

Dissertationes Forestales 177

Harvesting operations in eucalyptus plantations in
Thailand

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Academic dissertation

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ABSTRACT

The eucalyptus has recently become an important timber species in Thailand, particularly in relation to timber supply within the pulp industry. Demand for raw material is continuously increasing, but harvesting techniques continue to rely on old-fashioned methods of harvesting, which are motor-manual and labour-intensive operations. These harvesting operations typically provide relatively low productivity and are time consuming. This study addressed the timber harvesting potential in Thailand including: average productivity, identifying ineffective work phases, and how work performance can be improved. Therefore, the study was conducted to analysis existing timber harvesting systems as a whole and compare alternatives, and to explore improvements in forest harvesting systems in Thailand through work study, working postures analysis, and simulation. Work study allowed the researcher to understand in detail the conventional harvesting systems and obtain information regarding work activities and time allocations. Harmful tasks and awkward working postures were evaluated by working posture analysis. Simulation allowed the researcher to examine the impact of changing harvesting systems.

The study confirmed that motor-manual operations have rather low production rates compared to intermediate and fully mechanized harvesting techniques, which are applied in other parts of the world. The most unproductive work phase is cross-cutting, and further research should pay attention to this work phase. According to the working postures analyses, the most problematic working postures found for manual tasks included stacking, delimiting, and loading. Simulation findings suggested that reorganization of job sequences is one major possibility for improving productivity. Log length and tree size also displayed a significant effect on overall productivity. Further research should consider enhancing the system with partial mechanization, such as farm tractors, skidders and multi-tree-handling harvesters. Education and training are also important measures to increase not only work performance, but also to improve work safety.

Keywords: eucalyptus, harvesting systems, time consumption models, productivity, simulation

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Helsinki, April 2014

Nopparat Manavakun

ABBREVIATIONS

CTL	Cut to Length
DBH	Diameter at Breast Height (1.3 m above ground)
FAO	The Food and Agriculture Organization
FT	Full Tree
HP	Horsepower
ILO	The International Labour Organization
LUBA	Loading on the Upper Body Assessment
MAI	Mean Annual Increment
NSR	The Nordic Council on Forest Operations Research
OCRA	Occupational Repetitive Actions
OWAS	Ovako Working Posture Analysing System
PPE	Personal Protective Equipment
REBA	Rapid Entire Body Assessment
RFD	The Royal Forest Department
RIL	Reduced Impact Logging
RULA	Rapid Upper Limb Assessment
SMH	Scheduled Machine Hours
TL	Tree Length
WMSDs	Work-related Musculoskeletal Disorders

TERMINOLOGY

Cut to length method	Logging method where felled trees are processed into wood assortments in the stump area and the processed wood assortment are then transported to roadside.
Tree length method	Logging method where delimbed and topped stems are extracted to at least roadside intact.
Full tree method	Logging method where the entire tree biomass above the felling cut (above the stump) is extracted to roadside intact.
Humidex	An index number used to describe how hot the weather feels to the average person, by combining the effect of heat and humidity.
Personal Protective Equipment	Protective clothing, helmets, goggles, or other garments or equipment designed to protect the wearer's body from injury.
Reduced Impact Logging	The intensively planned and carefully controlled implementation of timber harvesting operations to minimize the environmental impact on forest stands and soils.

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1 INTRODUCTION

1.1 Forestry in Thailand

Thailand is located in a tropical region, the temperature is high year-round with small differences between seasons, as well as heavy precipitation during the rainy season. There is a large number of tree species in the natural tropical forest. The two main types of natural forests in Thailand are evergreen forest and deciduous forest. In 1961, more than half of Thailand was covered by forest, but since then the forested areas have rapidly decreased, to less than 30% in 1988 (Waggener 2001). This is due to heavy deforestation through unsustainable timber production, slash and burn tactics, shifting cultivation, land resettlement and the construction of facilities (FAO 2009). Consequently, in 1989, the government announced a ban on logging in natural forests (Waggener 2001) in order to preserve the remaining forests and promote reforestation. As a result of the logging ban, the forested area has slightly increased, the forest cover currently accounting for approximately 37% of the land area (FAO 2010). However, it has not yet reached the goal of the national policy, which is 40% forest cover in Thailand: 25% for conservation, and the remaining 15% for production purposes (Nalampoon 2003). From an ownership perspective, the majority of the forestland is public (88%), and the remaining forest is privately owned.

Since logging from natural forests is banned, wood production has shifted from natural forests to forest plantations. The Royal Forest Department (RFD) launched a series of measures to promote afforestation and the development of plantation forests. For example, in 1994 the RFD launched a forest plantation promotion project that targeted private owners and local farmers to establish commercial plantations. The government partially subsidized the farmers for this purpose (Waggener 2001; Cheng and Clue 2010).

There are four primary tree species in Thai forest plantations: teak (*Tectona grandis*), rubber (*Hevea brasiliensis*), acacia (*Acacia mangium* and *A. auriculiformis*) and eucalyptus (*Eucalyptus camaldulensis*, *E. urophylla* and *E. deglupta*) (Cheng and Clue 2010). Rubber is the largest forest plantation species, accounting for 42% of the forest plantation area, while eucalyptus accounting for 9% (Figure 1).

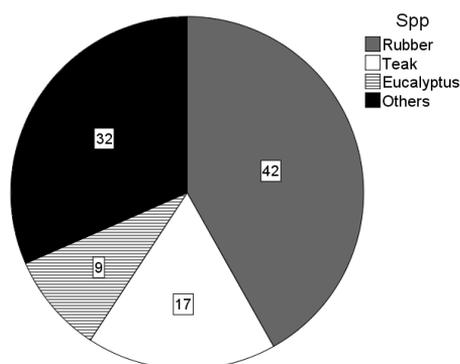


Figure 1. Plantation area percentage by species (FAO 2009).

The largest sectors of the wood industry in terms of production volume in Thailand are pulp and paper, sawmilling and particleboard (FAO 2009), and the demand for small trees for pulp and wood chips has increased (Jamroenpruksa 1997; Royal Forest Department 2006). Accordingly, the number of forest plantations has also rapidly increased, particularly eucalyptus plantations. Due to their good growth performance, climatic adaptability and utilization, eucalyptus trees have expanded and become the most important commercial tree species (Fumikazu 2001). Eucalyptus wood is used for various purposes, including pulp and paper, wood chips, poles, particleboard, construction, sawn wood, plywood, veneer, fuel wood and bioenergy purposes (Royal Forest Department 2006; Benjachaya 2009; FAO 2009), with the pulp and paper sector dominating the overall forest industry (70–80% of total eucalyptus wood volume consumed) (Luangviriyasaeng 2003; FAO 2009). Furthermore, minor products obtained from eucalyptus include oil distilled from the leaves, and tannin from bark (FAO 2009).

The estimated area of eucalyptus plantations in Thailand varies between 480 000 and 600 000 ha (FAO 2001; Luangviriyasaeng 2003). The current annual new planting area is about 40 000 ha, mainly by private companies and a large number of small farmers (Luangviriyasaeng 2003). Smallholder farmers account for between 80–90% of total pulpwood production (Woods et al. 2011). According to FAO (2009), the recorded mean annual increment (MAI) in Thai eucalyptus plantations varies between 8–25 m³/ha depending on site quality.

1.2 State of the art

Timber harvesting has become an essential practice to fulfil the demand for pulpwood in Thai industry. Generally, the specific environmental factors affecting forest operations can mainly be categorized into terrain, climatic, and tree characteristics conditions (Staaaf and Wiksten 1984; Sessions 2007; Uusitalo 2010). In unique tropical forests, those features have a significant impact on logging methods and equipment selection. From the perspective of a logging organization, those factors can be divided into internal factors and external factors. The internal factors can be identified as the controllable factors, whereas the external factors are other factors that are out of the organization's control (Figure 2). In Thailand, the internal factors include machine availability, budget, labour skill and labour ability. The external factors comprise climate, terrain, tree characteristics, forest law and forest policy.

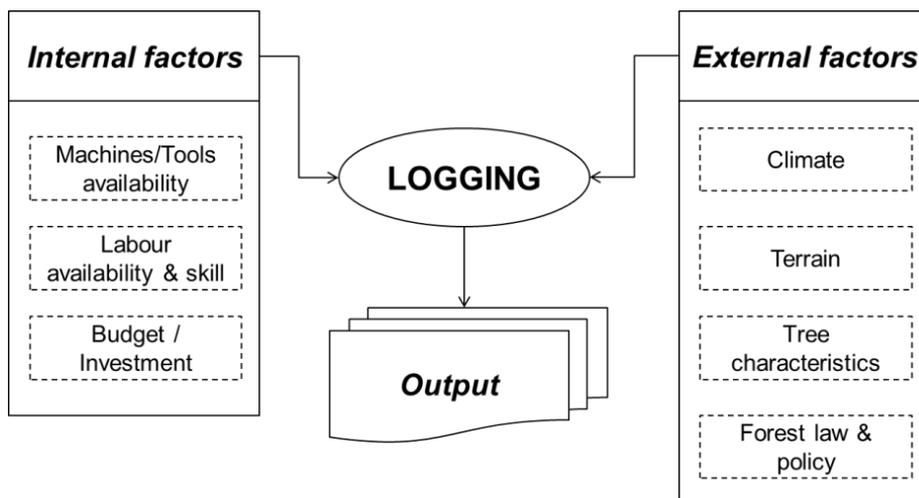


Figure 2. The factors that have a significant influence on forest operations in Thailand (according to Staaf and Wiksten 1984; Greulich et al. 1999; Sessions 2007; Uusitalo 2010).

1.2.1 Internal factors

The motor-manual harvesting system is the dominant method in developing countries, such as Thailand. Due to inexpensive labour, expensive machinery and a shortage of skilled machine operators and technicians, the introduction of highly mechanized systems has been delayed (Henrich 1987; Guangda et al. 1999).

The harvesting technology in Thailand ranges from basic technology (i.e. hand-tools, chainsaws, brush saws) to moderate technology (i.e. farm tractor). Unfortunately, no data has been available about the work efficiency of timber harvesting systems in Thailand. Practice and development so far have been based on learning by doing, while scientific research and support are missing.

Furthermore, about half of pulpwood procurement cost in Thailand today comes from the cost of harvesting operations (Pongsomboon S. pers. comm. in 2011). The increasing operating cost of timber harvesting as well as possible labour shortages in the future are driving forces for timber industries to pay attention to the rationalization and mechanization of timber harvesting. The timber industries are looking at developing their own harvesting technology that will be suited to the local circumstances, i.e. the tree characteristics, availability of technology and social impacts.

1.2.2 External factors

The weather in Thailand is generally hot and humid across most of the country throughout the year. Thailand has a tropical climate according to Köppen's climate classification flowchart (Mexey 2008). Seasons are generally divided into the hot season (March-May), cool season (November-February), and rainy season (June-October), but in reality, it is relatively hot most of the year (Authanawanitch 2007). Temperatures vary between 20°C in

December and 38°C in April with an average humidity of 82%, and average annual rainfall of 1600 mm (United Nations Thailand 2008; The Thai Meteorological Department 2013). In this study, the mean temperature during data collection was recorded in the field as 30°C with 75% humidity. According to the humidex value, workers under those conditions feel like they are working in a temperature of 40–42°C, which is classified as giving a strong feeling of indisposition, discomfort, and one should avoid exertion and physical effort (OHSCO 2007). Motor-manual harvesting operations are physically demanding, in addition to working in uncomfortable conditions. Normally, the working capacity decreases when working in uncomfortable circumstances. This tough working environment may lead to lower work productivity.

Tree characteristics include tree size, tree volume and wood quality. Eucalyptus trees in Thailand are rather small, with a shorter rotation period compared to many other countries, resulting in relatively low tree volumes. The current forest technology in Thailand applies light machinery and is mostly based on modified agricultural tools and machineries.

Logging in natural forests is banned as a result of massive illegal logging and deforestation in previous decades. The government want to protect and preserve the natural forest areas as much as possible; therefore, forest law and policy has changed and enjoys more strict enforcement. For instance, it is complicated to obtain harvesting licenses and chainsaw possession licenses, especially the chainsaws which have engine equal or greater than 1HP and guide bar equal or greater than 30 cm (12"). These are somewhat frustrating processes and ultimately turn out to be an obstacle for forest work development. Many contractors turn to applying agricultural tools and machines in forestry work instead of using specific-built machines for forestry work.

Both internal and external factors have shaped the current harvesting system into bad conditions: low work efficiency, heavy workload, and high operating costs. These are the driving forces to seek ways to improve the current harvesting system, to obtain better work efficiency, and to improve workers' well-being. Scientific research in the field of forest operations is currently lacking in Thailand. This research is also meant to serve as a starting point in this field, and to provide a stepping-stone for more advanced research in the future regarding eucalyptus timber harvesting.

1.3 Objectives of the study

The goals of the present study are to comprehend the main existing eucalyptus timber harvesting systems, to compare different alternatives and to explore possible improvements to forest harvesting systems in Thailand. The objectives of the study can be further refined into a set of research questions:

1. What are the work phases? What are the work elements that consist in work phase? What are time consumption for both work phases and work elements, respectively? (Time distribution)

2. What is the productivity of each work phase? What are the variables that significantly influence the time consumption? How do those factors influence the time consumption models? These questions make it possible to estimate productivity when creating an operational plan. They also offer a general idea about system productivity. (Work study)

3. Do work postures and workload in eucalyptus harvesting operations increase risks of work-related musculoskeletal disorders (WMSDs) in the work phases? How serious are the possible risks? (Ergonomics study)

4. Where are the systems bottlenecks? How does a system's potential productivity change when introducing alternative harvesting components? How does worker performance influence system efficiency? (Simulation)

2 BACKGROUND

2.1 Role of plantation forestry

Growing populations and income have resulted in increasing demand for wood and land for agriculture and for development, and consequently forest areas have declined (Siry et al. 2001). The continued decline of forest resources has raised concerns about wood shortages and negative environmental consequences. Forest plantations have become increasingly important in providing a substitute and supplying forest products all over the world (Shepherd 1986; Carle et al. 2002).

FAO (2000) defined a forest plantation as “a forest established by planting or/and seeding in the process of afforestation or reforestation. They are either of introduced species, or intensively managed stands of indigenous species, which meet all the following criteria: one or two species at planting, even age class, regular spacing.” Plantations are also known as man-made forests or artificial forests.

The main driver of plantations is to produce wood. Moreover, they have been established with a number of additional objectives, ranging from prevention of deforestation, absorption of carbon, protection of soil and water, rehabilitation of lands exhausted from other land uses, provision of rural employment, diversification of the landscape, maintenance of biodiversity, and continued wood supply (Savill et al. 1997; Siry et al. 2001; Carle et al. 2002; Evans and Turnbull 2003). Afforestation contributes environmental, social and economic benefits (Carle et al. 2002). Forest plantations may also reduce poverty and contribute to economic development. Well-managed plantations have higher yields of wood than natural forests. Plantations produce wood quickly and of a more uniform size and quality than natural forests. Siry et al. (2001) noted that, in the long term, the role of plantations in global forestry will depend on government policies, technological progress, markets, land availability, industrial globalization and environmental issues. In this study, the focus is on the utilization of eucalyptus plantations.

2.2 Management of eucalyptus plantation

2.2.1 Global level

Eucalyptus is noted for its rapid growth, adaptability to a wide range of climates and suitability for a variety of end products (Fumikazu 2001; Couto et al. 2011). Eucalyptus is highly productive, some species are well adapted to dry, infertile sites, and can also grow on unproductive agricultural land (Luangviriyasaeng 2003).

Today, eucalyptus is found in more than 90 countries around the world, especially in tropical and sub-tropical regions such as, Australia, Papua New Guinea, Chile, South Africa, Brazil, Uruguay, China and Thailand. To date, eucalyptus is spread over more than 22 million hectares around the world (Grupo Empresarial ENCE 2009). However, only 13 million hectares of these plantations are of interest for industrial production (Grupo Empresarial ENCE 2009). Purposes of planting eucalyptus are mainly for wood production, i.e. pulp production and energy production. The common eucalyptus species for pulp production are such as *E.calmaldulensis*, *E. nitens*, *E.dunnii* from south-eastern Australia. When establishing a eucalyptus plantation, major issues that plantation management should take into account are site and climate, tree improvement, species/clone selection,

silvicultural practices (i.e. spacing, rotation period, fertilization, weeding), timber harvesting and regeneration.

Genetic improvement of eucalyptus is currently under development and has been implemented in order to improve the quality of clones that are suitable for different sites, soils and circumstances, for example improving tolerance to drought, wetlands, resistance to disease and adaptability to a wide range of environments. The choice of species/clones to plant in any particular situation depends on the purpose of the planting, the site and climate, the level of establishment investment and the available equipment (Shepherd 1986). It is not simple to choose one eucalyptus species/clone over the others that thrive over a range of sites. Clonal plantations from selected trees are commonly used for industrial plantations, because of high productivity and uniform growth.

The spacing between trees at which a crop grows affects the degree of competition in the stand. This influences mortality and total production per unit area. Spacing is likely related to tree size, to which individual trees will grow, several aspects of wood quality and susceptibility to pests and diseases (Savill et al. 1997). The decision on what is optimal spacing depends on the purpose of the plantation and the end product. Various spacing has been used in eucalyptus plantations, as presented in Table 1.

In terms of silvicultural practices, eucalyptus is a light-demanding species, requires a completely cultivated and weed-free site, often with the addition of fertilizer, for rapid early growth. Many eucalyptus species are very fire resistant. Eucalyptus is sensitive to weed competition, and the need for intensive weeding is emphasized by Eldridge et al. (1993). Weed control is needed for eucalyptus, but not thinning. Fertilization regimes may include an application before planting to provide starter nutrients for the trees. After the first three years, the use of NPK-fertilizer at a proportion of 15–15–15 once a year is recommended in order to increase production.

Rotation period is also an important tool for controlling tree size: the longer the rotation, the larger the trees that can be grown (Evans and Turnbull 2003). Rotation period also noticeably influences yield, profitability and regeneration methods (Evans and Turnbull 2003). The rotation may differ from place to place; it also varies with species, site quality and spacing (Table 2).

Table 1. Examples of spacing used in eucalyptus plantation (Evans and Turnbull 2003).

Spacing (m)	Growing space (m ² /tree)	Number of trees per ha	Countries
1×1	1.0	10 000	Ethiopia
3×3	9.0	1 111	Brazil
4×4	16.0	625	Philippines
4.5×4.5	20.3	494	Papua New Guinea

Table 2. Examples of rotation period and mean annual increment of eucalyptus plantations from different parts of the world.

Countries	Rotation (years)	MAI (m ³ /ha/yr)	References
Brazil	7	35–55	Sociedade Brasileira de Silvicultura (2008)
South Africa	8–10	20	Sociedade Brasileira de Silvicultura (2008)
Chile	10–12	30	Sociedade Brasileira de Silvicultura (2008)
Portugal	12–15	12	Sociedade Brasileira de Silvicultura (2008)
Spain	12–15	10	Sociedade Brasileira de Silvicultura (2008)
China	10	7–20	Australian Centre for International Agricultural Research (2004)
Uruguay	7–9	22–40	Olmos (2012)
Thailand	5	8–25	FAO (2009)

Once the originally planted eucalyptus trees are felled, the next crop is generally regenerated by coppicing. Coppicing may be repeated several times. In order to cause as little damage to stumps as possible, harvesting requires careful planning and execution. In the felling operation, workers are recommended to leave a stump height of 10–12 cm above the ground (Geary 1983; Archibald 2002). If stump height is higher than the recommendation, it influences the quality of the coppice, e.g. problems with windthrow and instability. The equipment selection also has an impact on coppice establishment. For example, the use of a chain saw provides better stump quality than using an axe or hand tools (Geary 1983). A smooth and slightly sloping surface is an ideal stump for coppicing regeneration, in order to prevent fungal infection (Archibald 2002). Regarding timber extraction, light machinery, animal or even manual extraction are preferred. Well-planned and designed extraction is required to minimize damage.

2.2.2 Case of Thailand

The silvicultural practices (i.e. weeding, spacing, fertilizing and regeneration) in Thailand varies much between sites. Eucalyptus trees are most commonly planted in blocks, but are also planted in lines along canals or roads, and planted on the border of agricultural fields (Figure 3). In case of blocks, trees are planted at a certain spacing, for instance, 2×2, 2×3, 3×3 or 3×4 m. Spacing also highly dependent on plant and planting cost, weed competition and market. The rotation of eucalyptus in Thailand is approximately five years, sometimes even shorter in well-managed plantations, which are planted with a suitable clone on a good quality site. Eucalyptus species that commonly plant in Thailand are mainly come from south-eastern Australia such as *E. camaldulensis*, *E. tereticornis*, *E. urophylla*, nowadays the breeding clone are widely used. There is no specific criterion of time for clear felling; it largely depends on the forest owners' economic situation and market forces. There are several factors that may have an impact on rotation age irrespective of tree size. For instance, when forest owners face an economic crisis, they would like to sell their timber in order to improve working capital. In some cases, plantations were planted on unproductive sites, with clone selection not matching site properties, resulting in low yield of timber. –



Figure 3. Eucalyptus planting patterns: planted in block (left), planted on the border of paddy field (middle), and planted along the canal/road (right).

In this case, the forest owner may want to convert the plantation area to another kind of land-use. Market forces are also essential factor and may affect decision making in timber harvesting. Sometimes, cash crops may have a very high price compared to timber price, encouraging some forest owners to convert plantation areas to agricultural land.

Contract farming (out grower scheme) has expanded and become an important arrangement for eucalyptus production in Thailand (Boulay and Tacconi 2012). Forest industry companies want to secure their supply in the context of strong competition among buyers, and they use contract farming to promote eucalyptus among farmers who have not grown this species before (Boulay 2010). It has been impossible for a company to gather a sufficient area of plantations of its own, and companies having to rely on farmers for the wood supply have promoted eucalyptus by providing good quality and low-priced seedlings, cheap fertiliser, technical advice and training. Companies also guarantee the purchase of the timber at the end of the rotation and often guarantee a fixed minimum price for mature trees. Farmers have had to commit to selling their entire production to the contracting company (Boulay and Tacconi 2012). Many farmers prefer to sell standing trees by contract farming to ensure their income, whereas others prefer to harvest timber on their own and sell the wood to the company based on volume (FAO 2009).

2.3 Harvesting operations in eucalyptus plantations

2.3.1 Global level

A harvesting method refers to the form in which wood is delivered to the logging access road, and depends on the amount of processing (delimiting, bucking, barking and chipping) that occurs in the cut-over (Pulkki 2004). The three main harvesting methods are cut-to-length, tree-length, and full-tree harvesting. In the cut-to-length (CTL) or shortwood method, trees are felled, delimited and bucked to various assortments (pulpwood, sawlog, veneer bolt, etc.) directly in the stump area. In the tree-length (TL) method, trees are felled, delimited and topped in the cut-over. Delimiting and topping can occur in the stump area or

at a point before the roadside. In the full-tree (FT) method, trees are felled and transported to the roadside with branches and the top intact. Transport to the roadside is mainly operated by cable or grapple skidders. The full trees are processed at the roadside or hauled as full trees to central processing yards or the mill.

Eucalyptus harvesting systems and harvesting methods vary from place to place, depending on the available resources, technology, tradition, labour costs and other circumstances. Many levels of technology have been implemented globally in eucalyptus harvesting operations. There is a wide range of forest harvesting technology, from manual work to full mechanization. Three examples of harvesting systems are commonly applied in eucalyptus plantations (Figure 4). Normally, a logging company can combine the logging system in many ways, for instance, manual felling with mechanized extraction, processing and loading. It depends on equipment availability and circumstance suitability.

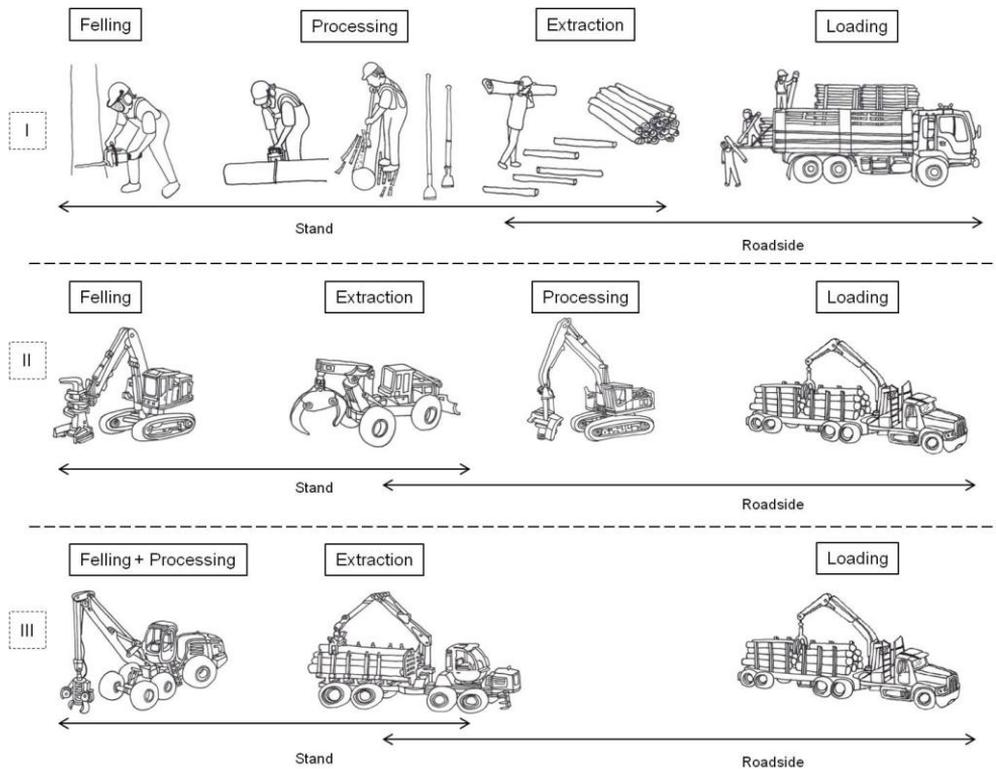


Figure 4. Examples of harvesting systems for eucalyptus plantation based on logging method: (I) manual harvesting, (II) FT method using feller-buncher, skidder and processor, and (III) CTL method using harvester and forwarder. (Drawing by Khanittha Nualtaranee).

