefore when a bucking run is completed, the tree springs sideways. As a rule the side under compression is cut first and the side under tension is cut last. Training the chain saw operator according to instruction prepared by Conway (1979) and Sarikhani (2001) can help to overcome these problems.

1.5.3 Skidding

Forest transportation falls into two stages. The first is called primary transportation which includes all movement of logs or trees, after felling and processing, from the stump to the landing. Primary transportation may be performed by tracked machines (crawler tractors), wheeled skidder, forwarder, harwarder, any one of several cable system, or aerial logging system. Ground condition is one of the most important considerations to choose either of these systems. Different classifications have been applied all over the world for terrain difficulty. For example, Kantola and Harstela (1988) divided the terrain difficulty into five classes: level (0-15 %), gentle (15-30 %), moderate (30-50 %), steep (50-70 %), and very steep (>70 %). In Iran, the maximum slope gradient permitted on skid trails varies between 30 and 55 %, depending on the equipment available. The extraction of forest products from compartments is a difficult, risky, expensive and time-consuming operation, especially in mountainous areas. An important issue concerning forest haulage is the extraction of forest products without loss of quality where the value of grade 1 (log for veneer production) and (saw log) is considerable (Sarikhani 2001).

Over the last decade, numerous studies about skidding have been done in Iran. They have focused mostly on finding the production rate, production cost, as well as determining the influencing factors on time consumption and skidding productivity. For example, the time consumption model of skidding by the Clark 667 skidder is affected mainly by skidding distance, longitudinal slope, number of logs, and volume per cycle (Feghhi 1989, Sobhany and Ghasem Zade 1989). Eghtesadi (1991) studied the influencing factors on skidding performed by the TAF skidder in relation to variables such as skidding distance, longitudinal slope, number of logs, and volume per cycle. Pilevar (1996) compared two different harvesting systems, cable crane and ground skidding system. He pointed out that in skidding the skidder productivity depends on skidding distance, volume in each turn and slope. Naghdi (1996) studied productivity and costs in uphill and downhill skidding. The production rate of uphill and downhill skidding was 10.9 and 12.7 m^3/effective hour, respectively. He also studied the productivity of skidding for the tree length method and cut-to-length method. The productivity of the tree length method was higher than the cut-to-length method.

Ground skidding by means of skidder has also been studied in many countries with different criteria being investigated. Powell (1978) compared the machine performance of the FMC 200 series skidder under various terrain and operational conditions. He provided performance data on time, productivity and cost from the FMC skidder's operation and assessed the environmental impact of skidding in areas with steep slopes and sensitive soils.

Kluender and Stokes (1996) found that grapple skidders were consistently faster and more productive than cable skidders; however, grapple skidder has not been used in Iran. Harvest intensity affected grapple skidding productivity, but not cable skidding productivity. This was explained by the fact that the grapple skidder had to approach each stem individually, while the cable skidder had a reach.

Egan and Baumgras (2003) in West Virginia, USA examined the relation among several ground skidding and harvested stand attributes. They found a direct relation between skidding distance and cycle time, and an inverse relationship between percent of trees removed in the stand and total cycle time. The number of residual trees per hectare and number of trees per hectare in the pre-harvest stand were not significant in explaining total skidding cycle time. Skidding is directly constrained by the number of pieces and maximum volume per cycle.

A detailed time study about skidding was done by Wang et al. (2004). They found that the skidding cycle time was mainly affected by payload size and skidding distance. They also tried interaction between different variables in the different components of skidding. Stand density, slope, undergrowth, soil and volume per tree, and skidding distance were the most important factors in winching and ground skidding. The cost of skidding is typically the most expensive component in whole tree harvesting operation and directly depends on skidding distance (Mitchell 2000).

Skidding distance, slope, undergrowth and density of stand are the most important influential factors in skidding. Skidding distance is perhaps the single most important variable affecting skidding cost and productivity (Conway 1979, Feghhi 1989, Eghtesadi 1991, Naghdi 1996, Pilevar 1996, Naghdi 2005, Javadpour 2006, Nikoy Seyahkal 2007). If other variables remain constant, the further a machine has to travel from the logs to the landing, the lower is the productivity and the higher are the unit costs. Skidding distance varies, depending on different variables such as setting size, road location, terrain and slope (Conway 1979). Stand density increases the skidding time, but it concentrates the volume in one place and therefore the skidder does not have to move around as much. Proper layout of skid trails can reduce skidding costs by 38 % and ground area disturbed by 50 % (FAO 2002a). Slope is another variable that has considerable effect on skidding productivity (Conway 1979, Feghhi 1989, Eghtesadi 1991, Naghdi 1996, Pilevar 1996, Naghdi 2005, Javadpour 2006, Nikoy Seyahkal 2007). In extreme situations, steep slopes may preclude the use of either tractors or skidders. Slope can be adverse (uphill) or favorable (downhill). The rule is to skid downhill to the landing whenever possible. Skidding uphill should be avoided if possible. Undergrowth offers little difficulty, as ground skidding equipment usually follows the same trail from the woods to the landing numerous times during the skidding cycle. The place where under brush can have an affect is in bunching and choker setting. More time is required to prepare a load for skidding under heavy brush conditions (Conway 1979).

1.5.4 Loading

The landing is where the skidded logs are decked and the truck is loaded. At the landing, skidder, truck and loader are working. Loading should always be considered when building log decks. The landing site should be level, well drained, and large enough to accommodate all activities (Conway 1979). The actual size of the landing depends upon the size and number of skidding units, size of loader and the number and size of trucks being used in a particular operation. Side slopes should be limited to 10 % (Conway 1979). For an efficient operation the number of trucks must be balanced with the loader capacity to avoid delay waiting to load. If possible, roadside decks should be built on both sides of the road depending on the terrain and the road width. In this case a decking procedure allows the loader to load the truck on either side of the truck (Conway 1979).

Log loading is a key component in any logging system, since it is the means by which forest products (tree-length stems, logs, or bolts) are transferred from the ground to some form of conveyance that completes the transportation cycle (Conway 1979).

Loading can be done in different ways: manual, semi-mechanized, and mechanized. In manual loading, which is often applied in developing countries, there are poorly capitalized operations. In semi-mechanized loading, logs may be lifted and rolled by cable and different kind of tractors (Eeronheimo 1988). Mechanized loading is the most common method for loading in many countries, including Iran. It is done by either using a swing-boom, knuckle-boom, front-end loader, self-loading trucks (Conway 1979); however, in Iran log loading is done using only a front-end loader.

When loading, the truck driver is responsible for a correct distribution of the load. They must also check that the truck is not overloaded. After loading, he/she has to check that the stakes are well placed, and tools and accessories are secured, to prevent them from falling (Kantola and Harstela 1988).

While there are several studies on skidding in Iran, very few studies on loading by front-end loader have been performed. Azizi (2001) compared loading by GMC loader and Volvo BM 4500 grapple loader. The results found that productivity of loading with the GMC loader was less than the grapple loader. Javadpour (2006) studied productivity and cost of loading at roadside landing (undesigned) and forest landing (designed). In the designed landing (forest landing), a special landing was constructed for decking the logs in the forest, but in the undesigned landing, the roadside was used for decking logs. He found that the productivity at the forest landing is higher than at the roadside landing.

1.5.5 Hauling

Secondary transportation provides the link between the harvesting site and the mill. Given the rapidly increasing costs of transportation in the forestry sector, there is a growing need to explore all the components involved (Ljubic 1982). In order to investigate and optimize operation costs, a systematic study of forestry transportation is vital (Ljubic 1985). The size of vehicle carrying out the road transportation depends on the dimension of the timber, road condition, traffic regulation, and the availability of the machinery and capital to purchase or lease the equipment (Eeronheimo 1988). The main emphasis in the long-distance transportation in Iran is on truck transport. Other kinds of transportation, such as bundle floating, barge transport and railway transport, are not practiced in Iran because of inappropriate conditions and insufficient facilities. Trucks used in logging vary widely in size and load-carrying capabilities. Choosing a truck with different capacities depends on different variables such as topography, climate, size of operation, haul distance, volumes available, and the product to be hauled. Additionally local highway regulations restrict the gross vehicle weight, length, width, and height of loaded log trucks traveling on public roads (Conway 1979). In the Hyrcanian forests, the average truck volume for hauling logs is about 10-15 m^3 in the Western part of the forests while in the Eastern part it is 10-20 m^3 where truck with trailer is used for hauling in the tree length method (Naghdi 2005).

The basic factors affecting timber transport include the size of the operation, the geographic location of the forest and the mill and the distance between them, the assortment of timber for which the mill is designed, as well as the availability of suitable transportation (Conway 1979, Eeronheimo 1988). When circumstances permit, timber may be loaded directly onto trucks at the stump, eliminating the need for a separate forest transport phase. In any instance, the logs in the forest should be moved to the storage place at the right time, otherwise the quality of the wood decreases because of fungi or insects attacks. Therefore planning of long distance transportation should be done carefully.

The quality of the road surface has a major effect on the power required and the fuel consumption and volume transported (Ljubic 1985). The difference, for a loaded truck-trailer combination, between a good asphalt and upgraded, hard, and dry gravel (speed 72 km/hour) is noticeable with the gravel road requiring 40 % more power output and increasing fuel consumption by 35 % (Ljubic 1985). This shows the considerable economic benefit which come from high quality road. It shows the importance of controlling the speed.

The role of speed is important in hauling on the power required and also fuel consumption. When the speed of a loaded truck on a gravel road was increased from 54 km/hour to 72 km/hour, due to increasing both air and tire rolling resistance, power output required and fuel consumption increases as 45 and 40% respectively (Ljubic 1985).

The time consumption model of hauling is usually comprised of transport distance, load size, and mean driving speed as well as the number of logs (Gullberg 1997). The load size mainly depends on the load area, log length, and the proportion of solid volume. The driving speed is more difficult to calculate theoretically and is therefore estimated through analysis of field studies (Gullberg 1997).

1.5.6 Unloading

Once a truck has entered the mill, it must be taken to the unloading areas where the rope or chain is released by the truck driver or his assistant. To unload the logs from the truck, the fork of the loader is positioned under the logs, which are kept firmly in place by closing the curved top clamps until the head (of boom) is near the ground then the logs are released by opening the head. The loader then continues to unload other logs. When the truck is ready to be unloaded, the driver is required to move away from the area, then the loader operator is able to start unloading. In some operations the logs must be loaded and unloaded several times before it reaches the mill pond or log yard (Conway 1979). The actual unloading time of trucks is small (a large log stacker can approach a truck, clamp a load, and lift it clear of the bunks in about 30 seconds). Before a load of logs approaches an unloading point, it is weighed to determine the volume for ascertaining the value of the load (Conway 1979). Weighting the truck is the most time consuming element of the unloading work phase. Another important issue in the time consumption of unloading is efficient scheduling of trucks and achievement of equipment to handle the incoming traffic (Conway 1979).

Unloading depends mostly on the company condition (e.g. company size) where unloading is done and available machinery. A-frame dump, heavy lift crane, log stacker, front-end loader, knuckle boom loader, or a tractor with a hydraulic lift attachment are mostly used for unloading in different conditions and situations (Conway 1979). Among the different kinds of machines mentioned above, the front-end loader is the only machine for unloading in Iran. In the short-log method, unloading is done by the truck dumping its load. In the long-log and tree length method, front end loaders are used for unloading purposes. Front-end loaders are very useful machines in the factory yard because sorting and reloading to the other destination is done by the loader (Action plan 2000). The maximum productivity for a specific machine is obtained when the grapple is full. In unloading performance by front-end loader, two or three logs are removed from truck per cycle.

Overall, time consumption of unloading in Iranian conditions is not considerable; this is partly explained by the fact that the weighing of the timber truck, before unloading, is not done in Iran which significantly decreases time consumption.

1.6 Cost calculation for harvesting work

The cost calculation for different work phases is one of the most important parts of the evaluation of work efficiency (Kantola and Harstela 1988). Logging costs are calculated for determining the wood price and costs in production management, for planning and budgeting, to determine the right level of mechanization, and to compare different logging and transport methods. Cost calculation is also used to find the optimal phase, economically, to replace the machine, to establish piece work and bonus rates as well as to determine the profitability of the operation (Finne 1987). According to Sobhany (1991), information on the productivity, cost and application of harvesting equipment and system is a key component in the evaluation of management plans for the rehabilitation and utilization of the Hyrcanian forests.

Costs are classified by fixed costs and variable costs. Fixed costs are constant over a definite period and thus independent of the level of production. They will continue whether or not any timber is harvested. They include most of overhead costs and capital investments. Variable costs depend on the amount of production. The costs of fuel, lubricants, service, maintenance, repair and wages increase in relation to machine cost (Kantola and Harstela 1988).

Costs may be divided into labor and machine costs. The cost of labor is comprised of direct wages and fringe benefits including annual leave, etc (Kantola and Harstela 1988). Machine costs are more complicated than labor costs. As much as a machine price is higher an hourly cost of the machine is higher. The annual work capacity determines the size of the machine need to be purchased.

Machine times include scheduled in-shift time (SMH) and scheduled out of shift time. SMH is broken down into productive machine time (PMH) and machine down time due to service and repair and non-mechanical delay (Kantola and Harstela 1988).

Mechanical availability and machine utilization is used to show the efficiency of the machine. Machine availability is the ratio between productive machine hour and sum of productive machine hour and maintenance time. Mechanical availability is mainly dependent on the reliability of the machine. Technical weakness of the machine and unskilled operators influences the machine availability (Kantola and Harstela 1988).

Machine utilization indicates the reliability of the machine and operational efficiency of the organization are using the machine. Machine utilization is derived by dividing the productive machine hour by scheduled machine hour. Machine utilization rate is always less than machine availability (Harstela 1993).

Since the machine and operator's cost changes with over time, it is necessary to estimate the uncertainty regarding the changes. Uncertainty by word means lack of certainty which is a state when there is more than one possible outcome available for an experiment. So the true value can not be achieved, however its expected value can be measured by assigning probability to each outcome. Uncertainties in parameters such as price of services and equipments vary by time. The sensitivity Analysis of uncertainties is used for predicting the dependent variable (e.g., unit cost) in a case when the prices of services and equipment changes.

1.7 Post-harvest damage assessment

During the harvesting, especially in winching and skidding, the residual stand is always damaged. Residual stand damage includes damage to the stem (scarring or removal of bark), crown (breaking), and root (exposed). The extent of damage is highly related to the methods used. Ground skidding with skidder, which is used in primary transportation because of the low cost and high efficiency, is highly damaging to the residual stand and forest soil (Naghdi 2005). For post harvesting assessment of a logging operation, getting an accurate measure of residual stand damage is important (Stephen and Craig 1997). An application for residual stand damage study occurs when different harvesting systems are being compared for their ability to decrease damage to the residual stand (Stephen and Craig 1997).

Damage to the residual stand has been reduced significantly through the introduction of low impact logging in developing countries (FAO 1998a, 1998b, 1998c, FAO 2002a, 2002b, 2002c). Using techniques, such as pre-harvest inventory, pre-harvest planning of roads, skid trails and landings, as well as appropriate felling and processing techniques has lead to a reduction in the level of damage to the residual stand (Sist et al. 1998). Hendrison (1990) pointed out that damage to the residual stand can be minimized by means of better timber harvesting planning and proper harvesting operation techniques. Ostrofsky (2001) found that rotation lengths, cutting period, type of equipment used, operational plan, and operator skills influence the residual stand damage and also stand quality.

One of the most important points about damage to the residual stand is the severity and frequency of damage. Any damage to the bark may result in injury to the cambium or sapwood which can be graded as deep or light injury (Stephen and Craig 1997). Serious damages to the residual stand can affect the income of the forestry industry, forest owner, and future crops. This type of damage can result in the death of the tree or volume losses due to decay (Han and Kellogg 2000).

Different studies about the damage to the residual stand have been conducted in Iran. For example, Rashidi (1995) studied mechanical damage to the residual stand in a *Fagus orientalis* stand in Emam Zadeh Ebrahim, Guilan. His study showed that 31.8 % of wounds were to the roots, 54.4 % of wounds were below 1 m from the ground and 14.5 % were above 1 m. Most, 81 %, of the wounds were deep, while the remainder being light. Hosseini et al. (2000) analyzed the impact of two different timber extraction systems (cable system and ground based skidding system) on the natural regeneration in two compartments in the Hyrcanian forests in Northern Iran. The amount of damage to all stages of the regeneration was significantly higher in the skidding operation than in the cable operation. Naghdi's (2005) research found that the percentage of damage to the residual stand and saplings by using skidder was up to 44.2 %. The average was 34.9 and 30.4 % in the tree length and cut-to-length method, respectively. Nikoy Seyahkal (2007) revealed that damage to the residual stand in conventional logging was 23.5 % higher than that of low impact logging.

Globally there is a long history of research regarding damage to the residual stand which shows the importance of the issue. Vasiliauskas (2001) compiled a comprehensive literature review of studies on damage to residual stand. Westveld (1926) was among the first researchers that pointed out the significance of injury to coniferous reproduction due to logging operations. He studied post logging damage in all trees and seedlings with a diameter greater than 2.5 cm. Perry (1929) followed Westveld's (1926) study, this time focusing on damage to western yellow pine *Pinus ponderosa* regeneration under various logging methods. He studied damage to four sample plots: to assess the impact of caterpillar and high wheels, Lidgerwood skidder, caterpillar and high wheels equipped with Willamette skidding drum (long-logs), and horses and high wheels. Wales (1929) studied damage to residual stand due to skidding by tractor in the pine forests of Arizona, USA. He introduced guidelines, including 12 suggestions for driver and choker setter, in order to reduce damage caused by tractor skidder.

Damage to the residual stand may occur during different phases of the harvesting operation. Kuenzel and Sutton (1937) reported stands which were greatly damaged due to poor directional felling. Kelley (1983) reported that 27 to 47 % of the residual stand was damaged during the felling operation, especially in the area where cutting was the most dense. Although damage to the residual stand due to the felling operation is considerable it has been proved that ground skidding is one of the most important phases of wood extracting from the point of view of damage to residual stand (Shea 1960, Hunt and Krueger 1962, Pawsey 1971, Vasiliauskas 1993). In a study by Meyer et al. (1966) skidding damage to the residual stand has been compared for an articulated rubber-tired skidder using two different methods: log skidding and tree length skidding. The study found that the damage to the residual stand in the tree-length skidding was higher than that of log skidding.

Different criteria and parameters used for reporting damage. For example, Bettinger and Kellogg (1993) described the damage in terms of percentage of damaged trees by species, total scar area per hectare, and percentage of scars in three scar size categories by species. Lamson et al. (1985) used number of trees per hectare destroyed, percent of residual basal area destroyed, bent over or leaning, broken crown branches, and number of trees per hectare with exposed sapwood wounds on the tree bole or root, due to the logging operation. Fairweather (1991) used basal area by species and percent of basal area damaged. Damage may be reported in more detail such as diameter, species, and type of injury and interactions of them such as species by diameter classes (Naghdi 2005). Damages may also be reported by type or severity of injuries. Injuries to boles and roots can be classified into five classes: none, light, moderate, and severe and broken over (Meyer et al. 1966). Uhl and Viera (1989) classified injuries to trees into four classes: very hard, broken crown, offing root, and barking off.

A thorough, 100-percent inventory of damage to the residual stand gives accurate rate of damage; however, sampling plots are used mainly to determine the damage as a result of attempts to save both time and costs. Lamson et al. (1985) studied damage to residual stand due to harvesting in 12 ha of forest being harvested. They used 22 randomly distributed 0.08-ha (800 m^2) sample plots. All trees inside the plots studied were classified into four groups including rooting off trees, barking off, leaning of trees and broken crown. Bettinger and Kellogg (1993) used 35 randomly located 0.04-ha (400 m^2) sample plots which represented 25 % of the total stand area. They found 39.8 % of the residual trees sustained some damage, however the percentage of damage was lower than in any similar study in the Pacific Northwest. Han and Kellogg (2000) studied damage to the residual stand using four sampling methods including systematic sampling, randomly plot, systematic transect method, and sampling plot along skidding trails and cable corridor. The results showed that the systematic sampling result is closer to a 100-percent inventory. Because residual damage evaluations are done for a variety of reasons, no single sampling strategy is applicable for all objectives. However, it is still possible to construct a good, general purpose strategy which can be widely applied to a large number of applications (Stephen and Craig 1997).

1.8 Aim of the study

Currently in Iran economic interests prevail in timber harvesting. However, over the last few years the growing concern regarding environmental issues and nature conservation increasingly influences forestry planning and harvesting activities. In order to have a better understanding of damage caused by harvesting to the residual stand and possible ways to reduce the negative impacts, empirical studies are necessary. The thesis is based on a primary assumption that reduced log lengths (practicing the short-log instead of the long-log method) in Iranian harvesting system in a specific geographical situation might help to diminish the negative impact on the residual stand, thus implementing a more sustainable forest management approach. It is necessary to study the whole phenomenon from felling to delivery to the mill in order to determine and compare the production rates and costs of each method at the same time taking into account the negative effects of both applied methods to the residual stand.

Although numerous studies on skidding performance have been done in the Hyrcanian forest, no research results have been published regarding felling, processing, and unloading. Similarly, little attention had been paid to studies about loading and timber trucking performance in the region. Additionally harvesting performance has not been studied in detail in Iran; therefore, no model is available for the elements of harvesting work phases. Moreover, the short-log method and long-log method have not been studied and compared as two separate methods.

Improved knowledge, including production rate and cost and environmental effect, regarding the implementation of different methods is imperative to fill in the gap in the knowledge in this field. The goal of this study is to determine the production rates, costs, and residual stand damage of short-log and long-log logging in the different work phases. The specific objectives of this study are:

1) To find the production rates (m^3/hour) and costs ($\$/m^3$) of harvesting operation on the basis of the short-log and long-log methods in the Iranian conditions;

2) To develop a model for the time consumption and productivity of felling, processing, skidding, loading, hauling, and unloading operation in each method, to determine the partial model of the work phases, and to find the most influencing factors in each work phase;

3) To assess and measure the damage after logging along winching strips and skid trails in the short-log and long-log method and to determine the best available method that meets the conservation aims.

2 MATERIAL AND METHODS

2.1 Stand description

The study was conducted in Northern Iran, in the Nav Watershed in the Hyrcanian forests. The study area was located between 37°61’ and 37°20’ N, and between 48°39’ and 48°44’ E (Figure 2).

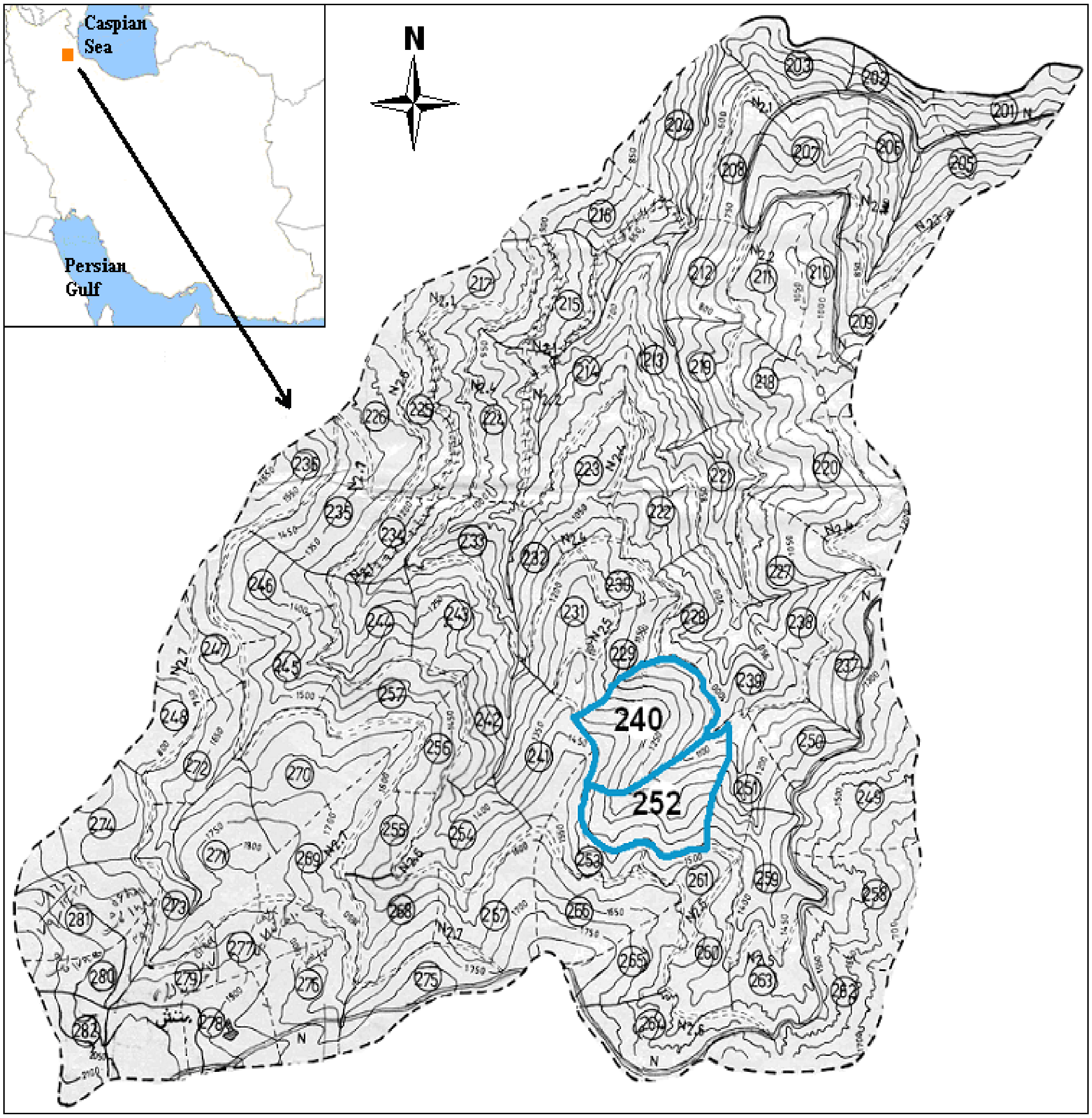


Figure 2. Location of the study area (scale of the map 1: 25 000). Study area is marked with thick line.

The nearest meteorological station is situated in Pilambara (37° 34' N, 49° 5' E). On the basis of the meteorological observations and according to Köppen's classification (Kimmel 2001), the climate of the area is temperate; the mean annual temperature is 15°C, and average daily amplitude 0-6°C. In general, the relative humidity is high; with the annual rain fall varying between 1500-2000 mm per year (Action Plan 2000). The season from June to September is relatively dry and warm. However, seasonal variations are possible, and rainfall of more than 60 mm per month may occur during the dry season which may hinder harvesting activities. The Nav watershed is located in an altitude between 600–1800 m above sea level. There are significant differences in altitude, biodiversity and weather conditions within the area. With an increasing altitude the diversity of tree species decreases. Basic information regarding soil and geographical conditions in the Nav area was obtained from the forestry plan (Action Plan 2000). Geologically this area belongs to the ancient basement formation. Acidic soils (pH <5.5) predominate, which are suitable for the growth of broadleaves, for example, oriental beech *Fagus orientalis*. On the basis of information mentioned in the Action Plan (2000) the dominant soils are classified as Rendzine, brownish in color and weathered to a considerable depth. The soil texture of the Nav formation varies from sandy clay loam to clay loam and that of the basement soils are clay. The drainage is described as medium to good (Action Plan 2000).

Stand composition, canopy height and size class distribution vary considerably from place to place, but most of the area is dominated by *Fagus orientalis* (56.3 %). Common hornbeam *Carpinus betulus* constitutes 14.6 %, Caucasian alder *Alnus subcordata* (7.3 %), Norway maple *Acer platanoides* (6.3 %), and other species (15.6 %) (Action Plan 2000). A total standing volume of all species is about 400 m³/ha (trees > 5 cm DBH) in an undisturbed forest (Action Plan 2000). Diameter class distributions are mostly well balanced in undisturbed forests with some species reaching diameters of up to 150 cm and more. The average height of taller trees is usually 20-40 m, and some individuals may reach a height of 45 m or more (Action Plan 2000). Commercial species tend to be fairly well represented. The whole area of the Nav II compartment is 3527 ha of which 2606 ha is production forest, 233 ha disturbed forest, and 687 ha of protected forest with slopes steeper than 60 % (Action Plan 2000).

2.2 Study sites

Although the stand characteristics vary within and between the compartments, the difference is rather lower inside the compartments. In order to compare the results and level the stand characteristic variation, two adjacent stands were considered: parcel 252 for the short-log method, and parcel 240 for the long-log method (each parcel covers an area of around 50 ha). Both parcels are located on a narrow, steep-sided valley running perpendicular to the Alborz mountain range. The area is located 5 km from a public road connecting the main road and parcels to each other.