System I: Trees are felled and processed into logs with chainsaws. Then logs are manually delimbed, debarked, sorted and stacked. Logs are then loaded onto trucks using manpower.

System II: Trees are felled with a feller-buncher, extracted to roadside with grapple/cable/clambunk skidders, and then delimbed and processed into logs with a processor. Logs are then sorted, stacked with a loading grapple and loaded onto a truck with excavators fitted with hydraulic grapples or using a truck-mounted hydraulic crane.

System III: Trees are felled, debarked and processed into logs with a harvester. Then logs are extracted to roadside with a forwarder, and loaded onto trucks using excavators fitted with hydraulic grapples or using a truck-mounted hydraulic crane.

Harvesting productivity depends on the number of workers and machines being used, size of harvesting area and capital cost. According to a literature review, eucalyptus harvesting productivity from different parts of the world can be summarized as in Table 3. The productivity is presented in terms of m^3/h instead of $m^3/man\text{-hour}$, because there is limited information regarding numbers of workers and machines available, and the costs are a bit obscure.

Table 3. The examples of eucalyptus harvesting systems, stem size, and productivity from different parts of the world.

Country	Productivity (m^3/h)	Average stem size ($m^3/tree$)	Harvesting system	References	Year
South Africa	4.90	0.12–0.22	Motor-manual	Shuttleworth B. (pers. comm.)	2012
China	0.58	0.05–0.18	Motor-manual	Engler et al.	2012
Brazil	0.84	0.08–0.10 /0.18–0.22	Motor-manual	Hakkila et al.	1992
Brazil	1.00	0.25	Motor-manual	Cerqueira Filho L.S.C. (pers. comm.)	2013
South Africa	38.93	0.29	Feller buncher, skidder, processor, slasher	Hogg	2009
Brazil	72.12	0.19	Feller buncher, skidder, slasher	Seixas	2009
Brazil	110.00	0.25	Feller buncher, skidder, slasher	Cerqueira Filho L.S.C. (pers. comm.)	2013
Brazil	90.00	0.25	Feller buncher, skidder, chipper	Cerqueira Filho L.S.C. (pers. comm.)	2013
USA	28.67	0.18	Feller buncher, skidder	Spinelli et al.	2002
Chile	73.8	0.19	Feller buncher, skidder, flail drum, slasher	McEwan	2008
Australia	73.5	0.15	Feller buncher, skidder, chipper	Ghaffariyan et al.	2011
Uruguay	33.65	NA	Feller buncher, skidder	Larocci	2006
Brazil	22.44	0.25	Harvester, forwarder	Seixas	2009
Brazil	20.00	0.25	Harvester, forwarder	Cerqueira Filho L.S.C. (pers. comm.)	2013
Portugal	8.00	0.09	Harvester, forwarder	Magagnotti et al.	2011

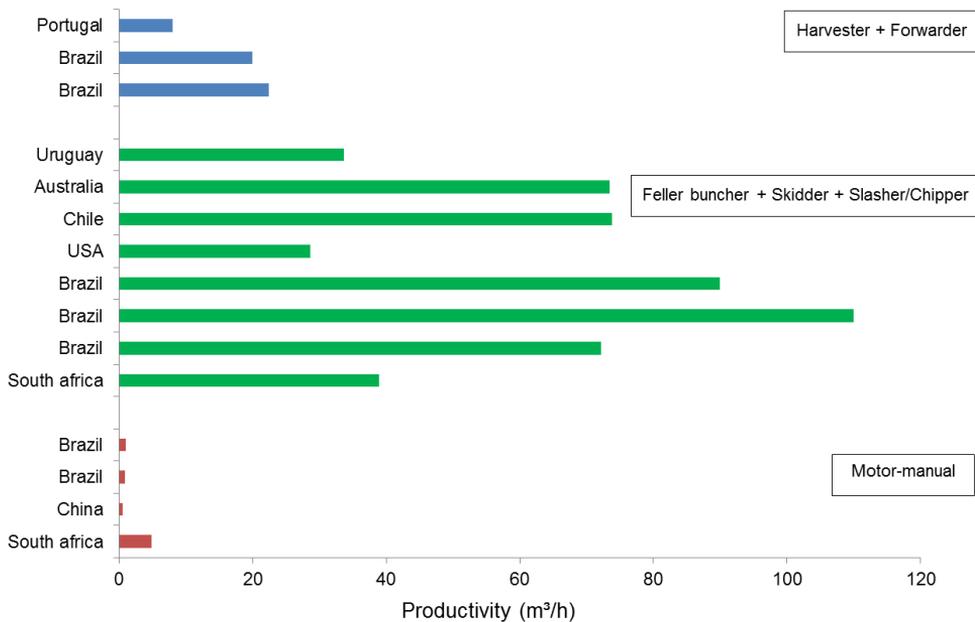


Figure 5. The productivity comparison on eucalyptus harvesting sorting by countries and harvesting systems. This figure is based on data from Table 3.

In the productivity comparison from different parts of the world, it is noticeable that FT harvesting by feller buncher, skidder and slasher or chipper is the most productive harvesting system, followed by CTL methods using harvester and forwarder, and manual harvesting systems is the poorest system, relatively. Moreover, productivity increases as a function of stem size.

The two main harvesting methods that are applied for eucalyptus are FT and CTL. FT is a common practice in Brazil, South Africa, Chile and Uruguay. The major tree-felling machine for FT is a feller-buncher. Other operations, like delimiting and cross cutting, can also be accomplished by machines, i.e. processor, slasher or chain-flail debarker. The CTL method is applied in Brazil, South Africa, Portugal, China and Thailand. With this method, harvesters and chainsaws are the major tools for tree felling. Examples of harvesting productivity and estimated operational costs are presented in Table 4.

Table 4. Examples of harvesting methods, productivity, and cost.

Country	Harvesting method	Machines	Productivity (m ³ /h)	Cost (€/m ³)	References
China	CTL	Chainsaw	0.60	2.13	Engler et al. 2012
South Africa	CTL	Chainsaw	4.90	5.4–7.7	Shuttleworth 2011; Pulkki 2001
Brazil	CTL	Chainsaw	1.90–2.30	2.36	Hakkila et al. 1992
Brazil	CTL	Harvester	17	3.04	Seixas 2009
Portugal & Spain	CTL	Harvester	5–14	3.10–10.08	Spinelli et al. 2002
Brazil	FT	Feller-buncher	90–100	0.70	Seixas 2009
Uruguay	FT	Feller-buncher	70	NA	Larocci 2006

The feller-buncher appears to be the most effective felling machine, with relatively low operational cost. While, manual felling with chainsaw provides the lowest productivity among others. It is difficult to compare productivity between feller-buncher and harvester, because harvester is also doing extra work like processing the logs.

The harvesting method influences the machine selection for timber extraction. The most common machines for extraction in FT are skidders (cable/grapple/clambunk) and farm tractors (grapple/winch/trailer). A forwarder is a common machine for timber extraction with the CTL method. Some examples of forest machines, productivity and cost of timber extraction are presented in Table 5. The skidder is very productive machine for timber extraction.

Table 5. Examples of timber extraction methods, productivity, and cost in eucalyptus plantations.

Country	Harvesting method	Machines	Productivity (m ³ /h)	Cost (€/m ³)	References
Brazil	FT	Skidder	100	0.55	Seixas 2009
Brazil	FT	Skidder	50	1.24	Seixas 2009
Uruguay	FT	Skidder	50–55	NA	Larocci 2006
Brazil	FT	Farm tractor (with grapple)	11–12	2.10	Hakkila et al. 1992
Brazil	CTL	Forwarder	32	1.07	Seixas 2009
Spain	CTL	Forwarder	9–22	2.4–4.4	Spinelli et al. 2004

2.3.2 *Eucalyptus* harvesting in Thailand

The eucalyptus harvesting system in Thailand is considered a “hot logging” system: logs are not stored or decked in the stands, but are loaded onto trucks as soon as possible. As contractors are normally paid according to weight, the faster they harvest and transport the wood, the more profit they earn in a given period of time. In a hot-logging system, if one process is halted, the rest of the processes have to be suspended.

Generally, the final felling of eucalyptus wood in Thailand is based on the CTL method. Intermediate thinning is not applied. No specific maximum allowance harvesting area is clearly defined, because there is no national code of practice for timber harvesting in Thailand. However, most forest owners follow the guidelines of sustainable forest management, in which the annual removal allowance should not exceed the yield increment (Netprachit 2007). Therefore, the actual annual removal depends on the discretion of forest owners. From the road network point of view, there are no permanent strip roads in harvesting stands; these road networks in practice are designed manually on site.

Motor-manual operations are still predominant in Thailand, where relatively inexpensive labour is available. Additionally, the advantages of applying motor-manual are its ability to provide low capital costs, generate employment, and offer a low environmental impact. However, safety is an issue, as accident rates tend to be higher compared to other methods (FESA 2010).

Normally, tree felling is carried out using brush saws (Figure 6), but instead of using felling aids to direct tree fall, the majority of fellers have assistants with a push pole. Hand tools (knives and axes) are the main tools for delimiting and marking the log length (Figure 6). Bucking is also performed using brush saws, and stems are normally cross cut into 2-m pulpwood logs. All logs are then forwarded to the roadside by a farm tractor or human power. Loading is done manually or with a modified farm tractor equipped with a front-end grapple (Figure 6). This kind of modified tractor collects the logs, forwards them to roadside, and loads them onto the trucks. Once the loading is completed, the logs are transported to the mills. This system offers some advantages: notably a small landing size is required, and there is minimal damage to the logs.

Based on my interviews with forest workers regarding tree-felling tools, chain saws were formerly the main equipment for cutting, but most of them were too big and heavy for cutting small trees. Many workers used chain saws in the cutting process before, but then they switched to using brush saws after they saw other workers using them. Some workers even noted that using brush saws provides a better working posture. From legislation point of view, the current chainsaws are mostly transmitted from former use (engine > 1HP, guide bar > 30 cm). To apply those chainsaws in forest operations, the chainsaw possession license is required. This has resulted in a sweeping change of cutting tools from chainsaws to brush saws in Thailand. However, chain saws are still used in some places, but not in a high number compared to brush saws.

Based on a discussion with an industry representative (Pongsomboon S. pers. comm. in 2011), a cutting team of prevailing harvesting systems normally consists of 8–10 workers, depending on the system and work arrangement. Typical tools are brush saws (Table 6), hand tools (axes and knives) and modified farm tractors equipped with a front-end grapple. Cutters predominantly use Makita (RBC411) and Robin (NB411) brush saws for felling and cross-cutting. The circular saw blade sizes are between 20–25 cm (8”–10”), with the number of saw teeth, depending on the users’ preferences, varying between 12–24 teeth.



Figure 6. Typical tools in the prevailing timber harvesting of eucalyptus. A) Hand tools: an axe and knife normally used for delimiting; B) brush saws are used for felling and bucking; and C) a farm tractor (New Holland 6600, 78 HP) equipped with a front-end grapple applied in loading.

Table 6. Brush saw specifications.

Model		MAKITA	ROBIN
		RBC411	NB411
Dimensions: length × width × height (without cutting blade)	Mm	1 705 × 620 × 435	1 690 × 585 × 430
Mass (without plastic guard and cutting blade)	kg	7.3	7.3
Volume (fuel tank)	L	1.1	0.95
Engine displacement	cc	40.2	40.2
Maximum engine performance	HP	1.97 at 7 000/min	1.97 at 7 000/min
Engine speed at recommended mass.	RPM	8 500	8 500
Spindle speed			
Maximum spindle speed (corresponding)	RPM	6 800	7 000
Fuel consumption	kg/h	0.98	0.93
Specific fuel consumption	g/HPh	846	846
Idling speed	RPM	2 600	2 600
Clutch engagement speed	RPM	3 600	3 600
Carburettor (float-carburettor)	Type	MIKUNI VM	MIKUNI VM
Ignition system	Type	Solid state ignition	Solid state ignition
Spark plug	Type	NGK BRM7A	NGK BRM7A
Electrode gap	Mm	0.6–0.7	0.6–0.7
Mixture ratio (Fuel: MAKITA 2-stroke oil)		25:1	25:1
Gear ratio		13/19	14/17

Tree-felling techniques

Felling a tree comprises two working phases: an undercut and a back cut. The undercut serves as the guiding or aiming slot for the tree. It is a notch placed on the side of the tree in the direction of falling. The back cut is the final cut and is made on the opposite side from the undercut. The back cut disconnects almost the entire tree from the stump, leaving a hinge that helps to control the tree's fall. In Staaf and Wiksten (1984), the back cut is called the *felling cut*. Following Pearce and Stenzel (1972), Conway (1982), and Uusitalo (2010), *back cut* is used in this study with the same meaning as felling cut.

Using brush saws for felling trees is a little complicated and slightly different from using chainsaws. In the middle of the saw blade, there is a gear case, which limits the cutting length: less than half of the saw blade radius can be utilized for cutting. The initial cutting-line length is approximately 10 centimetres (Figure 7). Before starting the cut, the worker needs to accelerate the engine to full throttle and perform a cut with a uniform pressure. According to observations in the field, there are three methods for felling trees depending on the tree size.



Figure 7. The saw blade dimensions.

I) Tree with a diameter < 10 cm

Normally an undercut is not required, and only a back cut is made (Figure 8A). The saw blade is most often applied to the right side of the tree, relative to the cutter. Felling may sometimes require an assistant to control felling direction.

II) Tree with a diameter between 10–20 cm

Firstly, an undercut is made, which provides a hinge point for the direction in which the tree will be felled. Secondly, the back cut is made, a little higher than the undercut level. The back cut is kept on the opposite side of the undercut, parallel with the back of the undercut, until the tree falls down (Figure 8B).

III) Tree with a diameter > 20 cm

Felling starts with an undercut on the side of the desired felling direction. When the blade does not fit across the trunk, the back cut has to be extended by pivoting from one corner to another. The saw blade is re-inserted on the opposite side of the undercut and drawn across the trunk in a semi-circular direction (Figure 8C). If the trees are particularly large, an assistant with a push pole may be used to aid in controlling the felling direction.

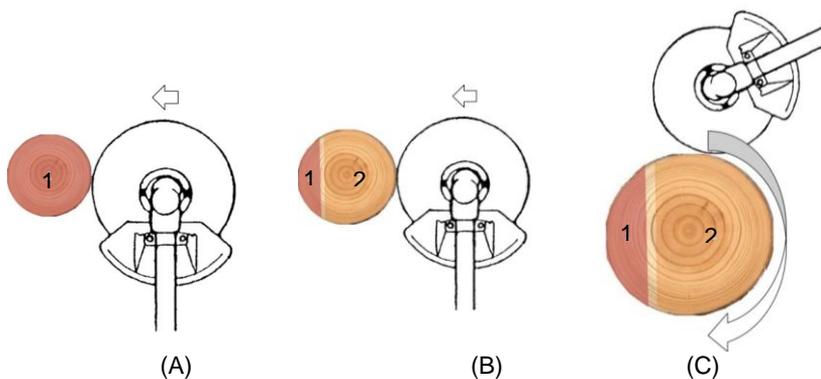


Figure 8. Tree felling techniques: (A) tree with a diameter < 10 cm, (B) tree with a diameter between 10–20 cm, and (C) tree with a diameter > 20 cm.

Cross-cutting technique

The circular blade of brush saws is in a horizontal normally position when felling trees. The blade angle is a bit different for cross-cutting trees. Workers usually adjust the angle of circular blade from horizontal to vertical (Figure 9). By changing the blade angle, it maintains the same position of the arms as for felling, and facilitates the cross-cutting.

Stacking techniques

After completing the bucking process, the resulting logs are stacked into either lines or piles. The stacking patterns depend on the method of loading. For example, in the case of a truck driving through the cutting area, logs are preferred to be stacked in parallel lines. The truck driver would drive between the lines of logs and workers do loading simultaneously (Figure 10). In case of using a modified farm tractor mounted with front-end grapple, the logs are preferably stacked in small piles scattered in the cutting area (Figure 11). The farm tractor commonly drives in the cutting site, collects and then forwards the logs onto a timber truck that parks at the roadside. Another stacking technique is a big log pile along the roadside. This bunching is relevant when primary transport is carried out by a small vehicle (farm tractor with small trailer). This case applies when the truck cannot drive in the cutting area and a modified farm tractor mounted with a front-end grapple is unavailable. It is necessary to extract the logs out from the cutting area to the roadside first, then logs are loaded onto a truck at the roadside (Figure 12).



Figure 9. Cross-cutting technique.



Figure 10. Logs are stacked in parallel lines.



Figure 11. Logs are stacked in small piles scattered within cutting site.



Figure 12. Logs are stacked in big piles along the road side.

Manual loading techniques

There are several methods of manual loading that are mainly based on workers' experience and skill. These loading patterns differ from place to place. According to observations of this study, manual loading techniques can be categorized into the following:

I) A pair technique: one worker is on a truck, and the other stays on the ground. The worker who stands on the ground lifts logs from the ground and passes them to the worker who stands on the truck. The workers who are on the truck have the responsibility for arranging the logs on the truck. A team consists of 8 to 10 workers, which means there will be 4 to 5 pairs of workers working together. This kind of loading technique applies with logs that have been stacked in parallel lines (Figure 13). The truck slowly drives between those lines, and loading is done simultaneously.

II) In this case the workers are not working in pairs but split into two lines. Only a couple of workers are on the truck, and the rest of them are on the ground lifting logs from ground to the truck. The workers who are on the truck have a responsibility in arranging the logs on the truck (Figure 14).

III) If logs have been stacked in a big pile, the truck driver generally parks the truck close to the log pile location. This case applies when a truck is unable to drive through the cutting site, but has to park at the roadside for loading. Workers normally stand in a line, passing the log from one person to another until the truck is fully loaded (Figure 15). If one pile does not fill the truck, the truck driver may need to drive to another pile in order to fill the truck.



Figure 13. Manual loading using pair technique: one worker is on the ground, another is on the truck. The worker who stands on the ground passes logs to his partner. Normally a group of workers consists of four to five pairs.



Figure 14. Another manual loading technique: only couple of workers are on the truck, and the rest are on ground passing logs to the workers who are standing on truck. The workers who are on truck have the responsibility for arranging the logs on the truck.



Figure 15. Manual loading at the road side. Logs are stacked in big piles along the road side, the truck parks very near to a log pile. Workers pass logs from pile to the truck from one to another.

As there are several working techniques available, contractors are free to select and combine the techniques for each work phase. A typical combination of work phases (Figure 16) starts with felling using brush saws, followed by manual delimiting, and then bucking using brush saws. While the bucking is being completed, stacking can be carried out simultaneously by piling in lines or small piles. Afterwards, loading is operated manually. For this loading process, the work flow is halted, because all the forest workers have to suspend their work and assist with loading.

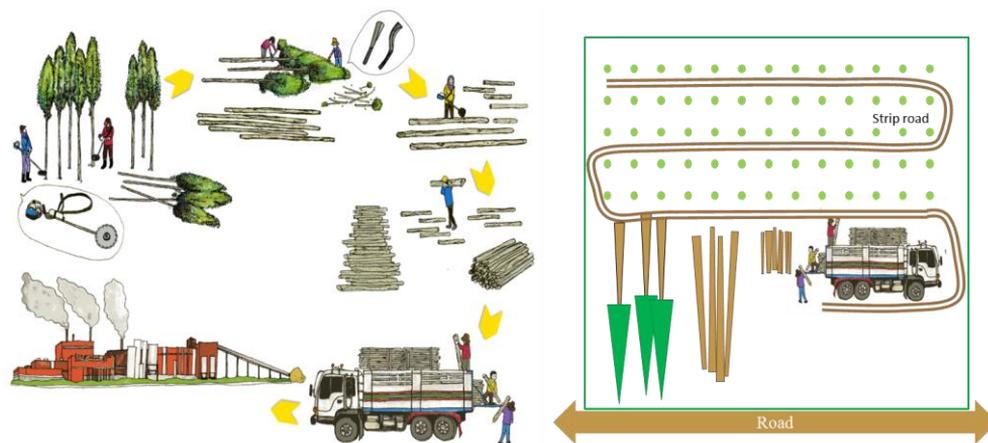


Figure 16. Example of a typical harvesting system in Thailand. (Drawing by Khanittha Nualtaranee).

3 FOREST WORK SCIENCE

3.1 The evolution of forest operations

The discipline of forest operations has been continuously evolving, starting from rules of thumb and developing today into a modern networking system. Heinimann (2007) specified the development stages of forest operations as a scientific discipline with five paradigms: utilization, Tayloristic, mechanization, systems, and network paradigms (Figure 17).

At the very beginning, the *utilization paradigm* was mainly a systematic survey of tacit knowledge embodied by practices that evolved from trial and error and were defined by rules of thumb. Industrial engineering introduced systematic studies of work processes through time studies at the beginning of the 20th century. Forest work science emerged in this *Tayloristic paradigm*. In 1911, Taylor introduced the principle of scientific management, and his concept changed the conceptual view of labour into a mechanistic clockwork system (Taylor 1911). Taylor's concept of time studies got into forestry and resulted in the first description of the piece-volume-law that time consumption per unit of volume decreases with increasing volume per work piece (Braniff 1912). The first Institute of Forest Work Science was founded in Germany in 1927. This became the beginning of forest work science.

The *mechanization paradigm* came after Second World War, when the development of logging machinery was promoted. In parallel, the study of body measures and physiological performance was established as a new scientific discipline known as "human factor engineering" or "ergonomics". In the *systems paradigm*, the focus was to provide analytical tools and methods for the design and control of new systems to implement operations that had never been performed before. Simulation of harvesting systems first emerged within the logging development program of the Canadian Forest Service (Silversides 1988). The first simulation model was very simple. Operations research was simultaneously applied with the aim of increasing efficiency of the man-machine system in a certain context. Today, forest operations apply the *network paradigm*, where information technology becomes the key technology driver to allocate tasks dynamically. This opens new ways of cooperation and interaction between humans and complex systems.

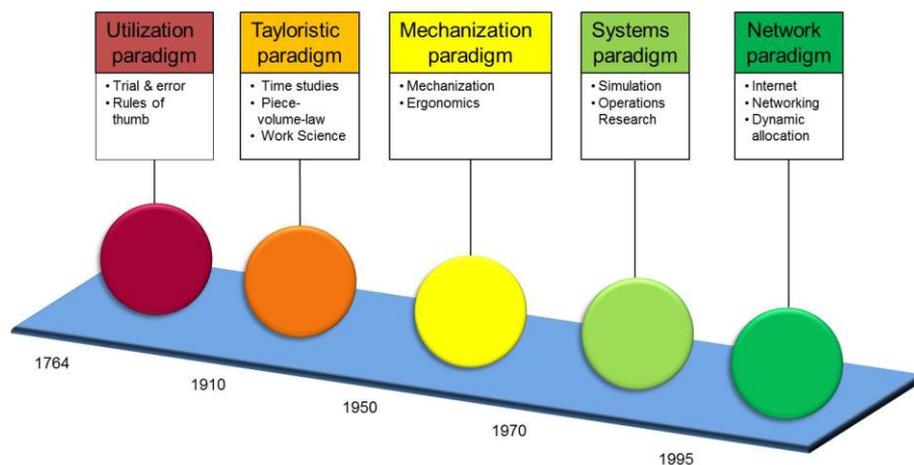


Figure 17. Patterns of evolution characterizing the evolution of forest operations engineering and management as a scientific discipline according to Heinimann (2007).

3.2 Work science

According to the traditional Nordic definition, work science is concerned with work, its productivity, and share of society's output (Harstela 1991). Work science can be classified as a highly applied scientific discipline linking natural sciences, technical sciences, human beings, technology and ergonomics together (Figure 18). Harstela (1991) classified forest work science into organization study, method study and work measurement (Figure 19). In addition, Uusitalo (2010) added ergonomics study and terramechanics to forest work science.

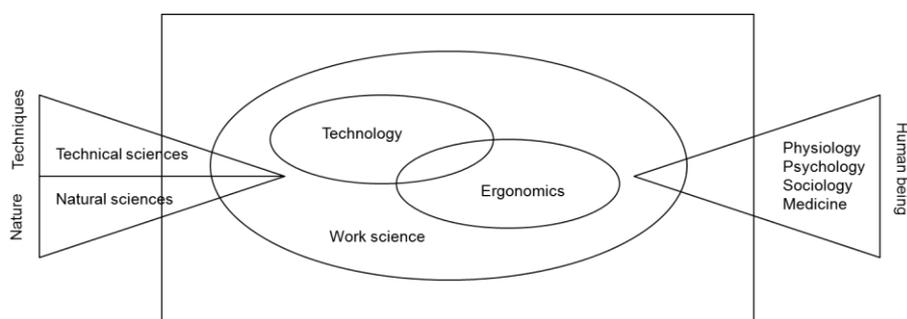


Figure 18. The linkage between work science and other scientific disciplines according to Harstela (1991).

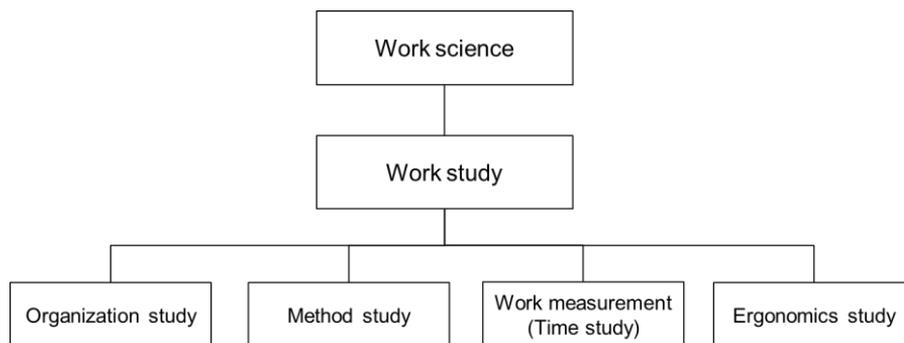


Figure 19. Work science in forestry consists of organization study, method study, and work measurement (according to Harstela 1991; Uusitalo 2010).

Work study is one branch of work science (Figure 19). It can be defined as the systematic examination of existing and proposed ways of doing work, in order to establish or improve the efficiency of production, the effective use of resources, and to set up standards of performance for the activities being carried out (Kanawaty 1992; Björheden 1995). The key purpose of work studies is to measure the working time and the amount of work done, and to investigate all the factors that influence the efficiency and economy of the system being studied (Sundberg and Silversides 1988; Björheden 1995). In forestry work, time studies have been used to determine harvesting production rates and worker efficiency (Björheden 1991; Harstela 1993). Work study has been widely applied in studies on forest harvesting, either in the overall harvesting system, or in separate work phases such as felling, processing, and extraction (Sobhany and Stuart 1991; Björheden 1998; Spinelli et al. 2002; Laitila et al. 2007).

3.3 Time and productivity study

3.3.1 Time study

There are two different well-known time nomenclatures that have been broadly applied in forest science. In Nordic forest work studies, the time concept that is presented by the Nordic Forest Work Study Council (NSR) is widely accepted and typically used. This time concept provides a good basic framework for time classification in forest work and is suitable for mechanized forest work (Figure 20). It divides production time into gross effective time and effective time. The effective working time (E_0) is working time excluding all delays. Since normal work always also includes short breaks, gross effective working time is more precise in describing true work productivity. The widely used concept of gross effective working time (E_{15}) implies the inclusion of delays 15 minutes or less in duration. This could lead to inaccurate results when estimating effective time because delays are included in the model.

A group of specialists (IUFRO 3.04) introduced a new work study time concept in 1995. One of the focal points of this time concept is the reduction of the time accounted as unnecessary time. Another point is the minimisation of time wastage within categories that

are important for the completion of the work task (i.e. main work time and complementary work time). Today both standards are widely applied in forest operations. As forest harvesting in Thailand is mainly labour-intensive operations, the time concept proposed by IUFRO is generally used.

Work study principally requires proper timing techniques. The timing techniques have developed quickly over the decades, from a very basic stop watch to an electronic timer, field computer and automated data collector (Figure 21, Table 7). A stopwatch is suitable for studying simple harvesting systems like motor-manual work. Field computers are applicable to both manual and mechanized harvesting systems, and can be used either directly in the field or applied with video recording. An automated data logger has become a popular tool for data collection in mechanized forest harvesting. It is suitable for collecting all type of information (i.e. machine functions, movement, location, and operator comments) that can help to improve the productivity of operations or the utilization of equipment. In addition, the CAN-bus is widely applied in modern forest machinery like the harvester and forwarder. The CAN-bus can be utilized to automatically record large amounts of time study materials with highly detailed and accurate data related to machine activities.

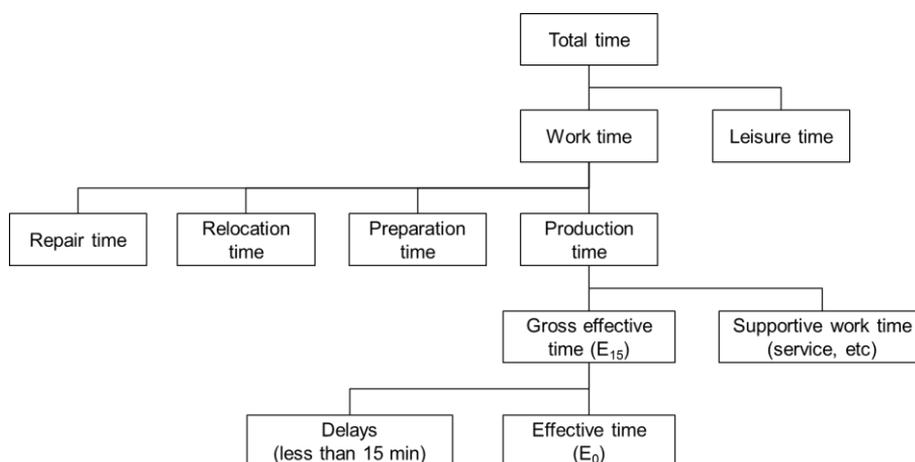


Figure 20. The division of working time into components applicable to mechanized forest work (NSR 1978).



Figure 21. Measuring equipment used in time studies. (A) Digital stopwatch, (B) field computer, and (C) electronic data logger (MultiDAT).

Table 7. The development of timing techniques according to Nuutinen (2013).

	1970s	1980s	1990s	2000s	2010s
Digital watch					
Field computer					
Automated data collector					

3.3.2 Methods for data collection

In order to conduct reliable and detailed time studies, it is important to comprehensively determine the actual steps of the study itself. According to Harstela (1991) and Niebel (1988), the following steps have to be taken into account:

- 1) Selection of the work to be studied.
- 2) Planning the measurement procedure and division of the work phase into work elements. Each work element should have clearly defined starting and ending points.
- 3) Selection of the measurement techniques. The measurement technique should be compatible with local circumstances: working complexity and available measurement tools.
- 4) Selection of the workers. Usually workers should be fully trained, performing the work with average skill and effort.
- 5) Recording all the relevant data. All the relevant data relating to the circumstances of the work should be noted, i.e. machine specifications, worker background, weather, terrain conditions, and tree characteristics.
- 6) Examination of the recorded data. The recorded data are subjected to critical examination to distill the facts, ensure that the most suitable methods and working techniques are used, and irrelevant elements are separated from the relevant ones.

3.4 Ergonomics

Working conditions for forest workers are very often poor, resulting in low efficiency. In developing countries, especially where cheap labour is more available, physical labour plays an important role in several disciplines. Labour-intensive operations in forestry are also considered physically demanding jobs. They often cause workers to exert themselves in an uncomfortable or unhealthy body posture. Physically heavy work, inappropriate working methods, working techniques and tools cause not only occupational accidents, diseases and unnecessary fatigue, but also low productivity (FAO 1992).

Ergonomics is the scientific discipline concerned with the interaction between humans and objects and the design of systems in which people participate (Salvendy 1997). The purpose of ergonomics is to improve the safety, health and well-being of workers with the ultimate objective of raising their level of efficiency through research, education, legislation and other relevant measures.

Ergonomics consists of two major elements: technical and human parts. The technical part concerns the practical aspects of optimizing workplaces, machines and tools. The human part focuses on the description and knowledge of physical and psychological characteristics of human beings.

The emphasis of ergonomics research was first on motor-manual logging practices and the analysis of physical strain experienced by workers. As forest operations have become largely mechanized, the focus of ergonomics study has shifted towards machinery, and more recently towards human-machine interaction (Uusitalo 2010). Ergonomics research has been applied in several aspects in forest work, for example:

- working techniques, tools, and method;
- work strain and fatigue;
- the influence of heat, noise, vibration, and other environment factors on work performance;
- worker physical working capacity and physical work load;
- accidents and safety measures.

In most cases, ergonomics studies have focused on the workers' physical workload. The most common approach to evaluating physical workloads is the observational method (Takala et al. 2010). The Ovako Working Posture Analysing System (OWAS) has been applied to measure physical workload especially in the industrial sector (Mattila and Vilkki 2003) and can be used in forestry sciences. In parallel, there are other measures, i.e. Rapid Upper Limb Assessment (RULA), Rapid Entire Body Assessment (REBA), and Occupational Repetitive Action (OCRA), which have been applied in the same manner, particularly in the forest industry sector (Jones and Kumar 2007; Jones and Kumar 2010; Qutubuddin et al. 2013). Nevertheless, method selection is generally based on the study question, for example, on which part of the body one would like to focus: whole body, left-right organs or upper or lower limbs.

OWAS is a tool to support improvements in the workplace, including the improvement of tasks, job redesign and new working method development, by identifying and assessing working postures. The OWAS method was first developed for the Finnish steel industry in 1970s, but has since then been applied over the years in various industries in many countries and occupations. It has been widely applied in several disciplines, such as health care services, construction, agricultural and forestry. There are some studies relevant to the application of the OWAS method in forest operations, such as investigating the physical work load in harvesting operations (Lee and Park 2001; Zanuttini et al. 2005; Calvo 2009),

examining the effects of training programmes on the work postures (Väyrynen and Kononen 1991), comparing work safety (Granqvist 1993) and suggesting the adoption of correct posture during work (Fiedler et al. 2011).

The OWAS method allows the estimation of the degree of static load of workers in the workplace by analysing their posture, identifying four work postures for the back, three for the arms, seven for the legs and three categories for the weight of load handled (Schilden 1989). Each of these factors has an attributed code value (Figure 22). Each classified posture is defined by a four-digit code in which the numbers indicate the postures of the back, the arms, the legs and the external load.

The technique classifies combinations of these four categories by the degree of their impact on the musculoskeletal system for all posture combinations. This categorization based on risk assessment was originally constructed by physicians, work analysts, and workers and then revised and validated by an international group of experts (Karhu et al. 1977). The degrees of the assessed harmfulness of these posture–load combinations are grouped into four action categories which indicate the urgency for workplace intervention (Table 8).

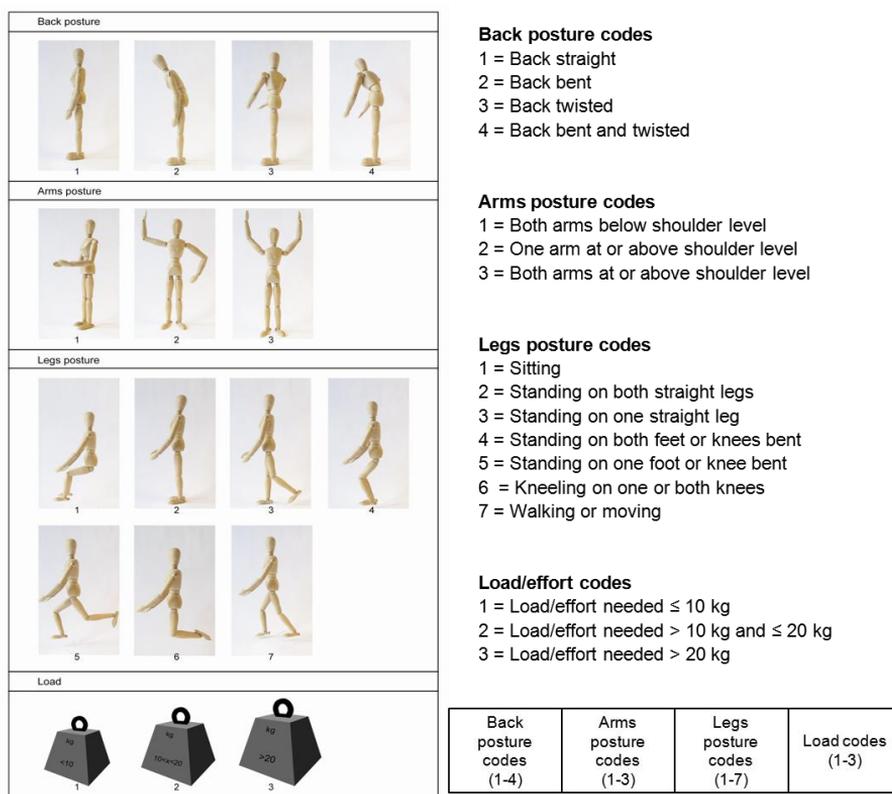


Figure 22. Working posture classifications in the OWAS method.

Table 8. The OWAS action categories for prevention. (Mattila and Vilkki 2003; Kee and Karwowski 2007)

Action category	Classification	Action
AC 1	Normal and natural postures	No actions required
AC 2	Slightly harmful postures	Corrective actions required in the near future
AC 3	Distinctly harmful postures	Corrective actions should be done as soon as possible
AC 4	Extremely harmful postures	Corrective actions for improvement required immediately

OWAS risk indicator (I) can be determined by means of the following formula [Eq. 1].

$$I = [(a \cdot 1) + (b \cdot 2) + (c \cdot 3) + (d \cdot 4)] \cdot 100 \quad (1)$$

Where a, b, c and d are the observation frequency percentage in action categories 1, 2, 3 and 4, respectively.

This indicator is expressed as a value in the range 100 to 400, with the value obtained corresponding to a proportional level of risk and consequent intervention to be implemented. The hazard increases as the risk index increases, and a maximum risk occurs when the risk index is 400. If the risk of musculoskeletal disorder is high, then the action category indicates the need for and urgency of corrective actions.

3.5 Simulation studies

Simulation is defined as a technique that imitates the operation of a real system as it evolves over time (Winston 2004; Bank et al. 2010). A simulation model can be used to investigate a wide variety of “what if” questions about a real system. Potential changes to the system can first be simulated in order to predict their impact on system performance (Banks et al. 2010). To understand and improve system performance, numerous approaches can be used, for example, simple spreadsheet calculations, complex mathematical programming, heuristic methods, linear programming and dynamic programming (Mikkonen 1983; Dahlin and Sallnäs 1992; Kivinen 2004; Uusitalo 2010). Simulation is the only approach for predicting performance when the models are subject to a significant level of variability (Robinson 2004). Many simulation programs provide an animated display of the system, giving better understanding of the model. Simulation allows users to reflect on the randomness and interdependence of variables in the system (Asikainen 1995). Users can include randomness through properly identified probability distributions taken directly from study data. With simulation, users can view the waiting time, number of items, minimum and maximum service time, data distribution and the time plot. These figures are useful for further analysis and improvement.

Simulation models can be classified according to use of time and probability functions (Figure 23).

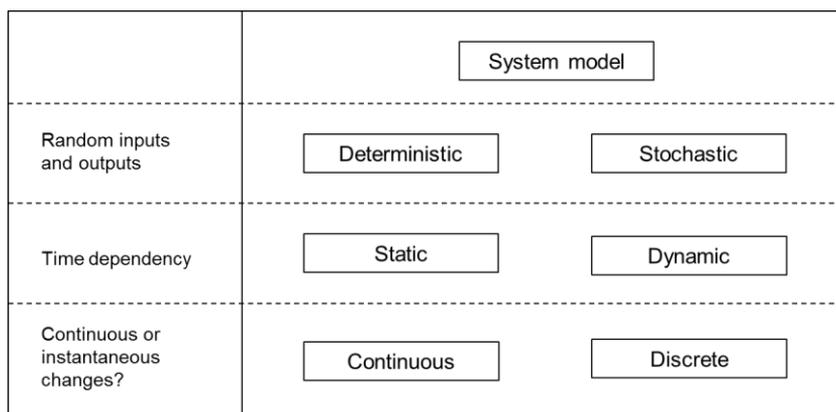


Figure 23. Model classification (Leemis and Park 2004).

A deterministic simulation model contains no random variables, which means that a certain set of input data will always provide the same set of output at every modelled replication (Asikainen 1995). A stochastic simulation model contains one or more random input variables, resulting in output data not necessarily being identical between simulations. Stochastic simulation runs will also produce different output data for each replication, even though the inputs remain the same.

A static simulation model represents a system at a particular point in time; it is often used to evaluate the expected impact of policy change and risk involved in decision-making. A dynamic, or stochastic, simulation represents system characteristics that evolve over time (Winston 2004).

In a continuous simulation, the state variables change continuously over time. In forestry, particularly forest management, simulation studies are typically continuous simulations, i.e. forest growth simulation. A discrete simulation is one in which the state variables change only at discrete points in time (Winston 2004; Banks et al. 2010). Event points are linked together in sequence as time moves forward. Discrete-event simulation is a key simulation application for analysing system performance in forest operations because the timber harvesting work is a series of work phases, moving forward from one work phase to another at discrete points in time.

The major benefit of applying a simulation is that it allows for prediction of the effect of changes to existing systems and predicting the performance of a new system under varying sets of circumstances without interrupting the current system. In addition, simulation provides the ability to compress or expand time for evaluation purposes. Simulation presents a mechanism for comparing results; however, it does not provide the means for determining optimal solutions to problems. A summary of some advantages and disadvantages of using simulation, as described by other authors (Pegden et al. 1995; Law and Kelton 2000; Anderson et al. 2005; Banks et al. 2010), is presented in Table 9.

Table 9. Summary of simulation advantages and disadvantages.

Pros	Cons
<ul style="list-style-type: none"> + Determination of the best choice among scenarios before implementing; + Problem identification. Simulation provides a place to explore systems for the identification of problems; + Preparation through “what-if” analysis. What-if questions can be answered without disrupting the current system and while holding other characteristics constant; + Manipulation of time periods. Simulation provides the ability to compress or expand time for evaluation purposes; + Bottleneck analysis. It is possible to quickly evaluate methods for addressing the identification of the bottleneck; + When studying the real system is expensive or does not yet exist, simulation can address these problems. 	<ul style="list-style-type: none"> – Simulation is not an optimal solution technique; – Special knowledge is required. Model building requires special training; – Difficult to interpret. It can be difficult to determine the accuracy of the results; – Time consuming. Sometimes, simulation modelling and analysis may take a long time to develop, tying up valuable resources and becoming expensive; – Simulation software is often expensive.

A simulation study is usually divided into several steps (Figure 24). One of the most crucial steps is the problem formulation, as the problem has to be clearly described and understood. Afterwards, model conceptualization should start with a simple model and build towards greater complexity. Another important aspect of any simulation study is confirmation that the simulation model accurately describes the real system. Thus, verification and validation must take place before using simulation results. Simulation runs are applied to estimate measures of performance for the simulated system. Eventually, the recommendations from simulation results may be implemented.

With the purpose of achieving reliable simulation outputs, precise input data from a real system of interest is required (Hogg 2009; Banks et al. 2010). Where data are available or collectable, they can be acquired from previous studies (Asikainen 1995) or from observed data (Kelton et al. 2003). System observation is time consuming, but provides understanding and the chance to identify potential system improvement methods that can be tested in the simulation study.

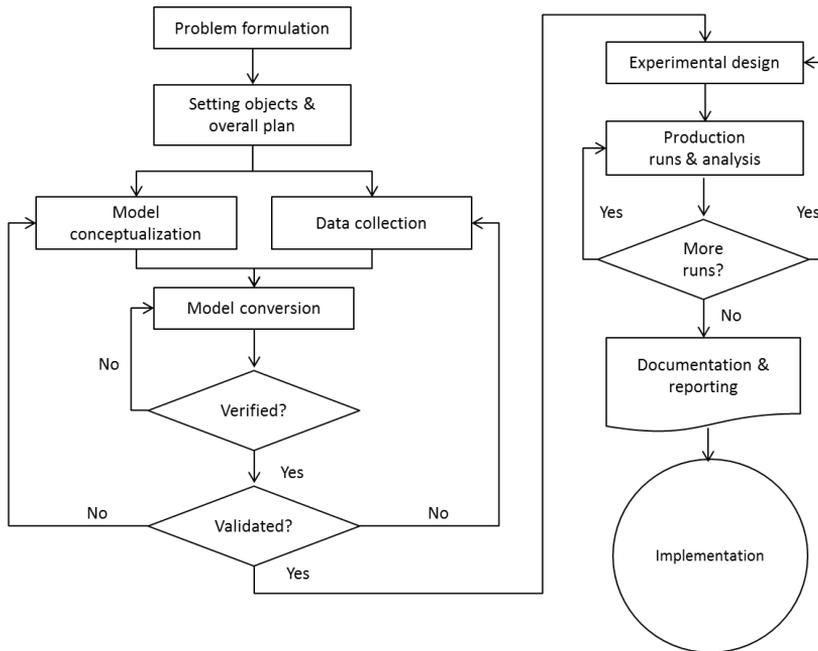


Figure 24. Steps in a simulation study (Banks et al. 2010).

3.5.1 Simulations in forest operations

Simulation is a very useful and widely used management science technique (Winston 2004). It is widely used in many disciplines including forestry, especially in the field of forest engineering. As better simulation programming packages have become available, the modelling and simulation of logging operations have become easier and more precise. This has resulted in an increasing interest in applying simulation as an operation research method within the fields of forest engineering. The goal of most logging system simulations has been to determine productivity, costs and the effect of changes to the system on productivity and costs (Goulet et al. 1979). There have been numerous relevant studies concerning simulation in forest engineering, for example in timber harvesting, timber transportation and logistics, bucking optimization and forest machine modification and innovation (Table 10).

Table 10. Some examples of simulation applications in forest operations. (Most of the studies used stochastic simulation.)

Area	Studies
Timber harvesting	LeDoux and Butler 1981; Stuart 1981; Vanclay 1994; Asikainen 1995; Wang and Greene 1996; Sikanen 1999; Wang and Greene 1999; Hartsough et al. 2001; Wang and Ledoux 2003; Talbot et al. 2003; Väättäinen et al. 2006; Hogg 2009; Asikainen et al. 2010; Wolferstetter 2010; Väättäinen 2010; Lamminen et al. 2010; Hogg et al. 2010
Timber transportation and logistics	Asikainen and Tolvanen-Sikanen 1995; Gallis 1997; Asikainen 1998; Asikainen 2001; Väättäinen et al. 2005; Fjeld 2012a; Fjeld 2012b
Bucking optimization	Uusitalo et al. 2004; Nordmark 2005; Kivinen 2007; Malinen et al. 2007; Wilhelmsson et al. 2012
Machine modification and innovation	Löfgren 2003; Brander et al. 2004; Servin et al. 2008; Robmann and Alves 2009; Ersson et al. 2012

The trend of simulation used in forest operations shows that, in the beginning, simulation was mainly applied to logging operations, with some studies carried out in timber transportation in the late 1990s (Table 11). The interest in applying simulation in timber harvesting activities declined after the 2000s. Simulation studies currently tend to concentrate on logistics, bucking optimization and machine modification and development. These simulation themes seem to be present in on-going research for the future. In keeping with the paradigm concept of Heinimann (2007), which states that mechanization worldwide is playing an important role, most simulation studies are now focusing on machinery aspects.

Table 11. A timeline of simulation application in forest operations (based on Table 10).

	1980s	1990s	2000s	2010s	
Timber harvesting	■				
Timber transportation and logistics			■ >>>		
Bucking optimization				■ >>>	
Machine modification and innovation				■ >>>	

4 MATERIALS AND METHODS

As pulp and paper production is increasing in Thailand, wood procurement needs to be increasingly efficient in order to meet the demand. The field measurement in this study was carried out in eucalyptus plantations, which are one of the main raw material resources in Thailand. The study objects were regular on-going harvesting operations, given by the logging companies. No special arrangements for the study were made. The key objectives of this study were to extract the current timber harvesting figures and analyse them to improve the harvesting system efficiency.

4.1 Study materials

4.1.1 Stands

This fieldwork was conducted in central, north-eastern and eastern parts of Thailand (Figure 25). The time data and relevant variables were collected during the final fellings of eucalyptus with a five-year rotation on average. The key characteristics of the harvesting stands are presented in Table 12. All harvesting stands consisted of a monoculture of eucalyptus planted with a fixed spacing. The choice of eucalyptus clones may vary from place to place depending on the site quality, topography, climate and other factors.



Figure 25. Map of the experimental plot distribution and pulp mill locations.

Table 12. Key characteristics of the harvesting stands.

Site	Area (ha)	DBH (cm)	Height (m)	Age (yr)	Survival* (%)	Density (stems/ha)	Growing stock (m ³ /ha)	Work phases observation
1	136.4	7.2	5.9	5	69.2	1 152	39.4	Manual loading
2	3.0	16.7	19.7	5	55.6	617	99.8	Felling; manual loading
3	4.5	7.6	10.8	4	89.3	1 984	69.2	Manual loading
4	14.9	15.5	17.8	5	99.0	823	133.7	Felling; manual loading
5	49.1	5.4	5.1	NA	NA	890	20.0	Manual loading
6	NA	7.2	10.2	4	75.0	864	33.2	Mechanized loading
7	49.3	8.7	17.9	6	82.7	1 378	61.7	Stacking; combined delimiting & stacking; mechanized loading
8	95.7	9.2	10.9	6	73.4	1 223	61.2	Stacking; combined delimiting & stacking; mechanized loading
9	8.9	10.3	14.7	5	70.7	1 177	74.5	Felling, bucking, stacking; combined delimiting & stacking; mechanized loading
10	19.2	10.0	12.5	5	75.6	839	49.9	Bucking; delimiting
11	13.6	14.7	19.1	5	99.0	825	110.4	Bucking; delimiting
12	10.1	13.7	18.4	5	97.7	814	93.8	Felling; bucking; stacking; combined delimiting & stacking,
13	15.4	9.3	10.7	5	40.0	666	34.1	Manual loading
14	16.2	7.4	10.3	5	60.0	1 200	38.1	Manual loading
15	7.2	17.2	15.9	6	75.0	625	116.9	Felling
Mean	32.9	11.0	14.0		74.8		56.2	

*Survival rate is defined as the ratio of the number of planted seedlings to the number of trees at final felling.

Different forest management policies have been applied in the harvesting sites, resulting in different stand characteristics. For example, harvesting site “4” has a very high-growing stock of 133 m³/ha, whereas harvesting site “5” has only 20 m³/ha of growing stock. This is caused by the intensity of forest management. In harvesting site “4”, the forest owner selected a proper clone for the site properties including appropriate management, while harvesting site “5” was a coppicing stand and the plantation was abandoned for some years. Due to the unproductive site, the forest owner would like to convert the eucalyptus plantation to another cash crop. Hence, the forest owner decided to harvest the stand and did not bother to consider the yield of eucalyptus nor the optimal rotation period.

The fieldwork was conducted during May–July 2010 and February–April 2011. The study was not conducted during rainy season because no harvesting activities occurred during that time. Climate statistics for the study period were reported by the Thai Meteorological Department (Table 13).

Table 13. Climatic statistics during study recorded at the weather station (Thai Meteorological Department 2013).

Month	Year	Average temperature (°C)	Average rainfall (mm)
May	2010	30.6	119
June	2010	29.5	190
July	2010	28.5	213
February	2011	26.4	19
March	2011	26.0	191
April	2011	28.3	103

In general, tree volume and DBH are closely correlated with each other. However, their frequency distributions were skewed in different directions. Those of DBH, stump diameter, and tree volume were positively skewed, while height was negatively skewed (Figure 26). The average stump diameter and DBH are 16.4 and 13.8 cm respectively. Tree size has a rather big variation; DBH ranges from 5 to 33 cm, and the average tree volume is 0.135 m³ (Table 14).