The total surface area of parcel 240 (Figure 3a) is 58 ha of which 9 ha is under protection, with the remainder being suitable for harvesting. The forest type belongs to the phytosociological association Fageto-Carpinetum dominated by *Fagus orientalis* and accompanied by several broad-leaved tree species such as *Carpinus betulus*, *Alnus subcordata*, *Acer platanoides*, Caucasian lime *Tilia rubra*, and European pear *Pyrus communis.* In parcel 252 (Figure 3b), which totals 41 ha of forest area, the harvesting area comprises 33 ha, with an additional 8 ha under protection. The forest species composition and the association in this area are similar to that of parcel 240 (Table 1). There is no detailed information available on the average height and diameter of the trees, but according to Action Plan (2000), all trees including young, mature and old trees are relatively balanced but the percentage of old trees in parcel 252 is higher than in parcel 240 (Action Plan 2000). In the regenerating seedling and sapling layer *Fagus orientalis* predominates. The structure of the forest is uneven aged, two-storied and mixed.

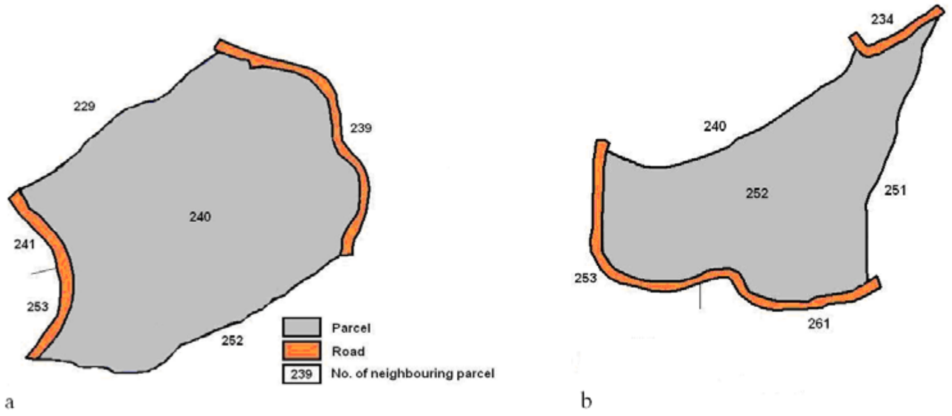


Figure 3. Maps of the parcel 240 (a) and 252 (b); scale 1: 25 000. Source: Action Plan (2000).

Table 1. Stand descriptions for parcels 240 and 252.

Study area	Parcel 240	Parcel 252
Silvicultural treatment	Single tree selection method	Single tree selection method
Elevation range (m)	1250 (1050-1450)	1250 (1050-1450)
Aspect	North-west	North
Treatment size (ha)	58	41
Slope (avg.)	0-30 % (16%), 30-60 (64%), 60-80% (10%), 80-100% (7%), > 100% (3%)	0-30 % (10%), 30-60 (44%), 60-80% (34 %), 80-100% (10%), > 100% (2%)
Regeneration condition	Medium to good	Medium to good
Grade and capacity of forest	2 and production potential is good	2 and production potential is good
Crown cover percentage	60-65 %	50-60 %
Weedy species indicator species	Ferns (*Polypodium vulgare, Pteris cretica, Phyllitis scolopendrium*, *Hypericum androsaemum*)	Ferns (*Polypodium vulgare, Pteris cretica, Phyllitis scolopendrium*, *Euphorbia amygdaloides, Hypericum androsaemum*)
Soil PH	5-5.7	5-5.7
Gross volume (m^3/ha)	233	227
Percentage of species per volume	*Fagus orientalis* (39.3 %), *Carpinus betulus* (24.6 %), *Alnus subcordata* (4.5 %), other species (31.6 %)	*Fagus orientalis* (41.3 %), *Carpinus betulus* (9.8 %), *Alnus subcordata* (4.3 %), other species (44.6 %)

2.3 Data collection

2.3.1 Time study performance

During normal harvest operations, detailed records of felling, processing, skidding, loading, hauling and unloading events were kept (Figures 5-7). The time study of felling was conducted in 2005; processing, skidding and loading in the same study area and working group were studied in the summers of 2006 and 2007. Time studies were conducted to assess timber harvesting performances, productivity and costs under comparable conditions of the short-log and long-log timber harvesting. The study covered regular working hours of the machines and operators. Field studies concentrated on collecting operational and financial data that are essential for subsequent evaluation. A video camera and electronic chronometer simultaneously measured both partial times and accumulated time in minutes and seconds. All work phases were filmed and recorded just as if the operators were in a normal working situation without any special arrangements. The annual production period varied, depending largely on local climatic conditions. In time studies, using video camera, it is recommended to write down information about various parameters such as log length, weather condition, and other information on special sheet prepared earlier.

Although the time concept introduced by IUFRO (1995) is comprehensive, due to practical difficulties for data collection and practicality of the results, the NSR time concept (Figure 4) has been used. However delay time was taken in greater detail and broken down into three elements as proposed by Naghdi (2005). It includes technical, personal and operational delay. Technical delay is largely unavoidable delay while operational delay and personal delay is greatly avoidable.

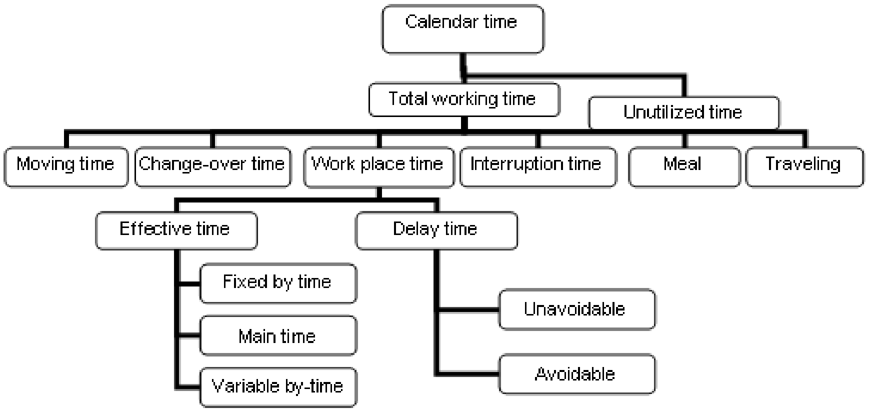


Figure 4. Time concepts, according to the NSR recommendation (Source: Harstela 1993).

Cut-to-length method was studied using two different methods: short-log and long-log. In the short-log method, trees were bucked in the forest, with the maximum log lengths being 5.20 m. A maximum length of 2.60 m was applied when the diameter was large (DBH > 1 m). In the long-log method trees were bucked in different lengths with minimum length of 7.80 m at the stump area. Special trucks for long-log hauling were able to carry logs with the maximum length of 7.8 m. Therefore, if the logs exceeded this length, they needed to be rebucked in order to be fit onto the truck.

Different variables were measured in each work phase. In felling, time consumption, inter-tree distance, tree species, tree volume were recorded. In processing, time consumption, distances between cut trees, tree species, logs volume were recorded. In skidding, for each trip, time consumption, log size, number of logs skidded, terrain, slope, skidding distance, and winching distance were recorded. In loading, time consumption, loaded volume, and number of logs loaded per cycle were collected. In hauling, time consumption, hauled volume, hauling distance, truck speed, and number of logs per cycle were recorded. In unloading, time consumption, volume unloaded and number of logs per payload and cycle was collected.

Although stump diameter was measured in cm, it was classified in 5 cm diameter classes (e.g. class 30 cm starts from 27.49 cm and ends at 32.49 cm). The time consumption data were also analyzed according to 5 cm classes.

In the study, bucking in the short-log method was done only in the forest, but in the long-log method it was done both in the forest and landing. The video material was analyzed according to the stop-watch study principle using the time counter of the video camera. The accuracy of the counter was 1/24 seconds (Nurminen et al. 2006).

A reversible metric tape and a diameter tape were used for measuring log lengths and diameters. Skidding was carried out by a skidder except during the winter season and bad weather conditions when the skid trail was not suitable for skidding. The data were used to calculate productivity and costs. A Suunto inclinometer was used for measuring slope in the skid trails. Calculation of slope was weighted as follows (Nikoy Seyahkal 2007):

$$S = \frac{\sum_{i=1}^{n} d_i s_i}{\sum_{i=1}^{n} d_i} \quad (\text{ i=1,2,…,n}) \qquad (1)$$

Where S = average slope along skid trail, percent;
d = distance between two points in the sample, m;
s = slope between two points in the sample, percent;
i = sample number;
n = number of samples.

Working time on the study operation was eight hours per day, but the effective hours differed in each working phase. Nevertheless, at least 2 hours lunch break and rest should be considered. Additionally, directors and related staff of the Shafaroud Company (harvesting performance in the study area is done by Shafaroud Company) were asked to provide data on equipment and personnel employed in harvesting procedure. For this purpose a form was developed to identify equipment types and purchase prices as well as the number of workers and their annual wages in logging and transport (including road construction), maintenance, processing, and supervision. Total crew wage per hour was calculated on the basis of the number of crew members and their annual wages in Shafaroud, divided by the total annual work time per hour.

2.3.2 Acquiring the number of required samples

Taking into account that conclusions may be drawn on the basis of this study having a certain degree of statistical validity a sufficiently large number of observations must be recorded (Saarilahti and Isoaho 1992). For practical and economical reasons, it is not possible to study the whole phenomenon; therefore a preliminary inventory was necessary to find the required number of samples. Regarding the statistical literature of work phases, the decision was taken on the number of samples needed for preliminary inventory (Table 2). The variance and mean of the certain parameter of population (s^2) is obtained from the preliminary inventory. Then the sample size required for a reliable estimate on the average can be calculated by formula [Eq. 2, Eq. 3] (Saarilahti and Isoaho 1992, Zobeiry 1994).

$$n = \frac{t^2 \times (S_X\%)^2}{(E\%)^2} \tag{2}$$

$$S_x\% = \frac{S_X \times 100}{\overline{X}} \tag{3}$$

Where n = sample size;
t = the value from normal distribution table (e.g. t = 1.96 for a 95 % confidence interval);
S_x = standard deviation from preliminary inventory;
E = tolerance error for the confidence interval (10 %);
$\overline{X}$ = Average value (time consumption value) from preliminary inventory.

Table 2. Number of required and observed samples in the short-log method (SLM) and long-log method (LLM).

Work phase	Method	Required	observed
Felling	---	55	143
Processing	SLM	25	52
	LLM	27	54
Skidding	SLM	28	51
	LLM	35	72
Loading	SLM	15	35
	LLM	17	43
Hauling	SLM	12	22
	LLM	15	25
Unloading	SLM	14	20
	LLM	14	20
Total	SLM	149	323
	LLM	163	357

Figure 5. Felling performance in Iran: a) Performance of sink-cut or face cut); b) performance of back-cut. The back-cut is usually made 2.5 to 7.6 cm (Conway 1979) above the sink-cut depending on the tree size.

Figure 6. Typical conditions of wood procurement in Iran. a) Felled tree in the forest, plenty of time should be consumed for clearing (or cleaning) along the stem of cut tree; b) Ground condition and felled tree ready for processing; c) delimbing and topping is done in dangerous position; d) performance of cross-cutting of *Fagus orientalis*; e) prepared skid trail for skidding; f) roadside landing.

Figure 7. Primary and secondary transportation in Iran: a) wheeled skidder, equipped with cable, skidding the log; b) hooking of log; c) front-end loader carrying the log for loading; d) loading performance at the roadside landing by loader; e) dump-truck used for carrying short-log; f) special truck for long-log.

2.3.3 Damage to residual stand

Residual damage along winching strips and skid trails was assessed in parcels 240 and 252 in similar conditions. Due to time constraints, only skid trails where trees were actually extracted were assessed for residual damage; no assessments were made along other skid trails. Damage to the residual stand along the winching strip was studied in sites randomly located within the working area. In order to determine the percentage of damage and type of damage at log extraction stage along skid trails, the transect method was used. Species and DBH were recorded for all trees along the winching strips and skid trails and each tree was examined for any kind of damage (Figure 8). All injured saplings and trees with a DBH >5cm were measured and recorded, and classified according to 5 main classes of damage: 1) one wound per tree; 2) 2-3 wounds per tree; 3) more than 3 wounds per tree; 4) leaning; 5) broken crown. For crown damage, trees were considered damaged if the main stem was broken or 50 % of the crown was missing. In addition, total number, diameter and tree species around the skid trails and winching strips, total damaged trees, location of wound(s) on each tree (on roots, up to 1 m, above 1 m), size of wounds (less than 100 cm^2, between 100-1000 cm^2 and more than 1000 cm^2) and degree of injuries (deep and light) were recorded. The length of the winching strips differed, but the width of the winching strips was kept constant at 6 m (3 m from each side). In the skid trails the length of the trails differed but the width of the skid trails for studying the residual stand after skidding was kept constant at 4 m. All trees and seedlings with a diameter greater than 25 cm up to 3 m around the main winching strips were recorded and studied for any kind of damage. Because of the different surface area of the winching strips, the calculation of percentage damages was weighted as follows (Naghdi 2005, Nikoy Seyahkal 2007, Zobeiry 2007):

$$M_w = \frac{\sum_{i=1}^{n} g_i s_i}{\sum_{i=1}^{n} s_i} \qquad [i=1, 2, \ldots n] \tag{4}$$

Where M_w = average percentage of damaged trees along winching strip, percent;
g = percentage of damage along winching strip in the sample;
s = surface area of winching strip in the sample, ha;
i = sample number;
n = number of samples.

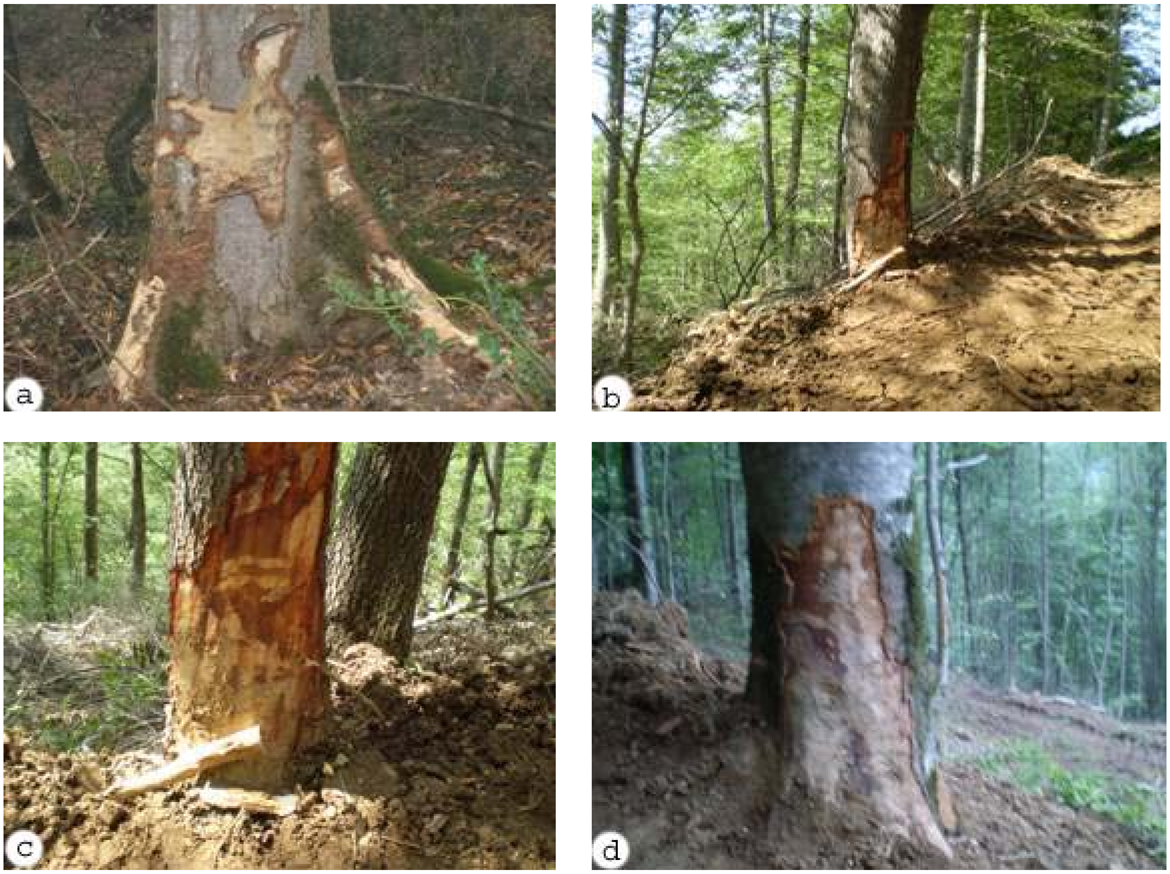


Figure 8. Damaged trees after harvesting: a) damaged tree along winching strip; b) damaged tree along skid trail; c) *Alnus subcordata* barked off by skidder blade; d) *Fagus orientalis* damaged due to skidding.

2.4 Machine, working group and working conditions

Both the short-log and long-log method used the same equipment and tools as well as operators in this study. A Stihl chain saw was used in felling and processing. A Timberjack C-450 model skidder was used in skidding. Front-end loader is mostly used for loading in Iran because neither the truck nor the skidders are equipped for loading. However, it would be an option to buy trucks equipped with crane or grapple loader. Unloading is done by means of front-end loader in the long-log method while in the short-log method it was done by truck dumping.

The company staff plan and execute the harvesting activities. The harvested timber is sold to factories or sawmills. In this study, three trucks were used: two trucks for the short-log (Mercedes Benz 2624) and one for the long-log (Mercedes Benz 2628). In Iran, front-end loader is mostly used in the long-log timber truck unloading because the truck is not equipped for unloading. In the short-log, the truck driver performs the unloading by dumping the logs. The front-end loader model for loading and unloading was a Volvo 4500 BM.

Harvesting groups in Iran consist of felling crew, skidding crew (processing and skidding workers), and loading crew. In all work phases, the operator of each machine was skilful and had more than 20 years work experience in different conditions. The average age of the workers was in the range 45-55 years old. In order for the results to be comparable, the same workers were used in both methods. In felling, processing, skidding, loading, hauling, and unloading 4, 2, 3, 3, 2, and 2 persons were working, respectively. All the workers are hired permanently. All harvesting groups in the working area are supervised by a foreman who is controlling the harvesting activities and reporting any failure in performance.

Felling was done in the winter when the ground is covered by snow. Processing was done in spring and summer. Both downhill and uphill skidding is practiced in the area but in this study only downhill skidding was investigated.

2.5 Work phase classification

All activities (associated with harvesting operations in Iran) from felling tree to delivering to mill are classified into six work phases; felling, processing, skidding, loading, hauling, and unloading. Each work phase was broken into several time elements to cover all spent time for the specific work phase.

Felling

- Walk to tree: begins when feller starts walking towards the tree to be cut and ends when feller reaches the tree.
- Clearing (acquiring): begins when feller starts clearing around tree and judging where tree will fall and ends when feller is ready to cut tree.
- Sink-cut: begins when the operator starts to cut horizontally, and ends when he has sawed out a pie-shaped piece of wood facing in the direction where the tree is supposed to fall.
- Back-cut: begins when the operator starts to cut 2.5-5 cm above sink-cut in opposite direction, and ends when the tree hits the ground.
- Miscellaneous time: each work which is a part of work phase, but is not included in the mentioned elements is in this category (e.g. fuelling).
- Delays.

Processing

- Walk to cut tree: begins when the operator starts to move with chain saw and ends when the operator stops to perform processing near felled tree.
- Clearing: begins when the operator starts to remove unwanted small trees and disturbing undergrowth and ends when the operator starts the next activity.
- Measuring: begins when the helper moves and starts to measure from the bottom of the tree by means of stick (1.3 m) and ends when measuring finishes. The assistant marks the place for cross-cutting.

- Delimbing and topping: begins when the operator moves and starts to cut the top and branches and ends when all branches are cut.
- Bucking: when the operator starts to cross-cut the felled tree on the marked place and ends when the cross-cutting finishes.
- Miscellaneous time.
- Delays.

Skidding

- Travel unloaded: begins when the skidder leaves the landing area on the skid trails and ends when the skidder stops in the stump area.
- Releasing (opening and extension of cable): begins when the skidder driver releases the cable (choker setter starts to pull the winch cable out) and ends when the choker setter approaches the logs that will be hooked.
- Hooking (setting choker): begins when choker setter sets the choker close to the logs, at a distance of 0.5-1.0 m from the log end, and ends when the helper moves to a safe place and sends signals to the tractor or skidder operator to start winching (or cable loop fastened).
- Winching: begins when the driver starts to winch and ends when the logs are mounted on the back of the skidder on skid trail or load arrives at the skidder.
- Travel loaded: begins when the skidder starts to move on skid trail and ends when the skidder is on the landing.
- Unhooking: begins when the chaser or skidder driver (most of the time) leaves the skidder for unhooking of cable and ends when pulling-in the cable is finished.
- Piling: begins when the skidder starts to move and deck the logs on the landing and ends when load is piled in final position and the skidder starts preparing for the next cycle.
- Delays.

Loading

- Log selection: begins when the loader starts to move towards the right log and ends when the loader operator selects the log considering the truck driver's recommendation.
- Embracing or grappling: when the fork is lowered to the ground and positioned beneath the logs and ends when the log is located in the fork and is ready to be loaded onto the truck.
- Loading: starts when the loaders lift the log and ends when the loader releases the log onto the truck.
- Sorting or positioning: starts when the driver starts to position the log on the truck and ends when the loader returns to do the next cycle.
- Fastening and securing the load: begins when the helper starts to fasten the load and ends when the truck is ready to leave the landing.
- Delays.

Hauling

- Driving unloaded: begins when the truck leaves the yard and ends when the truck stops at the landing area for loading. Preparing for loading is included in the driving unloaded.
- Loading: begins when the loader starts to choose the first log and ends when the driver assistant fastens the security rope or wire.
- Driving loaded: begins when the truck leaves the landing and ends when the truck arrives in the yard.
- Unloading: begins when the helper opens the security wire and ends when all logs are unloaded onto the ground.
- Delays.

Unloading

- Opening the load (rope): begins when the helper starts to open the truck and ends when the truck moves to get position for unloading.

- Preparing for unloading: begins when the truck is positioned in the right place and ends when the truck is ready for unloading.
- Log selection: begins when the loader moves to the loaded truck and ends when the loader approaches the truck.
- Embracing or grappling: when the fork is raised to the truck and run beneath the log and ends when the log is rolled and located on the fork and is ready to be removed from the truck.
- Unloading: starts when the fork is lowered and ends when the loader puts the logs on the ground.
- Delays.

Delay times

Delay times are time that is not related to effective working time. Delay time is unwanted time consumption in each work phase. Delay time is not expected to occur regularly but literature and work studies suggest it is likely. There are three kinds of delay time:

-Personal delay time, any interruption or non-working time such as resting or any other breaks related to the personnel were placed in this category.

-Technical delay has different types including chain saw chain breaking and replacing with a new one, sharpening of chain, pinching chain, down time of skidder, loader and truck which was put in this category.

-Operational delay is related to inappropriate planning. For example, when there was no accessible fuel in working time and therefore should be brought from another place, or required spare parts are unavailable, it was put in this category. In skidding, loading and hauling, when the log was not ready for skidding or the operator had to wait for preparing logs, it was put in this category. In unloading, when two trucks simultaneously were arriving and needed to be unloaded belongs to this kind of delay.

2.6 Data analysis

2.6.1 Time study analysis and calculation of productivity

Total effective time (without interruptions longer than 15 minutes) in all work phases in the short-log and long-log method were recorded and mean log volume per cycle were calculated and included in the Equation (6), yielding productivity per hour in each work phase. Volume of each log was calculated using Smalian's formula by multiplying the average cross-sectional area of the stem by the stem length [Eq. 5]. The average cross-sectional area is based on diameter measurements, including bark, made at both ends of the log.

$$x_{vl} = \left(\frac{g_1 + g_2}{2} l \right) \qquad (5)$$

Total effective time was converted into delay-free productivity and gross-effective productivity by using the formula below:

$$p_e = \frac{60 x_{vl}}{\mathrm{t}_{\mathrm{tot}}} \qquad (6)$$

$$p_{ge} = \frac{60 x_{vl}}{t_{tot} + t_{delay}} \qquad (7)$$

Where x_{vl} = log volume, m^3;
g_1 and g_2 = basal area at each end of log, m^2;
l = log length, m;
p_e = productivity, m^3/effctive hour;
p_{ge}= gross-effective productivity, m^3/gross-effective hour;
t_{tot}= total time consumption, min/cycle;
t_{delay} = delay times, min/cycle.

2.6.2 Modeling

In the work study, the most common method for modeling and analyzing is multivariate regression. The variables applied are qualitative and quantitative requiring careful interpretation. With different types of models, including descriptive models, mechanical models, pattern recognition models, Bayesian probability models, and multivariate statistical models, the relation between dependent and independent variables can be explained (Nikoy Seyahkal 2007).

In the study, multivariate regression was used for modeling. Two different techniques were utilized to create a model for the time consumption. Firstly, a delay-free time consumption model was formed separately for each element of the work phase. Regression analysis with appropriate transformation of variable was used in those elements, in which the time consumption can be explained by an independent variable, for example, diameter. Other elements of the model were formed by using average time consumption value (Nurminen et al. 2006). The time consumption model was created by combining the elements. According to the objective of the study, this technique made it possible to connect time consumption characteristics to a certain element of work phase and examines them in more detail.

Using the overall time consumption model, total effective time in each cycle was calculated. Subsequently regression analysis, with variable transformation, was used for modeling each work phase. With this technique, a regression model was formed to estimate the total time consumption of the work cycle directly as a function of the most influential factor(s) (e.g. diameter). Generally, overall time consumption model has been used in several studies in Iran (Feghhi 1989, Eghtesadi 1991, Pilevar 1996, Naghdi 1996, Naghdi 2005, Javadpour 2006, Nikoy Seyahkal 2007).

2.6.3 Statistical analysis

SPSS 14.0 and Minitab15.0 for Windows were used as the statistical packages for the data analysis. As statistical parameters used for selecting the best-fit model the P-value, F-value, and R^2 were chosen. The F-value and the P-value are statistical measures used to determine the amount of influence that an independent variable has on the dependent variable. The P-value represents the level of significance of the statistical test (Ott 1993). The P-value can be set at different alpha levels depending on how precise the results need to be, for this study alpha was set at 0.05. The F-value is the t-value squared (t^2). The greater the F-value, of the independent variables, the more influence the variable has on the dependent variable. The R^2 value is a reflection of the validity of the model and is used mostly for validation of the model but a high value of R^2 does not guarantee that the model fits the data well. To test the co-significance of coefficient, an F-test and t-test was applied. The null hypotheses were rejected if the test results indicated p-values larger than 0.05 that the null hypotheses were not true and the differences in the time consumption resulted only from random variation (Nurminen et al. 2006, Pallant 2001). Stepwise was applied over enter, forward and backward selection because it has no requirements regarding data size and has the ability to recheck the t-values corresponding to the independent variables that were previously entered in the regression equation (Mendenhall and Sincich 1996).

Different statistical tools were applied to test the validity of the models. The primary tool for most process modeling application is graphical residual analysis. Different types of plots of the residuals from a fitted model provide information on the accuracy of different aspects of model. Another technique was using confidence interval of model which was produced as the SPSS output. In this technique, two cycles of observation were set aside for modeling randomly. The data are used later for testing procedure. It was also checked if the observed cumulative probability versus predicted cumulative probability is near centre line.

The analysis of covariance was performed using Minitab ANCOVA calculation by selecting general linear model.

2.7 Cost calculation

2.7.1 Data collection for calculating machine cost

The operation cost of each machine was based on fixed cost and variable cost. System cost is calculated by totaling machine cost and labor cost. For calculation of cost, instruction prepared for harvesting planning by Iranian forest organization was used (Instruction for…1999). Cost calculations were based on the assumption that the machine operator works the whole year except the rainy season when the logging area is not accessible. Felling is considered to total 40 days, processing 150 days, skidding 150 days, loading, hauling and unloading 275 days are considered. Processing and skidding are related to primary transportation and are mostly performed simultaneously. Loading, hauling and unloading are related to secondary transportation, and can be done even when skidding and processing are not performed. Table 3 shows the average number of working hours on different machines in the procurement of wood in Iran. Working hours of machines and workers are different. If the work-time exceeds 8 hours overtime has to be paid. Usually workers stay if required and are paid overtime by company.