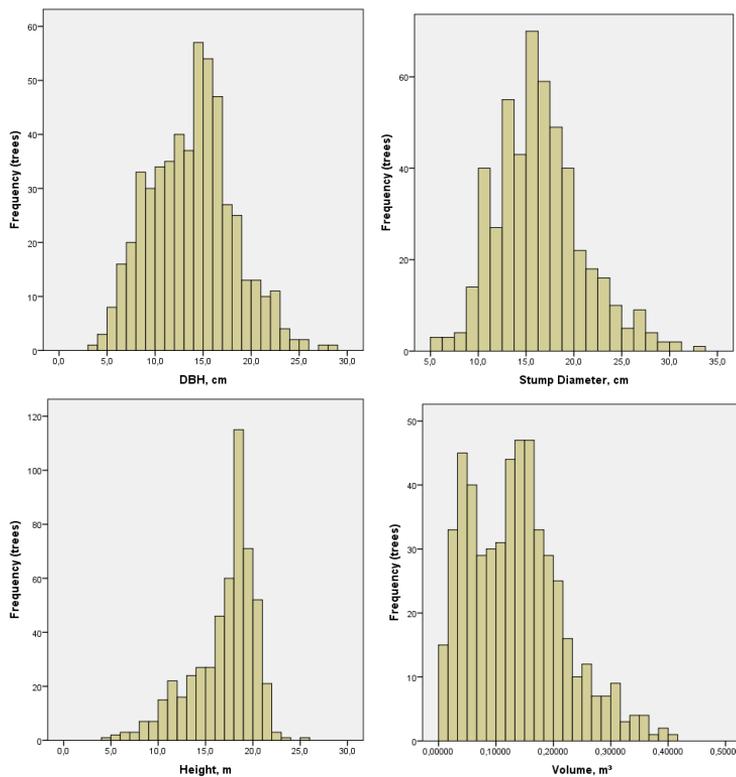


Figure 26. The frequency of tree characteristics sorted by DBH, stump diameter, tree height, and tree volume.

Table 14. Descriptive statistics of felled trees characteristics.

Variables	Min	Max	Mean	SD
Stump diameter, cm	5.10	33.1	16.4	4.49
DBH, cm	3.80	28.2	13.8	4.32
Tree height, m	4.07	25.5	16.9	3.39
Tree volume, m ³	0.004	0.414	0.135	0.081

4.1.2 Harvesting systems

The harvesting systems of eucalyptus in Thailand all belong to System I (Figure 4) and can be further categorized into three general harvesting systems (Systems A–C) as presented in Table 15. The prevailing harvesting systems vary from place to place, based on the available tools and resources, and on local conditions.

4.1.3 Workers

The numbers of forest workers are limited, and few options are available. The operations in this study took place at different locations and with different workers at each site. It is too costly and impractical to use the same group of workers in all work places, because the work places are located a long distance from each other. The study was conducted in parallel with the actual harvesting activities. Thus, the worker factor cannot be controlled. The overall numbers of forest workers involved in this study are 89. They are predominantly male, as only 17% of the workers are female. The numbers of forest workers are different among work phases (Table 16).

The majority of the studied forest workers are in the middle age group, which is 36–55 years old (Figure 27). About 47% of workers have between one to five years of forest working experience (Figure 28).

Table 15. Harvesting systems working components and harvesting tools

	System A	System B	System C	System D*
Felling	Brush saws	Brush saws	Brush saws	Brush saws
Extraction	–	–	–	Farm tractor
Delimiting	Hand tools	Hand tools	–	Hand tools
Bucking	Brush saws	Brush saws	Brush saws	Brush saws
Stacking	Manual	Manual	–	–
Delimiting & stacking	–	–	Manual	–
Loading	Manual	Modified farm tractor with front end grapple	Modified farm tractor with front end grapple	Modified farm tractor with front end grapple

* System D is a virtual harvesting system that is only used for a simulation study

Table 16. Numbers of workers who involved in this study according to work phases.

	Numbers	Male/Female
Felling	7	7/0
Bucking	8	8/0
Delimiting	4	1/3
Stacking	8	8/0
Combined delimiting & stacking	9	9/0
Manual loading	50	38/12
Mechanized loading	3	3/0
Total	89	74/15

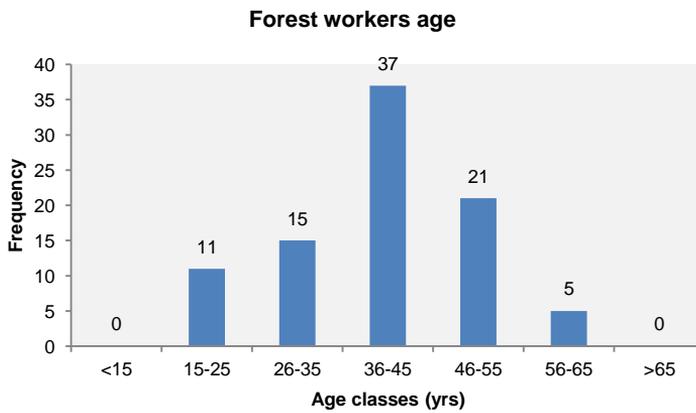


Figure 27. Distribution of forest worker age classes.

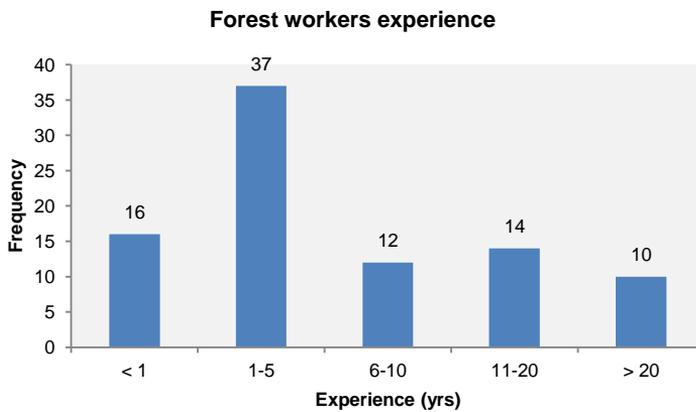


Figure 28. Distribution of forest worker experiences.

4.2 Study methods

4.2.1 Video observation

The field study details were recorded using a video camera, and the total time of observation was 144 hours (Table 17). It was noted that video recording initially affected the working pace, as the excitement among workers generated an atypical work pace during initial observations, as mentioned by Harstela (1993). Therefore, these first observations were omitted from the data analysis, and were not counted in the 144 hours of observation.

The video material was analysed from a screen using a handheld computer (Psion) installed with a specific time study program called UmtPlus (Laubrass 2008). The time study program is a handy tool and provides high accuracy. Each work element was recorded together with the time consumption (cmin), and continuous timing was applied in the time studies. The time study software automatically recorded the cumulative time, and a time element was calculated as the difference between two recorded times. Detailed information was recorded on the processes of felling, bucking, delimiting, stacking, combined delimiting and stacking, manual loading and mechanized loading. During the time study, work phases were broken down into work elements (Table 18).

The work processes in this study do not follow the same procedures as a harvester. A multifunction machine, like a harvester, generally fells and processes the wood tree by tree. In this study work processes are carried out work phase by work phase for either the entire or a portion of the harvesting stand i.e. trees are felled first and only afterwards other processes will be carried out step by step. Forest workers normally processed the felled trees based on proximity, causing difficulty in following the working steps for one tree from start to the end of the last process. Accordingly, work cycles were classified as follows:

Felling	seconds/tree
Bucking	seconds/log
Delimiting	seconds/tree
Stacking	seconds/log
Delimiting & stacking	seconds/log
Manual loading	minutes/truck
Mechanized loading	seconds/load

Table 17. Video observation hours

	Hours	Work cycles
Felling	18.45	505
Bucking	16.28	1 668
Delimiting	7.86	96
Stacking	15.14	847
Combined delimiting & stacking	10.99	978
Manual loading	55.65	12
Mechanized loading	20.05	350
Total	144.42	4 456

Table 18. Descriptions of the work elements.

Work phases	Work elements	Description
Felling	Walking	Begins when worker starts walking towards the tree to be cut and ends when worker reaches the tree.
	Cleaning	Begins when worker starts clearing around the tree and ends when worker is ready to cut the tree. (Optional)
	Determine direction	Begins when worker starts judging where tree will fall and ends when worker is ready to cut the tree. (Optional)
	Undercut	Begins when the worker starts to cut and ends when the undercut is done and ready to process the back cut.
	Back cut	Begins when worker starts to cut the tree from the opposite side of undercut and ends when the tree hits the ground.
Bucking	Walking	Begins when the worker starts to move with a brush saw and ends when the worker stops to operate bucking near the felled tree.
	Cleaning	Begins when the worker starts to remove unwanted debris, branches, and disturbing undergrowth and ends when the worker starts the next activity.
	Delimiting	Begins when the worker moves and starts to cut the top and branches and ends when all branches are cut. (Optional)
	Bucking	Begins when the worker starts to buck the felled tree on the marked length and ends when the cross-cutting finishes.
Delimiting	Walking	Begins when the worker starts to move with hand tools (knife, axe) and ends when the worker stops to perform delimiting near the felled tree.
	Delimiting	Begins when the worker starts to remove branches with hand tools and ends when the worker stops delimiting/topping.
	Marking	Begins when the worker starts to measure the log and mark the position of bucking with hand tools and ends when the worker stops marking. (Optional)
Stacking	Walking	Begins when the worker starts to move and ends when the worker stops to operate stacking.
	Hooking	Begins when the worker starts to use a knife to lift/move log from the ground and ends when the worker gets the log in his/her hands and the worker is in a standing position.
	Carrying	Begins when the worker starts to move/drag/carry the log and ends when the worker stops at the log pile.
	Piling	Begins when the worker starts to release/drop the log onto the pile/line and ends when the log is put on top of the log pile.
Combined delimiting & stacking	Walking	Begins when the worker starts to move with hand tools and ends when the worker stops to perform delimiting near the processed log.
	Delimiting	Begins when the worker starts to remove branches with hand tools and ends when the worker stops delimiting/topping.
	Stacking	Begins when the worker starts to move/lift the log from the ground and ends when the worker piles the log onto line/pile.
Manual Loading	Loading	Begins when the workers start to load the first log from piles onto the truck and ends when there are no more logs to be loaded, or when truck payload is full.

(continued)

Table 18 continued. Descriptions of the work elements.

Work phases	Work elements	Description
Mechanized Loading	Drive without load	Begins when the driver starts to drive from the roadside where the truck is parked and ends when the driver stops to start loading.
	Loading	Begins when the driver starts to load logs from a small pile and ends when the grapple of the loader is full of logs and is in a ready position to drive back. Includes the reload if one grapple is not enough to achieve the loading capacity from one pile and logs have to be collected from another pile.
	Drive with load	Begins when the driver starts to drive back with a full load and ends when the driver stops driving at the roadside to operate unloading. Includes driving between piles in case of collecting logs from more than one pile.
	Unloading	Begins when the driver starts to unload logs onto the truck and ends when the grapple of the loader is empty and the driver starts to drive backwards in order to start a new cycle.

4.2.2 Variables

Variables that were expected to influence the result were measured. The expected independent variables differ between work phases (Table 19). Variables may drop out of the regression if they are found to be insignificant.

In the field, log diameter and DBH were measured with a calliper. Distances, tree height and log length were measured with a measuring tape, with tree height measured after felling. To determine the volume of logs, Smalian's formula [Eq. 2] was used (Avery and Burkhart 1994; Tufts 1997).

$$V = \frac{A_1 + A_2}{2} \times L \quad (2)$$

where

V = log volume, m³

A₁ = cross-sectional area at small end of log, m²

A₂ = cross-sectional area at large end of log, m²

L = log length, m

For stem volume, the volume was estimated by a volume function for eucalyptus in Thailand [Eq.3] (Viriyauncha et al. 2005). This volume equation requires the input of DBH and tree height:

$$V = 0.00006514 \times DBH^{1.78698} \times Ht^{1.0009} \quad (3)$$

where

V = stem volume, m³

DBH = diameter at breast height, cm

Ht = tree height, m

Table 19. Work phases and candidate independent variables

Work phases	Independent variables	Terms
Felling	Walking distance between trees	X _{dis_tree}
	DBH	X _{dbh}
	Stump diameter	X _{std}
	Tree height	X _{ht}
	Tree volume	X _{v_tree}
Bucking	Walking distance between logs	X _{dis_log_log}
	Log diameter	X _{dia_log}
	Log length	X _{l_log}
Delimiting	Log volume	X _{v_log}
	Walking distance between trees	X _{dis_tree}
	DBH	X _{dbh}
Stacking	Stump diameter	X _{std}
	Tree height	X _{ht}
	Tree volume	X _{v_tree}
	Walking distance between log and pile	X _{dis_log_pile}
Combined delimiting & stacking	Log diameter	X _{dia_log}
	Log length	X _{l_log}
	Log volume	X _{v_log}
	Walking distance between log and pile	X _{dis_log_pile}
Manual loading	Log diameter	X _{dia_log}
	Log length	X _{l_log}
	Number of logs	X _{logs}
Mechanized loading	Driving distance with load	X _{fd}
	Driving distance without load	X _{ed}
	Load volume per grapple	X _{v_grapple}
	Number of logs per grapple	X _{logs}
	Number of log piles that has been loaded per turn	X _{piles}

4.2.3 Regression

Time consumption modelling in this study is divided into two sections:

- Time consumption per work cycle
 - Time consumption of each work element
 - Time consumption of each work phase, calculated by summing the work element models
 - Overall time consumption of work phase, which represents the total work phase time within one model
- Time consumption per cubic meter

Two different techniques were applied in constructing models, in accordance with Nurminen et al. (2006). Firstly, an effective time consumption model was formed separately for each element of the work phase. Different transformations and curve types were tested to obtain as symmetrical residuals of the regression models as possible and to achieve the best value for the coefficients of determination in the final models (Nurminen et al. 2006; Laitila et al. 2007). Regression analysis with the variables and appropriate transformation of variables was used in modelling the time consumption of the work phases whenever the time consumption could be explained by one or several independent variables (Laitila et al. 2007). Variable transformation was needed in some cases in order to improve the linearity. Secondly, in the case of no explanatory independent variable, work elements were modelled using average time consumption values (Nurminen et al. 2006).

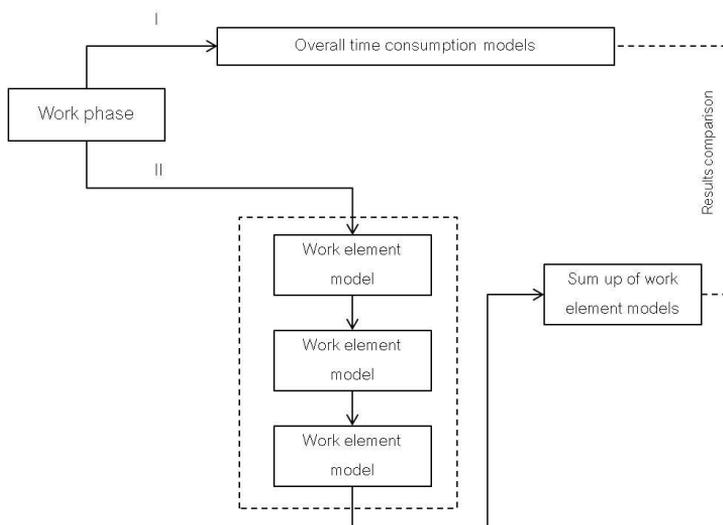


Figure 29. The time consumption models data analysis and comparison procedure.

Time consumption was modelled separately for each main work phase, and the total time was computed as the sum of the expected work phase times (Nurminen et al. 2006; Nurminen and Heinonen 2007). Finally, the total time consumption was converted into productivity (Nurminen et al. 2006). Productivity per effective hour was determined by dividing the output by the total effective time consumption (Kärhä 2006). Furthermore,

productivity can also be converted to productivity per man-hour by dividing productivity per effective hour by numbers of workers.

Multivariate regression (stepwise method) was applied for the modelling. A statistical software package (SPSS v.18) was employed for data processing and analysis. SPSS was mainly applied in selecting the goodness-of-fit model, based on the F-value, P-value, and r^2 data. Consequently, regression models were tested to determine whether a fitted regression model adequately represented the data via the residual plot, or P-P plot, a simple scatterplot of the residuals versus the fitted values (Freese 1967; Fox 2011).

4.2.4 Ergonomics

The samples of work posture analysis were sub-samples of the work study material. The sample size was 20% of the total population, limited to 19 workers (15 male and 4 female). Ergonomics analysis included felling (chainsaws and brush saws), cross-cutting (chainsaws and brush saws), manual delimiting, manual stacking, combined manual delimiting and stacking, manual loading and mechanized loading operations. The chainsaw is still used in a small number of cases; the acquired data about chainsaws is insufficient for analysing the time study, but is applicable from the working posture samples perspective.

Video files were analysed with specific computer software for analysis of working postures on the basis of the OWAS method – the so-called “WinOWAS” (Tampere University of Technology 1996). The fixed time interval for coding postures was 30 seconds (Mattila and Vilkki 2003; Stempski 2008; Stempski 2009). Body postures: back, arms, legs and external load were evaluated and coded via computer screen.

Example 1: Tree felling with brush saw



Table 20. Example of a posture classification and codes for different body parts in the OWAS system.

Postures	Positions	Codes
Back	Straight back	1
Arms	Both arms are below shoulders	1
Legs	Standing on one straight leg	3
Load/effort	Load is less than 10 kg	1

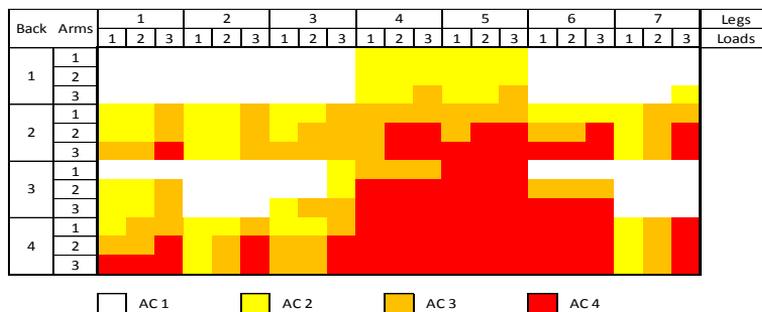


Figure 30. Action category for each individual OWAS classified posture combination.

An example of the numerical code 1131 indicates that the worker's back is straight. He works with both arms below shoulder level, has his weight on one straight leg and handles a load less than 10 kg. From the table of action category analysis (Figure 30), this posture code 1131 is classified as normal postures (AC1), so no action is required.

Example II: Tree felling with chainsaw



Table 21. Example of a posture classification and codes for different body parts in the OWAS system.

Postures	Positions	Codes
Back	Back bent and twisted	4
Arms	Both arms are below shoulders	1
Legs	Standing on both knees bent	4
Load/effort	Load is between 10–20 kg	2

An example of the numerical code 4142 indicates that the worker's back is twisted and bent. He works with both arms below shoulder level, has his weight on both bent knees, and handles a load between 10–20 kg. From the table of action category analysis (Table 21), this posture code 4142 is classified as extremely harmful postures (AC4), corrective actions for improvement are required immediately (Figure 30).

4.2.5 Discrete-event simulation

Simulation models were constructed in order to investigate harvesting performance and compare alternatives. In this study, the emphasis was on stochastic (discrete-event) simulation models. The simulation tools included a graphical user interface, animation and automatically collected outputs to measure system performance. A large number of commercial simulation packages are available. In this study, all the simulations employed a ready-to-use simulation package called “SIMUL8”, version 17 (Simul8 Corporation 2003).

SIMUL8 is a computer package for discrete-event simulation produced by SIMUL8 Corporation, first introduced in 1995. It allows the user to create a visual model of the system being investigated by drawing simulation objects or elements directly on the screen (Shalliker and Ricketts 2005). Once the system has been modelled, a simulation can be undertaken. The flow of work items around the system is shown by animation on the screen so that the appropriateness of the model can be assessed. The performance of the system is described statistically. Statistics of interest may include average waiting times, utilization of work centres or resources (Shalliker and Ricketts 2002). SIMUL8 can be used to optimize throughput, maximize resource utilization, identify bottlenecks, reduce decision risks and manage processes (Simul8 Corporation 2003). The main focus of SIMUL8 is on service industries, for example in a bank, call centre or hospital (Banks et al. 2010).

As mentioned above, there are three main harvesting systems but in the simulation study a virtual harvesting system (System D) was included (Table 15). Harvesting System D starts with felling with brush saws. Trees are choked and pulled to the tractor with a winch, called “winching”. Tree ends are then lifted off the ground and skidded to the roadside by a farm tractor. Delimiting and bucking take place at the roadside. Logs are not stacked in the stand. A mechanized loader will then take responsibility for loading logs onto the trucks after bucking. Benefits of System D are reduction of walking time and centralization of the wood processing in one place. It also facilitates the collection of logging residues for other uses.

The simulation conceptualization consists of the sequence of timber harvesting: felling, processing and loading (Figure 31). In the figure, the dashed line illustrates the grouping of work sections. For instance, a felling section worker starts by walking to a target tree to be felled, and then making the undercut and back cut, respectively. Afterwards, the worker

considers whether there are any trees left for felling; if so, the worker repeats the same cycle of the felling processes. In the loading section, once the stacking is done, a truck driver will be directed to drive a truck into the harvesting site. In some cases, this may lead to delays for loading if a truck is not already at the harvesting site beforehand.

The length of a simulation run was set to one week, assuming eight hours of work per day with a half-hour warm-up period. The simulated hours per day were based on the practical situation. The warm-up period is used to ensure that when measurements of the model are initiated, the queues and the machines have achieved a steady state (Concannon et al. 2007). A single simulation run is usually not sufficient, since it seeks to generate an expected range of results and not just a single data point. Therefore, simulation should include multiple runs with different sets of random numbers (Concannon et al. 2007). The more runs of simulations carried out, the more precise the results will be. The specified number of runs in each scenario varied depending on the factors in each model. SIMUL8 has a function called “conduct trial”, which calculates the required number of runs of the simulation to provide results at the end of the trial with a 95% confidence interval.

The tree size, log length, winching distance and skidding distance can be varied in the simulation but not varied in the real system. Furthermore, simulation is able to examine the effects of system reorganization, i.e. System D. Thus, several levels of variables were taken into consideration in the simulation study, including four DBH classes, two log lengths, two skidding distances and four winching distances (Table 22). Winching distance refers to the distance between logs and tractor, distance that logs are pulled from the original place to the tractor with a winch. Skidding distance represents distance the trees are transported by partly or fully dragging in contact with the ground to the roadside. The number of workers and resources involved with the harvesting process in simulation is presented in Table 23.

The entity (trees) arrival rate was given as an average value (10 seconds). Different work phases had separate distributions, which were the obtained from dataset (Table 38). The same time distribution was used for felling, but the lower bound was shifted according to different DBH classes. In the bucking process, an external file was applied to express the number of bucking points for different log lengths. The predicted numbers of cross-cutting points required per tree were based on tree height and log lengths. The distribution of winching and skidding times are derived from time consumption models of Spinelli and Magagnotti (2011a) and are then converted to probabilistic distributions for each distance. The simulation results provide the number of logs produced. Eventually, the average log volume was multiplied by the number of produced logs to estimate system productivity. All the results of the simulations are presented based on probability distributions from the datasets.

Afterwards, sensitivity analysis was applied to determine how different probability distributions will impact the simulation results. In this sensitivity analysis, the simulation study which was based on dataset probability distributions is compared with probability distribution from the regression model. The probability distributions from the regression models were calculated by replacing independent variables from dataset into a regression model that was obtained from time studies. Later the dependent variable was fitted into probability distribution (Table 42).

Table 22. The variables that are taken into consideration in the simulation.

Log lengths, m	DBH classes, cm	Winching distance, m	Skidding distance, m
2	5.01–10.00	5	50
3	10.01–15.00	10	100
	15.01–20.00	15	
	20.01–25.00	20	

Table 23. The number of workers and resources that are involved in the harvesting process.

Work phases	Resources	Number of workers
Felling	Brush saw	1 (Only feller) or 2 (Feller and assistant), optional
Bucking	Brush saw	2
Delimiting/stacking; combined delimiting and stacking	Hand tools	5
Manual loading	Man power	8
Mechanized loading	Tractor mounted with grapple	1
Timber extraction	Winching tractor	1

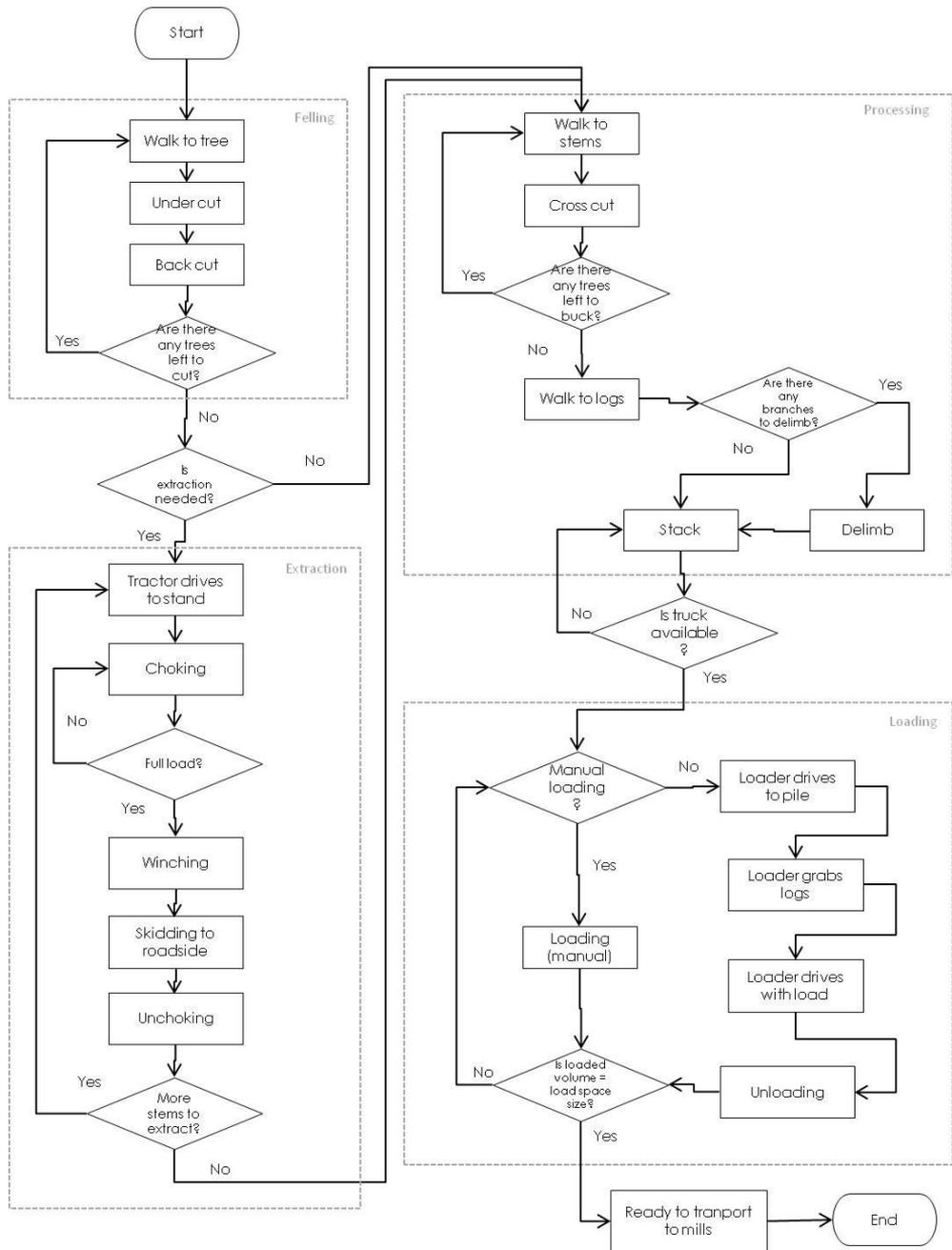


Figure 31. Flowchart of the simulation conceptualization.

5 RESULTS

5.1 General perspective

The results section presents the working time division, time consumption per work cycle (single work element and overall work phase time consumption models), time consumption per cubic meter, existing systems comparison, work load, discrete–event simulation and cost analysis. Work study and ergonomics study were applied to address the research questions regarding the basic time consumption, productivity, work load and operating costs of typical harvesting systems. Once the inefficient work phases in the current systems were clearly identified, discrete-event simulation was applied to investigate the effect of changing work components and the effect of relevant variables on overall productivity.

Since data was collected in several stands, the descriptive statistics for the relevant variables such as tree height, stump diameter, DBH and log volume have been tested with correlation analysis in order to depict how strongly pairs of variables are related. A correlation analysis of the tree characteristic variables was carried out before modelling.

The correlation matrix gives a good overview of the relationships between variables. It shows that all variables – tree height, stump diameter, DBH and tree volume – are strongly positively correlated with each other (Table 24). Especially DBH and tree volume have a very high positive correlation. As the dimensional variables such as diameter and height are used to estimate log volume, this implies a strong correlation among variables. The least correlated variables are stump diameter and tree height.

5.2 Time distribution of work phases

Each work phase is composed of different work elements with various average time consumption per work cycle. The relative working times and the structure of work time among the work phases are presented in Figure 32. Average time per work cycle is shown on the top of each bar.

Table 24. Correlations between DBH, stump diameter, tree height, and tree volume (n = 505).

	Height	Stump diameter	DBH	Volume
Height	1	0.447**	0.593**	0.681**
Stump diameter		1	0.809**	0.781**
DBH			1	0.960**
Volume				1

** Correlation is significant at the 0.01 level

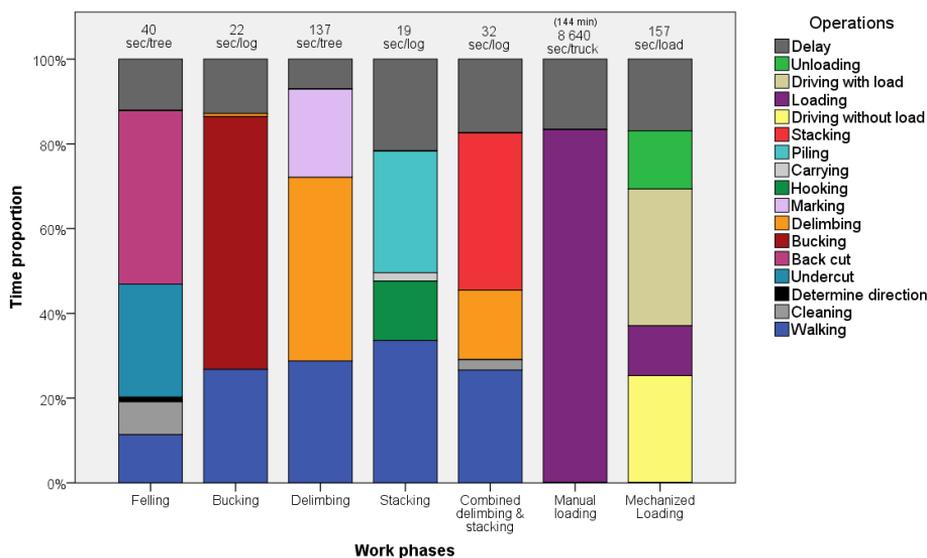


Figure 32. The time distribution of felling, bucking, delimiting, stacking, combined delimiting and stacking, manual loading, and mechanized loading. For the work element explanations, please see Table 18. Average time per cycle is shown on top of each bar.

This time division pinpoints which work elements most need improvement. It is clear that walking and driving are the major time-consuming elements that occur in every work phase; many of the work phases contain walking or driving greater than 20 percent of total time. Additionally, the key work elements that take a lot of time in each work phase are different between work phases. For instance, the back cut is the most time-consuming in the felling phase; the bucking takes most of the time in the bucking phase, and stacking is the main work element in the combined delimiting and stacking phase. Regarding the average work cycle time, the shortest work cycle time is stacking, while manual loading has the longest working time cycle.

5.3 Time consumption models

5.3.1 Work phase time consumption per work cycle

The overall time consumption model was used to estimate the time as a function of independent variables [Eq. 4–9]. One model can represent the work phase time consumption per cycle. The regression shows that the distance travelled, either walking or driving, is an important factor for all work phases as it appears in every work phase model. Log diameter and DBH are also the essential variables that have an impact on time consumption models for felling, bucking, delimiting, combined delimiting and stacking phases. In mechanized loading, beside driving distances, the number of logs per grapple also has an impact on the loading time. The time consumption models can be interpreted such that operating time increase as a function of distance, log lengths and log size. The

statistical characteristics of regression analysis for the overall models are presented in Table 25. Note that the time consumption models for felling and delimiting are presented in second per stem, and then change to second per log for bucking and stacking phase. This conversion from stem to logs, the number of logs per tree is simply determined by dividing a tree length with certain log length (2 m).

$$t_{of} = -0.527 + 2.090 x_{std} + 2.102 x_{dis_tree} \quad (4)$$

$$t_{ob} = -3.181 + 1.284 x_{dia_log} + 2.0 x_{dis_log_log} \quad (5)$$

$$t_{od} = -22.050 + 1.316 x_{dis_tree} + 8.213 x_{DBH} \quad (6)$$

$$t_{os} = 6.162 + x_{dis_log_pile} + 0.089 x_{v_log} \quad (7)$$

$$t_{ods} = 7.007 + 0.980 x_{dis_log_pile} + 0.496 x_{dia_log} \quad (8)$$

$$t_{ol} = 81.598 + 1.367 x_{fd} + 0.700 x_{ed} - 0.478 x_{logs} \quad (9)$$

Table 25. The descriptive statistics of overall time consumption models for each work phase (based on whole data).

Category	R ²	F-Test		n	Terms	Coefficient	S.E.	T-Test	
		F-value	P					t-value	P
Felling	0.26	87.54	<0.001	505	Intercept	-0.527	3.255	-0.162	0.871
					X _{std}	2.090	0.188	11.114	<0.001
					X _{dis_tree}	2.102	0.326	6.448	<0.001
Bucking	0.43	634.57	<0.001	1668	Intercept	-3.181	0.558	-5.699	<0.001
					X _{dia_log}	1.284	0.052	24.852	0.001
					X _{dis_log_log}	0.020	0.001	24.813	<0.001
Delimiting	0.70	107.80	<0.001	96	Intercept	-22.050	15.017	-1.468	0.145
					X _{dis_tree}	1.316	0.170	7.728	<0.001
					X _{DBH}	8.216	1.274	6.449	<0.001
Stacking	0.61	662.22	<0.001	847	Intercept	6.162	0.317	19.410	<0.001
					X _{dis_log_pile}	1.000	0.029	35.004	<0.001
					X _{v_log}	0.089	0.019	4.586	<0.001
Delimiting & stacking	0.34	252.27	<0.001	978	Intercept	7.007	0.755	9.279	<0.001
					X _{dis_log_pile}	0.980	0.048	20.461	<0.001
					X _{dia_log}	0.496	0.084	5.900	<0.001
Mechanized loading	0.80	459.44	<0.001	350	Intercept	81.598	4.967	16.428	<0.001
					X _{fd}	1.367	0.075	18.126	<0.001
					X _{ed}	0.700	0.079	8.853	<0.001
					X _{logs}	-0.478	0.121	-3.967	<0.001

Where t_{of} is overall time consumption for felling (sec/stem), t_{ob} is overall time consumption for bucking (sec/log), t_{od} is overall time consumption for delimiting (sec/stem), t_{os} is overall time consumption for stacking (sec/log), t_{ods} is overall time consumption for delimiting and stacking (sec/log), t_{ol} is overall time consumption for mechanized loading (sec/turn), x_{std} is stump diameter (cm), x_{dis_tree} is walking distance between trees (m), x_{dia_log} is log diameter (cm), $x_{dis_log_log}$ is walking distance between logs (m), $x_{dis_log_pile}$ is walking distance between log and pile (m), x_{DBH} is diameter at breast height (cm), x_{v_log} is log volume (l), x_{ed} is driving distance without load (m), x_{fd} is driving distance with load (m), and x_{logs} is number of logs per grapple (logs).

5.3.2 Work element time consumptions per work cycle

Felling

The time consumption model of the felling phase has been divided into walking, cleaning, undercut and back cut. The work element description is given in Table 18. The time required to walk from one tree to another (t_{f1}) is significantly determined by the walking distance and can be modelled by linear regression [Eq. 10]. The distance has a significant impact on walking time in several work phases in this study. The understory density and litter influence the cleaning time around the tree required before the worker can proceed with the cutting process. However, the time consumption for cleaning (t_{f2}) is not affected by any recorded variables, and a mean value of 7 seconds per stem was applied for this work element. The undercut time consumption (t_{f3}) depends on the stump diameter [Eq. 11]. In this study, the harvested trees were small: the average stump diameter and tree volume were 16 cm, and 0.135 m³, respectively (Table 14). When trees are rather small, an undercut is sometimes not required. On the other hand, the back cut is a compulsory work element for every tree. The back cut time consumption (t_{f4}) depends on the tree height and stump diameter [Eq. 12]. The delays were mainly attributed to refuelling, lubrication and sharpening of the saw blade. The delay time in the felling phase was estimated as a mean value of 60 seconds per stem. The statistical regression analysis of the individual work elements and the overall time consumption models are presented in Table 26. Note that all variable explanations are provided below Table 26.

$$t_{f1} = 0.868 + 1.553 x_{\text{dis_tree}} \quad (10)$$

$$t_{f3} = -9.636 + 1.297 x_{\text{std}} \quad (11)$$

$$t_{f4} = -1.975 + 0.737 x_{\text{ht}} + 0.380 x_{\text{std}} \quad (12)$$

The model of the total effective time consumption for felling was formed by combining the work element models [Eq. 13].

$$t_f = t_{f1} + t_{f2} + t_{f3} + t_{f4} \quad (13)$$

The distribution of regression standardized residuals was tested. As all observation points lie approximately on a straight line, the residuals are fairly normal distributed (Figure 33A). The test for normality with cumulative distribution function (CDF) showed data are normal distributed (34.11 ± 12.90). Moreover, the linearity of the phenomena is confirmed in the scatter plots of standardized residuals against the standardized predicted value of the dependent variable (Figure 33B). The points on this plot are widely scattered and do not cluster in any significant way, thus confirming the homogeneity of variance. It implies the linear model is suitable in this case.

Table 26. Statistical characteristics of the regression analysis for felling time consumption models are based on the whole data.

Category	R ²	F-Test F-value	P	n	Terms	Coefficient	S.E.	T-Test t-value	P
Felling									
Walking, t_{f1}	0.90	4021.69	<0.001	505	Intercept	0.868	0.094	9.253	<0.001
					X_{dis_tree}	1.553	0.024	63.417	<0.001
Cleaning, t_{f2}				218	Mean	$\bar{x} = 7.39$	$s = 6.01$	$s^2 = 6.17$	SE = 0.41
Undercut, t_{f3}	0.22	120.88	<0.001	505	Intercept	-9.636	2.095	-4.600	<0.001
					X_{std}	1.297	0.118	10.994	<0.001
Backcut, t_{f4}	0.13	38.61	<0.001	505	Intercept	-1.975	2.191	-0.901	0.368
					X_{ht}	0.737	0.136	5.408	<0.001
					X_{std}	0.380	0.102	3.720	0.001

Where t_{f1} is time consumption for walking (sec/stem), t_{f2} is time consumption for cleaning (sec/stem), t_{f3} is time consumption for undercut (sec/stem), t_{f4} is time consumption for back cut (sec/stem), x_{dis_tree} is walking distance between trees to be felled (m), x_{std} is stump diameter (cm), and x_{ht} is tree height (m).

In addition, the performances of workers were evaluated. The workers who were involved in this study had different skill levels, educational backgrounds and work locations (Table 27). The productivity of the felling phase varied greatly between workers (Figure 34). An ANOVA test indicates that working performance differed significantly among the workers, $F(6, 498) = 57.44$, $p < 0.01$. In Figure 34, the average working performance (100%) was calculated as the mean for all workers. The mean productivity for all workers was 11.72 m³/h. At an average stem size of 0.135 m³, the best worker worked at a mean individual performance of 148% relative to the average performance level, and the worst worker at a mean individual performance of 51%. The relative productivity difference decreased for larger stem sizes. Working performance notably did not follow the normal tendency of increasing harvesting productivity as a function of stem size for all of the workers.

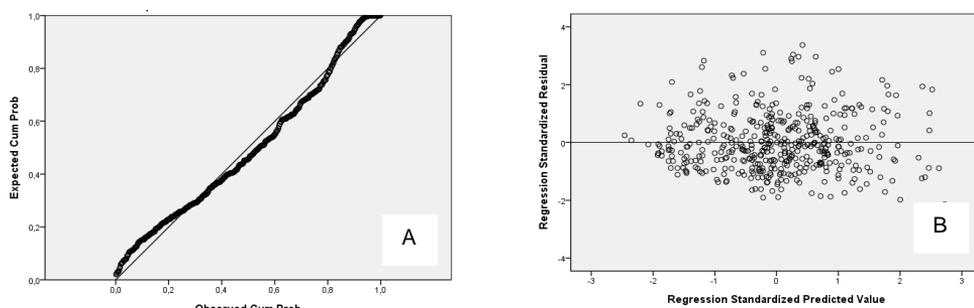


Figure 33. (A) Normal P-P plot of regression standardized residuals and (B) scatter plot of standardized residuals and predicted values.

The working conditions for each worker in the felling phase included blade size, saw teeth, DBH, stem size, age and experience. According to Table 27, all workers applied the same blade size, the influence of blade size on felling productivity could not be studied. The number of saw teeth seems unlikely to influence the productivity. However, stem size, DBH, and workers' routine have an impact on productivity. Figure 34 shows that productivity of workers C, F and G, who were working with large trees (average DBH ≥ 15 cm), increased as a function of stem size. In addition, the performance of workers C and G included assistant for controlling felling direction because of the large trees. Their performances were quite low when compared to others. On the other hand, workers A, B, D and E most of the time cut small trees, but also some larger trees that grew in the harvesting stand. For these workers, productivity declined when harvesting large trees.

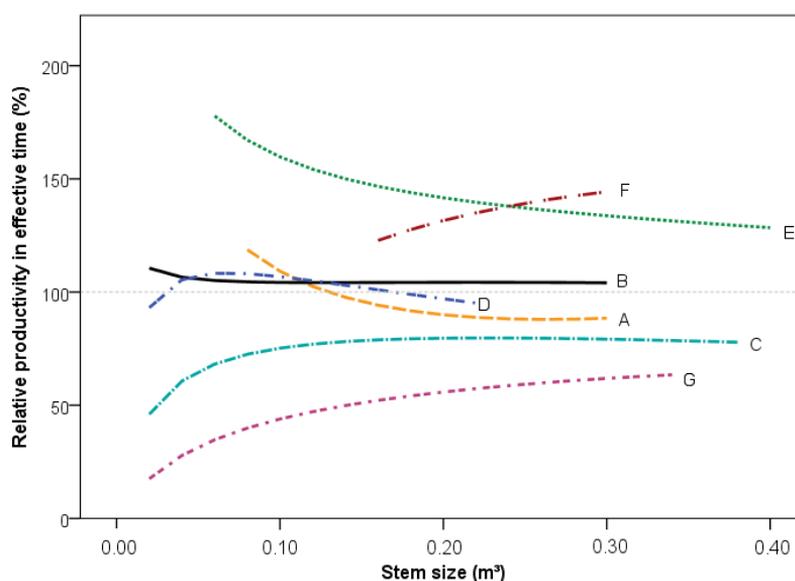


Figure 34. The felling performance as a function of stem size; 100% represents the average productivity of all workers of 11.72 m³/h. Each line represents different workers. (Note that workers C and G have an assistant for controlling felling direction)

Table 27. Summary of the working conditions of each worker in felling circumstance.

Workers	Blade size cm	Saw teeth	DBH cm	Stem size m ³	Age yrs	Experience yrs
A	25.4	14	13.6	0.128	34	-
B	25.4	14	13.8	0.132	42	<1
C	25.4	12	17.2	0.168	51	10
D	25.4	24	10.2	0.061	38	13
E	25.4	14	13.2	0.130	44	2
F	25.4	16	15.4	0.155	42	2
G	25.4	20	16.7	0.198	40	2

Bucking

The time for walking (t_{b1}) strongly depends on the walking distance [Eq. 14]. In practice, the bucking process always starts from the bottom of trees and progresses to the top. Sometimes, bucking can be done on multiple trees at the same time. When bucking is completed for some trees, a worker is required to walk back to the bottom of the next tree to start a new work cycle. The time consumption of cleaning (t_{b2}) was estimated at a mean value of 5 seconds per log. This cleaning element is an optional component and is carried out when some branches or debris needs to be removed from the operating area. The delimiting time consumption (t_{b3}) was modelled as an average value of 4 seconds per log. Delimiting is also an optional element and is required when some branches impede operations. Moreover, the time consumption of bucking (t_{b4}) increases as a function of log diameter and log length [Eq. 15]. In some cases, the log length and distance between logs might not be the same distance. Sometimes, worker may do cross-cutting for several logs at one walking time if logs are adjacent to each other. The delay time in bucking is estimated at a mean value of 7 seconds per log. From observation, delays are mainly a result of refuelling, lubrication and saw teeth sharpening. All variable explanations are provided below Table 28.

$$t_{b1} = 0.757 + 1.6 x_{\text{dis_log_log}} \quad (14)$$

$$t_{b4} = -9.209 + 1.283 x_{\text{dia_log}} + 3.037 x_{\text{l_log}} \quad (15)$$

The time consumption model for bucking (sec/log) is the sum of work elements time consumption:

$$t_b = t_{b1} + t_{b2} + t_{b3} + t_{b4} \quad (16)$$

Table 28. Statistical characteristics of the regression analysis for bucking time consumption models.

Category	R ²	F-Test F-value	P	n	Terms	Coefficient	S.E.	T-Test t-value	P
Bucking									
Walking, t_{b1}	0.86	10422.96	<0.001	1657	Intercept	0.757	0.045	16.657	<0.001
					$X_{\text{dis_log_log}}$	1.600	0.000	102.093	<0.001
Cleaning, t_{b2}				84	Mean	$\bar{x} = 5.18$	$s = 4.09$	$s^2 = 16.71$	SE = 0.45
Delimiting, t_{b3}				46	Mean	$\bar{x} = 3.82$	$s = 1.97$	$s^2 = 3.88$	SE = 0.29
Bucking, t_{b4}	0.30	362.59	<0.001	1668	Intercept	-9.209	1.145	-8.043	<0.001
					$X_{\text{dia_log}}$	1.283	0.048	26.729	<0.001
					$X_{\text{l_log}}$	3.037	0.494	6.146	<0.001

Where t_{b1} is time consumption for walking (sec/log), t_{b2} is time consumption for cleaning (sec/log), t_{b3} is time consumption for delimiting (sec/log), t_{b4} is time consumption for bucking (sec/log), $x_{\text{dis_log_log}}$ is walking distance between logs to be bucked (m), $x_{\text{dia_log}}$ is log diameter (cm), and $x_{\text{l_log}}$ is log length (m).

Delimiting

The walking time (t_{d1}) is defined as a linear function of the walking distance [Eq. 17]. The effective delimiting time consumption (t_{d2}) slightly depends on DBH [Eq. 18]. The marking (t_{d3}) is an optional element, applied by some harvesting teams to promote homogeneous log lengths. On average, marking the log length took 32 seconds per stem. Additionally, the delay time was estimated at a mean value of 37 seconds per stem. For variable explanations, please see Table 29. The total effective time consumption model for delimiting was concluded by combining all work element models [Eq. 19].

$$t_{d1} = 3.372 + 1.025 x_{\text{dis_tree}} \quad (17)$$

$$t_{d2} = -11.342 + 5.673 x_{\text{DBH}} \quad (18)$$

$$t_d = t_{d1} + t_{d2} + t_{d3} \quad (19)$$

Stacking

Stacking consists of walking from pile to log, hooking log from ground, carrying log and putting log onto pile. A linear regression was constructed to estimate the walking time (t_{s1}) as a function of walking distance [Eq. 20]. The time consumption of hooking (t_{s2}) does not depend on any independent variables. Hence, a mean value of 2 seconds per cycle was employed for the hooking element with the average log volume being 0.011 m^3 . The carrying time (t_{s3}) slightly depends on walking distance between log and pile [Eq. 21]. Sometimes, this carrying element is not required if the logs are located adjacent to the log pile. The time consumption of piling (t_{s4}) depends on the log volume [Eq. 22]. The average delay time for stacking was 20 seconds per log.

$$t_{s1} = 1.269 + 0.796 x_{\text{dis_log_pile}} \quad (20)$$

$$t_{s3} = 2.770 + 0.332 x_{\text{dis_log_pile}} \quad (21)$$

$$t_{s4} = 3.377 + 0.102 x_{v_log} \quad (22)$$

$$t_s = t_{s1} + t_{s2} + t_{s3} + t_{s4} \quad (23)$$

The total effective time consumption model for stacking was estimated by summing all work element models [Eq. 23]. Explanations of the model variables are provided in Table 30.

Table 29. Statistical characteristics of the regression analysis for delimiting time consumption models.

Category	R ²	F-Test		n	Terms	Coefficient	S.E.	T-Test	
		F-value	P					t-value	P
Delimiting									
Walking, t _{d1}	0.87	607.98	<0.001	96	Intercept	3.372	1.911	1.764	0.081
					X _{dis_tree}	1.025	0.042	24.657	<0.001
Delimiting, t _{d2}	0.32	44.47	<0.001	96	Intercept	-11.342	11.663	-0.975	0.332
					X _{DBH}	5.673	0.851	6.668	<0.001
Marking, t _{d3}				92	Mean	$\bar{x} = 31.73$	s =	s ² =	SE =
							21.83	476.58	2.28

Where t_{d1} is time consumption for walking (sec/stem), t_{d2} is time consumption for delimiting (sec/stem), t_{d3} is time consumption for marking (sec/stem), X_{dis_tree} is walking distance between stems to be delimiting (m), and X_{DBH} is diameter at breast height (cm).

Table 30. Statistical characteristics of the regression analysis for stacking time consumption models.

Category	R ²	F-Test		n	Terms	Coefficient	S.E.	T-Test	
		F-value	P					t-value	P
Stacking									
Walking, t _{s1}	0.86	5059.52	<0.001	847	Intercept	1.269	0.096	13.178	<0.001
					X _{dis_log_pile}	0.796	0.011	71.130	<0.001
Hooking, t _{s2}				1062	Mean	$\bar{x} =$	s =	s ² =	SE =
						2.22	1.54	2.36	0.05
Carrying, t _{s3}	0.19	12.405	<0.001	66	Intercept	2.770	0.785	3.528	0.001
					X _{dis_log_pile}	0.332	0.094	3.522	0.001
Piling, t _{s4}	0.05	53.658	<0.001	1068	Intercept	3.377	0.188	17.917	<0.001
					X _{v_log}	0.102	0.014	7.325	<0.001

Where t_{s1} is time consumption for walking (sec/log), t_{s2} is time consumption for hooking (sec/log), t_{s3} is time consumption for carrying (sec/log), t_{s4} is time consumption for stacking (sec/log), X_{dis_log_pile} is walking distance between log to be stacked and pile (m), and X_{v_log} is log volume (l).

Combined delimiting and stacking

After a tree has been cross-cut into short logs, logs are then delimiting and stacked into piles. Some logs may not need delimiting if they come from the bottom of the tree. On the other hand, logs that come from the tops of the trees may take longer to delimit because of a larger number of branches. The walking time consumption (t_{ds1}) for combined delimiting and stacking strongly depends on the walking distance [Eq. 24]. The time consumption of cleaning (t_{ds2}) has no independent variables involved in the model. Hence, an average time consumption of 7 seconds per cycle was applied to cleaning. Similarly, the delimiting time consumption (t_{ds3}) is given as a mean value of 12 seconds per cycle. The stacking time (t_{ds4}) slightly depends on the walking distance and log volume [Eq. 25]. Furthermore, the time consumption of delay is given as a mean value of 22 seconds per log.