The machine costs are calculated when the machine is being used. In order to calculate cost, it is needed to know how many hours it is working and how many hours it is planned (scheduled) to work. According to the information provided, the monthly salaries of the truck drivers, machine operators (skidder, bulldozer and loader) and their assistants are more or less the same. Prices of the chain saw and other equipment in 2006 provide the basis of this calculation. Personal costs included all costs related to worker, fringe benefits and some bonus and rewards. Productive Machine Hour (PMH) and Scheduled Machine Hour (SMH) for the chain saw are considered to be 900 hours and 1200 hours, respectively, so that the utilization of the chain saw is 75 %. Salvage values for chain saw and skidder was considered to be 10 %, 25 % for the loader, and 40 % for the truck, of the purchase price (Hedin 1980, Naghdi 2005).

Table 3. Summary of detailed machine cost calculation parameters (prices are for summer 2006).

Work phase Cost factors	Felling (chain saw)	Processing (chain saw)	Skidding (skidder)	Loading (loader)	Hauling (truck)	Unloading (loader)
Purchase price, US$ *	1045	1045	270270	130000	97000	130000
Salvage value, US$	104.5	104.5	27027	32500	38800	32500
Economic life, years	4	4	10	5	5	5
Chain life, hours	240	240	………	………..	………	……..
Tire life, hours	……..	………	4000	4000	2000	4000
Tire price, US$	…….	………	1950	720	270	720
Number of tires	……..	………..	4	4	10	4
Fuel cost, US$/hour	0.5	0.5	4.2	2.1	1.6	2.1
Repair factor, f	0.6	0.6	0.9	0.9	0.9	0.9
SMH, hours	320	880	1200	2200	1650	2200
PMH, hours	160	740	900	1375	2200	1650
Utilization, % Ut = (PMH×100 / SMH)	75.0	75.0	75.0	62.5	75.0	75.0

* According to the information gathered in this study, the purchase price of the two trucks was nearly the same.

2.7.2 Fixed costs

Fixed costs are constant over a definite period and thus independent of the level of activities or utilization. They include depreciation of purchase price, interest expenses as well as insurance costs.

Interest (annual average)

Interest is charges for the use of credit or money or fees paid on borrowed assets. Capital tied in logging equipment imposes costs to the company which depend on the rate of interest. Interest is calculated as follows (Naghdi 2005):

$$A = \frac{(P-S)(N+1)}{2N} + S \tag{8}$$

$$I = A \times i \tag{9}$$

Where P = purchase price, US$;
A = annual investment, US$;
S = salvage value, US$;
N= economic life, year;
I = interest, US$;
i = interest rate =15%.

Depreciation

Depreciation is reduction in the value of fixed or capital assets, as a result of use, damage, weathering, or obsolescence, and abandonment. It can be estimated according to a number of methods; the straight-line method, sum of digit depreciation, and diminishing balance depreciation (Sundberg 1988). The following formula shows the calculation of depreciation (Naghdi 2005):

$$D = \frac{(P - S)}{N} \tag{10}$$

Where D = deprecation, US$.

Insurance

Insurance is a form of risk reduction which is primarily used to insure against the risk of possible loss. Insurance is calculated as below (Naghdi 1996, Naghdi 2005):

$$T = (D+I) \times 10\% \tag{11}$$

Total fixed cost

The total fixed cost is the sum of the interest, depreciation, and insurance. Since the total fixed is calculated annually it needed to be converted per hour. The total fixed cost was 31, 67, 67, and 62 % of the total machine cost for the chain saw, skidder, loader, and truck, respectively.

$$TFC = I + D + T \tag{12}$$

TFC (hour) = TFC/PMH

Where TFC = total fixed cost; US$/hour;
PMH = productive machine hour.

2.7.3 Variable costs

Variable costs depend on the level of activities or utilization. The costs of fuel, lubricants, service, maintenance, repair, chain, and tires are variable costs.

Maintenance and repair cost

The ultimate measure of the reliability of equipment is the cost to maintain it. Maintenance cost typically includes the cost of labor and parts to perform repairs. Maintenance cost is calculated as a coefficient of depreciation. Maintenance cost is calculated by following formula (Naghdi 1996, Naghdi 2005):

$$MR = \frac{P - S}{N \times PMH} \times f \qquad (13)$$

Where MR= maintenance cost, US$;
f = repair factor.

Oil and fuel cost

Fuel and oil cost (FLC) is the cost of fuel and oil consumption for lubricating fluids and powering the machines. Fuel costs depend on the real consumption of fuel and it is highly dependent on the engine power and the utilization of the forestry machine. Overall, 15 % of fuel cost is considered as an oil cost.

Chain cost

Chain cost refers to replacing the chain of the chain saw. In the Iranian condition with hard wood trees the chain life is approximately 240 hours.

$$CC = \frac{CP}{CL} \qquad (14)$$

Where CC = chain cost, UD$/hour;
CP = chain price, US$;
CL = chain life, hours.

Tires

Tire cost is the cost of replacing the tire with new one. The tire cost compromise 2.4, 2.2, and 6.1 % of the total machine cost in the skidder, loader, and truck, respectively. Tire cost is calculated using formula (Naghdi 2005):

$$TC = \frac{(PT \times NT)(1 + i)}{N(hours)} \qquad (15)$$

Where TC = tire cost, US$/hour;
PT = tire price, US$;
NT = number of tires;
N= 4000 hours.

Total variable cost

The total variable cost is the sum of maintenance cost, fuel and lubrication cost, chain cost (in the chain saw), and tires cost (in the skidder, loader, truck). The ratio between total variable cost and total machine cost was 69, 33, 33, and 38 % in the chain saw, skidder, loader, and truck, respectively.

$$TVC = MR + FLC + CC + TC \qquad (16)$$

Where TVC = total variable cost, US$.

2.7.4 Labor cost

Labor cost for each work phase depends on the number of persons that are involved in each phase and salary of each worker and the length of time they are hired to do the work. In Iran, almost all workers in the company are paid monthly. Hourly cost derives from monthly salary divided by annual production hours.

$$LC = N_W \times S_W \times T \quad (17)$$

Where LC = labor cost, US$/hour;
N_W = number of workers;
S_W = salary of worker, US$/hour;
T = time hired, hours.

2.7.5 Unit cost

Unit cost of production in different work phases was calculated by dividing the system cost by the average productivity per hour. System cost is a sum of machine and labor costs. Machine cost is obtained by totaling fixed costs and variable costs. Table 4 shows the summary of costs that was calculated for chain saw, skidder, loader, and truck. Because of using the same chain saw in the processing and felling, the cost of chain saw was calculated for both felling and bucking as the same. All costs are reported for productive machine hours.

$$\text{Unit cost (US\$/m}^3\text{)} = \frac{System\cos t(US\$/hour)}{Av.productvity(m3/hour)} \quad (18)$$

Table 4. Operation costs of different machines in wood procurement. The percentage of hourly cost in the different work phases are shown in brackets.

Cost	Work phase					
	Felling (chain saw)	Processing (chain saw)	Skidding (skidder)	Loading (loader)	Hauling (truck)	Unloading (loader)
Total fixed cost, US$/PMH	0.41	0.41	59.20	26.52	15.13	22.10
Total variable cost, US$/PMH	0.92	0.92	30.70	12.89	9.33	12.89
Total machine cost, US$/PMH	1.33	1.33	89.90	39.41	24.50	34.99
Total labor cost, US$/hour	12.80	6.40	9.64	9.60	6.45	6.40
System cost, US$/PMH	14.13 [5.8%]	7.73 [3.2%]	99.54 [41.0%]	49.01 [20.2%]	30.95 [12.7%]	41.39 [17.1%]

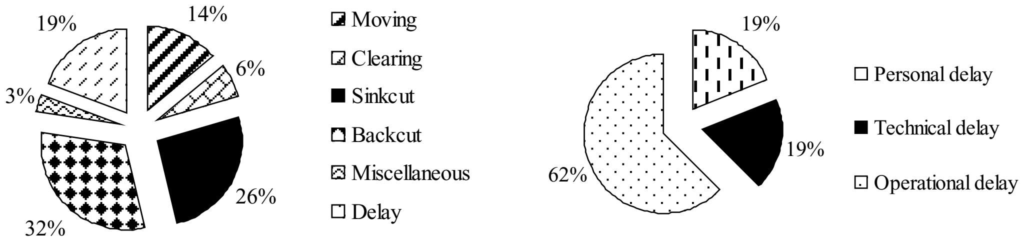
3 RESULTS

3.1 Time consumption and productivity

3.1.1 Felling

Distribution of time consumption of felling

The time consumption distribution of the felling work phase is shown in Figure 9a. Back-cut is the most time-consuming element in felling, followed by sink-cut and delay time. The breakdown of the different types of delay is shown in Figure 9b. Operational delay is the most time-consuming delay time in felling.



a

b

Figure 9. Distribution of time consumption in manual felling (a) and delays (b).

Figure 10 shows the time consumption of felling and total time consumption of felling with different diameters. Average felling time includes only sink-cut, back-cut, while total time consumption of felling includes time consumption of all felling elements. Time consumption of felling increases with increasing diameter. The relation between stump diameter and time consumption (without delay) constitutes an exponential model and these variables were highly correlated (for more detail see Appendix 1).

A statistical analysis showed that the influence of the tree species on the productivity was not significant in this study (F = 2.28, P = 0.083).

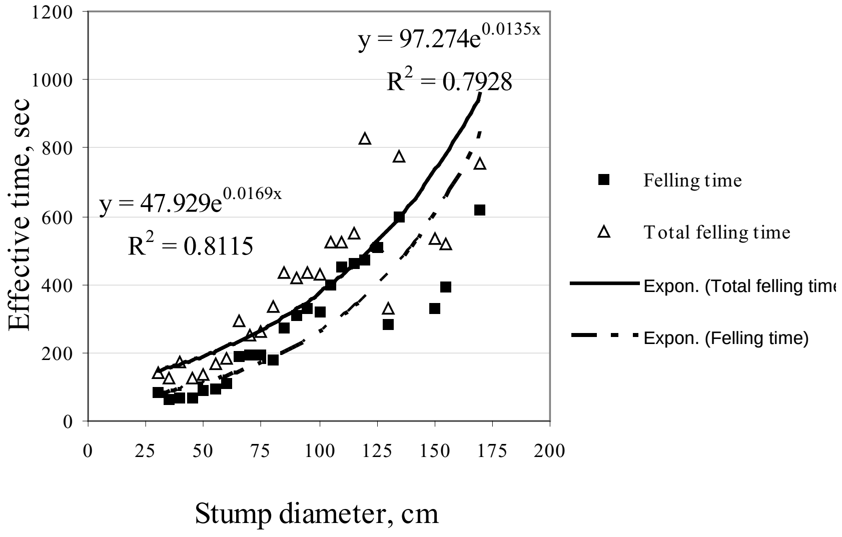


Figure 10. Time consumption of felling for different stump diameters.

Table 5 shows the descriptive statistics of different elements of felling. The average time consumption of clearing and miscellaneous time is used for constructing total time consumption model. All data in the table is rounded to the nearest representative value. According to the results, average time consumption to perform one cycle, without delays, of felling work phase took 310 seconds; therefore an average of 11.5 trees per hour can be felled. The average time consumption and standard deviation of back-cut is the highest among the felling elements. The maximum time consumption for the back-cut was 5.4 times higher than the average time that shows the back-cut can be very time consuming element.

Table 5. Average, minimum, maximum, and standard deviation of different elements of felling.

Element	Parameter	Mean, sec	Min., sec	Max., sec	Std. dev.	N
Walking	t_{f1}	53	5	227	40	142
Clearing	t_{f2}	25	2	84	11	142
Sink-cut	t_{sc}	100	9	422	73	142
Back-cut	t_{bc}	119	6	641	118	142
Miscellaneous	t_{f4}	13	0	205	36	142

Time consumption for the felling elements

The felling work phase includes elements such as walking, clearing, felling (cutting), miscellaneous time, and delay. The models are presented here for walking, felling, sink-cut, and back-cut to estimate the effective time consumption as a function of independent variables.

1) Walking

Walking means the time spent approaching the tree to be felled. Time consumption for walking greatly depends on distance and slightly on slope and was defined in linear regression analysis [Eq.19].

$$t_{f1} = -6.820 + 1.321x_{f\,d} + 0.854x_{ls} \qquad (19)$$

Where t_{f1} = time consumption for walking, sec;
x_{fd} = distance between two trees to be felled, m;
x_{ls}= longitudinal slope, percent.

2) Clearing

The time consumption for clearing (t_{f2}) was calculated as a mean value. However, the density of the understory, slope, and weather conditions might influence the clearing time, however, it was not revealed in the study. The mean clearing time was 24.7 sec/tree.

3) Felling

The time consumption for felling highly depends on the stump diameter [Eq. 20]. Felling element was divided into two sub-elements such as sink-cut and back-cut which was influenced by the stump diameter of the trees [Eq. 21, Eq. 22]. In this study, average stump diameter of all sample trees was 75 cm.

Felling $$t_{f3} = -85.165 + 3.831x_d \qquad [x_d \geq 25 \text{ cm}] \qquad (20)$$

Sink-cut $$t_{sc} = -21.247 + 1.545x_d \qquad [x_d \geq 14 \text{ cm}] \qquad (21)$$

Back-cut $$t_{bc} = -64.871 + 2.302x_d \qquad [x_d \geq 28 \text{ cm}] \qquad (22)$$

Where t_{f3} = time consumption of felling, sec /stem;
t_{sc} = time consumption of sink-cut, sec /stem;
t_{bc} = time consumption of back-cut, sec /stem;
x_d = stump diameter, cm.

4) Miscellaneous time

Miscellaneous time (t_{f4}) was calculated as a mean value. The mean of miscellaneous time was 13.0 seconds/tree.

5) Delay time

Manual felling delay was observed during the study. Delay was usually due to the maintenance of the saw and included lubrication and sharpening of the chain when it was dull. Delay time in felling is calculated as an average and the mean value of delay times in felling was 61.6 seconds/tree.

Total time consumption model of felling

The total time consumption model of a delay free work cycle was defined by totaling the time consumption of the elements [Eq. 23].

$$t_f = t_{f1} + t_{f2} + t_{f3} + t_{f4} \tag{23}$$

Where t_f = total effective time consumption for felling, sec/stem;
t_{f1} = time consumption for walking, sec/stem;
t_{f2} = time consumption for clearing, sec/stem;
t_{f3} = time consumption for felling, sec/stem;
t_{f4} = miscellaneous times, sec/stem.

Overall time consumption and productivity model of felling

The models are presented here in order to estimate time consumption and productivity of felling as a function of independent variables [Eq. 24, Eq. 25].

$$t_{of} = -60.130 + 3.932x_d + 1.764x_{fd} \tag{24}$$

$$P_{ef} = -0.767 + 1.625x_d - 0.564x_{fd} \tag{25}$$

Where t_{of} = overall time consumption model of felling, sec/stem;
P_{ef} = productivity of felling, m^3/effective hour.

Table 6 shows the statistical analysis of the partial and overall time consumption and productivity models. F-value and P-value shows that the presented models are statistically significant.

Table 6. Statistical characteristics of the models based on regression analysis.

Model	Dependent variable	R^2	F-test		N	Term	Constant/ coefficient	Estimated std. error	t-test	
			F-value	P					t-value	p
Walking	t_{f1}	0.84	266.9	<0.001	103	Constant	-6.820	3.946	-1.728	0.087
						x_{fd}	1.321	0.057	22.998	<0.001
						x_{ls}	0.854	0.150	5.701	<0.001
Sink-cut	t_{sc}	0.59	196.9	<0.001	138	Constant	-21.247	8.831	-2.406	0.017
						x_d	1.545	0.110	14.035	<0.001
Back- cut	t_{bc}	0.57	179.3	<0.001	137	Constant	-64.871	13.698	-4.736	<0.001
						x_d	2.302	0.172	13.389	<0.001
Felling	t_{f3}	0.62	222.0	<0.001	137	Constant	-85.165	20.477	-4.159	<0.001
						x_d	3.831	0.257	14.906	<0.001
Overall	t_{of}	0.66	131.6	<0.001	135	Constant	-60.130	22.986	-2.616	0.010
						x_d	3.932	0.301	13.049	<0.001
						x_{fd}	1.764	0.343	5.148	<0.001
Productivity	P_{ef}	0.57	137.0	<0.001	140	Constant	-0.767	9.288	-0.083	0.934
						x_d	1.625	0.119	13.595	<0.001
						x_{fd}	-0.564	0.138	-4.076	<0.001

Figure 11 shows the graphical statistical measure in order to check the validity of the models. In normal probability plot, plots are laid in a reasonably straight diagonal line from bottom left to top right (Figure 11a). The figure shows no major deviation from normality. Figure 11b shows the scatter plot of the standardized residuals. In the figure, distributions are rectangular with most concentration occurring in the center.

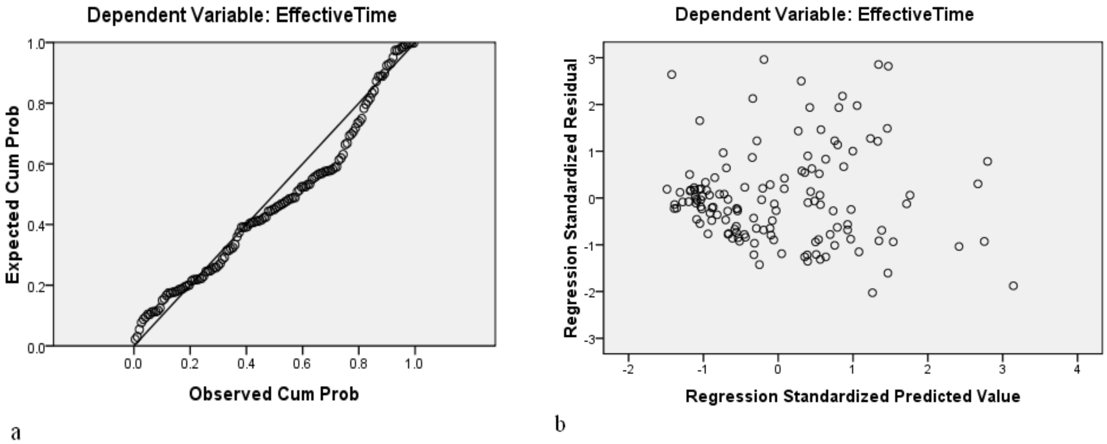


Figure 11. Normal P-P plot of regression standardized residual (a) and scatter plot of standardized residual and predicted value (b).

Figure 12 shows the delay free productivity of felling in different distances and diameters. The highest productivity occurs when the diameter is high (100 cm) and distance between two trees to be felled (inter-tree distance) is short (10 m). The figure is drawn from Eq. 25.

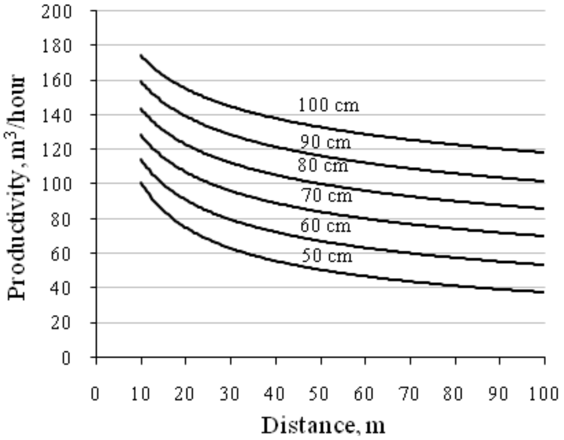


Figure 12. Productivity of felling as a function of felling distance for different stump diameters.

3.1.2 Processing

Distribution of time consumption

Average, minimum, and maximum time of processing elements as a proportion of total gross-effective time was calculated for the short-log and long-log method. In order to calculate this, the value of each element in each cycle was divided by the total gross-effective time. The average, in addition to the ranges, of all cycles is given in Table 7. Delimbing and topping was the most time consuming element of processing, followed by bucking.

Table 7. Average time elements of processing as a proportion of gross-effective time. The range of time proportions is shown in brackets.

Processing element	Short-log, %	Long-log, %
Walking	10.1 [2-34]	13.3 [2-38]
Clearing	10.2 [0-34]	11.2 [0-41]
Measuring	10.2 [4-27]	8.0 [3-12]
Delimbing and topping	26.4 [9-53]	31.2 [11-63]
Bucking in the forest	26.3 [8-44]	7.4 [0-21]
Bucking in the landing		12 .0 [5-43]
Miscellaneous time	3.0 [0-16]	3.6 [0-42]
Delay time	13.8 [0-55]	13.2 [0-43]
Total	100	100

Table 8 shows the detailed time study results for the processing work phase for the methods applied. The mean values of different elements of processing were used in constructing the total time consumption model for the elements which did not depend on any variables such as clearing, measuring and miscellaneous times. The difference between maximum and minimum time consumption of bucking, delimbing and topping was considerable. The main reason for such a difference may be related to different diameters of the felled trees.

Table 8. Descriptive statistics of different element of processing work phase.

Element	Method	Parameter, sec	Mean, sec/stem	Min., sec/stem	Max., sec/stem	Std. dev.	N
Walking	Short-log	t_{P1}	55	13	122	26	52
	Long-log		55	5	122	27	54
Clearing	Short-log	t_{P2}	68	0	235	63	52
	Long-log		44	0	131	27	54
Delimbing and topping	Short-log	t_{P3}	170	22	324	84	52
	Long-log		155	21	428	96	54
Measuring	Short-log	t_{P4}	63	15	187	37	52
	Long-log		37	0	123	29	54
Cross-cutting	Short-log	t_{P5}	178	15	471	108	52
	Long-log		107	14	514	110	54
Miscellaneous	Short-log	t_{P6}	15	0	108	29	52
	Long-log		13	0	112	31	54

The total time consumption and productivity of processing for both of the methods are presented in Table 9. The average time consumption of processing in the short-log method was higher than in the long-log method by 21 %. The total time consumption of processing increased when tree size increased for both methods. According to the information provided in Table 9, when the diameter of trees increased from 50 cm to 100 cm, time consumption of processing increased 3.4 and 4.5 times in the short-log and long log method, respectively. The productivity of tree processing is also greatly influenced by the diameter of the tree. When tree diameter changed from 50 cm to 100 cm, productivity increased by 54 % in the short-log method and 62 % in the long-log method. Time consumption needed to perform one cross-cut is presented in Appendix 2. The relation between one cross-cut at a specific diameter constituted an exponential model with a high correlation. Time consumption of bucking of different diameters is presented and compared in Appendix 3. The relationship between diameter at the butt and time consumption of bucking element was used to develop the power model. The time consumption of bucking large diameter trees was much higher than small diameter ones. In the short-log method, time consumption was higher than in the long-log method.

Table 9. Time consumption and productivity of processing in the short-log and long-log method. The percentages of the observation are in the brackets.

Diameter, cm	<50	50	55	60	65	70	75	80	85	90	95	100	>100
Short-log method													
Avg. processing time, sec	184	276	394	397	451	556	609	629	702	724	905	926	1096
Min. processing time, sec	122	227	300	278	269	496	489	521	418	688	-	875	982
Max. processing time, sec	287	349	463	484	616	650	805	807	924	758	-	978	1209
Avg. volume processed, m^3	0.94	1.87	2.65	3.01	3.50	4.58	6.17	5.79	7.04	7.55	9.45	10.01	12.08
Min. volume processed, m^3	0.69	1.71	2.21	2.56	3.10	4.11	4.91	5.34	6.39	6.80	-	9.04	12.05
Max. volume processed, m^3	1.08	2.10	3.22	3. 40	4.10	5.13	6.60	7.20	8.47	8.50	-	10.99	12.60
Avg. productivity, m^3/hour	21.2	25.6	25.8	28.2	29.7	30.0	32.4	34.3	42.4	37.5	37.6	39.6	41.0
Min. productivity, m^3/hour	8.7	17.6	17.2	22.1	19.8	24.2	23.0	23.8	24.9	35.2	-	37.2	35.9
Max. productivity, m^3/hour	31.9	33.3	38.6	40.7	47.2	36.4	44.6	48.2	72.9	40.4	-	42.0	46.2
Number of observations	4 [8%]	3 [6%]	3 [6%]	6 [12%]	7 [13%]	4 [8%]	6 [12%]	7 [13%]	3 [6%]	4 [8%]	1 [2%]	2 [4%]	2 [4%]
Long-log method													
Avg. processing time, sec	175	226	321	311	359	489	529	582	649	546	-	1037	946
Min. processing time, sec	127	181	280	241	316	333	423	394	569	391	-	-	894
Max. processing time, sec	263	314	401	472	391	637	748	645	729	663	-	-	998
Avg. volume processed, m^3	0.76	1.63	2.36	2.98	3.53	4.99	6.27	7.05	7.93	8.25	-	12.01	12.00
Min. volume processed, m^3	0.46	1.14	1.14	2.21	2.62	4.11	5.89	6.23	7.27	7.47	-	-	12.33
Max. volume processed, m^3	1.03	1.92	2.65	3.27	4.04	5.33	6.95	7.24	8.59	9.58	-	-	11.31
Avg. productivity, m^3/hour	16.1	25.7	27.5	35.7	35.7	38.6	44.7	44.9	45.1	57.5	-	41.7	45.2
Min. productivity, m^3/hour	9.7	16.0	15.4	23.1	26.4	27.6	29.1	35.2	35.9	44.2	-	-	40.8
Max. productivity, m^3/hour	22.2	29.2	32.6	42.3	46.0	57.3	58.4	60.1	54.3	88.2	-	-	49.6
Number of observations	9 [17%]	4 [7%]	7 [7%]	9 [17%]	4 [7%]	5 [9%]	5 [9%]	5 [9%]	2 [4%]	4 [7%]	-	1 [2%]	2 [4%]

Figure 13 shows the productivity of bucking as a function of volume. Productivity increases with increased tree size in both methods. The relation between the productivity and volume of the tree constituted a power model. The productivity was higher in the short-log method than that of the long-log method. The analysis of covariance (ANCOVA) was performed in order to determine whether there is a difference between the two methods in productivity, independent of any volume differences between the methods that may exist. The P-value indicated that there is strong evidence of a difference between productivity of the short-log and long-log method, even after adjusting for volume (F = 8.21, P-value = 0.005). The P-value associated with volume showed that volume is related to productivity and need to be take into account (F = 67.5, P-value < 0.001).

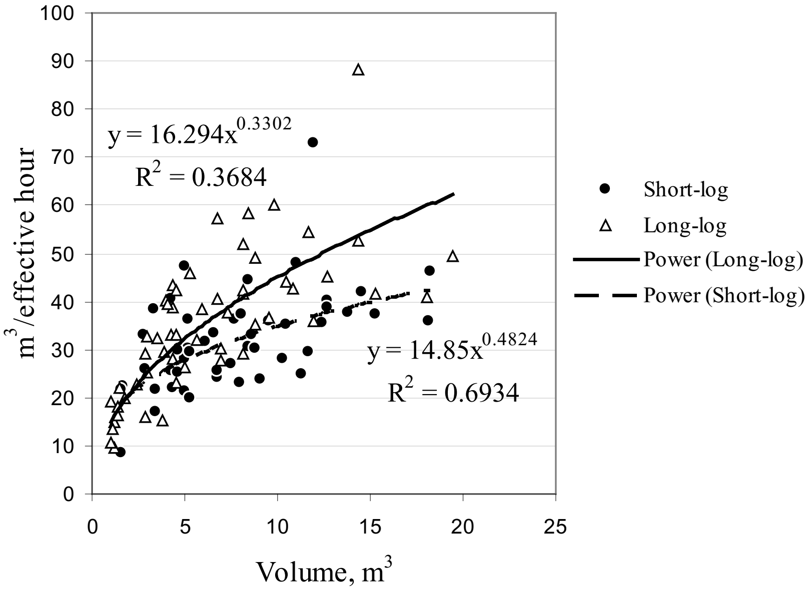


Figure 13. Productivity of processing as a function of volume in short-log and long-log method.

Time consumption models for processing elements:

The time consumption without delays, of walking, cross-cutting, delimbing and topping were modeled as a function of independent variables. Average time consumption is presented for other processing elements. Statistical analysis of these partial and overall models is presented in Table 10.

1) Walking

Time consumption for walking greatly depends on the distance between the two trees to be processed and the longitudinal slope, and was defined in linear regression analysis [Eq. 26]. The model can be used for both methods.

$$t_{P1} = -0.33 + 1.197x_{pd} + 0.676x_{ls} \tag{26}$$

Where t_{p1} = time consumption for walking, sec;
x_{pd} = distance between two trees to be processed, m.

2) Clearing

The time consumption for clearing (t_{P2}) was calculated as a mean value: 68 seconds/stem for the short-log method and 44 seconds/stem for the long-log method.