Table 31. Statistical characteristics of regression analysis for combined delimiting and stacking time consumption models.

Category	R ²	F-Test F-value	P	n	Terms	Coefficient	S.E.	T-Test t-value	P
Delimiting & Stacking									
Walking, t _{ds1}	0.87	6568.544	<0.001	978	Intercept	1.262	0.08	15.791	<0.001
					X _{dis_log_pile}	0.791	0.01	81.047	<0.001
Cleaning, t _{ds2}				83	Mean	$\bar{x} = 6.90$	s = 5.20	s ² = 27.06	SE= 0.57
Delimiting, t _{ds3}				322	Mean	$\bar{x} = 11.87$	s = 8.15	s ² = 66.42	SE= 0.45
Stacking, t _{ds4}	0.13	70.269	<0.001	1219	Intercept	5.103	0.249	20.454	<0.001
					X _{dis_log_pile}	0.249	0.025	10.036	<0.001
					X _{v_log}	0.063	0.016	0.123	<0.001

Where t_{ds1} is time consumption for walking (sec/log), t_{ds2} is time consumption for cleaning (sec/log), t_{ds3} is time consumption for delimiting (sec/log), t_{ds4} is time consumption for stacking (sec/log), X_{dis_log_pile} is walking distance between log to be stacked and pile (m), and x_{v_log} is log volume (l).

$$t_{ds1} = 1.262 + 0.791 X_{dis_log_pile} \quad (24)$$

$$t_{ds4} = 5.103 + 0.249 X_{dis_log_pile} + 0.063 X_{v_log} \quad (25)$$

The total effective time consumption model for combined delimiting and stacking was estimated by combining all work element models [Eq. 26]. The summary characteristics of the regression models for combined delimiting and stacking are presented in Table 31.

$$t_{ds} = t_{ds1} + t_{ds2} + t_{ds3} + t_{ds4} \quad (26)$$

Manual loading

In practice, the manual loading operation requires a group of 8–10 workers working together. Loading trucks were observed 12 times during this study. Due to the variety of manual loading techniques applied, which vary from place to place, no standardized working pattern for manual loading was found. The time consumption of manual loading was calculated at a mean value of 144 minutes per cycle. The average truck volume was 23.55 m³ solid over bark (sob).

Mechanized loading

The time for driving without a load (t₁₁) obviously depends on the driving distance without a load. A linear regression was applied to estimate the driving without load time as a function of driving distance [Eq. 27]. The loading time consumption (t₁₂) depends on number of log piles to be loaded per turn [Eq. 28]. Sometimes, when one pile does not fulfil the grapple size, a driver has to drive from one pile to another and reload the grapple. One grapple contains approximately 0.36 m³. The driving with load time (t₁₃) also depends on

the driving distance and number of logs per grapple [Eq. 29]. Note that distances with a load and without a load may not be the same distance in every work cycle. In cases where the tractor has to reload the grapple from different log piles, difference arise in driving distance (Figure 35). The average time consumption of unloading (t_{14}) was estimated to be 26 seconds per turn. Moreover, the time consumption of delays in the mechanized loading phase was longer than for the other work phases, with an average value of 109 seconds per turn.

$$t_{11} = 9.934 + 0.913 x_{ed} \quad (27)$$

$$t_{12} = 6.458 + 10.299 x_{piles} \quad (28)$$

$$t_{13} = 20.914 + 1.068 x_{fd} - 0.271 x_{logs} \quad (29)$$

The effective total time consumption model for mechanized loading was defined by combining the time consumption for individual work elements [Eq. 30]. The summary characteristics for regression models for mechanized loading are presented in Table 32.

$$t_1 = t_{11} + t_{12} + t_{13} + t_{14} \quad (30)$$

Table 32. Statistical characteristics of the regression analysis for mechanized loading time consumption models.

Category	R ²	F-Test F-value	P	n	Terms	Coefficient	S.E.	T-Test t-value	P
Mechanized loading									
Without load driving, t_{11}	0.83	1678.21	<0.001	350	Intercept	9.934	1.094	9.079	<0.001
					X_{ed}	0.913	0.022	40.966	<0.001
Loading, t_{12}	0.15	63.09	<0.001	350	Intercept	6.458	2.081	3.103	0.002
					X_{piles}	10.229	1.288	7.943	<0.001
With load driving, t_{13}	0.81	745.40	<0.001	350	Intercept	20.914	2.600	8.045	<0.001
					X_{fd}	1.068	0.028	38.041	<0.001
					X_{logs}	-0.271	0.065	-4.186	<0.001
Unloading, t_{14}					Mean	$\bar{x} = 25.86$	$s = 8.53$	$s^2 = 72.77$	SE = 0.46

Where t_{11} is time consumption for driving without load (sec/turn), t_{12} is time consumption for loading (sec/turn), t_{13} is time consumption for driving with load (sec/turn), t_{14} is time consumption for unloading (sec/turn), x_{ed} is driving distance without load (m), x_{piles} is number of log piles that tractor has been loaded per work cycle (piles), x_{fd} is driving distance with load (m), and x_{logs} is number of logs per grapple (logs).

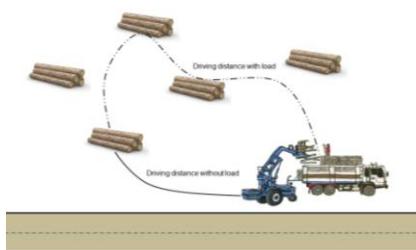


Figure 35. The difference of driving distance between driving distance with load and driving distance without load.

Since there are two approaches to obtain the time consumption of work phase (Figure 29), one concern is which approach is better. In order to compare the difference and fitness of modelling with empirical data, the time consumption value was derived from empirical dataset, which served as the independent variables (Figure 36). In terms of overall model time consumption, the coefficient of determination of the felling phase is relatively low ($R^2 = 0.260$). Neither model fits well with the empirical data. There is no large difference among overall work phase time consumption model and the total time of single work elements (Figure 36). The standard deviation is rather similar: 13.62 and 13.88 for overall work phase time consumption model and total time of single work element models, respectively (Table 33).

Table 33. The descriptive statistics of the total of single work element models and overall work phase time consumption models.

Residual	Min	Max	Mean	SE	SD	Variance
Overall work phase models	-32.73	65.30	0.692	0.601	13.618	185.454
Single work element models	-32.70	64.26	-0.899	0.312	13.877	192.578

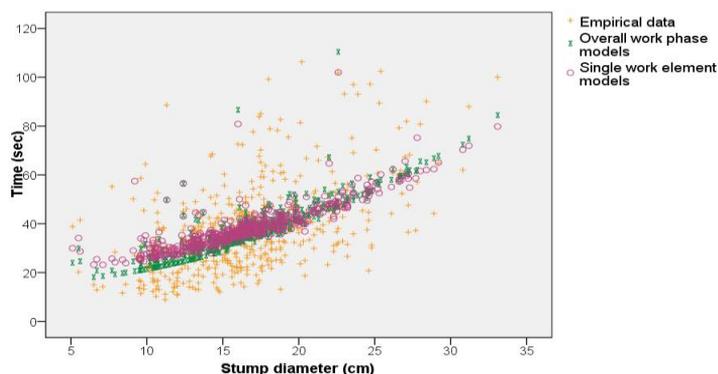


Figure 36. Comparison of sums of time consumption models and overall time consumption model with empirical data for felling phase.

5.3.3 Time consumption models per cubic meter

This section presents the time consumption model per cubic meter. These models were constructed for the purpose of predicting the expected time of harvesting and can afterwards be converted to productivity. In the modelling construction, data transformation was applied in order to make the data more normally distributed and to improve the validity of the measures. Data was generally transformed with a power transformation. The models give a similar outcome as the time distribution models per work cycle: that distance, diameter, DBH and tree height are the important independent variables which have a significant impact on the models. The descriptive statistics of time consumption models per cubic meter are presented in Table 34.

Table 34. The descriptive statistics of time consumption models per cubic meter for each work phase (min/m³).

Category	R ²	F-Test		n	Terms	Coefficient	S.E.	T-Test	
		F-value	P					t-value	P
Felling	0.50	97.76	<0.001	505	Intercept	71.916	4.533	15.796	<0.001
					X _{DBH}	-4.366	0.433	-10.07	<0.001
					X ² _{DBH}	0.125	0.015	8.477	<0.001
					X _{dis_tree}	0.537	0.108	4.990	<0.001
					X _{ht}	-3.854	0.602	-6.405	<0.001
					X ² _{ht}	0.113	0.019	5.923	<0.001
Bucking	0.40	270.90	<0.001	1668	Intercept	94.654	3.821	24.775	<0.001
					X _{dia_log}	-10.464	0.558	-18.76	<0.001
					X _{dis_log_log}	0.034	0.002	20.696	<0.001
					X ² _{dia_log}	0.366	0.025	14.585	<0.001
					X _l	-10.318	1.174	-8.790	<0.001
Delimiting	0.67	44.27	<0.001	96	Intercept	112.420	14.328	7.846	<0.001
					X _{ht}	-1.022	0.568	-1.800	0.075
					X _{dis_tree}	0.226	0.040	5.648	<0.001
					X _{DBH}	-9.392	2.414	-3.890	<0.001
					X ² _{DBH}	0.240	0.080	3.011	0.003
Stacking	0.68	606.94	<0.001	847	Intercept	106.507	3.343	31.858	<0.001
					X _{dia_log}	-16.945	0.754	-22.47	<0.001
					X _{dis_log_pile}	1.665	0.073	22.778	<0.001
					X ² _{dia_log}	0.642	0.040	16.122	<0.001
Delimiting & stacking	0.40	212.13	<0.001	978	Intercept	138.890	6.195	22.421	<0.001
					X _{dia_log}	-21.077	1.333	-15.81	<0.001
					X ² _{dia_log}	0.785	0.067	11.727	<0.001
					X _{dis_log_pile}	1.553	0.156	9.986	<0.001
Mechanized loading	0.75	350.01	<0.001	350	Intercept	9.714	0.278	39.945	<0.001
					X _{logs}	-0.187	0.007	-27.73	<0.001
					X _{fd}	0.048	0.004	11.305	<0.001
					X _{ed}	0.022	0.004	5.019	<0.001

Where X_{DBH} is diameter at breast height (cm), X_{dis_tree} is walking distance between trees (m), X_{ht} is tree height (m), X_{dia_log} is log mid diameter (cm), X_{dis_log_log} is walking distance between logs (m), X_{dis_log_pile} is walking distance between log and pile (m), x_l is log length (m), X_{logs} is number of logs per grapple (logs), X_{ed} is driving distance without a load (m), and X_{fd} is driving distance with a load (m).

5.4 Systems comparison

A comparison of the prevailing systems indicates that the most cost-effective was System C (Table 35). This system provided the highest productivity of 4.11 m³/h with the lowest unit cost of 2.70 €/m³. System A, the most common practice, provided the lowest productivity of 1.74 m³/h with a unit cost of 3.99 €/m³. The unit cost of System B was rather similar to System A, 4.03 €/m³, despite System B offering almost double the productivity of System A.

The time distribution analysis (Figure 37) suggests that delimiting took the largest proportion of time in Systems A and B, while the most time-consuming part of System C was the combined delimiting and stacking phase. The second largest share of time went to the bucking phase in all systems. Shorter log length, more logs have to be done. Shorter the log, the less volume can be produced. This may cause bucking to be an inefficient work phase.

Table 35. Summary of the productivity, hourly cost and unit cost of the three conventional systems (including felling, bucking, delimiting, stacking, and loading).

System	Productivity, m ³ /h	Hourly cost, €/h	Unit cost, €/m ³
System A	1.74	6.94	3.99
System B	2.76	11.12	4.03
System C	4.11	11.12	2.70

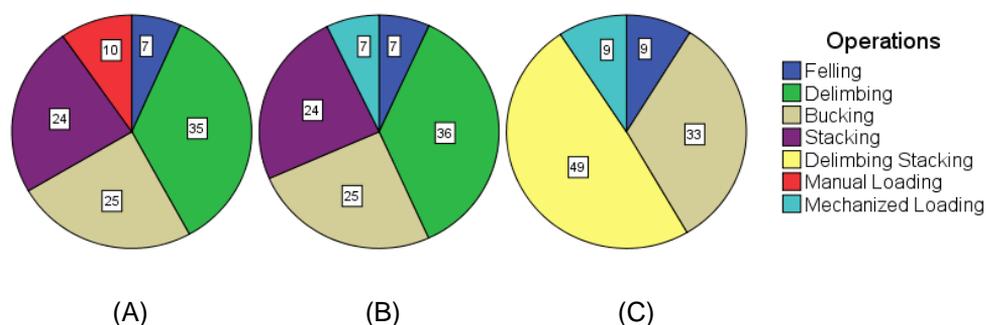


Figure 37. The relative time allocations (%) of the three conventional harvesting systems.

5.5 Ergonomics

The frequencies of body postures and risk indicators for different work operations indicate that most of the time workers work in normal postures (Table 36). However, there are some work phases – felling by chainsaw, cross-cutting by chainsaw and manual delimiting – identified as slightly harmful operations due to back position as a result of being bent down most of the time. Stacking, combined delimiting and stacking and manual loading, which accounted for over 20% of the time, were classified as action category 3, implying a distinctly harmful posture, with corrective action required as soon as possible. From the risk indicators, manual loading, felling and cross-cutting by chainsaws were identified as using slightly harmful postures for the workers (risk indicator $\geq 200\%$). This study confirmed that tool selection had an influence on risk of WMSDs. Both felling and cross-cutting can be done either by chainsaw or brush saw, but the results show that using chainsaws is more potentially harmful for the workers, regardless of the operation. This is as a result of often kneeling while working with the back noticeably bent. In addition, there are some other risks inherent to the use of chainsaws and brush saws (i.e. kickbacks). The overall risk index was 169.33%, which may be considered a mild risk level for which corrective action is required in the near future.

Several work operations contribute to action categories 3 and 4, after the analysis of the results of the timber harvesting operations, particularly manual loading, combined delimiting and stacking, stacking and felling by chainsaw, all of which had greater than 15% of the time devoted to actions in categories 3 and 4 (Figure 38A). This means that corrective action should be taken as soon as possible in each of those work operations. In addition, both backs and legs were in some awkward postures during harvesting operations (Figure 38B). Observations revealed that the majority of back postures were straight (44%), but 17% of the time the back was bent and twisted, which is classified as action category 2, with corrective action to be taken in the near future. Arm movements were mainly below shoulder level (89%). Considering leg postures, workers were walking or standing on one leg 26% of the time, and 11% of the time workers were standing with one bent knee, which is classified as action category 2. In addition, the external load was less than 10 kg, 72% of the time.

Table 36. The OWAS action categories and risk indicator for each work operation.

Operations	AC 1	AC 2	AC 3	AC 4	I
Felling (brush saws)	88.18	9.09	1.82	0.91	115.45
Felling (chainsaws)	35.45	32.73	13.64	18.18	214.55
Cross-cutting (brush saws)	85.83	7.50	0.83	5.83	126.67
Cross-cutting (chainsaws)	19.17	63.33	8.33	9.17	207.50
Delimiting	24.17	68.33	3.33	4.17	187.50
Stacking	62.50	10.83	24.17	2.50	166.67
Delimiting & stacking	52.73	16.36	22.73	8.18	186.36
Manual loading	46.43	17.86	25.00	10.71	200.00
Mechanized loading	97.00	2.00	1.00	0.00	104.00
Total	55.81	25.81	11.62	6.76	169.33

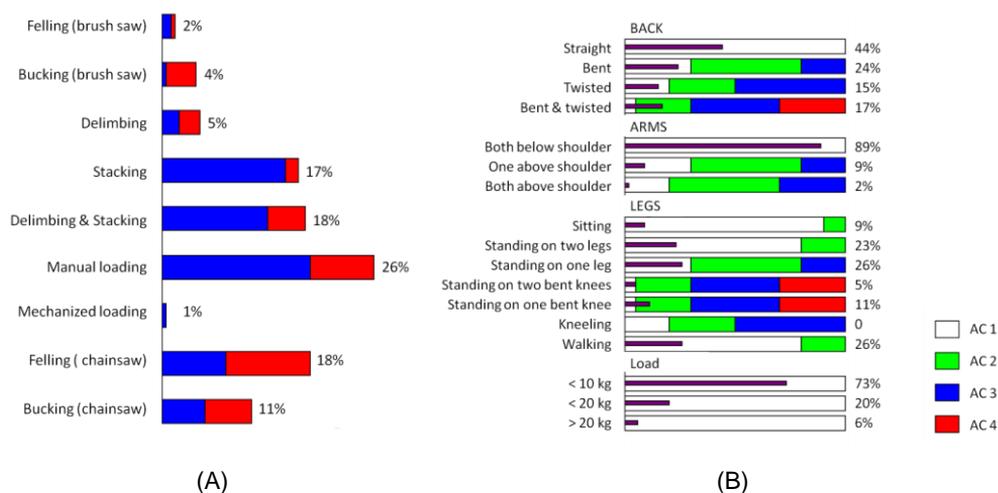


Figure 38. The proportion of work operations in action categories 3 and 4 (A) and frequency of body postures (B) (frequency of different action categories are presented in percentage of time).

According to the OWAS classification, the risk of WMSDs for the three conventional harvesting systems is illustrated in Figure 39. It can be readily noted that most of the body postures are assigned as normal, with action category 1 (greater than 60%) for all three systems. Postures having action categories 3 and 4 also exist in all systems, though these are both small proportions. This notifies stakeholders to pay attention to and increase awareness of WMSD prevention, work safety and efficiency improvement. Concerning risk indicators, the largest risk among the three systems (Table 15) was in System A, the most labour-intensive operation, with a risk indicator of 161.31%, whereas the smallest risk was System C, with a risk indicator of 133.64%.

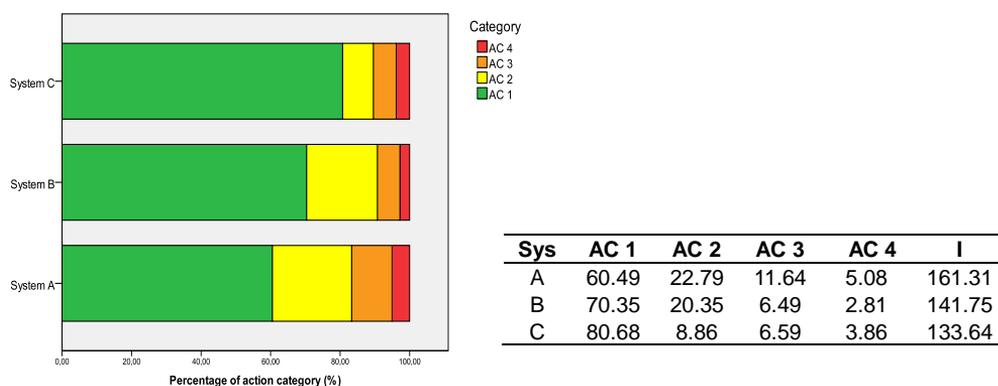


Figure 39. Comparison of frequency rates in the OWAS classes of three conventional harvesting systems.

5.6 Discrete–event simulation

Simulation was applied in parallel to investigate the impact of system component reorganization, tree size, log length, skidding and winching distances on system performance. To achieve reliable simulation results, the probabilistic distribution has to be carefully identified, and the most suitable distribution should be selected. To obtain the appropriate probabilistic distribution of each work phase duration, Stat-Fit, a SIMUL8 plugin, was used to find the statistical distribution providing the best fit to the data, and Kolmogorov-Smirnov was used to test goodness of fit. It also suggested which variables to include in the simulation. There are several probability distributions and expressions in this study (Table 37). For example, the distribution expression for the felling phase that derived from the empirical data (Table 38) is “5 + WEIB(1.61, 39.7)”, which means the distribution of the felling time follows a Weibull distribution with alpha (shape parameter) 1.61 and beta (scale parameter) 39.7, shifted to the right by 5. The parameters of Weibull are alpha, which is the scale parameter, and beta, which is the shape parameter.

Table 37. Mathematical expression for each distribution.

Distribution	Expression	
Beta	BETA (α_1, α_2, a, b)	$f(x) = \frac{1}{B(\alpha_1, \alpha_2)} \frac{(x-a)^{\alpha_1-1}(b-x)^{\alpha_2-1}}{(b-a)^{\alpha_1+\alpha_2-1}}$
Erlang	ERLA (m, β)	Two-parameter: $f(x) = \frac{(x-\gamma)^{m-1}}{\beta^m \Gamma(m)} \exp(-(x-\gamma)/\beta)$
Gamma	GAMM (α, β)	Two-parameter: $f(x) = \frac{x^{\alpha-1}}{\beta^\alpha \Gamma(\alpha)} \exp(-x/\beta)$
Lognormal	LOGN (σ, μ)	Two-parameter: $f(x) = \frac{\exp\left(-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2\right)}{x \sigma \sqrt{2\pi}}$
Pearson VI	PEAR VI ($\alpha_1, \alpha_2, \beta$)	Three-parameter: $f(x) = \frac{(x/\beta)^{\alpha_1-1}}{\beta B(\alpha_1, \alpha_2) (1+x/\beta)^{\alpha_1+\alpha_2}}$
Uniform	UNIF (a, b)	$f(x) = \begin{cases} \frac{1}{b-a}, & a \leq x \leq b \\ 0, & x < a \text{ or } x > b \end{cases}$
Weibull	WEIB (α, β)	Two-parameter: $f(x) = \frac{\alpha}{\beta} \left(\frac{x}{\beta}\right)^{\alpha-1} \exp\left(-\left(\frac{x}{\beta}\right)^\alpha\right)$

Where $\alpha, \alpha_1, \alpha_2$ are shape parameter, a and b are boundary parameter ($a < b$), B is beta function, m is shape parameter, β is scale parameter, γ is location parameter, Γ is gamma function, σ is continuous parameter, and μ is continuous parameter.

Table 38. Probability distributions from empirical data used in the work phases in the simulation.

Operations	Units	Distribution	Expression	Test	P-value
Felling	Sec	Weibull	5 + WEIB(1.61, 39.7)	K-S*	> 0.15
Bucking	Sec	Lognormal	2 + LOGN(2.44, 0.726)	K-S	> 0.15
Delimiting	Sec	Gamma	23 + GAMM(1.36, 111)	K-S	> 0.15
Stacking	Sec	Gamma	GAMM(3.33, 3.90)	K-S	> 0.15
Delimiting & stacking	Sec	Gamma	GAMM(2.75, 7.07)	K-S	> 0.15
Mechanized loading	Sec	Weibull	46 + WEIB(2.14, 155)	K-S	> 0.15
Manual loading	Sec	Uniform	UNIF (253, 471.069)	K-S	> 0.15
Station delimiting	Sec	Gamma	22 + GAMM(1.25, 60)	K-S	> 0.15
Station mechanized loading	Sec	Pearson VI	41 + PEAR VI(93.8, 2.66, 5.8)	K-S	> 0.15

*K-S is the Kolmogorov-Smirnov test

For System D, additional data regarding timber extraction of whole trees with a winching farm tractor was required. Unfortunately, data on productivity and time consumption for eucalyptus extraction are lacking for Thai conditions. Hence, the input data for extraction were derived from a literature review and were mainly based on a paper by Spinelli and Magagnotti (2011a). One reason for using their data is that their tree size (DBH 14–30 cm, tree volume 0.128–0.524 m³) was about the same as in this study (DBH 5–27 cm, tree volume 0.014–0.467 m³). In addition, the machine type and engine power (72 kW) used in their study were very similar to the farm tractor specification in Thailand. The time consumption and productivity models for skidding using a farm tractor are presented in Table 39.

Table 39. Models of the different work phases for skidding with a farm tractor (Spinelli and Magagnotti 2011a).

Work phases	Units	Models	R ²	P-value
Move in	min/turn	-3,058 + 0.434Dist ^{0.32} - 0.021kW	0.890	P < 0.001
Load	min/turn	1.561 + 0.386 Winch + 0.848 Pieces	0.719	P < 0.001
Move out	min/turn	-1.918 + 0.939 Dist ^{0.38} - 0.018 kW - 0.001Dist × Suspension	0.919	P < 0.001
Unload	min/turn	= 1.29 if half suspended = 0.86 if fully suspended		
Delay factor		= 0.43 if one operator = 0.23 if two operators		
Productivity model	m ³ /SMH	1.662 - 0.022 Dist ^{0.70} - 0.084 Winch + 2.699 Piece size + 0.040 kW + 1.136 Chokerman	0.677	P < 0.001

Where Dist is skidding distance (m), kW is tractor power (kW), Winch is winching distance (m), Pieces is number of pieces in the load, Suspension is an indicator variable (1 if load is fully suspended, 0 if half suspended), SMH is scheduled machine hours, Piece size is the average size of the pieces in the load (m³), Chokerman is an indicator variable (0 if the driver work alone, 1 if the driver works with the assistance of a choker man), and Delay factor is the delay time per network time.

According to the model validation, the constructed models were acceptable representatives of the empirical data. System A, representing the base scenario of the empirical data, produced on average 9.42 m³/h, while the productivity of the modelled systems was 9.37 m³/h, with a difference of 0.54%.

According to the simulation results, System D provided the highest productivity among the systems (Table 40). Likewise, harvesting productivity increased as a function of stem size and log length. System D has the potential to increase the productivity by two- up to six-fold from that of the base scenario (System A), depending on the log sizes and log lengths. The second- and third-best scenarios are Systems C and B, respectively. System B does not show any major difference compared to the base scenario when harvesting small trees, but the difference increases as a function of tree size. Harvesting Systems B and C use exactly the same harvesting equipment, but it is possible to improve their productivity by reorganizing the work phases. System C enhances the performance by approximately 40–50% compared to System B.

Tree size seems to have a greater effect on productivity than log length does (Figure 40). The productivity range of System D at a longer log length (3 m) is wider than at 2 m. The relative productivity per man-hour is shown for the systems, System A being the reference system with a relative productivity of 100% (Figure 41). The systems differ in their labour requirements, which vary between 8–11 workers. System D requires more workers than the others (11 workers), but still has a greater productivity per man-hour. System D is clearly the most productive harvesting system, followed by Systems C, B and A, in that order.