3) Delimbing and topping

The time consumption for delimbing depended highly on the diameter at the butt of the cut tree [Eq. 27]. All stems with a diameter greater than 20 cm were delimbed.

$$t_{P3} = -63.58 + 3.308x_{db} \qquad [x_{db} \geq 20 \text{ cm}] \tag{27}$$

Where t_{p3} = time consumption for delimbing and topping, sec;
x_{db} = butt diameter of the cut tree, cm.

4) Measuring

Time consumption for measuring was calculated as a mean value: 62 seconds/stem for the short-log and 37 seconds/stem for the long-log method. The time consumption of measuring in the long log method was totaled with measuring time at the landing. Time consumption of measuring was not related to any variable(s), however, it may be influenced by the trees' height and ground condition (topography and under growth tree cover); though this is not proved in this study.

5) Bucking

The time consumption for bucking in the short-log and long-log method (t_{P5}) greatly depends on the tree height and volume [Eq. 28, Eq. 29].

$$\text{Short-log} \qquad t_{p5} = 135.93 + 29.98x_v - 5.35x_h \tag{28}$$

$$\text{Long-log} \qquad t_{p5} = 229.72 + 33.868x_v - 10.439x_h \tag{29}$$

Where t_{p5} = time consumption for bucking, sec/stem;
x_h = tree height, m;
x_v = tree volume, m^3.

6) Miscellaneous times

Miscellaneous times (t_{p6}) were calculated as the mean value. The mean value was 15.3 and 13.1 seconds per tree in the short-log and long-log method, respectively.

7) Delay time

Time consumption for delays was calculated as a mean time consumption value in both methods. In the short-log method, it was 13 seconds for personal, 63 seconds for technical, and 21 seconds for operational delay. In the long-log method, it was 12 seconds for personal, 36 seconds for technical, and 22 seconds for operational delay (Figure 14).

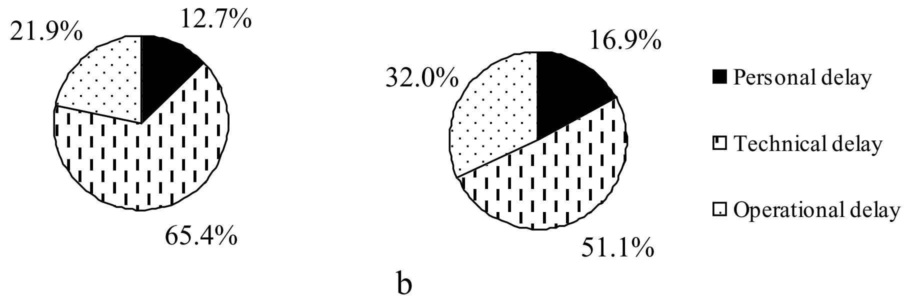


Figure 14. Time distribution of delay in the processing work phase in the short-log (a) and long-log (b) method.

Total time consumption model of processing

The total time consumption model of a delay free work cycle was determined by totaling the time consumption for all elements.

$$t_p = t_{p1} + t_{p2} + t_{p3} + t_{p4} + t_{p5} + t_{p6} \tag{30}$$

Where t_p = total effective time consumption for processing, sec/stem;
t_{p1}= time consumption for walking, sec/stem;
t_{p2} = time consumption for clearing, sec/stem;
t_{p3} = time consumption for delimbing and topping, sec/stem;
t_{p4}= time consumption for measuring, sec/stem;
t_{p5} = time consumption for bucking, sec/stem;
t_{p6} = Miscellaneous times, sec/stem.

Overall time consumption and productivity models of processing

The models are presented here in order to estimate time consumption and productivity of processing as a function of independent variables for both methods [Eq. 31 - Eq. 34]. In the short-log method, the average butt diameter of the trees was 72 cm, the average tree height was 34.3 m, and the average volume per stem was 7.50 m^3. In the long-log method, the average butt diameter of the trees was 65 cm, the average trees height was 33.0 m, and the average volume per stem was 6.47 m^3.

Short-log

$$t_{ops} = 179.658 + 49.024 x_v \tag{31}$$

$$p_{eps} = 22.088 + 1.275 x_v \tag{32}$$

Long-log

$$t_{opl} = -235.690 + 9.925 x_{db} \quad [x_{db} \geq 24 \text{ cm}] \tag{33}$$

$$p_{epl} = -23.413 + 1.794 x_h \quad [x_h \geq 12 \text{ m}] \tag{34}$$

Where t_{ops}= overall time consumption of processing in the short-log method, sec/stem;
t_{opl} = overall time consumption of processing in the long-log method, sec/stem;
p_{eps} = productivity of processing in the short-log method, m^3/effective hour;
p_{epl} = productivity of processing in the long-log method, m^3/effective hour.

The statistical characteristic of regression models of skidding elements are presented in Table 10. F-value and P-value shows that the presented models are statistically significant.

Table 10. Statistical characteristics of regression models for the processing elements (SLM = short-log method, LLM = long-log method, BM = both of the methods).

Model	Dependent variable	R^2	F-test		N	Term	Constant/ coefficient	Estimated std. error	t-test	
			F-value	P					t-value	P
Walking (BM)	t_{p1}	0.81	219.4	<0.001	105	Constant x_{Pd} x_{ls}	-0.33 1.197 0.676	3.951 0.058 0.154	-0.008 20.720 4.379	0.993 <0.001 <0.001
Bucking (SLM)	t_{p5}	0.89	206.49	<0.001	52	Constant x_v x_h	135.933 29.988 -5.35	59.382 2.854 2.279	2.289 10.507 -2.347	0.026 <0.001 0.023
Bucking (LLM)	t_{p5}	0.83	136	<0.001	54	Constant x_v x_h	229.722 33.868 -10.439	50.017 2.720 1.958	4.593 12.451 -5.331	<0.001 <0.001 <0.001
Delimbing and topping (BM)	t_{p3}	0.46	90.19	<0.001	106	Constant x_{db}	-63.580 3.308	24.594 0.348	-2.585 9.497	0.011 <0.001
Overall (SLM)	t_{ops}	0.79	195.65	<0.001	52	Constant x_{db}	179.658 49.024	30.191 3.505	5.951 13.988	<0.001 <0.001
Productivity (SLM)	p_{eps}	0.29	19.87	0.001	52	Constant x_v	22.088 1.275	2.465 0.286	8.962 4.458	<0.001 <0.001
Overall (LLM)	t_{opl}	0.76	166.09	<0.001	54	Constant x_{db}	-235.690 9.925	49.568 0.729	-4.755 13.613	<0.001 <0.001
Productivity (LLM)	p_{epl}	0.57	69.75	<0.001	54	constant x_h	-23.413 1.794	7.152 0.215	-3.273 8.352	0.002 <0.001

3.1.3 Skidding

Distribution of time consumption

Time consumption distribution of different elements of skidding are calculated and presented in Figure 15. In the short-log method travel unloaded took 24.8 % of the gross-effective time. This was the highest followed by travel loaded, winching, hooking, piling, releasing, delay, and unhooking. In the long-log method travel loaded was the most time consuming element, taking 30.7 % of the gross-effective time, followed by travel unloaded, piling, winching, hooking, delay, piling, and unhooking.

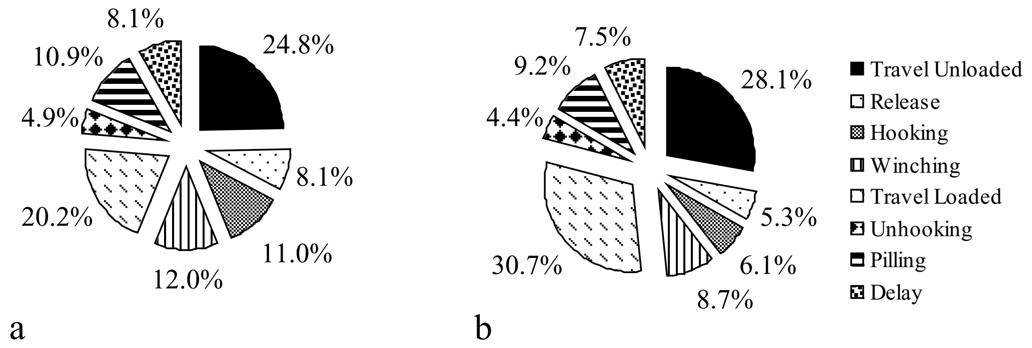


Figure 15. Time distribution of skidding elements in the short-log (a) and long-log (b) method.

Table 11 shows the time distribution between skidding elements among 192 observations. Travel loaded took approximately 28 % of the gross-effective time. This was the highest followed by travel unloaded, taking 26 % of the gross-effective time in the skidding operation. Time consumption in skidder roundtrip (travel loaded and travel unloaded) took 54 % of the gross-effective time. Other elements of skidding took 46 % of the gross-effective time.

Table 11. Time consumption distribution of skidding as a proportion of gross-effective time.

	Skidding element							
	Travel unloaded	Releasing	Hooking	Winching	Travel loaded	Unhooking	Piling	Delays
Avg. %	26.1	6.5	7.7	10.3	27.8	4.9	9.0	7.5
Min. %	5.5	0.7	0.7	1.7	5.4	0.9	0.1	0.0
Max. %	57.3	27.6	30.2	43.4	49.2	21.2	34.5	49.6

The time consumption of skidding was analyzed for both of the methods and is presented in table 12. In this table average, maximum and minimum time consumption and productivity of skidding with, and without, delay is shown. The average time consumption of skidding in the short-log method was 8 % less than in the long-log method while the average skidding productivity of the long-log method was 2.2 % higher than in the short-log method. The average volume skidded per cycle in the long-log method was 11.2 % higher than in the short-log method.

Table 12. Time consumption and productivity of skidding in the short-log and long-log method.

	Harvesting method			
	Short-log (log length <5.20 m)		Long-log (log length >7.80 m)	
	Effective time	Gross–effective time	Effective time	Gross–effective time
Avg. skidding time, min/cycle	15.30	16.65	16.65	18.35
Min. skidding time, min/cycle	6.14	7.39	7.55	7.64
Max. skidding time, min/cycle	23.32	33.59	37.9	40.31
Avg. volume skidded, m^3	2.77	2.77	3.08	3.08
Min. volume skidded, m^3	0.75	0.75	1.20	1.20
Max. volume skidded, m^3	6.17	6.17	6.14	6.14
Avg. productivity, m^3/hour	10.87	9.98	11.11	10.06
Min. productivity, m^3/hour	3.94	2.90	3.69	3.51
Max. productivity, m^3/hour	43.30	40.65	37.79	23.19
Number of observations	51	51	72	72

A summary of the skidding operation on the basis of log lengths is given in Table 13. The skidding productivity increased with increasing log length until the log length was 13 m. When the log length was between 13 and 15 m in length the productivity dropped if compared with the highest level (14 m^3/effective hour). The main reason for the drop in the skidding productivity in the skidding of longer logs might be related to the insufficient width of the skid trail. The skid trails were used in the previous silvicultural period and the skid trail width was the same for both of the methods. The time consumption of skidding increased 53 % when the length class changed from class 1 to class 6, while the productivity increased approximately 6 % when the length class changed from class 1 to class 6.

Table 13. Effect of log length on the time consumption and productivity (ET = effective hour, GT = gross-effective hour).

	Class 1		Class 2		Class 3		Class 4		Class 5		Class 6	
	2.6 - 5.20 m		7.8 - 10.4 m		10.4 - 13 m		13 - 15.6 m		15.6 - 18.2 m		18.2 - 20.8 m	
	ET	GT	ET	GT	ET	GT	ET	GT	ET	GT	ET	GT
Avg. skidding time, min/cycle	15.3	16.6	15.8	17.7	16.5	17.3	19.7	21.3	-	-	23.5	25.8
Min. skidding time, min/cycle	6.1	7.4	8.8	8.8	9.2	9.2	11.4	14.0	-	-	18.1	19.2
Max. skidding time, min/cycle	23.3	33.6	37.9	40.3	33.6	39.1	26.5	27.3	-	-	29.3	29.8
Avg. volume skidded, m^3	2.8	2.8	2.7	2.7	3.1	3.1	2.4	2.4	-	-	4.5	4.5
Min. volume skidded, m^3	0.7	0.8	1.2	1.2	1.2	1.2	1.2	1.2	-	-	2.9	2.9
Max. volume skidded, m^3	6.2	6.2	5.5	5.5	4.4	4.4	4.2	4.2	-	-	6.1	6.1
Avg. productivity, m^3/hour	10.9	10.0	10.7	9.6	14	13.3	10.1	9.3	-	-	11.5	10.5
Min. productivity, m^3/hour	3.9	2.9	3.7	3.5	3.4	3.4	5.5	4.5	-	-	7.6	6.1
Max. productivity, m^3/hour	43.3	40.6	37.8	23.2	23.1	23.1	20.8	18.1	-	-	13.1	12.3
Number of observations	51	51	53	53	9	9	6	6			4	4

Time consumption models for skidding elements

The models of skidding, presented here, are created for travel unloaded, releasing, hooking, winching, and travel loaded to estimate the effective time consumption of these elements as a function of independent variables. Average time consumption is presented for other skidding elements. Statistical analysis of these overall and partial models is presented in Table 15.

1) Travel unloaded

Time consumption for travel unloaded greatly depends on skidding distance. A linear regression model was constructed to estimate travel unloaded time as a function of skidding distance and slope. Maneuvering is part of travel unloaded. The average time consumption of maneuvering was 0.77 minute/cycle. When unloaded, the average travel speed was 5.7 km/hour.

$$t_{s1} = -2.635 + 0.013x_{sd} + 0.086x_{ls} \qquad (35)$$

Where t_{s1} = time consumption for travel unloaded, min;
x_{sd} = skidding distance, m.

2) Releasing (extension of cable)

Time consumption of releasing depended on the winching distance. The average speed of pulling the cable was 1.7 km/hour. Time consumption model for releasing time as a function of winching distance is presented below:

$$t_{s2} = -0.850 + 0.082x_{wd} \qquad [x_{wd} \geq 11 \text{ m}] \qquad (36)$$

Where t_{s2} = time consumption for releasing, min;
x_{wd} = winching distance, m.

3) Hooking

Time consumption for hooking slightly depended on the number of log in each cycle. Time consumption model for hooking has been constructed as a function of the number of logs.

$$t_{s3} = 0.163 + 0.772x_n \qquad (37)$$

Where t_{s3} = time consumption for hooking, min;
x_n = number of logs.

4) Winching

Time consumption for winching depended on the number of logs, winching distances, and log lengths in the short-log and long-log method in each cycle. The average speeds of winching were 0.72 and 0.69 km/hour in the short-log and long-log method, respectively. A time consumption model for winching has been constructed for both methods as a function as presented below:

$$\text{Short-log} \qquad t_{s4} = -1.084 + 0.704x_n + 0.070x_{wd} \qquad (38)$$

$$\text{Long-log} \qquad t_{s4} = -1.791 + 0.114x_{wd} + 0.120x_l \qquad (39)$$

Where t_{s4} = time consumption for winching, min;
x_l = logs length, m.

5) Travel loaded

Time consumption for travel loaded depended on the number of logs, skidding distance, and log lengths, in both the short-log and long-log method. The average skidder speed while traveling loaded was 0.46 and

0.37 km/hour in the short-log and long-log method, respectively. A time consumption model for travel loaded was constructed for the short-log and long-log method as below:

Short-log $$t_{s5} = -0.358 + 0.007x_{sd} + 0.408x_n \quad (40)$$

Long-log $$t_{s5} = -2.905 + 0.011x_{sd} + 0.279x_l \quad (41)$$

Where t_{s5} = time consumption for travel loaded, min.

6) Unhooking

Time consumption for unhooking was calculated as a mean time consumption value for both methods. Time consumption for unhooking was 45 seconds/cycle.

7) Piling

Time consumption for piling was calculated as a mean time consumption value for both of the methods. The time consumption for piling was 85 seconds/cycle.

8) Delay time

Time consumption for delays was calculated as a mean time consumption value for both of the methods. In the short-log method, time consumption for personnel, technical and operational delay was 8, 32, and 40 seconds per cycle, while in the long-log method; time consumption for personal, technical and operational delay was 14, 56, and 32 seconds per cycle, respectively (Figure 16).

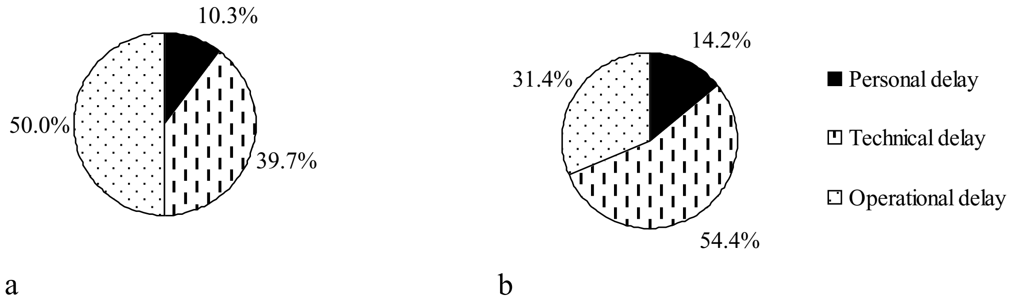


Figure 16. Time distribution of types of delay in the short-log (a) and long-log (b) method.

Total time consumption model

The total time consumption model of a delay free work cycle was determined by adding up the time consumption of all individual elements.

$$t_s = t_{s1} + t_{s2} + t_{s3} + t_{s_4} + t_{s_5} + t_{s_6} + t_{s_7} \quad (42)$$

Where t_{ess} = total effective time consumption for skidding, min/cycle;
t_{s1} = time consumption for travel unloaded, min/cycle;
t_{s2} = time consumption for releasing, min/cycle;
t_{s3} = time consumption for hooking, min/cycle;
t_{s4} = time consumption for winching, min/cycle;
t_{s5} = time consumption for travel loaded, min/cycle;
t_{s6} = time consumption for unhooking, min/cycle;
t_{s7} = time consumption for piling, min/cycle.

Table 14 shows the average time consumption values for unloading (t_{s6}) and piling (t_{s7}). The average value is applied for constructing a total time consumption model for elements that were not statistically proven to be related to any variables.

Table 14. Descriptive statistics of mean values based on work phase model.

Element	Parameter	Mean, min/cycle	Min., min/cycle	Max., Min/cycle	Std. dev.	N
Unhooking	t_{s6}	0.74	0.17	2.95	0.38	192
Piling	t_{s7}	1.42	1.81	14.25	0.91	192

Overall time consumption and productivity models

The overall time consumption and productivity models are presented in order to estimate time consumption and productivity of skidding as a function of independent variables in both methods [Eq. 43 - Eq. 46]. In the short-log method, the average number of logs was 2, the average skidding distances was 380 m, the average winching distance was 24 m, the average log length was 5.0 m, and the average volume was 2.77 m^3. In the long-log method the average number of logs was 1, the average skidding distance was 497 m, the average winching distance was 18 m, the average log length was 10.3 m, and the average volume was 3.08 m^3. By using the formula [Eq. 43, Eq. 45], the effect of skidding distance on time consumption of skidding was found to be a linear relationship and is shown in Appendix 6.

Short-log: $$t_{o\,s\,s} = 1.985 + 2.509x_n + 0.015x_{sd} + 0.081x_{wd} \quad (43)$$

$$p_{e\,s\,s} = 12.453 + 5.148x_{sv} - 2.904x_n - 0.014x_{sd} - 0.144x_{wd} \quad (44)$$

Long-log: $$t_{o\,sl} = -5.120 + 0.027x_{sd} + 0.198x_{wd} + 0.454x_l \quad (45)$$

$$p_{esl} = 13.681 + 3.775_{sv} - 0.017x_{sd} - 0.305x_l - 0.082x_{wd} \quad (46)$$

Where t_{oss} = overall time consumption of the short-log skidding, min;
t_{osl} = overall time consumption of the long-log skidding, min;
p_{ess}= productivity of the short-log skidding, m^3/effective hour;
p_{esl} = productivity of the long-log skidding, m^3/effective hour;
x_{sv} = volume skidded, m^3.

The effect of two of the most important variables in skidding (skidding distance and volume skidded) on its productivity is given in Figure 17. In both methods, productivity has an inverse relationship with skidding distance and direct relation with volume skidded; therefore the highest productivity was found when the skidding distance is short and volume skidded is high. The figure is based on the productivity model [Eq. 43, Eq. 45].

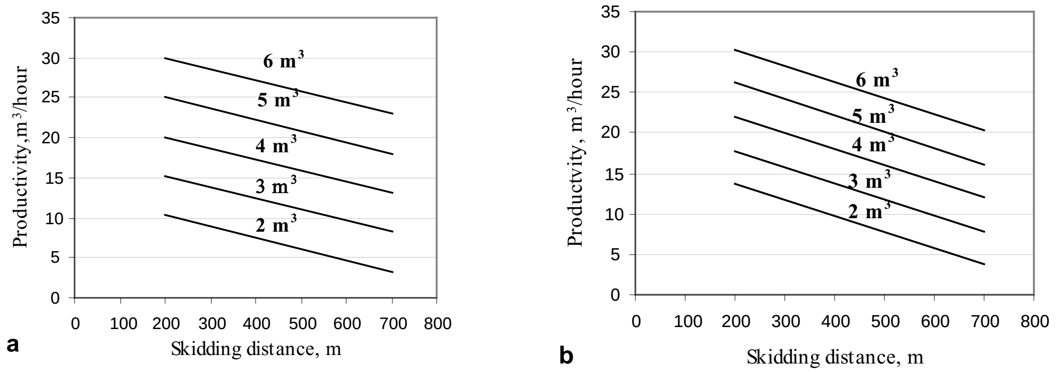


Figure 17. Productivity of skidding as a function of skidding distance for different volumes loaded in the short-log (a) and long-log (b) method.

The statistical characteristics of the regression models for skidding are presented in Table 15. F-value and P-value show the presented models are statistically significant. Overall time consumption models of skidding for both of the methods have also been checked with graphical statistical measures and it has been proved that the models are statistically significant (Appendices 4 and 5).

Table 15. Statistical characteristics of regression analysis based models (SLM = short-log method, LLM= long-log method, BM = both of the methods).

Model	Dependent variable	R^2	F-test		N	Term	Constant/ coefficient	Estimated std.error	t-test	
			F-value	P					t-value	p
Travel unloaded (BM)	t_{s1}	0.88	552.0	<0.001	191	Constant	-2.635	0.353	-7.465	<0.001
						x_{sd}	0.013	0.000	32.351	<0.001
						x_{ls}	0.086	0.015	5.555	<0.001
Releasing (BM)	t_{s2}	0.77	264.3	<0.001	83	Constant	-0.850	0.139	-6.102	<0.001
						x_{wd}	0.082	0.005	16.258	<0.001
Hooking (BM)	t_{s3}	0.35	98.6	<0.001	183	Constant	0.163	0.112	1.460	0.146
						x_n	0.772	0.078	9.929	<0.001
Winching (SLM)	t_{s4}	0.52	26.3	<0.001	51	Constant	-1.084	0.483	-2.245	0.029
						x_n	0.704	0.159	4.430	<0.001
						x_{wd}	0.07	0.019	3.705	0.001
Winching (LLM)	t_{s4}	0.68	75.5	<0.001	71	Constant	-1.791	0.397	-4.516	<0.001
						x_{wd}	0.114	0.010	11.955	<0.001
						x_l	0.120	0.032	3.704	<0.001
Travel loaded (SLM)	t_{s5}	0.83	119.1	<0.001	51	Constant	-0.358	0.259	-1.384	0.173
						x_{sd}	0.007	0.001	14.045	<0.001
						x_n	0.408	0.068	6.005	<0.001
Travel loaded (LLM)	t_{s5}	0.77	109.0	<0.001	68	Constant	-2.905	0.670	-4.337	<0.001
						x_{sd}	0.011	0.001	12.555	<0.001
						x_l	0.279	0.056	4.942	<0.001
Overall (SLM)	t_{oss}	0.76	48.703	<0.001	50	Constant	1.985	1.276	1.556	0.126
						x_n	2.509	0.316	7.932	<0.001
						x_s	0.015	0.002	6.855	<0.001
						x_{wd}	0.081	0.039	2.090	0.042
Overall (LLM)	t_{osl}	0.84	122.16	<0.001	71	Constant	-5.120	1.359	-3.766	<0.001
						x_{sd}	0.027	0.002	15.766	<0.001
						x_{wd}	0.198	0.032	6.266	<0.001
						x_l	0.454	0.108	4.189	<0.001
Productivity (SLM)	p_{ess}	0.81	48.39	<0.001	50	Constant	12.453	1.633	7.627	<0.001
						x_{sv}	5.148	0.402	12.814	<0.001
						x_n	-2.904	0.439	-6.608	<0.001
						x_{sd}	-0.014	0.003	-5.216	<0.001
						x_{wd}	-0.144	0.048	-3.036	0.004
Productivity (LLM)	p_{esl}	0.85	92.373	<0.001	70	Constant	13.681	1.029	13.299	<0.001
						x_{sv}	3.775	0.234	16.152	<0.001
						x_{sd}	-0.017	0.001	-13.140	<0.001
						x_l	-0.305	0.083	-3.688	<0.001
						x_{wd}	-0.082	0.023	-3.480	0.001

3.1.4 Loading

Distribution of time consumption

The time consumption for loading is analyzed. The time consumption of all the loading elements in each cycle is divided by total gross-effective time in each cycle. The average, minimum and maximum proportions of the loading elements are extracted and given in Table 16. Log selection took the longest share, followed by loading. Other elements took 45 % of the total gross- effective time (Table 16).

Table 16. Average time consumption of loading elements as a proportion of total gross- effective time.

Loading element	Short-log, %	Long-log, %
Logs selection	24.9 [8-35]	24.7 [13-34]
Embracing	13.9 [8-23]	13.6 [7-25]
Loading	30.0 [12-41]	31.2 [16-42]
Positioning of logs on the truck	9.2 [1-23]	9.6 [2-24]
Fastening the rope	10.3 [4-18]	10.0 [6-14]
Delays	11.6 [0-54]	10.8 [0-23]

Detailed statistical analysis of the loading elements that were not related to any variables is presented in Table 17. The mean value can be used for constructing the total time consumption model using the elements listed. Although these elements did not form any function with any factors, the independent variables (e.g. diameter) may affect time consumption of these elements.

Table 17. Descriptive statistics of the mean value based work phase models.

Element		Parameter	Mean sec/payload	Min. sec/payload	Max. sec/payload	Std. dev.	N
Log selection	Short-log	t_{l1}	401	184	686	126	35
	Long-log		457	169	796	157	43
Embracing	Short-log	t_{l2}	224	137	491	81	35
	Long-log		242	141	386	60	43
Positioning of logs	Short-log	t_{l4}	147	20	374	106	35
	Long-log		171	33	509	107	43
Fastening the rope	Short-log	t_{l5}	160	85	229	30	35
	Long-log		176	134	215	19	43

Table 18 shows total time consumption, average volume loaded and productivity of loading in the short-log and long-log loading. The average volume loaded and average productivity of the long-log method was 46 and 24 % higher than in the short-log loading, while the average time spent long-log loading was approximately 14 % higher than in the short-log method. Differences between maximum and minimum productivity was 18.6 (38.5-19.9) m^3/hour in the short-log method and 24.2 (51.1-26.9) m^3/hour in the long-log method, in other words the differences were considerable for both methods.

Table 18. Total time consumption and productivity of loading performance.

	Harvesting method			
	Short-log (log length <5.20 m)		Long-log (log length >7.80 m)	
	Effective time	Gross–effective time	Effective time	Gross–effective time
Avg. loading time, min/payload	23.7	27.6	27.0	30.3
Min. loading time, min/payload	15.8	15.8	16.9	20.5
Max. loading time, min/payload	31.1	42.8	37.3	44.9
Avg. volume loaded, m^3	10.5	10.5	15.3	15.3
Min. volume loaded, m^3	9.4	9.4	14.0	14.0
Max volume loaded, m^3	12.2	12.2	16.7	16.7
Avg. productivity, m^3/hour	27.3	24.3	34.0	31.0
Min. productivity, m^3/hour	19.9	13.9	26.9	20.7
Max. productivity, m^3/hour	38.5	38.5	51.1	42.1

Time consumption models of loading elements

The models presented here are created for loading to estimate the effective time consumption of this element as a function of an independent variable(s). Average time consumption is presented for other loading elements. Statistical analyses of these overall and partial models are presented in Table 19.

1) Log selection

Time consumption for log selection was calculated as a mean value. However, it may relate to the number of logs loaded per cycle. The average time for log selection was 401 and 457 seconds per payload (43 and 46 seconds per cycle) in the short-log and long-log method, respectively

2) Embracing

Time consumption for embracing was not related to any variables other than the logs diameter, landing condition, and loader operator's skill which may influence the time consumption of embracing. The average time consumption of embracing was 242 seconds in the short-log and 224 seconds in the long-log method for each payload (Table 17).

3) Loading

Time consumption of loading depended on the interaction between the number of logs and the logs' volume. A time consumption model for loading has been constructed for both of methods [Eq. 47, Eq. 48].

Short-log $$t_{l3} = -502.36 + 9.9110x_{nv} \qquad [x_{nv} \geq 50\ \mathrm{m}^3] \qquad (47)$$

Long-log $$t_{l3} = 90.785 + 3.038x_{nv} \qquad (48)$$

Where t_{l3} = time consumption for loading, sec;
x_{nv} = number of logs × volume, m^3.

4) Positioning logs on the truck

Time consumption for positioning logs on the truck was calculated as mean values. The average time consumption of positioning logs on the truck was 147 and 172 seconds per payload (19 and 18 seconds per cycle) in the short-log and long-log method, respectively.

5) Fastening the rope

Time consumption for fastening the rope is calculated as mean time consumption value. However, several factors such as load volume, cable type, truck dimensions and truck driver skills may effect the time consumption of fastening. The average fastening time was 160 and 176 seconds per payload in the short-log and long-log method, respectively.

6) Delay time

Delay time was calculated as a mean time consumption value for both the methods. In the short-log method, time consumption for personal, technical and operational delay was 54, 86, and 92 seconds per payload, but in the long-log method, time consumption for personal, technical and operational delay was 41, 71, and 89 seconds per payload, respectively (Figure 18).

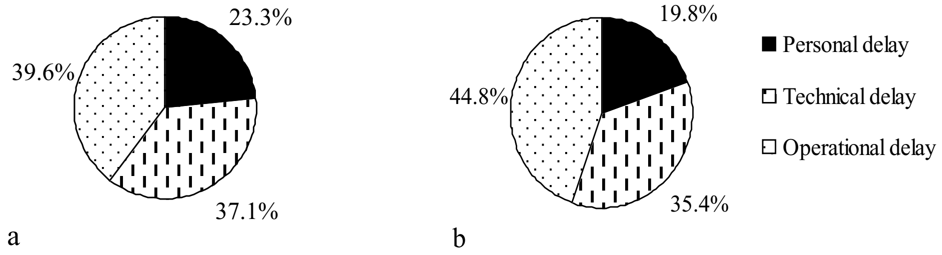


Figure 18. Time distribution of delay in the short-log (a) and long-log method (b).

Total time consumption model

The total time consumption model of a delay free loading was defined by totaling the individual time consumption elements [Eq. 49]:

$$t_l = t_{l1} + t_{l2} + t_{l3} + t_{l4} + t_{l5} \qquad (49)$$

Where t_l = total effective time consumption for loading, sec/payload;
t_{l1} = time consumption for log selection sec/payload;
t_{l2} = time consumption for embracing, sec/payload;
t_{l3} = time consumption for loading, sec/payload;
t_{l4} = time consumption for positioning of logs on the truck, sec/payload;
t_{l5} = time consumption for fastening the rope, sec/payload.

Overall time consumption and productivity models

The overall time consumption and productivity models are presented in order to estimate time consumption and productivity of loading as a function of independent variables in both methods [Eq. 50 - Eq. 53]. Average number of logs in each payload was 9.5 and 10.3 while the average volumes were 10.5 and 15.3 m^3 in the short-log and long-log method, respectively.

Short-log $$t_{ols} = -391.04 + 18.128 x_{nv} \qquad [x_{nv} \geq 22\ m^3] \qquad (50)$$

$$p_{els} = 54.081 - 0.267 x_{nv} \qquad (51)$$

Long-log $$t_{oll} = -1350 + 194.19 x_{lv} \qquad [x_{lv} \geq 7\ m^3] \qquad (52)$$

$$p_{ell} = 48.105 - 0.084 x_{nv} \qquad (53)$$

Where t_{ols} = overall time consumption of the short-log method, sec/payload;
t_{oll} = overall time consumption of the long-log method, sec/payload;
p_{els} = productivity of the short-log loading, m^3/hour;
p_{ell} = productivity of the long-log loading, m^3/hour;
x_{lv} = volume loaded, m^3/payload.

The characteristics of the regression models are presented in Table 19. F-value and P-value show that the presented models are statistically significant. R-square is low, proving that the model does not describe the prediction time for loading sufficiently.

Table 19. Statistical characteristics of regression analysis based models (SLM = short-log method, LLM = long-log method).

Model	Dependent variable	R^2	F-test		N	Term	Constant/ coefficient	Estimated std. error	t-test	
			F-value	P					t-value	p
Loading (SLM)	t_{l3}	0.36	18.78	<0.001	35	Constant	-502.36	229.81	-2.186	0.036
						x_{nv}	9.911	2.287	4.334	<0.001
Loading (LLM)	t_{l3}	0.18	8.96	<0.001	43	Constant	90.785	162.28	0.559	0.579
						x_{nv}	3.038	1.015	2.994	0.005
Overall (SLM)	t_{ols}	0.51	34.106	<0.001	35	Constant	-391.04	311.97	-1.253	0.219
						x_{nv}	18.128	3.104	5.840	<0.001
Productivity (SLM)	p_{els}	0.33	16.26	<0.001	35	Constant	54.081	6.667	8.112	<0.001
						x_{nv}	-0.267	0.066	-4.033	<0.001
Overall (LLM)	t_{oll}	0.29	16.79	<0.001	43	Constant	-1350.0	725.64	-1.861	0.070
						x_{lv}	194.19	47.390	4.098	<0.001
Productivity (LLM)	p_{ell}	0.12	5.758	<0.001	43	Constant	48.105	5.589	8.607	<0.001
						x_{nv}	-0.084	0.035	-2.400	0.021

3.1.5 Hauling

Distribution of time consumption of hauling

The detailed time consumption distribution of hauling elements is presented, for both methods (Table 20). Driving loaded and unloaded made up approximately 84 % of the gross-effective time of hauling in both methods. Driving loaded took the longest share and it was 10.4 % and 9.1 % longer time than that of driving unloaded in the short-log and long-log method, respectively. Unloading took the shortest time among the hauling elements.

Table 20. Average work phase times of hauling as a proportion of total gross-effective time (the range of time proportions is in the brackets for both methods).

Element	Short-log, %		Long-log, %	
Driving unloaded	36.9	[30-43]	36.0	[27-41]
Loading	13.53	[8-18]	12.8	[7-18]
Driving loaded	47.3	[43-52]	45.07	[39-50]
Unloading	0.57	[0-1]	4.04	[3-5]
Delays	1.68	[0-8]	2.67	[0-15]

Table 21 shows the average, maximum and minimum time consumption and productivity of hauling for both methods. Average time consumption in the short-log method was 19 % less than in the long-log method while the average productivity in the short-log method was 18.5 % less than in the short-log method.

Table 21. Detailed time study analysis of hauling in the short-log and long-log method.

	Harvesting method			
	Short-log (log length <5.20 m)		Long-log (log length >7.80 m)	
	Effective time	Gross–effective time	Effective time	Gross–effective time
Avg. hauling time, min/payload	212.9	216.5	253.3	258.7
Min. hauling time, min/payload	174.1	174.1	199.3	204.3
Max. hauling time, min/payload	271.4	271.4	312.6	320.6
Avg. volume hauled, m^3	11.0	11.0	15.3	15.3
Min. volume hauled, m^3	9.9	9.9	13.4	13.4
Max. volume hauled, m^3	12.8	12.8	16.6	16.6
Avg. productivity, m^3/hour	3.1	3.1	3.7	3.6
Min. productivity, m^3/hour	2.6	2.6	2.9	2.7
Max. productivity, m^3/hour	3.5	3.5	4.7	4.6

Time consumption models of hauling elements

The models presented here are created for driving unloaded and driving loaded to estimate the effective time consumption of these elements as a function of an independent variable. Statistical analysis of all models is presented in Table 22.

1) Driving unloaded

The average time for driving unloaded was 80 and 94 minutes per payload in the short-log and long-log method and average time for preparing the truck was approximately 1.5 minutes per payload for both of the methods. The average speed of driving unloaded was 45 and 40 km/hour in the short-log and long-log method, respectively.

Short-log $t_{h1} = -41.988 + 2.06x_{hd}$ $[x_{hd} \geq 21 \text{ km}]$ (54)

Long-log $t_{h1} = -64.77 + 2.559_{hd}$ $[x_{hd} \geq 26 \text{ km}]$ (55)

Where t_{h1} = time consumption for driving unloaded, min/cycle;
x_{hd} = one-way hauling distance, km.

2) Loading

Time consumption for loading the truck was calculated as a mean time consumption value. The average time consumption of loading was 29 minutes for the short-log method and 32 minutes for the long log method. The time consumption of loading depended on the interaction between load volume and number of logs (for more details see Chapter 3.1.4).

3) Driving loaded

Time consumption for driving loaded depended on the load volume and hauling distance [Eq. 56, Eq. 57]. The average time for driving loaded was 101 and 119 minutes per cycle in the short-log and long-log method, respectively. The average speed of driving loaded was 35 km/hour in the short-log method and 32 km/hour in the long-log method. The average volume hauled was approximately 10 and 15 m^3 per cycle in the short-log and long-log method, respectively.

Short-log $$t_{h3} = -42.921 + 1.344x_{hd} + 5.946x_{hv} \qquad (56)$$

Long-log $$t_{h3} = -116.947 + 2.427x_{hd} + 5.424x_{hv} \qquad (57)$$

Where t_{h3} = time consumption for driving loaded, min/cycle;
x_{hv} = load volume, m^3.

4) Unloading

The average time consumption for unloading was 1 and 10 minutes per payload in the short-log and long-log method, respectively. Further information regarding the time consumption for unloading is presented in Chapter 3.1.6.

5) Delay time

Time consumption of delay in the hauling work phase was calculated as a mean time consumption value in both methods. In the short-log method, time consumption of delay was 65 seconds for personal, 73 seconds for technical, and 75 seconds for operational delay, per payload. In the long-log method, time consumption for personal, technical and operational delay was 118, 120 and 87 seconds per payload, respectively (Figure 19).

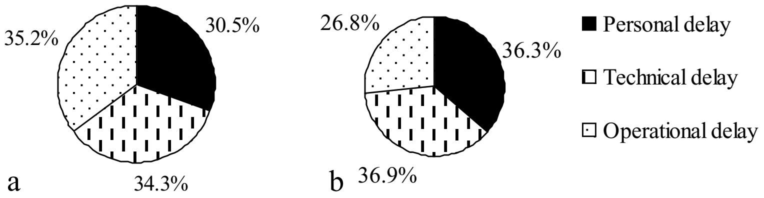


Figure 19. Time distribution of delay in the short-log (a) and long-log method (b).

Total time consumption model

The total time consumption model of a delay free work cycle was created by totaling the time consumption of individual elements.

$$t_h = t_{h1} + t_{h2} + t_{h3} + t_{h4} \qquad (58)$$

Where t_h = total effective time consumption for hauling, min/cycle;
t_{h1} = time consumption for driving unloaded, min/cycle;
t_{h2} = time consumption for loading, min/cycle;
t_{h3} = time consumption for driving loaded, min/cycle;
t_{h4} = time consumption for unloading, min/cycle.

Overall time consumption and productivity models

The overall time consumption and productivity models are presented in order to estimate time consumption and productivity of hauling as a function of independent variables in both methods [Eq. 59 - Eq. 62]. Hauling distance is an important factor influencing the time consumption of hauling and productivity. In the short-log method the average hauling distance was 60 km and the average truck speed was 39 km/hour while in the long-log method, the average hauling distance was 63 km and the average truck speed was 36 km/hour. Effect of hauling distance on the hauling productivity by using the formula [Eq. 60, Eq. 62] is presented in Appendix 7.

Short-log

$$t_{ohs} = 208.596 + 2.875x_{hd} - 4.236x_s \tag{59}$$

$$p_{ehs} = 0.734 - 0.038x_{hd} + 0.057x_s + 0.218x_{hv} \tag{60}$$

Long-log

$$t_{ohl} = 257.612 + 3.137x_{hd} - 5.557x_s \tag{61}$$

$$p_{ehl} = -0.390 - 0.045x_{hd} + 0.251x_{hv} + 0.084x_s \tag{62}$$

Where t_{ohs} = overall time consumption model of the short-log hauling, min/cycle;
t_{ohl} = overall time consumption model of the long-log hauling, min/cycle;
p_{ehs} = productivity model of the short-log hauling, m^3/hour;
p_{ehl} = productivity model of the long-log hauling, m^3/hour;
x_s = roundtrip speed, km/h.

The statistical characteristics for regression models are presented in Table 22. F-value and P-value show that the presented models are statistically significant. High value of R-square shows the independent variables describe the response variables well.

Table 22. Statistical characteristics of the partial and overall time consumption and productivity models (SLM = short-log method, LLM = long-log method).

Model	Dependent variable	R^2	F-test		N	Term	Constant/ coefficient	Estimated std.error	t-test	
			F-value	P					t-value	p
Driving unloaded (SLM)	t_{h1}	0.79	74.8	<0.001	22	Constant	-41.988	14.233	-2.950	0.008
						x_{hd}	2.060	0.238	8.653	<0.001
Driving unloaded (LLM)	t_{h1}	0.70	53.3	<0.001	25	Constant	-64.770	21.902	-2.957	0.007
						x_{hd}	2.559	0.350	7.303	<0.001
Driving loaded (SLM)	t_{h3}	0.74	26.71	<0.001	22	Constant	-42.921	24.840	-1.728	0.100
						x_{hd}	1.344	0.259	5.195	<0.001
						x_{hv}	5.946	2.462	2.415	0.026
Driving loaded (LLM)	t_{h3}	0.90	102.00	<0.001	25	Constant	-116.947	24.071	-4.858	<0.001
						x_{hd}	2.424	0.174	13.929	<0.001
						x_{hv}	5.424	1.359	3.990	0.001
Overall model (SLM)	t_{ohs}	0.95	219.0	<0.001	22	Constant	208.59	22.860	9.125	<0.001
						x_{hd}	2.875	0.194	14.805	<0.001
						x_s	-4.236	0.425	-9.979	<0.001
Productivity (SLM)	p_{ehs}	0.93	87.5	<0.001	22	Constant	0.734	0.564	1.302	0.209
						x_{hd}	-0.038	0.003	-13.405	<0.001
						x_s	0.057	0.007	7.992	<0.001
						x_{hv}	0.218	0.033	6.624	<0.001
Overall model (LLM)	t_{ohl}	0.97	490.8	<0.001	25	Constant	257.61	25.740	10.008	<0.001
						x_{hd}	3.137	0.200	15.705	<0.001
						x_s	-5.557	0.454	-12.230	<0.001
Productivity (LLM)	p_{ehl}	0.97	293.7	<0.001	25	Constant	-0.390	0.599	-0.651	0.522
						x_{hd}	-0.045	0.003	-13.200	<0.001
						x_{hv}	0.251	0.021	11.780	<0.001
						x_s	0.084	0.008	10.872	<0.001

3.1.6 Unloading

Distribution of time consumption

Time consumption distribution of different elements is given in the Figure 20. Figure 20a shows that the preparation for unloading is the most time-consuming element followed by truck dumping and opening the rope in the short-log method. In the long-log method, log selection was the most time-consuming element followed by unloading and embracing element (Figure 20b).

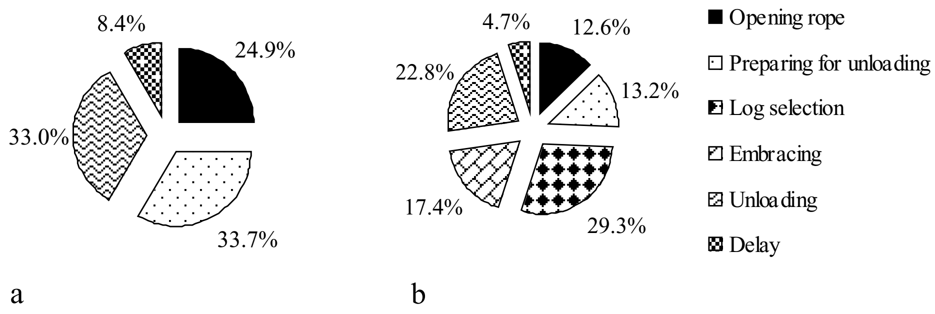


Figure 20. Time distribution of unloading, including delays, in the short-log (a) and the long-log (b) method.

The total effective time consumption was converted into delay-free productivity and gross-effective productivity. The results of time consumption and productivity are presented in Table 23.

Table 23. Time consumption and productivity of unloading in the short-log and long-log method.

	Harvesting method			
	Short-log method		Long-log method	
	Effective time	Gross–effective time	Effective time	Gross–effective time
Avg. unloading time, sec/payload	260	284	764	801
Min. unloading time, sec/payload	221	241	655	662
Max. unloading time, sec/payload	291	363	894	991
Avg. volume unloaded, m^3	10.3	10.3	15.3	15.3
Min. volume unloaded, m^3	9.3	9.3	13.5	13.5
Max. volume unloaded, m^3	11.5	11.5	16.0	16.0
Avg. productivity, m^3/hour	144.2	132.6	69.6	66.6
Min. productivity, m^3/hour	122.2	98.0	60.1	54.6
Max. productivity, m^3/hour	172.5	161.5	80.5	80.5

Table 24 shows descriptive statistics for the elements of unloading (e.g., opening the rope) that were not modeled. The mean value was used for constructing the total time consumption model. Maximum and minimum values show possible variation of the time consumption in each element.

Table 24. Descriptive statistics of mean value based work phase model.

Element	Method	Parameter minute	Mean sec/cycle	Min., sec/cycle	Max., sec/cycle	Std. dev.	N
Opening the rope	Short-log	t_{u1}	71	49	114	14.2	20
	Long-log		101	71	125	14.3	20
Preparing for unloading	Short-log	t_{u2}	96	65	135	20.5	20
	Long-log		105	72	138	18.8	20
Log selection	Long-log	t_{u3}	234	160	315	41.6	20
Embracing	Long-log	t_{u4}	142	81	202	30.9	20
Unloading (truck dumping)	Short-log	t_{u5}	94	73	119	16.2	20

Time consumption models for unloading elements

Unloading is the final work phase to complete the harvesting work cycle, in Iran. No model was constructed for unloading in the short-log method; however, it was modeled for the long-log method.

1) Opening the rope

The average time for opening the cable was 71 seconds in the short-log and 100 seconds in the long-log method.

2) Preparing to unloading

The average preparation time for unloading the trucks was 96 and 105 seconds per cycle in the short-log and long-log method, respectively.

3) Log selection

The average time consumption for log selection was 234 seconds per cycle in the long-log method.

4) Embracing

The average time consumption for embracing the logs was 142 seconds per cycle in the long-log method.

5) Unloading

Time consumption for unloading the logs from the truck depended on the interaction between volume and number of logs [Eq. 63]. The average time for unloading was 94 and 182 seconds per cycle in the short-log and long-log method, respectively.

$$t_{u5} = 64.807 + 0.817 x_{nv} \qquad (63)$$

Where t_{u5} = time consumption for the long-log unloading, sec;
x_{nv} = number of logs × volume, m^3/payload.

6) Delay time

Time consumption of delay was calculated as a mean time consumption value for both methods. In the short-log method, time consumption for personal, technical and operational delay was 11, 8 and 5 seconds per payload, respectively, while in the long-log method; time consumption for personal, technical and operational delay was 11, 10 and 16 seconds per payload, respectively (Figure 21).

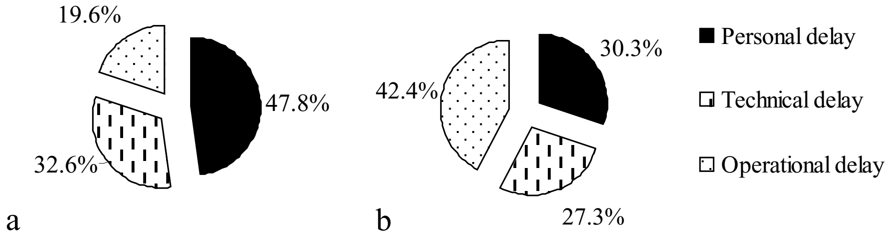


Figure 21. Time distribution of delay in the short-log (a) and long-log method (b).

Total time consumption model

The total time consumption model of a delay free work cycle was defined by totaling the time consumption of all elements.

$$t_u = t_{u1} + t_{u2} + t_{u3} + t_{u4} + t_{u5} \qquad (64)$$

Where t_u = total effective time consumption for unloading, sec/cycle;
t_{u1} = time consumption for preparing for unloading, sec/cycle;
t_{u2} = time consumption for opening rope, sec/cycle;
t_{u3} = time consumption for log selection, sec/cycle;
t_{u4} = time consumption for embracing, sec/cycle;
t_{u5} = time consumption for unloading, sec/cycle.

Overall time consumption and productivity model of unloading

Overall time consumption model of unloading was created only for the long-log unloading. Time consumption model of unloading was constructed by interaction between number of logs per payload and load volume [Eq. 65]. The productivity model of the long-log method was not statistically significant.

$$t_{oul} = 471.449 + 2.044x_{nv} \tag{65}$$

Where t_{oul} = overall time consumption of the long-log unloading, sec/cycle.

The characteristics for the regression models are presented in Table 25. P-value and F-value show that the models are statistically significant. However the coefficient of determination is low.

Table 25. Statistical characteristics of regression analysis based model (LLM = long-log method).

Model	Dependent variable	R^2	F-test		N	Term	Constant/ coefficient	Estimated std.error	t-test	
			F-value	P					t-value	p
Unloading (LLM)	t_{u5}	0.23	5.43	0.032	34	Constant	64.807	50.601	1.281	0.217
						x_{nv}	0.817	0.351	2.331	0.032
Overall (LLM)	t_{oul}	0.29	7.41	0.014	20	Constant	471.449	108.33	4.352	<0.001
						x_{nv}	2.044	0.751	2.72	0.014

3.2 Production cost

3.2.1 Production cost of work phases

The production cost of different work phases in the short-log and long-log method is presented in Table 26. The difference between the minimum and maximum cost of skidding was considerable. As mentioned earlier, unit cost is derived from dividing the cost per hour by productivity per hour. When productivity is high, the unit cost is low and vice-versa. The main factors affecting skidding productivity are skidding distance and volume skidded per cycle. When skidding distance is short and volume skidded is high, the productivity is high and consequently the unit cost is low. Average delay free unit cost of a harvesting cycle, including felling, was US\$ 21.3/m^3 and US\$ 19.8/m^3 in the short-log and long-log method, respectively. Overall, unit cost of short-log method was 7.14 % higher than that of the long-log method.

Table 26. Average, maximum, minimum production cost of different work phase of harvesting system in the short-log method (SLM) and long-log method (LLM).

	Felling	Processing		Skidding		Loading		Hauling		Unloading		Total	
		SLM	LLM	SLM	LLM	SLM	LLM	SLM	LLM	SLM	LLM	SLM	LLM
Avg. unit cost US\$/m^3	0.12	0.23	0.19	9.15	8.95	1.84	1.44	9.95	8.55	0	0.62	21.29	19.87
Min. unit cost US\$/m^3	0.03	0.10	0.08	2.29	2.63	1.27	0.96	8.87	6.56	0	0.51	12.56	10.77
Max. unit cost US\$/m^3	0.56	0.88	0.79	25.26	26.95	2.45	1.82	11.72	10.77	0	0.68	40.87	41.57

3.2.2 Unit cost distribution of work phases

Unit cost of each work phase was calculated as a proportion of total unit cost of all cycles. In the short-log method, hauling and skidding had the highest unit cost followed by loading, processing, and felling. In the long-log method skidding and hauling had the highest unit cost followed by loading, unloading, processing, and felling (Figure 22).

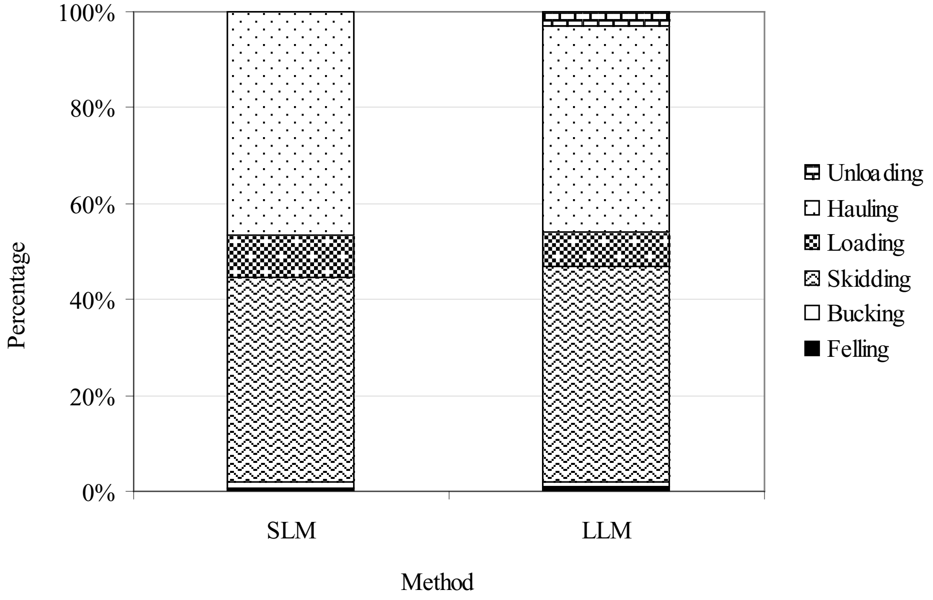


Figure 22. Distribution of unit cost of work phase in the short-log method (SLM) and long-log method (LLM).

3.3 Damage to residual stand

3.3.1 Distribution of tree and damaged tree species

A summary of tree damage along skid trails and winching strips are presented in Appendices 13-16. A total of 1131 trees were recorded along the winching strips and skid trails of which 365 trees were damaged, representing 32.2 % of total trees. *Fagus orientalis* which represented 53.1 % of total species composition in the both parcels (252 and 240), accounted for 48.2 % of all the damaged trees in the sample. *Carpinus betulus*, representing 19.7 % of total species composition in the stand, accounted for 21.8 % of all damaged trees sampled. Other species, representing 27.2 % of the total species composition in the stand, and accounted for 30.1 % of all the damaged trees sampled (Figure 23a, 23b)

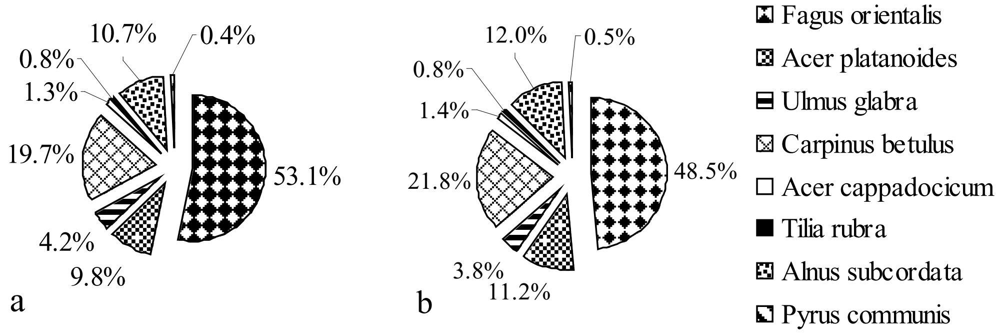


Figure 23. Percentage of tree species (a) and percentage of damaged trees in each species (b).

The largest amount of scarring damage occurred within the nearest skid trails centerline. Overall, 45.0 % of damaged trees had one wound per bole, 41.0 % had 2-3 wounds, and 14.0 % had more than 3 wounds per bole. In 63.4 % of cases, wounds were located within 1 m from the ground on the bole, 23.4 % on roots and 13.2 % were located above 1 m. Overall, in 45.9 % of the cases the wound surface area was less than 100 cm^2, in 43.75 % of the cases it was between 100-1000 cm^2, and 10.3 % of it covered more than 1000 cm^2. 70.0 % of the wounds were deep, with the remainder being classified as light.