Table 40. Relative productivity results from simulation categorized according to bucking lengths and DBH classes.

Log lengths (m)	DBH classes (cm)	Relative Productivity (%)			
		System A	System B	System C	System D
2	5.01–10.00	100	102	158	246
	10.01–15.00	100	138	205	321
	15.01–20.00	100	140	205	357
	20.01–25.00	100	206	309	603
3	5.01–10.00	100	153	243	347
	10.01–15.00	100	142	213	413
	15.01–20.00	100	189	282	508
	20.01–25.00	100	284	433	656

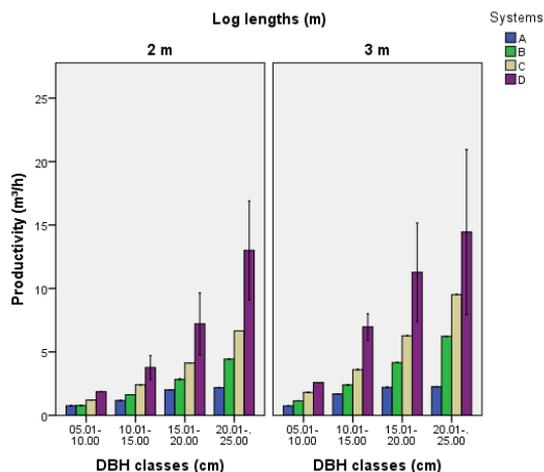


Figure 40. Comparison of productivity per hour as a function of tree size. Each bar represents different harvesting systems and column depicts different log lengths.

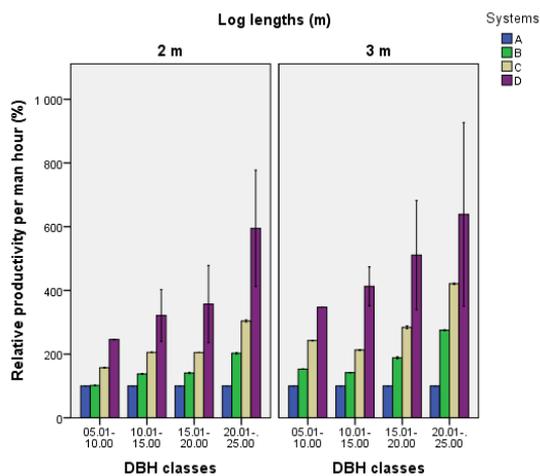


Figure 41. The productivity in man-hours as a function of tree size. Each line represents different harvesting systems and column depicts different log lengths.

A correlation test was applied to verify the hypothesis that bucking length, tree size, skidding distance and winching distance are correlated with harvesting productivity (Table 41). A strong positive correlation was found between stem size, log length and productivity, where skidding and winching distances are weakly negatively related to productivity. Furthermore, the correlation analysis indicated that only tree size and log length influenced productivity. Particularly, DBH classes have a stronger relationship with productivity compared to log lengths due to a larger coefficient. Besides, skidding and winching distances are insignificantly related to productivity.

Table 41. Correlation matrix between productivity and independent variables (n = 256).

		Log lengths m	DBH classes cm	Skidding dist. m	Winching dist. m	Productivity m ³ /hour
Log lengths, m	Correlation	1				
	Covariance	–				
DBH classes, cm	Correlation	0.000	1			
	Covariance	0.000	–			
Skidding dist., m	Correlation	0.000	0.000	1		
	Covariance	0.000	0.000	–		
Winching dist., m	Correlation	0.000	0.000	0.000	1	
	Covariance	0.000	0.000	0.000	–	
Productivity, m ³ /hour	Correlation	0.191**	0.636**	-0.025	-0.070	1
	Covariance	0.356	13.269	-2.335	-1.460	–

** Correlation is significant at the 0.01 level (2-tailed)

5.6.1 Sensitivity analysis

The sensitivity analysis compared two simulation results, the first derived from empirical data distributions (Table 38), and the second from time consumption model distributions (Table 42). There were differences between the two sets of results (Table 43). The differences vary among systems: System D has the least variation compared to other systems, with a difference of less than three percent. Systems A and B have slight differences in simulation results, with results that may increase up to 15 percent. For System C, the results from time consumption model distribution overestimate the productivity compared to the empirical data distribution in all cases. The biggest difference is the case of harvesting small tree size, with 29% difference in results. However, the results show the same bottleneck for both simulations.

The results are similar, with no clear trend in the differences using both methods. Productivity increases as a function of DBH, and System D is the most productive harvesting system for both methods, with System A representing the lowest productivity (Figure 42).

Table 42. Probability distributions from time consumption modelling used in the simulation.

Operations	Units	Distribution	Expression	Test	P-value
Felling	Sec	Beta	7 + BETA(172, 5.09, 21.5)	K-S	0.062
Bucking	Sec	Pearson VI	2 + PEAR VI(35.9, 6.02, 19.5)	K-S	> 0.15
Delimiting	Sec	Erlang	33 + ERLA(3, 34.4)	K-S	> 0.15
Stacking	Sec	Weibull	6 + WEIB(1.13, 7.23)	K-S	0.054
Delimiting & stacking	Sec	Erlang	8 + ERLA(2, 4.21)	K-S	> 0.15
Mechanized loading	Sec	Pearson VI	100 + PEAR VI(151, 4.27, 8.58)	K-S	> 0.15
Manual loading	Sec	Uniform	UNIF (253, 471.069)	K-S	> 0.15
Station delimiting	Sec	Gamma	22 + GAMM(1.25, 60)	K-S	> 0.15
Station mechanized loading	Sec	Pearson VI	41 + PEAR VI(93.8, 2.66, 5.8)	K-S	> 0.15

*K-S is the Kolmogorov-Smirnov test

Table 43. Comparison of simulation results from empirical data distribution and time consumption modelling. (% represents relative productivity output derived from work phase time consumption model, and deviation represents differentiate between the output from empirical data distribution and work phase time consumption model).

Log lengths (m)	DBH classes (cm)	Productivity (m ³ /day)							
		System A		System B		System C		System D	
		%	Deviation	%	Deviation	%	Deviation	%	Deviation
2	5.01–10.00	100	-0.23	93	-8.66	204	29.26	245	-0.81
	10.01–15.00	100	0.55	131	-4.10	239	16.82	320	-0.01
	15.01–20.00	100	-0.11	139	-1.17	244	18.72	360	0.66
	20.01–25.00	100	7.69	192	2.02	334	18.24	539	-2.39
3	5.01–10.00	100	4.51	137	-6.64	244	5.09	329	-1.02
	10.01–15.00	100	15.49	119	-3.15	206	11.44	359	0.32
	15.01–20.00	100	8.39	185	6.35	309	17.76	475	0.53
	20.01–25.00	100	6.65	270	4.64	465	17.76	582	-2.94

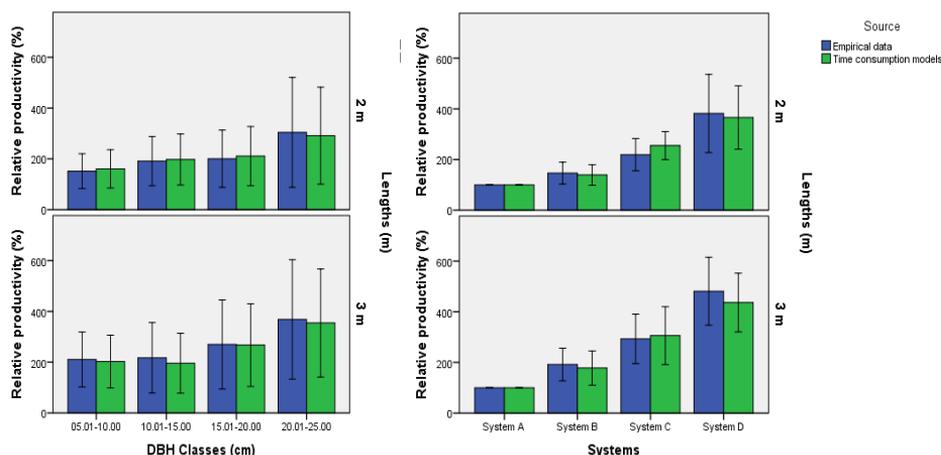


Figure 42. Comparison of simulation results from different inputs (Empirical data distribution and distribution from time consumption modelling). Left: harvesting productivity as a function of DBH. Right: harvesting productivity as a function of harvesting systems. (Error bars represent standard deviation)

5.7 Cost analysis

The contractors are normally got paid according to the log size, better pay for bigger logs. The results of an economic competitiveness analysis indicate that it is costly to harvest small trees, regardless of the harvesting system (Figure 43). In general, the net income for the contractor rises with increasing tree sizes. Considering the bucking of 2-m-long logs, System A is not a recommended system, and System B seems to be the worst case for implementing the harvesting of small trees. Systems C and D are economically feasible for large trees with a DBH greater than 15 cm, but nevertheless provide a low net revenue for the contractor. Similarly, for 3-m log length, the cost analysis apparently shows that

harvesting small stems (DBH < 15 cm) is expensive, and the resulting wood product has a low value, producing high harvesting costs per unit. Cost details were obtained from contractors (Table 44).

Table 44. Costing assumption, cost items and total costs.

Cost items	Units	Brush saw	Winching farm tractor	Farm tractor mounted with grapple
Purchase price	€	258	20 619	21 134
Economic life	Years	3	20	20
Salvage value	% of purchase	20	30	20
Interest rate	%	0	4	4
Fuel consumption	l/PMH	0.85	4	3
Overheads	% of subtotal	10	10	10
Crew	N	1	1	1
Depreciation	€/year	69	722	845
Annual use	PMH/year	2 000	2520	2520
Total fixed cost	€/PMH	0.03	0.50	0.54
Fuel	€/PMH	0.02	1.07	0.80
Repair and maintenance	€/PMH	0.03	0.23	0.27
Personal cost	€/PMH	0.64	0.64	0.64
Total variable cost	€/PMH	1.31	4.83	3.88
Overhead	€/PMH	0.13	0.53	0.44
Total cost	€/PMH	1.47	5.86	4.86

PMH is productive machine hour (excluding delays).

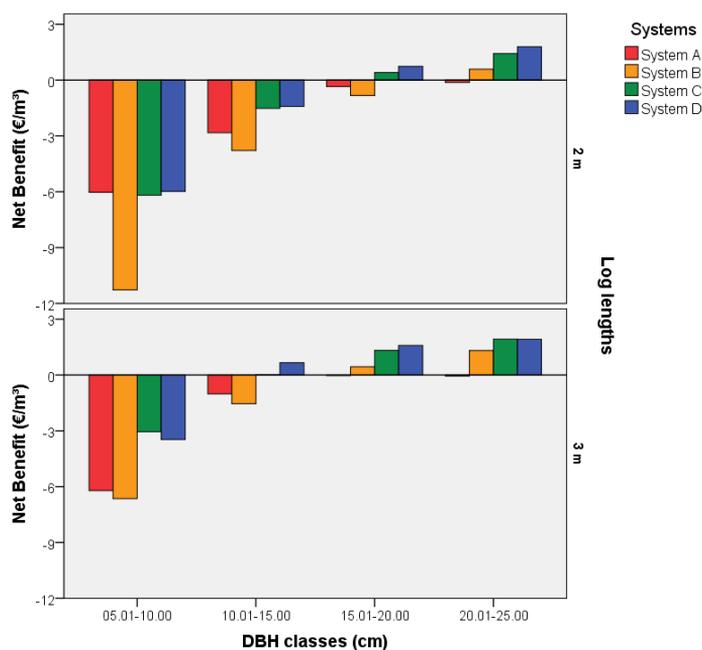


Figure 43. The net income of timber harvesting with the four systems.

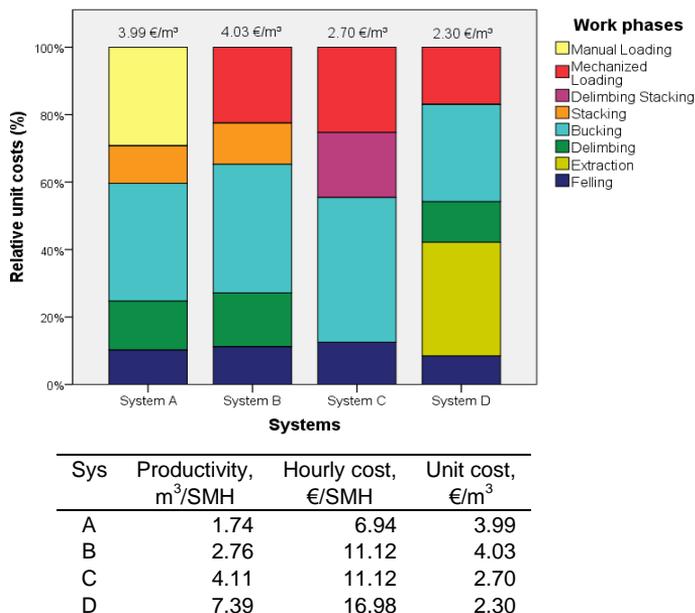


Figure 44. The relative unit cost structure of the four harvesting systems. (SMH is scheduled machine hours)

In terms of average productivity, the most economical system is System D, while the most expensive system is System B. It is clear that the largest component of harvesting costs derives from the bucking process in Systems A, B and C (32, 35 and 40%, respectively), whereas the biggest share in System D is the extraction process (32%) (Figure 44). However, bucking remains a rather large harvesting cost component for System D (approx. 24%). The second important key operation cost is the loading process, whether manual or mechanized loading is employed.

5.8 Workers' performance

As variability in the performance of workers can influence productivity, sensitivity analysis was applied to examine the influence of worker performance on harvesting productivity (Table 45). In order to compare workers, it was necessary to define a reference level, the average work pace being the reference level with a relative productivity of 100%. Sensitivity analysis was conducted to investigate the difference between the best and worst worker performance compared with the normal work pace. This sensitivity analysis is based on the analysis on the performance of a group of workers (8 workers).

Table 45. Effect of worker performance on harvesting productivity in the case of System A.

Log lengths	DBH classes	Harvesting productivity (m ³ /day)			Difference	
		Normal work pace	Best workers	Worst workers	Best (%)	Worst (%)
2 m	5.01–10.00	6.06	6.06	6.06	–	–
	10.01–15.00	9.32	9.32	9.32	–	–
	15.01–20.00	16.12	16.12	10.68	–	-33.76
	20.01–25.00	17.12	22.81	10.95	33.26	-36.01
3 m	5.01–10.00	5.97	5.97	5.97	–	–
	10.01–15.00	13.44	13.39	13.38	–	–
	15.01–20.00	17.72	22.24	11.14	25.49	-37.12
	20.01–25.00	17.14	23.91	11.36	39.45	-33.77

The results demonstrated that worker performance only had a significant impact on productivity in System A, the most labour-intensive operation. In addition, worker performance had no significant effect on the harvesting of small trees. However, it markedly influenced productivity when harvesting large trees with a DBH of greater than 15 cm. The ratio of the performance of the best worker to that of the worst worker was about 2:1. The best workers had a 25–39% higher productivity than the normal working performance. Meanwhile, employment of the worst workers resulted in a reduction in productivity of between 33–37% compared to the normal working pace, depending on stem sizes.

6 DISCUSSION

6.1 Materials

The studied stands were normal harvesting sites distributed across Thailand parallel with the actual harvesting activities. Data provided both pros and cons. The limitations of this material may influence the consequent data analysis. Dataset limitations included: involved parameters could not be controlled, tree characteristic varied among harvesting stands, forest workers could not be selected/allocated, representations were unequal, and harvesting tools were primarily agricultural machinery-based.

Most of the harvesting sites were located close to a pulp mill on areas that are suitable for growing eucalyptus. The study sites were given by the logging companies corresponding to a random sampling technique to some extent; therefore, it was not possible to study certain harvesting conditions. Random selection provides a sample highly representative of the population of interest; however, the involved parameters cannot be controlled in the system of interest. Systematic experiments should be carried out for further research in order to investigate the effect of variables that could not be examined in this study.

In order to broaden the scope of the empirical data, several categories of data were required: different stem sizes, areas and stand characteristics. Tree characteristics were quite varied among the harvesting stands due to different clone selection, site properties and management intensity. In addition, there were limitations in selecting and controlling the forest workers who were involved in this study. Each worker had to work at a specific harvesting site and could not be allocated to other areas. This may have influenced the differences recorded between workers in performance and productivity.

Most of the harvesting tools applied in this study were also limited to existing harvesting tools, which are primarily agricultural machinery-based. Brush saws are most commonly applied for tree felling and conversion in eucalyptus harvesting instead of chainsaws. In the past, chainsaws were applied similarly to other parts of the world, but recently there has been a cultural conversion from chainsaws to brush saws in eucalyptus harvesting. The local social, economic and environmental perspectives (i.e. tree size, capital cost, legislation) might have caused this change. Using brush saws for tree felling is now expanding and increasing in popularity, particularly for eucalyptus. Unfortunately, no scientific reports have been published about when and why brush saws replaced chainsaws in eucalyptus tree felling. Chainsaws are, however, still used in some areas. The chainsaws used were quite big, old, and not up-to-date. It is interesting to urge an idea of applying small chainsaws for tree felling. But, since it is quite difficult to obtain the chainsaw possession licenses, the government should look over the legislation in order to open up opportunities for further development in forest sector.

In this study, only two workers were found using chainsaw in tree felling and bucking. Data on using chainsaws is technically insufficient for work study analysis; therefore chainsaw is excluded from the time study. However, the chainsaw data could be utilized for the ergonomics study in order to compare the work safety of different tree felling tools. As the majority of workers prefer using brush saws for tree felling and cross-cutting, brush saw application has been essentially tested in order to reflect and correspond to the real system. In addition, the delimiting tools that workers currently apply are knives and axes. The current design of axes probably is not suitable for this kind of work. The changing of axe shape and length of handle could increase productivity and reduce work load (Figure 45). –



Figure 45. Example of efficient axes for delimiting. (Source: <http://www.husqvarna.com> and www.wetterlings.com)

Further improvement on hand tools could be worth testing of improving productivity and safety.

The results from this study are applicable to equivalent harvesting conditions (forest plantations, eucalyptus) and equipment usage. However, the results are limited to harvesting in the dry season, because there is no harvesting activity occurring during the rainy season in Thailand.

6.2 Methods

The work study approach was applied in this study to get an understanding of the overall harvesting systems and to examine the efficiency of the work phases. Two different time consumption models were created: 1) time per work phase, and 2) time per individual work element (the breakdown of work phase into work elements). The results from both approaches offered similar results to predict the required working time. It is difficult to judge which of the two approaches is better. Compared to an element model, the work phase makes it easier to estimate the required total time, not needing to sum up the work element models together. The aggregated time may be beneficial and suitable in preparing an operational plan for a whole system. It supports the forest manager or planner in equipment selection and operating time estimation. On the other hand, work element models can be applied in a detailed plan.

The timing technique used in the time study was based on video recording. Video recording has been applied in several forest work studies (i.e. Björheden (1988); Nurminen et al. (2006); Nuutinen et al. (2008)). This study was the first trial to employ video recording in time studies on timber harvesting in Thailand. The advantages of this technique are repeatability, the ability to slow down and speed up the motion, and the potential to save recordings for additional analyses, as noted by Puranen et al. (1996). However, video recording is limited in terms of the area of observation (Vedder 1998). In other words, the video recording cannot capture all activities together at once; the recording of work has to be split into several tasks. Moreover, the duration of video recording in this study met the minimum requirements for sample size acceptable for representing a reliable estimate outcome.

The ergonomics aspect was studied via the OWAS method. It is used not only to identify problems but also to determine recommendations for corrective action

(Grzybowska 2010). The OWAS method was initially designed for industrial research, but the results suggest that this kind of analysis can be applied to forest operations. With the help of video and computer programming, OWAS can be used efficiently in identifying awkward working postures for the back, arms and legs. Nevertheless, WinOWAS software was launched in 1996 (Tampere University of Technology 1996); it is old and incompatible with the new Windows operating system. No software developments have been implemented since it was first launched. Software updating would be valuable for ergonomics research in the future.

Nonetheless, the main drawback of OWAS method is that it only considers the posture of back, arms, legs and external load; the assessment of neck, elbows and wrists are missing. The OWAS method does not separate right and left extremities, nor does it consider repetition or duration of the sequential postures. For further research, other work posture measurements should be considered for forestry work and should be compared with the results of the OWAS method. For instance, Rapid Upper Limb Assessment (RULA) was developed for use in ergonomics investigations of workplaces where work-related upper limb disorders are reported. RULA is suitable where the demands on upper body are high, i.e. truck drivers and machine operators. RULA may be able to evaluate farm tractor drivers (mechanized loading in this study) who mainly sit in the cabin and use only the upper part of the body.

The ergonomics study was conducted according to an awareness of work safety and provided a basic idea about Work-related Musculoskeletal Disorders (WMSDs) risk in forest operations. Since it was a very simple analysis, many details were missing. To make a meaningful contribution to the Thai forestry work sector, research should be directed towards obtaining more details regarding ergonomics perspectives including demographic data, anthropometric assessment, biomechanical assessment, physiological and perceptual responses and effects of dietary supplements.

Simulation was applied to examine the impact of relevant variables on harvesting system productivity before its implementation in a real situation. This study highlighted the possibility of simulation to support the evaluation of timber harvesting component alteration with the idea of minimizing the costs and maximizing the benefits for the whole chain (Dahlin and Fjeld 2004). In this case, the farm tractor was introduced for timber extraction. Applying a farm tractor slightly changed the working components and shifted the harvesting method from CTL to FT. Simulation proved a useful tool for predicting the impact of changes, and for offering suggestions before implementing a new approach in a real system. Since the key feature of simulation is the ability to use stochastic inputs, it is able to examine the effect of various random variables on the output.

The simulation of this study was constructed to represent the real life harvesting systems using the commercial simulation package SIMUL8. The predicted result differed from the actual outcome by an average of 0.54% in overall productivity. Even though the software was not designed for forestry operations, the results imply that this type of commercial simulation package can be applied for such operations.

6.3 Results

6.3.1 Time consumption modelling

Felling

According to the result, the most time-consuming element in felling is the back cut, which accounted for 40% of the gross effective time. The cutting time, which is a combination of undercut and back cut, takes approximately two-thirds of the gross effective time. This suggests the need to reduce these time-consuming elements. The delay is roughly 12% of the gross effective time. The delay times were mainly accounted for by refuelling, lubrication, sharpening of the saw blade and maintenance. Brush saws are not designed for final felling. Because of the relatively small size of the engine (2HP), brush saws often overheat, requiring a short break to cool down the engine. Furthermore, the small size of their fuel tank (40 cc) makes refuelling necessary every half an hour.

The stump diameter and walking distance are the most significant variables affecting the felling time, corresponding to the findings of Kleunder and Stokes (1994), Lortz et al. (1997), Wang et al. (2004) and Behjou et al. (2009). There are some difficulties in controlling the brush saw when felling trees, as the workers do not have as much control of the saw as compared to a chainsaw. Moreover, the saw blade and saw teeth might also affect the time consumption. From the modelling standpoint, felling was found to be the most complex and difficult work phase in this study to model, largely because the unexplained variation in felling efficiency is large and only a few significant variables can be used in regression analysis.

The average productivity was 11.72 m³/h (with one or two workers involved in felling phase). No official similar studies have been carried out in Thailand. However, there are some reports on eucalyptus felling by using chainsaws in different parts of the world. For example, the felling productivity of eucalyptus in China, South Africa and Brazil, were about 0.60, 4.90 and 1.90–2.30 m³/h, respectively, depending on the stem size (Hakkila et al. 1992; Shuttleworth B. pers. comm. in 2011; Engler et al. 2012). It is rather difficult to compare the productivity because the number of workers involved in those studies was not reported and felling tools are different. In the present study, the productivity was nearly 20 times higher than felling productivity in China. The average tree sizes in China were 0.05–0.18 m³, while in this study the average tree size was 0.135 m³. The reasons that may cause the differences are the equipment, tree size, working skill and harvesting conditions.

Bucking

Pulpwood logs in Thailand are rather short, being only 2 m long. This is because of the limitations of debarker machines at pulp mills. The findings indicate that bucking is the most time-consuming work element, accounting for 60% of the gross effective time. In the bucking phase, delays accounted for approximately 13% of the gross effective time. The reasons for delays were similar to those of the felling phase. As bucking is considered the most time-consuming among the work phases, special attention should be paid to this work phase when seeking to improve harvesting efficiency.

The bucking time per log increases as a function of the log diameter and log length. Bucking long log takes longer time per log but shorter time per tree. Considering the stem cross-cutting, longer logs cause shorter processing times because there is less bucking time

per cubic meter and fewer bucking points per stem. Thus, making longer logs may enhance the overall productivity of the harvesting systems. However, it should be kept in mind that longer logs may result in longer stacking time because of the heavier weight.

From a productivity point of view, bucking offers very low productivity, only 3.18 m³/h. Tufts (1997) found the stem size, tree volume and the number of pieces processed per tree to be the variables with the greatest impact on bucking productivity. Bucking time consumption increased as a function of stem size, tree volume and number of processed bucking points. This confirms the findings of the present study, in which the bucking operation had a significant impact on harvesting productivity, mostly due to the fairly short log length.

Delimiting

The delimiting work phase was applied separately in Systems A and B, in which the delimiting must be done before the bucking process. Normally, there are 4–5 workers work together in the delimiting phase. The most time-consuming part of delimiting is the delimiting element itself, accounting for 43% of the gross effective time, followed by walking (29%) and marking (21%). The delay in the delimiting phase differs from that of felling and bucking, as it is mainly a personal delay such as taking a rest and drinking water. The average man-hour productivity of delimiting is 2.2 m³/h. This is fairly low compared to other work phases, probably due to the manual work operation. The findings for the delimiting phase are difficult to compare with other studies, since most of them have combined bucking and delimiting into one work phase referred to as processing.