3.3.2 Damages along winching strips

Along the winching strips of all trees with a DBH greater than 25 cm (435 trees), 64.6 % were *Fagus orientalis*, 17.5 % were *Carpinus betulus*, 7.8 % *Alnus subcordata*, 7.1 % *Acer platanoides*, with the remainder (3 %) being other species. In the short-log method, in 35 of the winching strips, 64 trees (of the 199 trees) with a diameter greater than 25 cm were wounded, broken or leaning as a result of the winching operation (Appendix 13). In the long-log method, of the 236 trees with a DBH greater than 25 cm that were studied in 35 winching strips, 88 trees were wounded, broken or leaning as a result of the winching operation (Appendix 14). The percentage of damage to the residual stand in the short-log and long-log method was 32.2 and 37.7 %, respectively. Overall, 3 or more wounds per stem were found to be the least common, for both methods. Percentage of one wound and 2-3 wounds per stem in the short-log method was 1.5 and 1 % less than in the long-log method, respectively, while the percentage of more than 3 wounds per stem in the short-log method (Figure 24a) was higher than in the long-log method (Figure 24b) by 2.6 %.

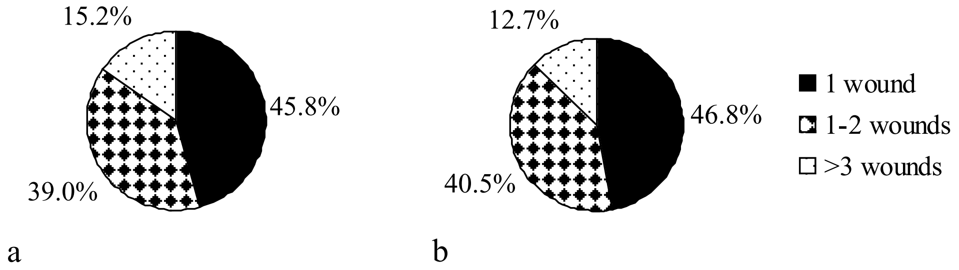


Figure 24. Percentage of number of wounds in the damaged tree along winching strips in the short-log (a) and long-log (b) method.

Overall, in both methods, 23 % of the damage was located on the roots, 66 % was located up to a height of 1 m on the bole, while 11 % was located above 1 m. In the short-log method, the percentage of damage to the roots was higher than in the long-log method by 8.1 %. Adversely, the percentage of damage up to 1 m and above 1 m in the long-log method was 2.7 and 5.4 % higher than in the short-log method (Appendices 13 and 14).

Both in the short-log and long-log methods, in 44.0 % of the cases the surface area of the wounds were less than 100 cm^2, in 45.0 % of the cases they were between 100-1000 cm^2, while 11.0 % of the occurrences covered more than 1000 cm^2. In the short-log method, the percentage of wounds with a surface area less than 100 cm^2 was higher than in the long-log method by 8.6 %, while the percentage of wounds with surface between 100-1000 cm^2 and more than 1000 cm^2 was higher in the long-log method by 4.4 and 4.2 %, respectively. Finally, the percentage of deep wounds in the long-log method was higher than in the short-log method by 5.1 % (Appendices 13 and 14).

3.3.3 Damages along skid trails

Damage to the residual stand along the skid trails occurs during the construction of the trails, as well as during log skidding. The total length of skid trails in compartments 240 and 252 were 4930 m. The total length of the investigated skid trails in the two compartments was 1450 m. The average number of damaged trees along the skid trails was 217 trees which represented 31.1 % of all trees along the studied trails. Appendices 15 and 16 summarize the results of the assessment of skidding damage. Overall, along the skid trails, 45.8 % of the trees were *Fagus orientalis*, 21.1 % were *Carpinus betulus*, 12.5 % were *Alnus subcordata*, 11.5 % were *Acer platanoides*, and 9.1 % were other species. The results of the short-log sample showed that of the 287 trees and seedlings with a diameter above 5 cm, 74 trees were wounded, broken or leaning as a result of the skidding operation. In the long-log method, of the 409 trees and seedlings with a diameter greater than 5 cm, 143 trees were wounded, broken or leaning as a result of the skidding operation. In total, 25.7 and 34.9 % of trees were damaged along the skid trails in the short-log and long-log method, respectively.

Overall (in both methods), 43.7 % of trees had 1 wound, 41.6 % had 2-3 wounds, while only 14.6 % had more than 3 wounds in the stem (Figure 25). Percentage of 1 wound per stem in the long-log method was higher than in the short-log method by 4.6 %. Percentage of more than 3 wounds per stem in the short-log method was higher than in the long-log method by 5.1 %.

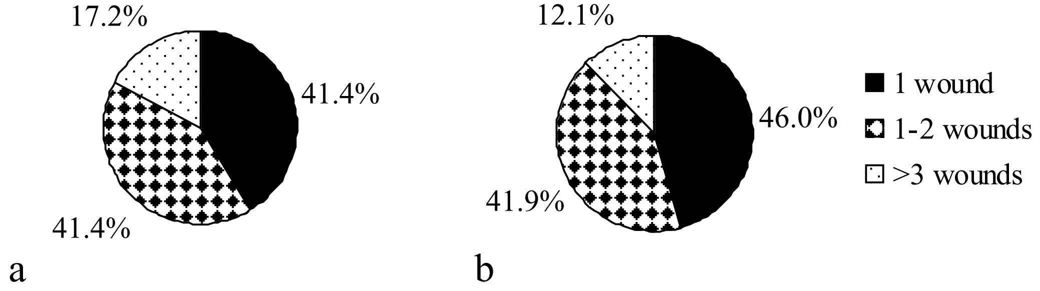


Figure 25. Percentage of number of wounds in the damaged tree along skid trails for the short-log (a) and long-log method (b).

In total, 23.3 % of the trees' wounds were located on the roots, 62.2 % up to 1 m and 14.4 % were located above 1 m. The percentage of damage to the roots in the short-log method was higher than in the long-log method by 2.4 %. The percentage of damage on the boles (up to 1 m and above 1 m) in the long-log method was higher than in the short-log method by 2.8 %. Overall (in both methods), 43.4 % of the wounds had a damaged area less than 100 cm^2, 46.7 % were between 100-1000 cm^2, and 9.9 % of the wound areas were more than 1000 cm^2. Percentage of wound area less than 100 cm^2 in the short-log was higher than in the long-log method by 4.7 %, however, the percentage of wound area more than 1000 cm^2 was almost twice as much as in the short-log method (11.3 vs. 6.9 %). In the short-log method, the percentage of deep wounds was less than in the long-log method by 5.7 % (Appendices 15 and 16)

3.4 Summary of results

The detailed summary of the results of the study is available in Table 27. According to the table, the time consumption of hauling took the longest share among harvesting work phases in both of methods. It is followed by loading and skidding in both of the methods.

The unit cost of the long-log method was lower than in the short-log method in all of the work phases except unloading. The total unit cost of logging (felling and hauling wood from forest to mill) in the short-log method was US$ 21.10/m^3; while in the long-log method it was US$ 19.67/m^3. It means that unit cost in the short-log method was 7.2 % higher than in the long-log method.

The ratio of effective hour to gross-effective hour was highest in the hauling and was lowest in the felling. It illustrates that delay time is larger in more labor intensive activities.

Overall, the short-log method caused less damage to residual stand than the long-log method (31% vs. 36%).The percentage of damage was 32.2 and 37.7 % along winching strips and 25.7 and 34.9 along skid trails in the short-log and the long-log method, respectively. These results clearly show that the short-log method causes less damage to the residual stand than the long-log method.

Table 27. Summary of results of wood extraction from forest to mill (SLM = short-log method, LLM = long-log method, ET = effective time, GT = gross-effective time).

	Method	Avg. time consumption, min	Avg. productivity, m^3/hour*	Avg. unit cost US$/$m^3$	ET/GT
Felling		5.14 [1.9 %]	114.00	0.12 [0.6 %]	0.80
Processing	SLM	9.15 [3.4 %]	33.50	0.23 [1.1 %]	0.82
	LLM	6.85 [2.1 %]	39.50	0.19 [1.0 %]	0.83
Skidding	SLM	15.30 [5.7 %]	10.80	9.15 [43.1 %]	0.92
	LLM	16.65 [5.2 %]	11.11	8.95 [45.1 %]	0.90
Loading	SLM	23.70 [8.8 %]	27.30	1.84 [8.6 %]	0.86
	LLM	27.00 [8.4 %]	34.00	1.44 [7.3 %]	0.89
Hauling	SLM	212.93 [78.7 %]	3.13	9.89 [46.6 %]	0.98
	LLM	253.35 [78.7 %]	3.71	8.50 [42.9 %]	0.97
Unloading	SLM	4.33 [1.6 %]	144.00	0.00 [0 %]	0.92
	LLM	12.73 [3.9 %]	69.00	0.62 [3.1 %]	0.95
Total	SLM	270.55 [100 %]	332.70	21.08 [100 %]	0.88
	LLM	321.72 [100 %]	271.32	19.67 [100 %]	0.89

* The total productivity value (332.7 and 271.3) in the table shows the potential amount of volume under different process of harvesting performance in an hour, however, in practice the felling is done in winter and the other work phase are done during the other seasons.

3.5 Sensitivity analysis

Figure 26 shows the sensitivity analysis according to change in the skidder and labor price in the productivity range (maximum and minimum). The price rate is derived from a review of the price and commodity over the last decade (Iranian Central …2007). In the present condition (PC), the system cost of skidder is 99.6 $/hour (Tables 3 and 4). The unit cost in the range of productivities is calculated by the formula [Eq. 18]. The sensitivity analysis of the felling, bucking, loading, hauling, and unloading are presented in Appendices 8-12.

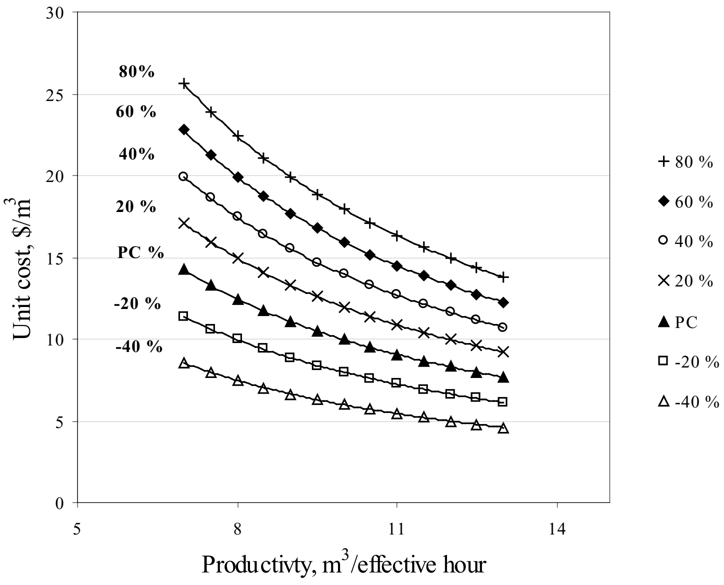


Figure 26. Sensitivity analysis of unit cost when the system cost of skidding changes by 20 % (PC = present condition).

4 DISCUSSION

4.1 General discussion

The purpose of this study was to construct models for each work phase of the harvesting system and compare two different harvesting methods in Iranian conditions. Due to different forest conditions such as the structure of the forest, stand composition, silvicultural methods, and operations as well as terrain conditions, the results and models are applicable for areas with the same working conditions and equipment (e.g. skidding results are valid only when downhill skidding is practiced or loading results are valid only when roadside landing is used). The result of this study is applicable only for the summer period with good weather conditions. With the exception of felling, which was done in the winter, the data for other work phases were collected in the summer. Normally the productivity in each work phase in summer is higher than in the other seasons in Iran. Rainy weather conditions can hinder skidding even in the summer.

Methodologically, the emphasis of this study was on the comparative area with less attention paid to the correlation aspects. The main problem of the correlation study is the multiplicity of influencing factors which was controlled by a detailed division of harvesting work phase into elements (Bergstrand 1991, Nurminen et al. 2006).

According to Harstela (1993), the productivity of a harvesting system is a function of the qualities of the labor force, and the characteristics of conditions as well as other factors of production. One of the main problems regarding the generalization of the study is related to labor; therefore a standard crew was used in order to minimize and monitor the influence of the workers on the study results. This is an important, although inadequate, approach to improve the ability to generalize the study results (Harstela 1993, Nurminen et al. 2006). The operators were observed for a rather short period of time, therefore there is a risk that their performance was affected by the particular situation, even if they were asked to work as normally as possible. Among the different factors which affect the worker's productivity, their motivation and skills are the most important (Hultberg 1987). Workers' motivation is a very important psychological issue; however, it is difficult to estimate the necessary wage to motivate the worker satisfactory. Workers' skills are mostly related to their experience, while training can improve skills and increase the productivity. The work performance of the subjects was abnormally high during the first two days of the study, as was found in studies by Vöry (1954) and Harstela (1993). Therefore, the first two days was excluded from the final data.

In the harvesting system employed in Iran, high variation in labor productivity might be related to the chain saw, skidder and loader operators since they have a key role in the productivity of the system. In this sense, the role of the other workers is less important. However, no previous studies have documented the effect of operator's factors such as operator's skills on time consumption and productivity of work phases in Iran, but the operator's role in the productivity of forestry machines have been proved in studies conducted elsewhere, for example, by Hartman and Gibson (1970), Ovaskainen et al. (2004), Väätäinen et al. (2005).

The video camera as a data collection tool proved to be appropriate and enabled the classification and analysis of very short elements, as previously found by Nurminen et al. (2006). It was the first time in Iran when a video camera has been used for a time study. Its success in this study opens the way for future use in time studies in Iran.

Up to now there were no detailed time studies for harvesting work phases in Iran, therefore this study provides innovative information and models of time consumption and costs. The models can be used for estimating the partial and overall time consumption of the work phases. This study also provides an insight into time consumption, productivity, and cost of different work phases of harvesting in Iranian forests on the basis of the two short-log and long-log method.

Two techniques were applied to create the models: work phase time consumption models, and overall time consumption models. Both techniques appeared to fit well with the observations and are reliable to predict the time consumption and productivity, as previously found by Nurminen et al. (2006). The advantage of the work phase based model was, above all, the possibility to observe the harvesting work in greater detail, to decrease the variation of time consumption as well as to reduce the number of influencing factors. A work element is often influenced by few factors, while the total time is influenced by more factors. If the division in work elements is detailed enough the work element might only be affected by a single factor or correspond to the average time.

In overall time consumption model, the affecting factors might influence the work elements but in different directions, thus the effect on the total time consumption is minimized. In overall time consumption model, with applying the average value for the model, the average time consumption of the work phase can be calculated. In order to study the effect of a single factor on the time consumption, only the value of the factor is changed while the other factor is fixed to the average values. Overall time consumption model gives the same results as work phase model in a simpler form (Gonzáles 2005).

The models for effective time consumption and productivity introduced in this paper, in different work phases, are valid and accurate in the area with the same working conditions. The results of this study can be applied to estimating the productivity and cost of harvesting performance, and for estimating the required personnel, tools and equipment. It is important, especially in felling, because it should be done at a certain time (e.g. winter). An assessment of equipment needs may assist in ensuring that harvesting is punctual. Organizing of processing and skidding should be constant. Harvesting productivity may be increased by knowing the most important factors affecting the work phases. One of the most important applications of the results of this study is to know the productivity and cost of the short-log and long-log methods, separately. Moreover, it provides information about the impact on the residual stand through the application of these two methods.

Overall, the total unit cost of the long-log method in processing, skidding, loading, and hauling was lower than that of the short-log method. This indicates that from a cost perspective the long-log method, in the western Hyrcanian forests, is superior to the short-log method, primarily due to higher productivity and lower unit cost. Only in the unloading work phase was the opposite the case with the productivity of the short-log method being higher than that of the long-log method and consequently the unit cost of the short-log method was lower than that of the long-log method. Total unit cost of all harvesting work phases was calculated in the study. In order to know the real cost of wood extraction from forest to mill, the cost of forest road construction and maintenance and interest on the investment, skid trail construction, planning and marking and other costs should be included.

4.2 Felling

Manual tree felling is a highly variable operation. There are many factors influencing the felling productivity. Many of these factors are difficult to identify and even more difficult to quantify. This paper identifies the variables that are the most significant and should be recognized prior to harvesting.

Walking, clearing, back-cut, sink-cut, and miscellaneous time was considered as elements of the felling work phase. Time consumption of reconnaissance and planning was not included in this study with only work place time being recorded and analyzed. Back-cut, sink-cut and delay time were the most important time-consuming elements in felling. This suggests that the productivity could be increased by diminishing the time consumption for these elements. Delay time is inseparable part of each work phase in harvesting in Iran. Delay time accounted for approximately 20 % of gross-effective hour. Technical delays such as sharpening and dealing with the chain of a chain saw breaking, pinching in the kerfs took approximately 19 % of the delay time. One of the reasons for a long delay time was usage of an old and depreciated equipment, unsuitable files and incorrect filing of the chain saw. Sometimes top bind causes pinching which could be avoided by further training the workers; however, in most cases it was unavoidable. Operational delay accounted for the largest share that needs to be considered. Operation delay may relate to management, supervision, and equipment availability. It may happen that a felling group does not have all the necessary tools needed for work, thus the delay is prolonged as they had to borrow the tools from the neighboring groups. Activities such as the chain breaking and filing as well as pinching in the kerfs can be part of working time (Sarikhani 2001), however, in this study it is considered as a technical delay. If we take into account these activities as a part of effective working hour, productivity of felling decreases approximately by 3.6 %.

Walking is the first element of the felling work cycle. There is a direct relation between walking and both distance and slope. In general, there are two types of slopes that effect time consumption of walking: uphill and downhill. Normally, walking downhill takes less time than the time is calculated by the model and adversely walking uphill takes longer time. However, the ranges have not been calculated. In the study by Long et al. (2002), time consumption of walking was mostly affected by inter-tree distances.

Silvicultural treatment is one of the most important influencing factors on time consumption of walking. In the single tree selection method, the trees spread out more in the forest than in the shelter wood and the clear cutting method, thus it takes a longer time. In this study, only 14 % of the gross-effective hour was related to walking time.

In clearing, most of the time is spent deciding on the felling direction. The results of this study show that the chain saw operator spent only 6 % of the total working time for choosing the felling direction which is insufficient in comparison with directional felling which is 15% (Nikoy Seyahkal 2007). In directional felling, cleaning time including decision making time for finding the appropriate direction which takes plenty of time. In some areas, the skid trails were not marked, thus the operator was free to choose the direction. It may, however, increase skidding time and cost. It is recommended to mark skid trails before performing felling. If the tree is located in an accessible place, there is no need to clear the other trees in the working area. However, in stands containing dense undergrowth, clearing may take a large amount of time. There is a close relation between clearing and the direction of felling. Normally, the chain saw operators choose the escape route in relation to the direction of felling.

Technically and practically, sink-cut and back cut are the most important elements of felling. The quality of felling performance is related to these elements. According to Conway (1979) poor performance of felling may result in the loss of 40 % value of the tree. In this study, 26 % of the gross-effective time was spent on the sink-cut, while 32 % was spent performing the back-cut. The higher percentage of back-cut is related to the use of a wedge to lead the tree in the specified direction in order to prevent damage to the residual stand and breakage to the tree being felled.

Data analysis and construction of the time consumption model showed that the stump diameter and distance were the most important variables affecting the felling time. A straight-line relationship of predicted values versus residual values in the residual plot ensured that the model explains the time consumption in relation to the factors (stump diameter and inter-tree distance). Felling productivity, with and without delay, was 9.4 and 11.6 trees per hour, respectively. Average tree diameter of all observations was approximately 75 cm and the average tree volume in the diameter (75 cm) is approximately 7 m^3. Tree diameter and inter-tree distance influenced the time consumption of felling, productivity, and unit cost of felling. A study by Kluender and Stokes (1996) showed similar results. They found that tree diameter is the most important factor in estimating felling time, while the distance between trees and harvesting intensity were also important.

Felling productivity was calculated on the basis of the number and volume (m^3) of trees felled per hour. In overall time consumption model for felling, a regression equation was developed to predict felling work phase time as a function of independent variables including stump diameter, inter-tree distance, and longitudinal and side slope, however, only stump diameter and distance were significant.

Inter-tree distance and stump diameter does not have the same effect on the productivity and felling cost. Tree diameter affects the productivity and cost more than the other variables. Time consumption of felling increased by 7.1 times when the tree diameter increased from 30 to 150 cm whereas time consumption of felling increased by 2.1 times when the distance increased from 5 m to 100 m [Eq. 24].

It should be borne in mind that the felling productivity in this study seems to be high (114 m^3/ effective hour), because it was calculated on the basis of the volume of the whole tree, not logs. Additionally, the volume calculated is only estimation and was obtained from the local volume tariff. Productivity of felling included only felled trees and not processing. In order to determine the commercial volume of each tree (branch diameter or stem diameter more than 20 cm) it is necessary to know the recovery rate. Recovery rate is derived from division of the volume of the logs by the tree volume. In this case, the average recovery rate was approximately 65 %. Delay time exceeding 15 minutes can affect the gross-effective productivity. The field study showed that the felling crew was working only 4 hours a day with 4 hours being ‘wasted’ on traveling and preparing to work. Therefore, productivity of felling should be applied regarding this important issue. Overall, productivity of felling may be influenced by the operator’s skills and motivation, silvicultural method, tree species, stand composition, undergrowth trees and seedling, weather condition, coldness of weather, oldness and brands of chain saw, chain condition (sharp or dull), and lean of tree as well as slopes. However, the influences of all these factors were not documented in this study but it is mentioned by (Conway 1979).

There were no similar studies available in Iran to compare the results. Nevertheless, according to a study performed in Congo (FAO 1997) that the study condition was similar to this study area (hardwood trees, manual feeling by means of chain saw and untrained operators), the average number of cut trees per day was 20 trees and the average trees volume was 6 m^3 that the productivity is 72 percent higher than in this study (11.6 tree per day).

The unit cost of felling is calculated in order to show the cost of felling performance in the area and also to find the cost of the harvesting work cycle. The unit cost of felling was the second lowest unit cost among the different work phases; it was US$ 0.12/m^3. The unit cost of felling was mostly affected by labor cost. Labor costs accounted for 90 % of the hourly cost while only 10 % was related to machine cost. Hourly cost of felling performance took 6 % of total hourly cost of all the harvesting work phases.

The felling groups were working close to each other. That is not only dangerous, but also decreases the productivity as a result of waiting time to avoid accidents occurring. It is recommended to control the felling equipment and tools before the felling time and also to train the fellers in order to familiarize them with the proper felling methods. It is also necessary to prepare a sufficient amount of felling equipment, such as wedges and files.

The methods introduced by Conway (1979) regarding the proper way to fell trees as well as by FAO (1998 a, 1998b, 1998c, 2002 a, 2002b, 2002c) about reducing the impact of logging and directional felling would help to increase the productivity of felling and improving the potential of the future stand. It also facilitates the more efficient use of resources.

4.3 Processing

The main part of manual processing in Iran, including delimbing and topping, takes place in the stump area, but bucking is usually done in the forest or at the landing. In this study, in the short-log method bucking was performed only in the forest, while in the long-log method it was done mainly in the landing. In order to increase the harvesting productivity, it is necessary to establish a strong relation between the chain saw and skidder operators. A chain saw operator was present at the landing to cross-cut long-logs.

Walking or moving is the first element of the processing work cycle. There is a direct relation not only with the distance, but also the terrain slope. When distances between two cut trees increases, time consumption of walking increases. Distance between two cut trees is related to silvicultural treatment and tree marking plan. The relation between time consumption of walking and influencing variables (distances and slope) was a linear function [Eq. 27]. However in steep terrain the equation may not predict time consumption precisely. The effect of distance between cut trees on the productivity of small size trees is more important than in large trees. The average speed of walking in this study is less than the average speed found by Harstela (1991). This may be caused by different features of the forest; especially slope, ground conditions and other influencing factors. In this study, walking took 8.7 and 13.7 % of the gross-effective hours in the short-log and long-log method, respectively.

Delimbing and topping accounted for 26.7 and 31.8 % of the gross-effective time for various tree species in the short-log and long-log method, respectively. The time consumption of delimbing is influenced mostly by tree diameter. Other factors that may affect the time consumption of delimbing and topping is branch thickness, condition of branches from being under tension or compression, and of course the number of branches. The minimum accepted diameter for a sawmill in Iran is 20 cm at the end of logs (Sarikhani 2001). The residues of cut tree with diameter less than 20 cm are used for other purposes such as by the plywood, fiber and particle board industries. Good cooperation between the forestry company and the related industry is very important in order to maximize profit.

Bucking a tree into logs is one of the most important issues in processing both for the seller and customer in many countries. The forest owner as the log seller must be able to cut trees into the logs that maximize their profit (Sessions 1988). If a tree is bucked into sub-optimal lengths, no manufacturing technology can realize its potential recovery. In bucking, each log length, except for pulp wood bolts and certain special products must be cut to a range of specific lengths plus some over trim that compensates for skidding damage and unsecured bucking (Conway 1979). Yarding or skidding equipment may not be effective if the logs are cut beyond the desired range (Conway 1979). In manual bucking in Iran, according to the technology available and prevalent traditional system, all logs are cut in 2.60 m multiplies, including an additional 10 cm which is considered for unsecured bucking and skidding damage.

After trimming in the mill, high quality logs in Iran are used for veneer production. All logs are classified into four grades: LV (log for veneer), LS (log for saw log), LT (log for traverse), and LI (industrial wood for particle and plywood industries) (Sarikhani 2001). A log in each grade is subsequently qualified into three grades: A, B, C (Sarikhani 2001). The highest quality of log (LVA) is used in the veneer production. Logs longer than 7.8 m should be rebucked in the landing in order to facilitate loading onto the truck. Bucking took the longest share of the time consumption of processing in both of the methods.

Delay time took around 14 % of the gross-effective time which is considerable. Usually delays exceeding 15 minutes are excluded from time studies (Harstela 1996). Technical delays took the longest share of the total delay time followed by operational delay and personal delay. Technical delays can be reduced by further training the workers (e.g. pinching chain may be avoided by appropriate performance of bucking).

Productivity of tree processing was 33.5 m^3/effective hour in the short-log method and 39.5 m^3/effective hour in the long-log method. Average volume of logs per tree was 4.93 and 4.39 m^3 in the short-log and long-log method. When the productivity is divided by the average commercial volume of a tree, the average number of processed trees is 6.8 and 9.0 trees per hour in the short-log and long-log method, respectively. Average productivity per hour has a direct relationship with stem size. When the diameter at the butt of stem was 50 cm, the productivity was 27.2 and 29.0 m^3/ effective hour but when the diameter was 85 cm, the productivity was 43.4 and 46.1 m^3/ effective hour in the short-log and long-log method, respectively.

Time consumption and productivity of processing depends on the trees sizes [Eq. 32 -35]. Other factors that may influence the productivity of processing is chain condition (sharp or dull), tree species (hardness of wood), operator's skills and experience, log condition, slope as well as distances between cut trees. The differences in time consumption between the two studied methods in all elements of processing, except bucking, were related to random variation.

Manual felling and processing are strenuous and tedious work. Factors such as age, experience of personnel and energy levels of the worker may influence the productivity.

In overall time consumption of processing, a regression equation was applied to predict processing time as a function of independent variables: diameter at the butt of the tree, distance between cut trees, and longitudinal slope. Diameter at the butt of trees was found to be the most influential factor on the processing time.

According to this study, unit cost of the long-log method was lower than in the short-log method by 21 %. Similar to felling, an hourly cost of processing is mainly comprised of labor cost (83 %). Hourly cost of processing took the lowest percentage among different work phases of harvesting. It made up only 3 % of the hourly cost of all the harvesting work phases.

4.4 Skidding

Although several studies about skidding, as an important work phase of wood procurement, have been done in Iran, until now no detailed time study of skidding had been conducted. This study provides time consumption and productivity of skidding using the short-log and long-log methods. The study also introduces partial and overall time consumption models. In the study, only work place time was recorded and applied.

Travel unloaded is the first element of skidding. Modeling of travel unloaded showed that it was highly dependent on the skidding distance and slope. Travel unloaded time increases with increasing distance and slope. Travel unloaded in the terrain with a slope greater than 35 % limits the skidder speed in downhill skidding because the skidder must do the return trip uphill, even though unloaded. Time consumption for travel unloaded was one percent less than travel loaded. Wang et al. (2004) found that travel unloaded time depends on travel distance. Time consumption in skidder roundtrip accounted for approximately 54 % of the total gross-effective time

Releasing time is directly related to winching distance [Eq. 35]. Pulling the cable in downhill winching seems to be longer than uphill winching because in downhill winching the cable should be pulled uphill and vice-versa. However the differences between these two winching methods have not been documented in Iran. Overall, in downhill winching, the time consumption for releasing is higher and pulling cable is more difficult than uphill winching. Releasing is modeled only based on winching distance. The other factors may influence time consumption of releasing is the condition of the cable and winch drum. An old, depreciated and overused cable and winch drum may increase the time consumption of releasing. The model presented for releasing is valid when the winching distance is longer than 10 m.