For the delimiting phase, as expected, the walking time had a strong correlation with the walking distance from tree to tree. Distance is approximately equivalent to tree height or even longer. In addition, the delimiting time depends on DBH. DBH is strongly correlated with tree height. The larger trees require a longer delimiting time due to the greater branch size and number of branches (FESA 2010). Engler et al. (2012) also pointed out that there is a slight correlation between the delimiting time and the tree diameter.

Stacking

Stacking normally proceeds after bucking, as is the case in Systems A and B. Stacking workers are commonly the same group as delimiting. In-field stacking is the process whereby logs either lie in long roughly aligned rows or are stacked in small piles for further loading. For example, stacking in lines facilitates manual loading, while stacking in small piles scattered across the cutting site is suitable for mechanized loading. The size of the stack is determined by the available volume, the log size and the loading method to be used. The stacking productivity depended on log volume and walking distance, with a mean productivity of 3.28 m³/h. Regarding the stacking phase, the walking time is strongly affected by the walking distance, while the stacking time is slightly dependent on the log volume. The findings for the stacking phase are hard to compare with other studies, since most studies have integrated these work phases (bucking, delimiting and stacking) into timber processing.

Combined delimiting and stacking

Combined delimiting and stacking is used in System C only. The aim of this combination is to eliminate double walking in Systems A and B, in which delimiting and stacking are separated in two work phases. The time consumption for combined delimiting and stacking is mainly allocated to the stacking element, representing 37% of the gross effective time. As a result of merging two work phases, the mean productivity was the lowest among the work phases (2.12 m³/h). In the work flow of Systems A and B, there are waiting lines before bucking, since workers cannot proceed to the bucking process until delimiting is completed. The combination of delimiting and stacking provided a better work flow by eliminating the waiting line for bucking, and allowing a continuous work process.

Manual loading

Since pulpwood logs are quite small and can be lifted manually, and inexpensive labour has been extensively available, manual loading has been widely applied in Thailand. Typically, manual loading is directly operated in the field. In fact, there are no permanent strip roads in a stand, but the road network is typically designed manually on site without any formal plan. Due to the variety of loading techniques, it has been problematic to define a work element that is compatible to all data observations. Thus, the time consumption and productivity of manual loading were not modelled, but the mean values were employed for this work phase. The average cycle time of loading is about two hours, accounting for 83% of the total gross effective time. Corresponding to Nurminen and Heinonen (2007), the load volume is not a particularly significant factor, since the load volume is almost the same in every work cycle. If truck sizes were different, then the load volume would influence the loading time.

Mechanized loading

Where modified farm tractors equipped with a front-end grapple are available, mechanized loading is preferred, because it saves time and costs compared to manual loading. When mechanized loading is applied, the trucks can either directly drive on the forest road or park at the roadside. A loader then drives on site to collect the logs and forwards them onto the truck. Hence, the parking location of the truck should consider the forwarding distance. When the forwarding distance of loader becomes too long, the truck driver has to consider moving the loading point.

Mechanized loading was divided into driving without a load, loading, driving with a load and unloading. Driving without a load is strongly affected by the driving distance. Loading depends on the number of log piles to be collected. Driving with a load is also dependent on driving distance and number of logs. There is a considerable difference between the minimum and maximum driving time, which is due to a large variation in the driving distance. An overall time consumption model was created as a function of driving distance both with and without load, and number of logs per grapple. It implies that the longer the driving distance, the greater the time consumption. Thus, in order to avoid excessive operating costs, the driving distance should be taken into consideration during the operation. The load size is normally moderated by the maximum grapple capacity. A large payload is good in terms of productivity, but it may exceed the capacity of a farm tractor. The distance is more important from an operating cost point of view. Another issue that

should be taken into account is the size of log piles. Big log piles make mechanized loading faster because the farm tractor does not need to drive much to collect logs. However, bunching a large pile takes longer in the stacking process. Workers have to carry logs longer distances in order to make a bigger pile. Thus, the balance between pile size and driving distance should be taken into consideration, and should be studied more theoretically.

6.3.2 Working performance

In Thailand, forest workers rarely have adequate and efficient training in logging operations. This study demonstrated that the worker has a vital influence on harvesting productivity, corresponding to Gullberg (1995) and Harstela (2004). Variation in worker performance may result from different physical and mental abilities, training, experience and motivation. The worker's skill has an important influence on harvesting productivity. The best worker was nearly two times better than the worst worker in terms of productivity. Similarly, Stampfer et al. (2002) found a two-fold difference in productivity between experienced and inexperienced workers in timber extraction by helicopter.

The performance of workers was found to influence felling productivity (Figure 34). The performance of some workers did not follow the normal relationship of increasing productivity with increasing stem size. All the workers used a similar brush saw specification and saw blade size (Table 27), although there was a small amount of variation in the number of saw teeth. Differences in machine properties should not cause such a large variation in productivity. Figure 34 and Table 27 show that worker "D", who has very long experience, may no longer be physically fit, which may have resulted in lower productivity compared to younger workers. Younger workers tended to work faster because they are more energetic than older workers. However, young workers are less experienced and are therefore more vulnerable to accidents (Balimunsi et al. 2011). The cutting techniques differ significantly depending on the size of the stem to be felled, whether it is less than 10 cm, between 10 to 20 cm or greater than 20 cm. The workers of this study operated at different harvesting sites with varying tree characteristics. Hence, each worker was familiar with his routines and the stand conditions. For example, the routines of workers A, B, D and E might involve felling small trees, and occasionally being confronted with the felling of large trees. When operating with a large stem size, the same working techniques as on small trees cannot be used. The worker needs to make a decision about the technique to be used, resulting in an increased lead-time and a reduction in productivity. Hence, this results in lower productivity as a function of increasing tree volume. On the other hand, for workers C, F and G, who are familiar with felling large trees, when faced with small trees, the working pace remains the same. The variation in cutting times is small, regardless of the stem sizes. Additionally, workers C and G have assistant for controlling felling direction, this may conduct longer procedure to find the right position for assistant. In case of ineffective teamwork, it could lead longer time in operation.

In forest operation management, worker performances are often disregarded. This study highlights that the different skill level between workers considerably influences the potential of the systems. Therefore, when planning forest operations, worker performance should be taken into account, even though it can be complicated and sensitive to include worker performance. At any rate, the managers should know a bit about their workers' background and working performance before making an operational plan.

6.3.3 System productivity and cost comparison

The results indicate that the application of System C provides a better option for contractors who have sufficient resources, such as modified farm tractors equipped with front-end grapples. From a unit cost perspective, the reorganization of tasks has the potential to simultaneously increase productivity and reduce the unit cost. For example, both Systems B and C employ the same tools, but the System C allows a higher productivity and cheaper unit cost. This implies that the order of tasks or reorganization of working components has an essential impact on the system balance. This has been shown also by Naghdi and Bagheri (2007).

In addition, System D, a semi-mechanized operation, provides the greatest productivity and the lowest operating costs. From the findings, it can be concluded that a more mechanical harvesting system is able to improve productivity. Similarly, Wang et al. (2004), Spinelli et al. (2011) and Spinelli and Magagnotti (2011b) found that the mechanized harvesting systems are significantly faster and drastically enhance worker safety.

The present study was compared with results from different parts of the world based on the information presented in Figure 5. Average productivity of this study is higher than that of motor-manual harvesting system in China and Brazil (Table 3), but lower than manual harvesting productivity in South Africa. The overall productivity of this study varied between 1.7 and 4.1 m³/h, which is three- to seven-fold higher than eucalyptus harvesting in China, where harvesting productivity has been reported to be only 0.58 m³/h (Englet et al. 2012). In South Africa, the productivity is almost twice that observed in this study, 4.90 m³/h.

It is obvious that a motor-manual system provides the poorest productivity among other systems, while an FT method applying feller-buncher and skidder is the most productive system (Figure 5). Thus, an FT method that concentrates timber to be processed at one point is an interesting idea to consider adopting in Thailand's case.

As long as trees remain small, the use of brush saws is fine. However, there is a possibility that silvicultural practices will change in the future with the aim of extending the rotation for achieving larger trees. If so, chainsaws, multi-handling harvesters, harvesting head based excavators or small-scale harvesters should be considered. Introducing more mechanized technology may lead to better productivity. However, it should be kept in mind that mechanized harvesting could result in higher operating costs in a low labour-cost context. In addition, direct modern technology transfer from developed countries to Thailand may not work properly because of differences in working conditions, such as tree species, tree characteristics and skills of the workers. However, a modified FT method using chainsaws for felling and processing, extraction by farm tractor or skidder, and loading by loader may be an option to improve productivity. Once the facility, skills and other support are ready, then full mechanization would be possible to apply. Another concern is that the unemployment rate will probably increase after replacing labour-intensive operations with mechanization. Thus, it may raise social impact issues afterwards.

6.3.4 Ergonomics

Brush saws have recently become commonly used for eucalyptus felling in Thailand instead of chainsaws, requiring low investment, and, with fairly small tree sizes, may have resulted in an improvement in work postures. However, there are some negative aspects since brush saws are still inherently dangerous; the workers are unable to totally control the saw, the open blade is on the end of a wand, and can snag and swing violently to the side, making it more prone to injure other workers. Chainsaws are also still applicable in some areas for tree felling. A comparison between using chainsaws and brush saws indicated that felling and cross-cutting by chainsaws is considered potentially the most dangerous task for the forest workers, similar to the findings of Lee and Park (2001). In this study, the risk indicator for felling by chainsaw was 214.55%, which is slightly less than the finding of Calvo (2009). Calvo found that the risk indicator of felling by chainsaw was 287%. This can imply that using chainsaws for felling is a stressful task, and corrective action may be required in the future. The reasons may be due to workers having to carry the heavy load of the chainsaw and the back being bent during felling.

Manual tasks of stacking, delimiting and loading in this study were considerably more risky than other work phases, with risk indices of 166%, 187% and 200%, respectively. Similarly, Calvo (2009) found a risk indicator for manual stacking to be relatively high, at 300%. The main reason for this divergence is the contrasted weight of load (tree sizes), as trees are larger in Calvo's (2009) study.

Based on the overall risk indication results, System C, which is an application of partial mechanization, is safer than the other systems. This suggests that mechanization has the potential to improve work safety in the work place. However, it should be clear that applying mechanized harvesting may require higher operating costs in a low labour cost context.

The preventions of work-related injury may be categorized as 1) education, 2) Personal Protective Equipment (PPE) and 3) mechanical improvement. Workers should be well-trained and well-informed about correct working methods before execution, particularly for manual loading, stacking, delimiting, stacking and felling by chainsaw. A short-term training program can educate forest workers about different awkward postures, its effects and prevention. Training helps to increase working efficiency and reduce the risk of WMSDs. Before working, the benefits of warm-up and stretching exercises may reduce injury risks. To reduce fatigue from hard work under tough conditions, adequate resting time, regular fresh and cool water, and sufficient nutritional supplements are able to improve physiological recovery of body and increase the energy level simultaneously.

The use of Personal Protective Equipment (PPE) such as safety boots, helmets, visibility clothing, gloves, eyes protection and ear protection is strongly recommended. The results suggest that mechanizing operations could be beneficial in terms of promoting work efficiency, reducing the danger and stress of forestry work. To reduce bending back and standing on one knee, mechanical assistance like a felling handle with a chainsaw, or backpack chainsaw/brush saw may reduce awkward postures when using chainsaw in tree felling (Figure 46).



Figure 46. Modified chainsaw mounted with felling handle: (A) Husqvarna 365H, (B) Apuri felling handle, (C) Stihl FR 130T, and (D) Husqvarna 535FBX. (Source: <http://www.husqvarna.com/ru/>, <http://www.apurituote.fi/>, <http://www.stihl.co.uk/>, and <http://www.husqvarna.com/za/>).

6.3.5 Discrete-event simulation

The simulation study demonstrated a strong correlation between tree size, net revenue and harvesting productivity. Productivity increased as a function of tree size, corresponding to Lageson (1997), Puttock et al. (2005) and Niemistö et al. (2012). In addition, tree size has a strong influence on the unit cost of harvesting, and increasing the tree size results in a decrease in the unit costs of harvesting (Lageson 1997; Puttock et al. 2005). Moreover, other factors may affect harvesting productivity, such as the machine type, stand density, harvesting intensity, slope, ground conditions and worker skill (Lageson 1997). One observation points out that the handling of large trees may be rather difficult for manual work. The results also show that a longer log length provides better productivity and a reduction in lead-time. This is similar to the study of Imponen and Pennanen (1989), who found that the harvesting and transportation of short pulpwood (2 m) is 5–15% more expensive than for 3- or 5-m pulpwood. In the present study, the effect of log length on productivity was not as strong as the influence of tree size. In addition, Tufts (1997) also found that tree size, tree volume and the number of pieces processed per tree have the greatest impact on harvesting productivity. Consistent with the findings of the present

study, a reduction in the number of pieces processed per tree resulted in lower time consumption as well as enhancing harvesting productivity.

According to the results, the winching and skidding distances in System D did not have a significant impact on overall productivity, but a longer distance implies an increase in the extraction cycle time. A short winching and skidding distance with limited variation in the distances (Table 22) may not have an impact on overall productivity. The limited distances of winching and skidding were based on real system data. In addition, the map of plantations indicates that the maximum distance is normally not greater than 100 m for skidding and 20 m for winching. Hence, the setting of minimum and maximum distances in this study was limited. Moreover, the actual skidding and winching time itself comprises a rather small proportion of the total skidding time consumption. Other operations (hooking, choking and other relevant processes) take much more time than skidding itself, accounting for greater than 90% of the total skidding time consumption. Hence, the skidding distance causes small differences in the lead-time of skidding. By contrast, Spinelli and Magagnotti (2011a) found large variation in skidding distances, ranging between 70–1 000 m in their study, which strongly affected the productivity. Log size is also an important factor affecting skidding productivity (Spinelli and Magagnotti 2011a). Plamondon and Favreau (1994), McDonald (1999), Abdullah et al. (2004), and Odhiambo (2010) similarly found that longer skidding distances increased the cycle times and skidding costs, while a shorter skidding distance increased the road density and road construction costs. In addition, McDonald (1999) discovered that obstacles increase the cycle times and skidding costs, and can become hazards for the overturning of machines.

The organization of work is an essential factor influencing harvesting productivity, even when using a similar harvesting technique (Engler et al. 2012). For instance, Systems B and C employ exactly the same equipment, but a reorganization of the work phases resulted in a significant increase in the outcome. System balance was improved most noticeably with increased tree size and log length, and reorganization of the workflow. Production improvements were clearly evident with simulated timber harvesting scenarios, which indicated that system performance may increase by up to six times from that of the base scenario, depending on the systems and variables. According to the present study, a change in the harvesting method from CTL to FT has the potential to increase productivity. This may be due to a reduction in the walking time for delimiting and stacking, and the driving time for the mechanized loader. Simulation results indicated the bucking, skidding and loading phases are the major cost drivers and the most time-consuming phases. Therefore, operations improvements, such as introducing mechanized work, should be emphasized in relation to bucking, skidding and loading work phases.

The sensitivity analysis (Table 43), the comparison of simulation results from empirical data distribution and time consumption modelling, showed that time consumption model distribution of System C overestimates productivity compared to empirical data distribution in all cases. The cause of overestimation of productivity in System C was the time model of combined delimiting and stacking. The combined delimiting and stacking was carried out with short logs after trees had been cross-cut. Some logs required delimiting, some did not. It is difficult to trace back and find a correlation between tree size and time consumption, so the average time was applied in this case. Meanwhile, the individual delimiting time consumption in Systems A and B was strongly depending on tree size. This is because delimiting phase was carried out tree by tree. It was possible to find a correlation between tree size and time consumption, which was not possible to do in the combined delimiting and stacking phase.

7 CONCLUSION AND FINAL REMARKS

7.1 Conclusion

This study represented foundational research in timber harvesting in Thailand because there were no data available before. Study results provided comprehensive information of current harvesting systems for system improvement and/or to apply to similar working conditions elsewhere. The outcome of this study can also be used in reorganization of the working system in order to improve the overall productivity. In the future, semi-mechanization should be applied in the case of Thailand; however, the workers should be well-trained and infrastructure (i.e. maintenance, technicians and spare parts) should be prepared before adopting semi-mechanization into a system. When semi-mechanization has been introduced into a system, this kind of study is also required in order to obtain system figures like productivity and operating costs for further development.

The work study found that cross-cutting is the most time-consuming and inefficient work phase, and special attention should be paid to this work phase in order to improve the overall work efficiency in harvesting. Felling and mechanized loading were the most productive work phases. The time consumption models were constructed as a function of several independent variables. Motor-manual harvesting operations are very time consuming, where mechanization provides a better possibility to increase overall productivity. The changes of working components and reorganization of the work sequence have a significant potential to improve the overall system balance. Tree size and log length are essential factors influencing system productivity. As the harvesting of small trees is very costly, the introduction of new working methods, such as multi-handling harvesting, may be of future interest for enhancing overall productivity. The performance of workers has also an impact on productivity, and consequently, while managing the operational plan, worker performance should be taken into consideration.

A shortage of training has an influence on productivity and the physical workload due to poor working methods and postures. Improvements in working methods, work organization and skill development often require small investments while offering a high rate of return. Training is an effective measure to improve the performance, efficiency and safety of workers, and it is possible to immediately implement in the system. Education and training should lead to broad competence, covering both theoretical and practical levels. The focus on training and skills development may include the establishment of a training programme that targets new recruits and low-skilled workers to improve their potential and productivity. Training is strongly recommended for improving system efficiency by allowing the workers to learn about the appropriate working techniques, the right harvesting system and work safety. The training should start from a very basic knowledge with theory and then specific practice regarding the right working techniques, tools maintenance, work safety and first aid. Forest workers should meet the minimum requirement of training before working in the real situation. Currently, there is no official training institute in Thailand. The establishment of a specific training institution should be considered, which would aim at supporting specific training for forest workers. Moreover, the code of practice for timber harvesting should be made available and distributed to workers, contractors and whomever else may have an interest.

7.2 Final remarks

7.2.1 Economic perspectives

The preferences for the harvesting system may be reformed and influenced by uncertainty over labour and machinery costs. In the current situation, System D is the most appropriate harvesting system compared to the others in terms of unit costs. Sensitivity analysis demonstrated that if the machinery cost is increased to greater than four times the present value, old-fashioned labour-intensive operations and harvesting System A will become preferable (Figure 47). In addition, if the machinery cost continues to increase until it is seven times higher than the present value, System C will be slightly cheaper than System D. Harvesting System B is estimated to be the most expensive harvesting system in all cases.

Since logging operation is limited to the dry season, machine utilization is consequently also limited. Mobile flexibility features should be taken into consideration when selecting the machine for a logging system in order to solve this machine utilization problem. For example, an agricultural machine modification or excavator based machine can be used for other purposes for the rest of the year. Machine flexibility can increase machine utilization when logging operations cannot be executed.

Once the labour cost becomes greater than the machinery cost, the preference for the harvesting system does not change (Figure 48). System D is the most preferable system, followed by Systems C, B and A, respectively. Industries should be aware of uncertainties in the situation such as the possibility of labour shortage because it may affect the alternative preferences.

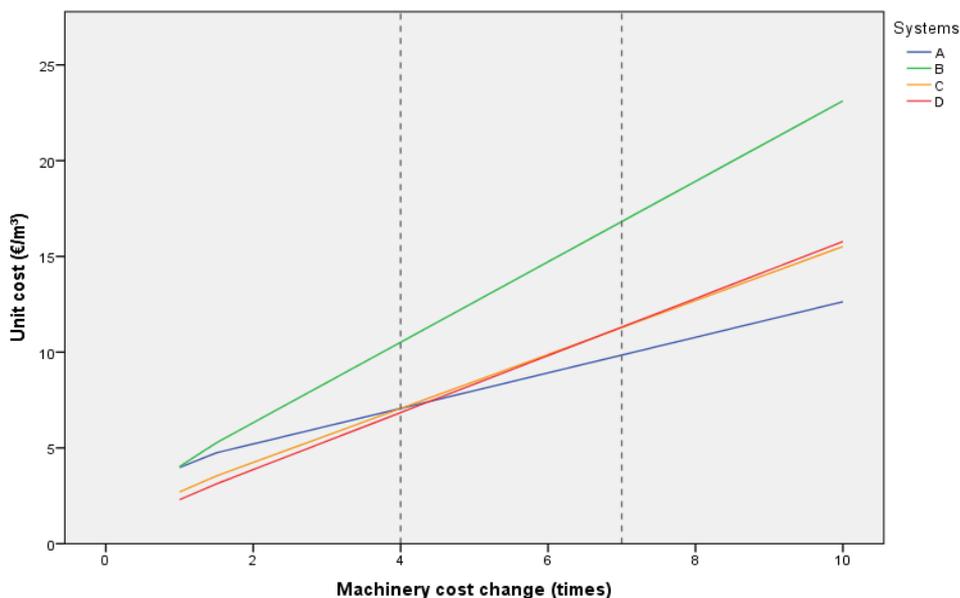


Figure 47. The impact of changes in machinery costs on the overall harvesting unit costs. (System A, B, C and D are described in Table 15.)

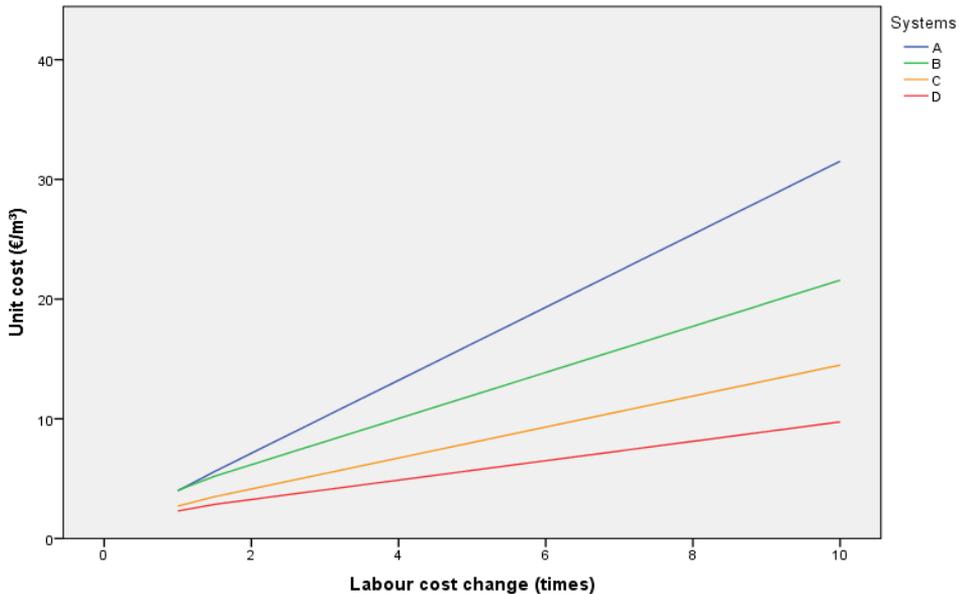


Figure 48. The impact of labour costs on the overall harvesting unit costs.

7.2.2 Technical perspectives

For further study, it would be valuable to expand the range of variables, such as the distribution of tree diameters, and skidding and forwarding distances. Since the present study was conducted at regular harvesting sites, the range of the variables was somewhat limited. Extension of the range of variables would make it possible to examine various effects on productivity and system balance further. As this study was conducted on actual harvesting practices, it was not possible to arrange a special experimental test. It would be valuable to conduct more experimental studies to test new equipment or harvesting methods.

Forest work is associated with low productivity, low wages, poor working conditions, a high energy demand and a high risk of physical accidents and illness (Jokiluoma and Tapola 1993; Balimunsi et al. 2011; ILO 2011). Furthermore, the proportion of the elderly in forestry has increased, and the trend is that young people are moving to the cities. Consequently, it is difficult to recruit new workers, unless productivity improves and justifies increased wages. A shortage of labour will become the main future challenge in the forest sector. In the long term, semi-mechanized timber harvesting should be considered to replace labour-intensive operations. Product development and mechanization in timber harvesting may promote work efficiency and reduce the danger and stress of forestry work (ILO 2011). Partial mechanization is feasible in those regions where motor-manual harvesting techniques are still dominant, and there are still some barriers (i.e. workers' skills, capital cost, infrastructure, services and education) to full mechanization (Silversides et al. 1988). The development should occur gradually.

Most forest workers have a lack of awareness of work safety, and safety equipment is not used. The use of personal protective equipment (PPE) is recommended. Employers

should provide safety equipment to their crews and regularly monitor its appropriate use, ensuring that the PPE is appropriate, correctly fitted, maintained in good condition and always used correctly. Accidents are normally caused by poor organization and supervision, poor planning, inadequate tools and equipment and a lack of skills and competence among workers, supervisors and managers (ILO 2011). One observation made during the study was that forest workers often worked too close to each other, and this could easily result in accidents. To reduce this risk, a minimum safety distance should be established during forest operations. In stacking operations, the task was done manually without using any lifting tools, thus increasing the workload. Working with fatigue increases the rate of accidents, illness, discomfort and consequently reduces productivity. In addition, forest workers should learn from other experiences related to occupational accidents in order to improve their safety awareness.

A variety of measures could have contributed to the improvement of safety and health. Safety and health promotion is a comprehensive set of measures involving numerous actions: adequate training, good working methods, safe work organisation, effective legislation, advice, motivation, cooperation, incentives, product development and proper personal protective equipment (Jokiluoma and Tapola 1993; Poschen 1993). Legislation on safety, health and working conditions plays an important role in setting minimum standards for the working environment and establishes the basic framework for cooperation between employers and employees (Jokiluoma and Tapola 1993). Enforcement is probably necessary in the case of Thailand, due to the lack of safety awareness and safety issues being taken too lightly. Enforcement is a crucial practice to meet work safety targets, and strong and clear regulation may also be needed.

Finally yet importantly, logging impacts were excluded in the present study. Reduced impact logging (RIL) should be considered in the long term. From the field study, logging impact was found, for instance soil compaction from driving farm tractors and load trucks in the stand was identified. RIL requires the introduction of guidelines that are designed to reduce the negative impacts of logging on residual stands and soil and water resources, with the aim of sustaining forests for future harvesting.

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