Time consumption of hooking is directly related to the number of logs. When the number of logs that should be winched increases in each cycle, hooking time increases, especially when the logs need to be hooked repeatedly. Hooking took 2.4 % more time in the short-log method than the long-log method. The use of a choker is not common in Iran, instead the skidding cable is wrapped directly around the logs. Using a choker may decrease time consumption of hooking. Wang et al. (2004) found that hooking time is significantly different among merchantable length, number of stems per cycle and cycle payload.

Travel loaded is the most time consuming element of skidding in both methods. Similar to travel unloaded, travel loaded is strongly related to skidding distances. The study showed that the log lengths were an important variable to construct the time consumption model of travel loaded in the long-log method. When the skidding route is straight, the log lengths may not influence time consumption, but as the vertical or horizontal angle between skid trail and skidder increases, the efficiency, especially in very long-logs, drops. Maximum efficiency is achieved in straight line pull. Other variables that affect the travel loaded time are the number of logs and the volume per load. Wang et al. (2004) found that travel loaded depends on merchantable length, number of felled stems per cycle and skidding distance. Travel loaded in the short-log method took 10 % more time than in the long-log method.

Wang et al. (2004) found that unhooking time depends on butt diameter, average merchantable length, and number of felled stems per cycle. However, the impact of other variables on the time consumption for unhooking has not been proven in this study.

Piling is the last element of skidding which took approximately 10 % of the total time consumption of the work phase in both of the methods. Piling, in the short-log method, took 1.7 % less time than in the long-log method. However, the effect of any variables on the time consumption of piling has not been proven, though log length may have an inverse effect on piling time.

Similar to other harvesting work phases, time consumption of skidding involves delay times. Different types of delays were considered in skidding. Operational delay and technical delay accounted for almost 85 % of the delay time. Percentage of personal delay was low; therefore it was not a significant part of the total delay time. In general, delay time took only 3 % of the skidding time, which was low in comparison to other elements.

In overall time consumption model of skidding, a regression equation was developed for each method to predict skidding time as a function of significantly independent variables: number of logs per turn, skidding distance, winching distance, log lengths, and volume per turn. Other variables were not statistically significant. The dependent variable, time per skid turn, included productive time excluding delay time. Statistically, the standardized residual of the models were rather symmetrical and normally distributed. According to the high level of the determination coefficient, and the results of the f-test, both models proved to fit with the observation.

The average time consumption of skidding for all cycles was 15.3 minutes and the average productivity was 10.9 m^3/effective hour in the short-log method while in the long-log method the average time consumption of skidding was 16.7 minutes and the average productivity was 11.1 m^3/effective hour. The productivity of skidding in the study was similar to the other studies conducted in the Hyrcanian forest. Feghhi (1989), Eghtesadi (1991), and Naghdi (2005) calculated 8.6, 10.4, 11.7 m^3/effective hour, respectively. Productivity of skidding in this study was less than in a study done by Pilevar (1996) where it was 14.3 m^3/effective hour and in the other study that was done by Naghdi (2005) in the skidding of the tree length method. The productivity of skidding was 17.1 m^3/effective hour, which was over 54 % higher than this study.

The width of the skid trails was the same for both methods, because new skid trails were reconstructed on the same trails that were built in the previous harvesting period (approximately 30 years ago). Volume skidded in each cycle was not only related to the log lengths but also depended on the number of logs in each cycle. Skidding productivity in the long-log method was higher than in the short-log method. In travel loaded, plenty of time was spent in curves in the long-log method while in the short-log method a large amount of time was consumed in hooking.

Although the effect of skid trail factors such as width and number of curves in the trail on the productivity of skidding has not been studied, presumably it influences time consumption of skidding. Another important factor which may affect the time consumption of skidding is the quality of delimbing performance. If the bucker does not cut the branches properly (butt of branches still left in the bole) it may increase time consumption and cause disturbance in the skid trail and damage to the boundary trees.

Unit cost of skidding was mostly affected by machine cost. Machine cost accounted for 90 % of the hourly cost of skidding while only 10 % was related to labor cost. The hourly cost (system cost) of skidding took approximately 41 % of hourly cost of the whole harvesting work phase which was the highest.

Naghdi (2005) found that unit cost of skidding in the tree length method was lower than in the cut-to-length method. Unit cost of skidding was US\$ 4.2/m^3 in the cut-to-length method and US\$ 6.1/m^3 in the tree length method. Unit cost of skidding in this study was US\$ 9.0/m^3 in the short-log method and US\$ 8.8/m^3 in the long-log method. The unit cost level in this study was approximately 50 % higher than in Naghdi's (2005) study. The main reason for such a difference is the different price for a skidder in both studies. In this study, according to information provided by the forest company, the skidder price was almost twice the price than that of Naghdi's (2005) study.

Unit cost of skidding made up 42 and 45 % of the unit cost of all work phases in the short-log method and long-log method, respectively. It emphasizes that special attention needs to be paid to the skidding costs in order to decrease the unit cost of the whole system. Unit costs of skidding increased with increasing distances in both methods. Skidding distance affects the hourly and daily output considerably (Conway 1979, Feghhi 1989, Eghtesadi 1991, Abeli and Dykstra 1981, Naghdi 1996, Wang et al. 2004, Naghdi 2005, Javadpour 2006, Nikoy Seyahkal 2007).

In this study the productivity and skidding costs in the short-log and long-log method were investigated and compared only from an economic and technical point of view. Another method is the evaluation of the efficiency by studying the energy consumption in each work phase (Sundberg and Silversides 1988). In this case, for calculation of productivity energy consumption is the input and volume skidded is the output.

4.5 Loading

The condition of the landing area is important in relation to the efficiency of loading. The objectives of a well designed, properly constructed, and efficiently operated landing are safety, cost minimization, landing size minimization, and proper transfer of logs to the transport system. The design and location of the landings should be established when planning the harvesting, preferably in connection with road planning. Temporary roadside storage is recommended where feasible. Landings should be as small as possible, taking into account the need to unhook logs from the extraction equipment, sort logs, store them temporarily, and provide for the loading of trucks (Conway 1979). In this study, only roadside landing was used.

Log selection is the first element of loading. Log selection accounted for the second largest share of the total time consumption after loading. However, the influence of any variables on the time consumption of the element was not found, but distance between truck and decked logs and availability of certain logs for loading may influence the time consumption of log selection. In the long-log method waiting for bucking increases the time consumption of log selection. Similar to log selection, time consumption of embracing is calculated as the mean value in the total time consumption model, because the model was not statistically significant.

Loading is one of the most important elements of loading performance including lifting the logs and putting onto the truck. It slightly depends on the log sizes (volume). Positioning or sorting of the log was not found to be related to any variables. The logs should be placed on the truck properly; otherwise the load may take a lot of space which decreases the productivity of long distance transportation, the next work phase. Usually the truck driver is responsible for the proper distribution of logs on the truck. The fastening of the cable onto the load is the last element of loading. Almost every truck is roped after the loading operation to prevent any logs falling. Chain and strong cable is used for fastening the logs. The fastening time varies between 1 to 3 minutes. Fastening the cable in the long-log method took a longer time than in the short-log method. Fastening of cable includes also controlling of load, truck and other necessary activities before truck leaves the landing.

Delays accounted for approximately 10 % of the loading time in both methods. Among the different types of delay, operational delay was the most time-consuming in loading, followed by technical delay and personal delay. A high percentage of operational delay time was related to preparing the logs for loading in the long-log method.

The loading work phase was modeled for both methods. The data analysis showed that it slightly depends on the interaction of volume and number of logs. In the overall time consumption model for loading, a regression equation was developed for each method to predict loading work phase time as a function of independent variables: number of logs per cycle, volume of logs in each cycle, and interaction between number of logs and volume. The interaction of number of logs and volume was found to be the best variable in order to construct the time consumption model. Other variables were not statistically significant. In similar studies conducted in Iran, the loading depended on the interaction of volume and number of logs per payload (Naghdi 2005, Javadpour 2006).

Productivity of loading in the study was less than in the other studies performed in the eastern part of the Hyrcanian forest. According to (Naghdi 2005), it was 56.8 m^3/effective hour in the tree length method and 41.9 m^3/effective hour in the cut-to-length method. Javadpour (2006) found the average productivity of loading by front end loader was 64.8 m^3/effective hour in the designed landing while the average productivity of undesigned or roadside landing was 31.0 m^3/effective hour. The average productivity of this study was 27.3 and 34.0 m^3/effective hour in the short-log and long-log method that was similar to the study done in the area by Javadpour (2006).

Similar to skidding, the unit cost of loading was mostly affected by machine cost. Approximately, 80 % of the hourly cost of loading was related to machine cost while only 20 % was related to labor cost. Hourly cost of loading accounted for 20 % of the hourly cost of all harvesting activities.

Naghdi (2005) found that unit cost of the tree length method was lower than that of the cut-to-length method. He showed that the unit cost of loading was 0.46 and US$ 0.63/m^3 in the cut-to-length method and tree length method, respectively. Unit cost of loading was US$ 1.84/m^3 for the short-log method and US$ 1.44/m^3 for the long-log method in this study. The unit cost of the short-log logging was 27 % higher than that of the long-log method. The unit cost of loading in this study was approximately 3 times higher than the unit cost found by Naghdi (2005). The main reason for the difference was increased loader price (approximately 3 times higher). Javadpour (2006) calculated the unit cost of loading to be US$ 1.88/m^3 in roadside landing, this is similar to the results of this study. The unit cost of loading made up 9 and 7 % of unit cost of all harvesting work phase in the short-log and long-log method, respectively

4.6 Hauling

Since no adequate and up-to-date information about the time consumption of timber trucking was available for Iran, an empirical time study was conducted to fulfill the gaps in the estimation of hauling productivity. In Iran, studies about hauling in comparison with skidding were minimal.

In forest work science the time consumption of machine work has traditionally been divided into effective time, that includes no delays, and gross-effective time that includes delays shorter than 15 minutes (Forest work…1978, Harstela 1991). The concept of gross-effective time, with an artificial limit of 15 minutes, may not completely fit with the realities of timber trucking, where the transportation time and the working hours of the driver can be considered to be the most relevant from the stand point of both planning the routes and costs optimization (Nurminen et al. 2006). Not only distance, but also the distributions of roads, including forest roads and public roads, as well as their gradient are important factors in the time consumption of long distance transportation (Ljubic 1985). On public roads, in normal conditions, the speed of the truck can exceed 60 km/hour, while on forest roads the truck's speed never exceeds 30 km/hour (Rafat Nia 1997). On public roads the truck's speed depends on such factors as the road surface conditions and steepness of the road. In the study, approximately 23 % of total time consumption of hauling is spent on the forest road, 51 % on steep public roads, and 26 % on public roads with a low-grade slope. On steep public roads, the truck speed was low which resulted in increasing the roundtrip time. The average speed of roundtrip was 39 and 36 km/hour in the short-log and long-log method, respectively. Speeds were found to be independent of slope grade for the slope less than 11 % and strongly influenced by slopes steeper than 11 % (Jackson 1986).

Hauling includes five elements: driving unloaded, loading, and driving loaded, unloading and delay time. Among the elements, driving loaded and unloaded is the most time consuming element that depended highly on hauling distances [Eq. 55, Eq. 56].

The hauling work phase was modeled for both methods. The analysis showed that it depends on the payload volume, hauling distance, and truck speed. Independent variables of volume, number of logs, distance, interaction between number of logs and volume were regressed against hauling time and driving time (unloaded and loaded) separately. Hauling distance was the most influential factor on the time consumption of driving unloaded while hauling distance and volume were the most influencing factors regarding the time consumption of driving loaded. In the overall time consumption and productivity model, hauling distance, truck speed, and volume hauled were the most important factors.

The effect of hauling distance, truck speed, and volume hauled on the time consumption of hauling in this study has been proved. The influence of truck driver's skills, motor power, tire inflation, road condition has been previously reported by (Ljubic 1984, Ljubic 1985) that can be considered in order to improve productivity in this section. The other factors that may influence the productivity and costs of forestry transportation are topography, steepness, climate, and size of operation, volumes available and manufacturing year of the truck.

Naghdi (2005) studied productivity of hauling in the cut-to-length method and tree length method. Productivity of hauling in his study was 6.1 m^3/effective hour in the tree length method and 3.3 m^3/effective hour in the cut-to-length method (Naghdi 2005). The productivity of hauling in this study was 3.13 and 3.71 m^3/effective hour in the short-log and long-log method which is very similar to the productivity of hauling in the cut-to-length method reported by Naghdi (2005).

In hauling, the machine costs account for 79 % of the total hourly costs (system cost), while labor costs made up 21 % of the share. Overall, hourly cost of hauling accounted for 13 % of the hourly cost of all the harvesting work phases. Unit costs of hauling calculated by Naghdi (2005) were 4.2 and US$ 2.5/m^3 in the cut-to-length and tree length method, respectively. Comparatively, the unit cost of hauling was US$ 9.95/m^3 in the short-log method and US$ 8.85/m^3 in the long-log method. The main reason for the difference was the increased truck price in the study as much as approximately 2.3 times higher than the Naghdi's (2005) study while the labor costs have also increased recently. In this study, unit cost of hauling accounted for 43 and 47 % of the unit cost of all the harvesting activities in the short-log and long-log method which was the highest among the different work phases. In the short-log method it was 12.4 % higher than in the long-log method.

If the conditions are suitable, making use of a bigger truck is more productive than a smaller one. The productivity of the long-log timber trucking is higher than the short-log timber trucking. As a rule, the bigger the truck is, the higher its productivity. A study by Naghdi (2005) found similar results.

4.7 Unloading

Time consumption and productivity of unloading was done for both methods in order to find the total cost of harvesting in Iran and the results of unloading is applicable in geographically similar areas where the same type of equipment are used. The performance of truck unloading was different between the short-log and long-log methods. In the short-log method four elements were considered as a component of the unloading work phase, while in the long log method it was six. In the long-log method, log selection and embracing the log were the elements not utilized in the short-log method. In the short-log method truck dumping took the largest share among the elements. In the long-log method log selection took the largest share, followed by unloading, embracing, opening rope, and preparing for unloading.

Like other harvesting work phases, the unloading work phase involved a great part of delay time. Delay time took 8 and 5 % of the total time consumption of unloading in the short-log and long-log method, respectively. Operational delay was the most time consuming delay in the long-log method, while personal delay was the most time-consuming delay in the short-log method. Operational delay accounted for 20 % and 43 % of the total delay time in the short-log and long-log method, respectively. In the long-log unloading, the longest share of operation delay is related to unloading the truck with the front end loader while in the short-log method unloading was done by truck driver. In the long-log method, sometimes the loader was busy, and the truck had to wait for unloading, but in the short-log method there was not such a problem. Front end loader has a key role in the productivity of unloading in the long log method because it is used not only for unloading but also for loading other trucks in the yard.

The time consumption for unloading was modeled only for the long-log method. In the short-log method no variables was found to make model. Regression equations were developed for individual elements of the unloading cycle as well as for the overall time consumption of unloading. The independent variables such as number of logs per payload, volume, and interaction between volume and number of logs regressed against loading time. The analysis showed that it slightly depends on the interaction between volume of logs and number of logs per payload. The time consumption for other elements was calculated as mean values.

The time consumption of unloading in the short-log method took 1.6 % of one cycle of the total time consumption of all work phases which was the lowest; however, in the long-log method it took 3.9 % which was the third least time consuming element after felling and processing. The average productivity of unloading was 144.2 m^3/effective hour in the short-log method and 69.6 m^3/effective hour in the long-log method; therefore productivity of unloading in the short-log method was twice that of the long-log method. The main reason for the differences is rapid and easy unloading performance by the truck drivers in the short-log method. The average time consumption for unloading in the long-log method was approximately three times more than in the short-log method. Since productivity has an inverse relationship with total time consumption, when the time consumption increases the productivity decreases. In order to increase productivity of unloading in the long-log method, proper organization regarding the use of the loader and timber truck transportation is necessary.

Unloading costs in the short-log method was set at zero as a result of the unloading performance of the truck driver (truck dumping). Unit cost of unloading in the long-log method was US$ 0.59/m^3 which was the lowest cost after felling and processing. The unit cost of unloading in the long log-method was related to the machine cost (as much as 84 %) with the rest being related to the labor cost. Overall, the hourly cost of unloading accounted for 17 % of the hourly cost of all harvesting activities.

4.8 Damage to residual stand

Well designed and constructed trails should be wide enough to allow wood extraction from the forest. The risk of damage to the boundary trees is low on such trails. Most of the damaged trees in this study (about 86 %) were heavily injured, making them highly vulnerable to fungi infestation. In many cases, the growth of forest stand (annual increment) can be affected by the damage. One of the most important issues in harvesting, except when clear-cutting is used, is logging damage to residual stands. Usually in the harvesting procedure, tree damage is to be expected and unavoidable, especially in mature, fully stocked stands.

The results of this study showed that the harvesting operation may cause significant damages to the residual stand. Approximately 32 % of the trees were damaged in the whole stand under studies. This damage might have been avoided through the application of more careful logging procedures and applying low impact logging methods. Low impact logging means the use of techniques, such as directional felling, in order to minimize damage to the residual stand. Most of the bole damage was caused by winching and skidding when logs struck the standing trees. The skid trail construction was also one of the important sources of damage to the boundary trees. The location of the boundary trees may be an important factor as to whether they are damaged in the construction of the skid. The trees located uphill of the skid trails were less damaged than those on the downhill side. The likely reason for this is that in the uphill side of the skid trail, the trees were located in a place where the bulldozer blade does not reach these trees; however evidence verifying this is not available. Damages to the standing trees, caused by the bulldozer hits, are usually deep and serious.

The number of curves in the skid trails, especially in the long-log skidding, may account for a significant portion of the damage to the boundary trees, though it has not been proven in this study. A high percentage of all the damaged trees had bark removed from the root and stem, while others were uprooted, were leaning or had their stem or crown broken. Damage to the residual stand could have been even more serious if damage to regeneration was also recorded

According to the information gathered in this research, for the winching strips, 67.2 % (short-log method) and 56.8 % (long-log method) of damage to the residual stand was found in the diameter class 25-50 cm, followed by diameter class 50-75 cm that contained 21.9 % (short-log) and 28.4 % (long-log) of the damaged trees. The share of damaged trees increased significantly in the small diameter classes, where the bark of the tree is too thin and highly vulnerable to damage. Another reason for the higher damage in this class was greater percentage of trees in the class (64.3 % (short-log) and 58.0 % (long-log)). For the small-size trees the risk of damage decreases due to their flexibility. This was also found by Hosseini et al. (2000). Uprooting of trees usually occurs in diameter classes below 40 cm DBH. In this case, the root system is not properly developed; therefore during the construction of the skid trails the trees may be uprooted. Usually the skidder operator attempts to avoid the big trees in order to speed-up the extraction work.

As a result of time constraints in the data collection damage to regeneration and soil compaction were not studied, although they are considered as important as the damage to the residual stand. The percentage of trees that were damaged by the harvesting operations (by winching and skidding) ranged from 31.6 to 35.8 % in the short-log and long-log method, respectively. Some of the injured trees would not recover because of serious breakage and other injuries that creates potential for decay. Almost all wounds in the damaged trees were deep, making them susceptible to fungal infestation. Due to the high percentage of injuries and severity of damage, in later years the stand will have a lower value. The severity of damage is defined when the damage to bole decreases one grade on the butt log. Decreasing one grade on the bole equals losing the value of the most valuable log in the tree.

The wounds on the injured trees are located in different areas. In most of the cases, the injuries are situated in the bottom 1 m of stem which represents the most valuable part of the tree. Several authors have also noted that most of the wounds occur at or near the base of the tree in logging time (Shea 1960, Bettinger and Kellogg 1993, Vasiliauskas 2001). In spruce stands, harvested by partial and shelter wood cutting, only 15 % of all trees wounds were situated above 0.5 m, with over 60 % of the trees being damaged at the root collar (Vasiliauskas 1993). In this study about 86.8 % of wounds were located below 1 m (wounds on root are also included) with the remainder being located above 1 m.

Damage to the trees results in their loss of value. Although the effect of deep or light injuries on the potential fungal infection of the damaged trees has not been previously studied in the Iranian forests, according to Shigo (1979, 1986), light damage does not affect the value of the residual trees whether soon after they are damaged or in the longer term. All minor wounds are able to recover without having any effect on the log grade.

The number of wounds on the damaged trees varied considerably; hence they were classified into three categories. Overall (along skid trails and winching strips in both methods), 45 % of all the damaged trees had 1 wound, while 41.0 % had 2-3 wounds, with the remainder (14.0 %) having more than 3 wounds. For all the damaged trees, 23.4 % of damages were located on the roots, 64.0 % were located on the lower 1m of the stem, with 12.6 % located above 1 m. In the short-log method, the percentage of damage to the roots was higher than in the long-log method by 5.3 %. This can be explained by the increased number of winched or skidded logs, by increasing the number of logs per cycle the chance of contact with root of trees increased.

Results of previous studies suggest that the sizes of the logging wounds can be classified into several groups. In this study three categories of wounds were applied: 1) less than 100 cm^2; 2) 100-1000 cm^2; and 3) more than 1000 cm^2 (Naghdi 2005). In North American conifer forests, scar sizes on damaged trees ranged from 0.13 cm^2 to 2968 cm^2 (Bettinger and Kellogg 1993). Sidle and Laurent (1986) found that only 5 % of all scars were bigger than 929 cm^2. In the study by Vasiliauskas (1993), the size of logging wounds on Norway spruce *Picea abies* reached 1000-3500 cm^2. Nevertheless, most of studies in spruce stands show that logging wounds are usually smaller than 100 cm^2 (Vasiliauskas 1993) with an average size in the range of 50-200 cm^2 (Aufsess 1978). In this study, overall (along skid trails and winching strips in both methods) 43.7 % of wound areas covered less than 100 cm^2, 45.9 % of the total scarring damage varied between 100 and 1000 cm^2, and 10.3 % was larger than 1000 cm^2. Comparing the methods found that the long-log method had more large wounded areas (100cm^2) than the short-log method by 1.12 %. This can be explained by more maneuvering required of the logging equipment for extracting longer logs and more occurrence of hanging-up during the extraction process.

Most trees wounded during forest operations are not randomly distributed within a stand, rather they are situated close to the skid trails and winching strips (Bettinger and Kellogg 1993, Naghdi 2005, Nikoy Seyahkal 2007). Siren (1982) noted that 90 % of wounded stems were less than 5 m away from the centerline of the extraction route. Naghdi (2005) reported that 85.2 % of damaged trees were less than 3 m away from skid trails, while 12.8 % of the damaged trees were between 3-5 m away from skid trails, while only 2 % of damaged trees were more than 5 m away from the centerline of skid trails. Nikoy Seyahkal (2007) revealed that along winching strips, 30-38 % of damaged trees occurred 0-0.5 m from the centerline of the winching strips which was followed by 17-23 % (0.5-1 m), 15-22 % (1.01-1.5 m), 13-16 % (1.51-2 m), 8-12 % (2.01-2.50 m), and 1-2 % (2.51-3 m) from the centerline. His study also found that about 50 % of damaged trees were located within 1 m of the centerline, when the inclusion zone was expanded to 1.5m then the share of the damaged trees went up to 75 %. Due to similar forest stands, working conditions and skidder operator of this study with Nikoy Seyahkal's (2007) study similar results might be obtained if the location of damaged trees from the centerline of skid trails were studied.

Damage to the residual stand might be reduced by proper planning and layout, training of workers and correct management and supervision. It is reported that residual stand damage was mostly decreased by careful planning and using skilful operators (Cline et al. 1991). Despite preventive measures, damage to residual trees cannot be completely eliminated in practice. Overall, damage to the residual stand in the long-log method was higher than in the short-log method.

4.9 Recommendations for reducing the damage in harvesting operations

One of the most important sources of damage to the residual stand is related to unskilled workers (Nikoy Seyahkal 2007). Due to the importance of worker's role on the quality of production it is recommended to train them ensuring their familiarity with new methods. Motivation of workers in order to decrease damage to the residual stand should also be considered as important. For instance, one of the ways to increase the quality of skidding performance is training the choker setters. The choker setters should pay attention to hooking. Sometimes they attached the winch cable to the middle of the logs instead of at the end. It may result in significant damage to the residual stand, increasing the time consumption, and the chances of hanging-up occurring.

In Iran no studies have documented the progress of wound on the damaged trees in the residual stand. Pathology studies, in order to find the prevalent kind of fungi attack on damaged trees and finding a treatment, helps to improve future stands.

Different species have different susceptibility to damage caused by the harvesting operation. Logically, the thick bark of some species increases the resistance to long term damage (Bettinger and Kellogg 1993). Different harvesting operations may have different effects on the residual stand. The number of damaged trees along the skid trail is related to the width of the skid trail also in addition to the number of skid trails. The total number and the proportion of skidding damages could therefore be significantly reduced by a reduction of the skid trail area.

When introducing a new forest plan, potential damage caused by wood extraction should be taken into account. A further possibility for reducing the number of damaged trees associated with extraction needs to be considered.

Without doubt, careful planning of the harvesting operation should be related to other fields of forestry such as silvicultural practices and forest conservation. In some cases it might be better to omit individual commercial trees that require long skidding distances or those that are difficult to harvest because of steep terrain or difficult soil conditions. It is also better to exclude individual trees that should be winched over long distances. Harvest planning should determine whether the harvesting of isolated trees is justified from economical, technical and conservation point of views. In some cases, for the extraction of individual trees, animal skidding is an alternative that should be taken into account.

In skid trails unnecessary blading should be avoided as it is one of the main sources of damage to the residual stand. The largest share of blading damage is caused by the bulldozer. Wheel skidders can also cause considerable damage if the operators' awareness or motivation is low (FAO 1997) and trees to be protected are not clearly marked. The number of skid trails has a direct relation to the amount of logging damage. Usually the greater is the skid trail area the greater the logging damage (Abrasion 2003). Planning the layout of the skid trails should be done carefully. The number of trails should be kept to a minimum, but winching strips should be longer, because construction of skid trails destroys the forest structure and increase the damage to the residual stand (Nikoy Seyahkal 2007). Old skid trails should be used whenever possible (Abrasion 2003). The main skid trails should be straight or have gentle curves. Secondary skid trails should enter the main trail at angles less than 45 degrees. This will reduce load swing and assist in minimizing damage to the residual stand (Abrasion 2003). Logs should not be too long for winching and skidding. It increases chance of hanging-up and thus may cause significant damage to the residual stand. Additionally, in order to prevent erosion, slope with possibly low steepness for skid trails and drainage should be selected.

Since 1970, in the developing countries (e.g. Congo, Surinam), low impact logging is applied practically as a more environmentally friendly method (Nikoy Seyahkal 2007). In the tropical regions, many studies have been done regarding reducing damage to the residual stand and improving the potential of future forests. Since the structure of the Hyrcanian forest and geographical conditions are similar to the Iranian forests, this experience of the practical application of this method might help to reduce the damage and simultaneously increase the productivity

4.10 Opportunities for future research

This study has provided information on the harvesting cost, productivity and stand damage after applying both short-log and long-log methods to the harvesting operations. Due to different characteristics of each stand, it is not clear if these results can be replicated in other parts of the Hyrcanian forests, however, the results may be generally applicable. Further study regarding the effect of the short- and long-log methods on damage to regeneration area, soil and skid trail conditions is also recommended. However, the operator's role, as an important factor that influences productivity, should be studied in each work phase of harvesting.

5 CONCLUSIONS

Currently the long-log method is more widely used in Iran than the short-log method. The short-log method is applied only when the diameter is large. Up to now, there were no attempts to compare the productivity and costs for the two methods and damages to the residual stand in Iran. In this research both methods were evaluated from a technical, environmental, and economical point of view.

1. It is proved that the stump diameter of the tree is the most influential factor affecting time consumption and productivity of felling while inter–tree distance also influences the time consumption and productivity of felling. The productivity of felling large diameter trees is higher than in felling trees with a small diameter.
2. The hypothesis that productivity of processing and skidding in the long-log method is higher than in the short-log method was proven. Although differences in the two methods were not high, particularly in skidding. In the processing all elements of the work phases were similar, only bucking was different, though not enough to result in significant difference in the productivity of the two methods. In skidding, the large number of logs per cycle compensates for the lower volume in the short-log method. Performance of skidding is done with wrapping the cable around the logs. Applying a choker to the harvesting system may significantly increase productivity.
3. The study confirmed the assumption that loading and hauling productivity in the long-long method is higher than in the short-log method. The high capacity of trucks (from approximately 10 m^3 in the short-log to approximately 15 m^3 in the long-log method) is an important reason for the high productivity in hauling and loading in the long-log method.
4. The hypothesis that unloading productivity in the short-log method is higher than in the long-log method was confirmed. But the share of unloading cost of total cost is low, thus it has a small effect.
5. Effective time of performing one cycle of harvesting system including felling, processing, loading, hauling, and unloading is 270 and 321 minutes in the short-log and long-log method, respectively. It shows that the time consumption of performing one cycle of harvesting (from felling to unloading) in the long-log method was approximately 19 % higher than in the short-log method. Nevertheless, the production cost of the short-log method was approximately 7 % higher than in the long-log method.
6. A large share of total harvesting cost is attributed to the transportation by truck of logs from the landing to mill, followed by skidding, loading, processing, felling, and unloading.
7. Damage to the residual stand in the long-log method is higher and heavier than in the short-log method. Also depth and severity of injuries were more serious in the long-log method than in the short-log method. In order to increase the awareness of conservation needs in harvesting practice, new requirements in forest management plans including the training of personnel and their motivation should be emphasized. This could also increase the efficiency in wood procurement from forest to mill.
8. Blading the skid trails causes serious injuries to the boundary trees and significant losses in volume potentially added to future forest stands. Replacing the currently practiced ground skidding system with a cable system in areas with steep slopes would preclude the construction of skid trails and consequent disturbance.
9. Overall, productivity of the long-log method is higher than the short-log method. Consequently the unit cost of the long-log method is lower than that of the short-log method. These results suggest that the long-log method is more economically justified, while the short-log method caused less damage to the residual stand and had lower environmental impacts. In any case it presumes the log lengths should not be over 10.4 m. This study did not take into account damage to regeneration and soil (soil compaction and formation gullies) caused by the harvesting operations. In any case, extraction of very long length logs should be avoided due to resulting damages to the residual stand.

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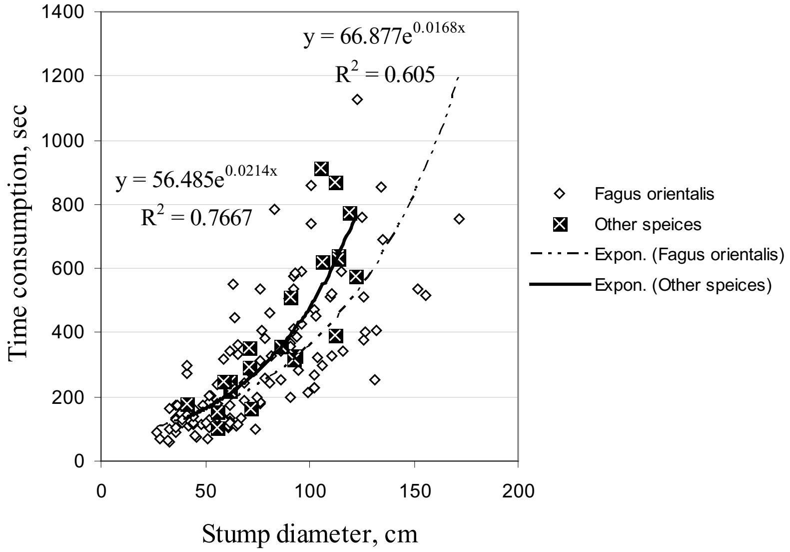
APPENDICES

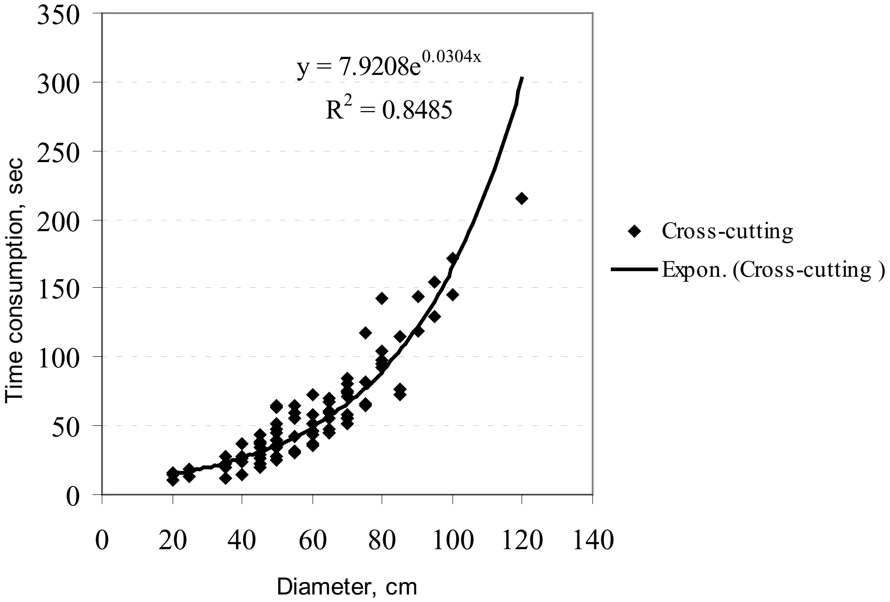
APPENDIX 1

Time consumption of felling in different stump diameters (other species includes *Carpinus betulus, Tilia rubra, Alnus subcordata, Acer platanoides*). *Fagus orientalis* is the most important commercial species in the Hyrcanian forest.



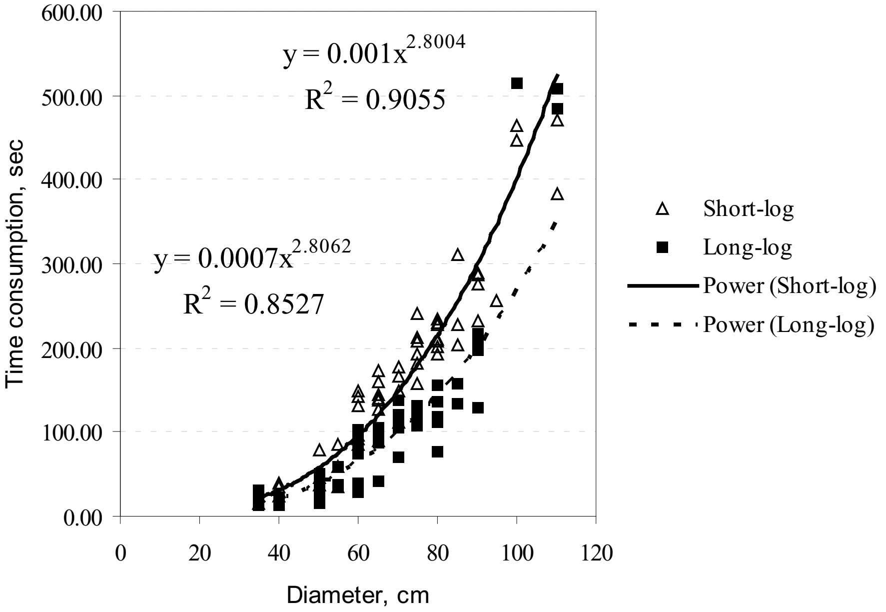
APPENDIX 2

Time consumption for one cut (cross-cut) as a function of diameter.



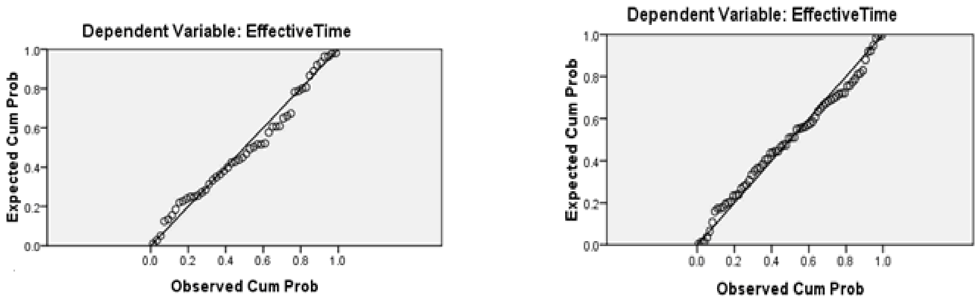
APPENDIX 3

Time consumption of bucking as a function of diameter at the butt. In bucking, there are usually several cuts per stem that depend on the diameter and height of tree. Time consumption of bucking in the long-log method includes bucking in the forest and landing.



APPENDIX 4

Normal probability plot of overall time consumption model in the skidding of the short-log (a) and long-log (b) method.

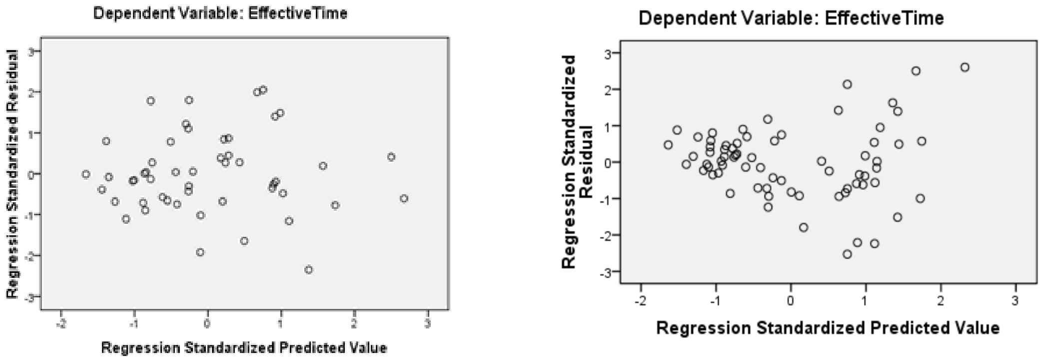


a

b

APPENDIX 5

The scatter plot of the standardized residuals of overall time consumption model in the skidding of the short-log (a) and long-log (b) method.

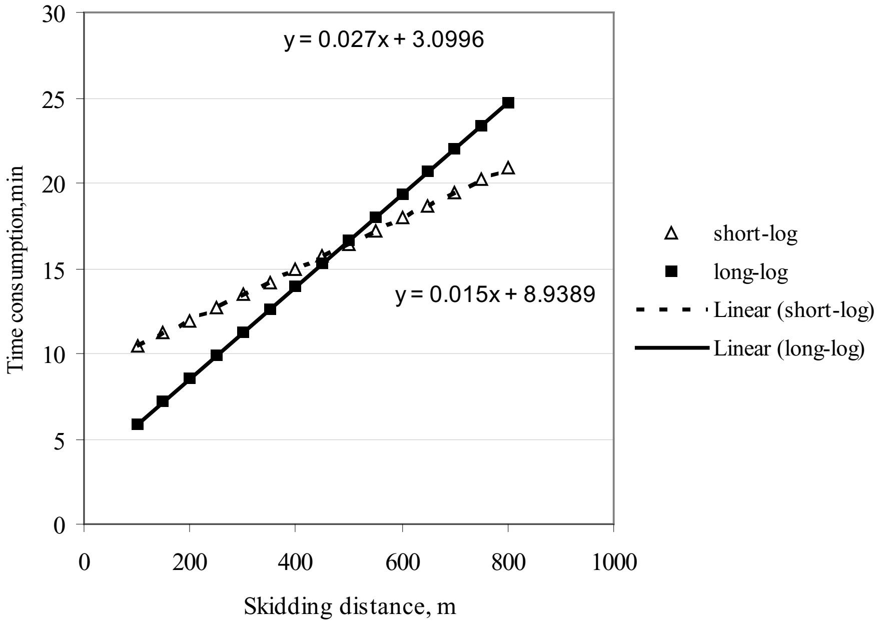


a

b

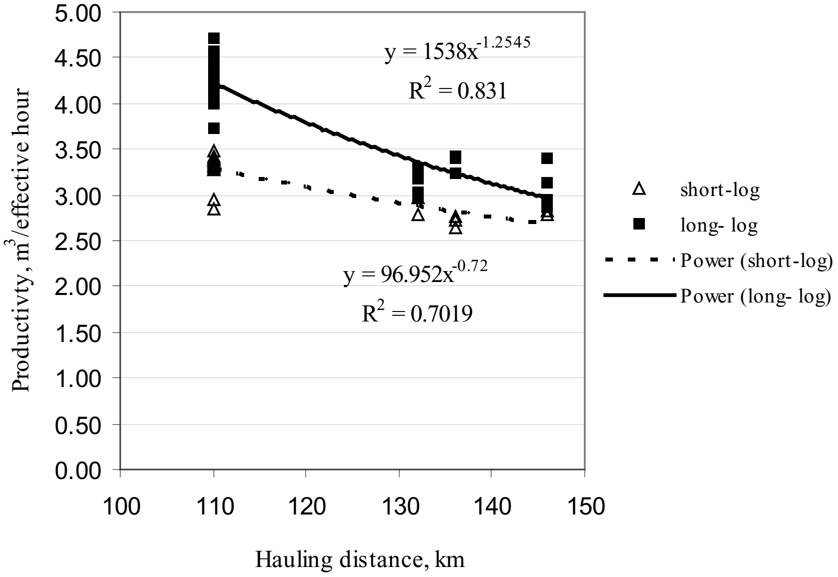
APPENDIX 6

Effect of skidding distance on effective time in short-log and long-log method.



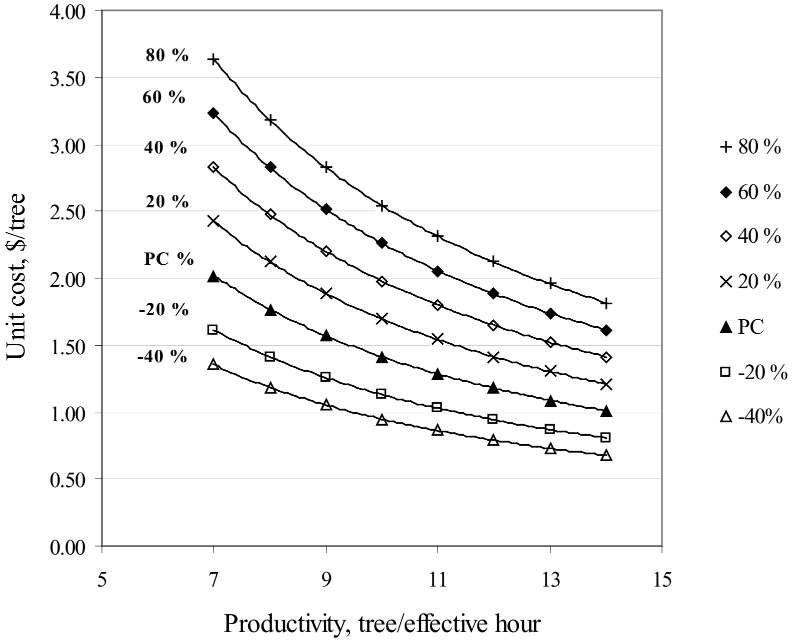
APPENDIX 7

The effect of hauling distance (roundtrip) on productivity of hauling using productivity model in the short-log and long-log method.



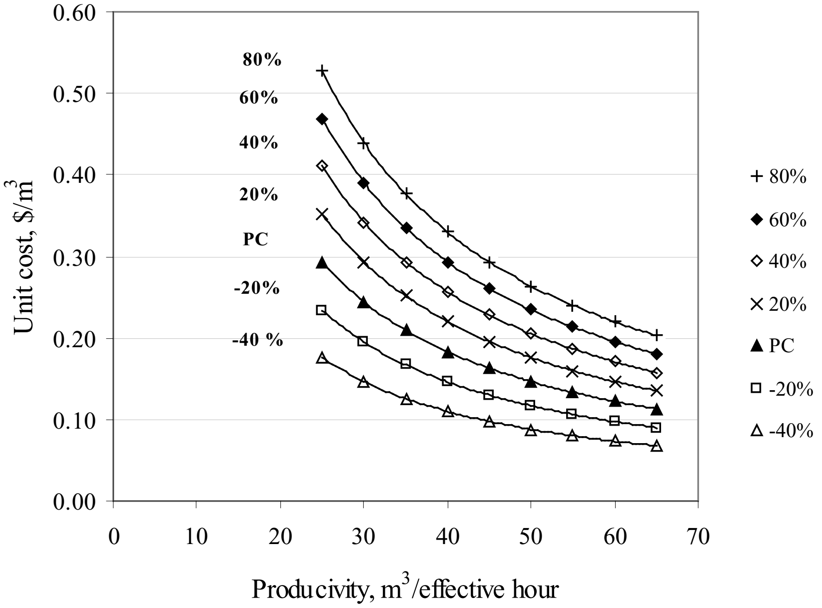
APPENDIX 8

Sensitivity analysis of unit cost when the system cost (the hourly cost of chain saw and felling crew) changes by 20 % in manual felling (PC = present conditions).



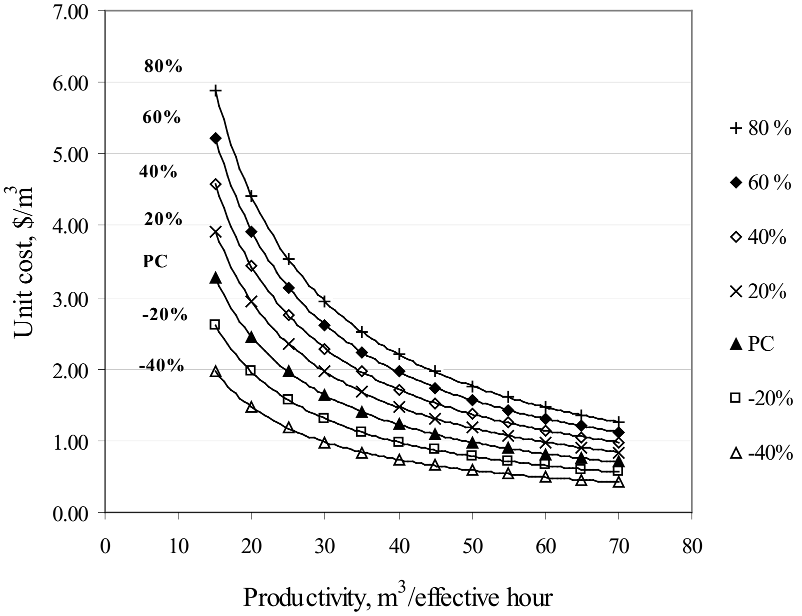
APPENDIX 9

Sensitivity analysis of unit cost when the system cost of processing (the hourly cost of chain saw and processing group) changes by 20 % (PC = present conditions).



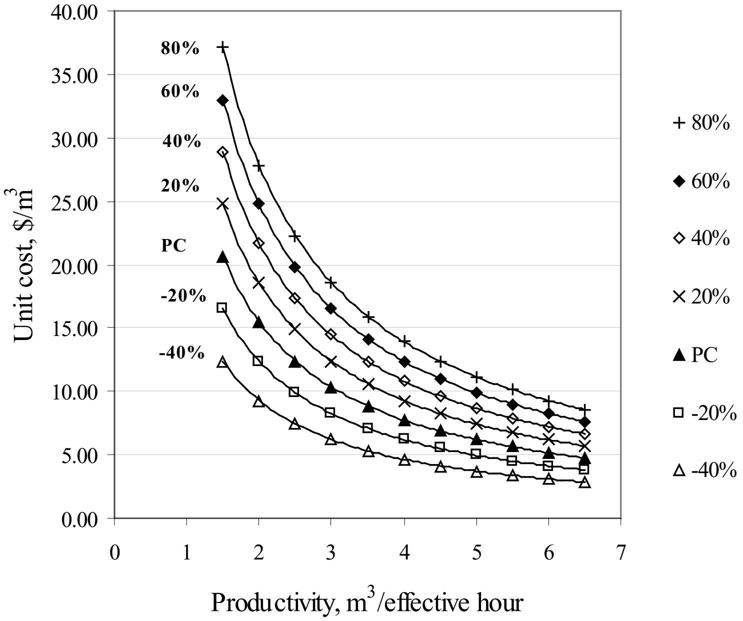
APPENDIX 10

Sensitivity analysis of unit cost when the system cost of loading (the hourly cost of loader and loading group) changes by 20 % (PC = present conditions).



APPENDIX 11

Sensitivity analysis of unit cost when the system cost of hauling (the hourly cost of truck, the driver, and his assistant) changes by 20 % (PC = present conditions).



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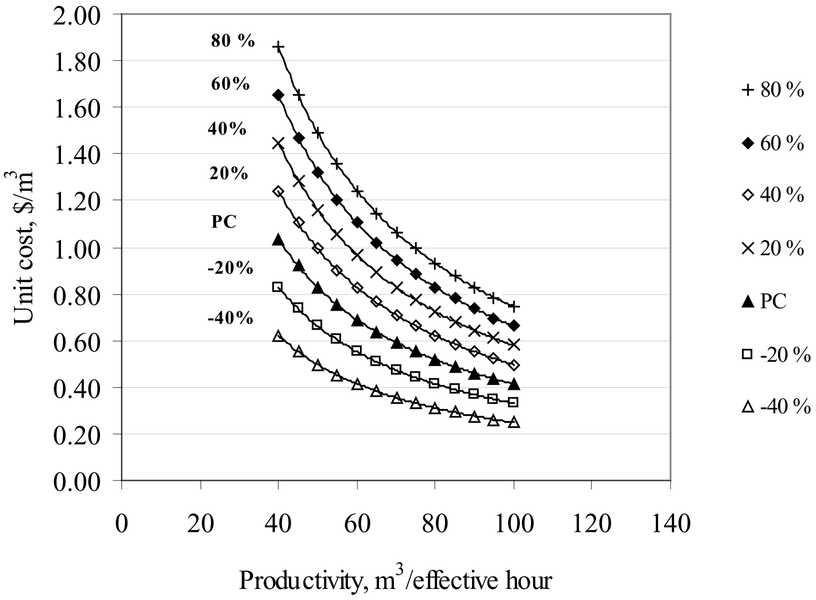
APPENDIX 12

Sensitivity analysis of unit cost when the system cost of unloading in the long-log method (the hourly cost of front- end loader, loader operators and his assistant) changes by 20 % (PC = present conditions).



APPENDIX 13

Summary of damage to residual stand along winching strips in the short-log method (the number in the parenthesis refers to damaged trees).

Species	Diameter class, cm			Number of wounds			Place of wounds			Type of injuries					Degree of wounds	
										Wounds			Other injuries			
	25-50	50-75	>75	1	2-3	>3	On root	Up to 1 m	>1 m	<100	100-1000	>1000	broken	leaning	light	deep
Fagus orientalis	71 (23)	38 (9)	17 (6)	19	11	6	13	20	3	18	14	4	0	2	12	24
Acer platanoides	12 (4)	5 (1)	0	3	2	0	1	4	0	4	0	1	0	0	2	3
Ulmus glabra	1 (1)	0	0	1	0	0	0	1	0	1	0	0	0	0	0	1
Carpinus betulus	33 (12)	8 (4)	0	4	7	2	2	9	2	4	9	0	1	2	6	7
Acer cappadocicum	1 (1)	0	0	0	1	0	0	1	0	1	0	0	0	0	0	1
Tilia rubra	2 (1)	0	0	0	1	0	0	1	0	0	1	0	0	0	0	1
Alnus subcordata	8 (1)	2	1 (1)	0	1	1	0	2	0	1	1	0	0	0	1	1
Total surface area, ha	0.433															
Total trees	128	53	18		59			59			59		5		59	
Percentage of trees in each class of total trees	64.3	26.6	9													
Total damaged in each class	43	14	7	27	23	9	16	38	5	29	25	5	1	4	21	38
Percentage of damaged tree to total damaged trees in each class	67.2	21.9	11	45.8	39	15.3	27.1	64.4	8.5	49.2	42.4	8.5	15	75	35.6	64.4

APPENDIX 14

Summary of damage to residual stand along winching strips in the long-log method (the number in the brackets refers to damaged trees).

Species	Diameter class, cm			Number of wounds			Place of wounds			Type of injuries					Degree of wounds	
	25-50	50-75	>75	1	2-3	>3	On root	Up to 1 m	>1 m	Wounds			Other injuries			
										<100	100-1000	>1000	broken	leaning	light	deep
Fagus orientalis	86 (28)	43 (16)	26 (10)	24	22	5	10	36	5	22	25	4	0	3	18	33
Acer platanoides	9 (5)	4	1 (1)	1	2	0	1	1	1	1	2	0	1	2	0	3
Ulmus glabra	2 (1)	1	1 (1)	0	1	1	0	2	0	0	2	0	0	0	1	1
Carpinus betulus	22 (10)	11 (6)	2 (1)	8	6	2	3	11	2	7	6	3	0	1	3	13
Acer cappadocicum	3 (2)	0	0	1	0	0	0	1	0	1	0	0	1	0	0	1
Tilia rubra	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Alnus subcordata	13 (4)	9 (3)	1	3	1	2	1	2	3	1	2	3	0	1	1	5
Total surface area, ha	0.425															
Total trees	137	68	31		79			79			79		9		79	
Percentage of trees in each class to total trees	58	29	13													
Total damaged in each class	50	25	13	37	32	10	15	53	11	32	37	10	2	7	23	56
Percentage of damaged tree to total damaged trees in each class	56.8	28.4	14.8	46.8	40.5	12.7	19	67.1	14	40.5	46.8	12.7	22	78	29.1	70.1

APPENDIX 15

Summary of damage to residual stand along the skid trails in the short-log method (the number in the parenthesis refers to damaged trees).

Species	Diameter class, cm				Number of wounds			Place of wounds			Type of injuries					Degree of wounds	
											Wounds			Other injuries			
	5-25	25-50	50-75	>75	1	2-3	>3	On root	Up to 1 m	>1 m	<100	100-1000	>1000	broken	leaning	light	deep
Fagus orientalis	53 (17)	33 (5)	21 (2)	7 (1)	10	4	3	6	8	3	8	8	1	2	6	6	11
Acer platanoides	22 (7)	11 (3)	4 (2)	3	4	5	1	3	6	1	6	3	1	1	1	3	7
Ulmus glabra	17 (3)	7 (1)	1	0	0	3	1	0	3	1	1	2	1	0	0	1	3
Carpinus betulus	27 (9)	14 (3)	10 (2)	2	4	7	1	4	8	0	4	7	1	0	2	5	7
Acer cappadocicum	5 (2)	1 (1)	1	0	0	0	1	0	1	0	1	0	0	0	2	0	1
Tilia rubra	2 (1)	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Alnus subcordata	25 (8)	12 (4)	5 (1)	1 (1)	6	5	2	3	9	1	7	6	0	0	1	4	9
Pyrus communis	1 (1)	0	1	0	0	0	1	0	0	1	0	1	0	0	0	0	1
Total surface area, ha	0.28																
Total trees	152	78	44	13		58			58			58		16		58	
Percentage of trees in each class to total trees	53	27.2	15.3	4.5													
Total damaged in each class	48	17	7	2	24	24	10	14	35	7	27	27	4	3	13	19	39
Percentage of damaged tree to total damaged trees in each class	64.8	22.9	9.5	2.7	41.4	41.4	17.2	25	62.5	12.5	46.6	46.6	6.9	19	81	32.7	67.2

APPENDIX 16

Summary of damage to residual stand along skid trails in the long-log method (the number in the parenthesis refers to damaged trees).

Species	Diameter class, cm				Number of wounds			Place of wounds			Type of injuries					Degree of wounds	
											Wounds			Other injuries			
	5-25	25-50	50-75	>75	1	2-3	>3	On root	Up to 1 m	>1 m	<100	100-1000	>1000	broken	leaning	light	deep
Fagus orientalis	104 (39)	64 (15)	29 (5)	8 (2)	30	18	6	12	29	13	18	27	9	2	5	16	38
Acer platanoides	22 (9)	12 (5)	4 (3)	2 (1)	5	7	3	3	10	2	9	5	1	0	3	3	12
Ulmus glabra	12 (6)	4 (1)	0	1	1	3	1	2	3	0	4	1	0	0	2	1	4
Carpinus betulus	53 (23)	26 (7)	11 (2)	4 (1)	11	16	2	5	20	4	11	14	4	2	2	9	20
Acer cappadocicum	2 (1)	2	0	0	0	1	0	0	1	0	1	0	0	0	0	0	1
Tilia rubra	2 (1)	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	1
Alnus subcordata	22 (12)	12 (6)	9 (2)	1 (1)	10	5	3	6	12	0	8	10	0	0	3	5	13
Pyrus communis	1 (1)	1	1	0	0	1	0	0	1	0	0	1	0	0	0	0	1
Total surface area, ha	0.33																
Total trees	218	121	54	16		124			124			124		19		124	
Percentage of trees in each class to total trees	53	30	13	4													
Total damaged in each class	92	34	12	5	57	52	15	28	77	19	52	58	14	4	15	90	34
Percentage of damaged tree to total damaged trees in each class	64.3	23.7	8.4	3.5	46	41.9	12.1	22.5	62.10	15.3	42	46.8	11.3	21	79	27	73