Dissertationes Forestales 156

Possibilities to use automatic and manual timing in time studies on harvester operations

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Academic dissertation

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ABSTRACT

To date, investigations of harvester work have relied on the time study method, which is the most common work measurement technique for work studies. Time studies are often used as a basis for arriving at important conclusions or using certain technologies or working methods in harvester operations wherein the most important focus is to understand the harvester's work process. In the era of mechanical cutting, research questions concerning harvester operations cover a wide scope. At the same time the development of time measurement techniques has provided various possibilities to obtain answers to these questions. However, despite the common consensus, the launched protocols and continuous cooperation within the forest engineering community, there is still heterogeneity in the time study approaches and techniques at the conceptual, theoretical and practical levels alike.

The general objective of this thesis was to assess the suitabilities of automatic and manual time study techniques in describing the functional steps of a single-grip harvester's work performance. The accuracy and variation of individual observers' manual recording capabilities and the possibilities of the automatic time study method were investigated in experimental studies. To that end, actual harvester time studies using manual and automatic timing were conducted to analyze the advantages and disadvantages of both timing techniques.

The results indicated that automatic time study recording is a more effective means of collecting a large amount of materials to obtain comprehensive picture of the work. The highly detailed and accurate division of work phases combined with information concerning various machine functions at the stem and log level increase the knowledge of harvester work, providing a better understanding of the structure of human-machine work. However, harvester operation may involve unforeseen situations that can confuse the automatic time study projection. There is still a need for visual and flexible observation of manual time studies when measuring a new work process. This is especially true in shorter studies with quite limited data and in fairly varying circumstances. Furthermore, automatic time studies may also be too expensive for such experiments. However, the measuring accuracy of manual timing is limited, especially in intensive time studies.

In this thesis, a new process-data model of harvester operation was identified for automatic time studies. The model can also be used for the planning of manual timing. Although further research is still needed, the new work phase classification is independent of the timing techniques and its hierarchic structure enables the work phases to be dimensioned in accordance with the log level depending on the theme of research.

Key words: single-grip harvester, work study, time study, work cycle, work phase.

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Joensuu,

Yrjö Nuutinen

LIST OF ORIGINAL ARTICLES

This thesis is based on the original papers listed below, which are referred to in the text by their Roman numerals. These papers are reprinted with the kind permission of the publishers.

I Nuutinen, Y., Väätäinen, K., Heinonen, J., Asikainen, A. & Röser, D. 2008. The accuracy of manually recorded time study data for harvester operation shown via simulator screen. Silva Fennica, 42(1), 63–72.

II Nuutinen, Y., Väätäinen, K., Asikainen, A., Prinz, R. & Heinonen, J. 2010. Operational efficiency and damage to sawlogs by feed rollers of the harvester head. Silva Fennica 44(1): 121–139.

III Nuutinen, Y., Kärhä, K., Laitila, J., Jylhä, P. & Keskinen, S. 2011. Productivity of whole-tree bundler in energy wood and pulpwood harvesting from early thinnings. Scandinavian Journal of Forest Research 26: 329–338.

IV Palander, T., Nuutinen, Y., Kariniemi, A. & Väätäinen, K. 2012. Automatic time study method for recording work phase times of timber harvesting. Forest Science. Published online October 4, 2012. Doi: http://dx.doi.org/10.5849/forsci.12-009.

Study I: Nuutinen and Väätäinen planned the data collection and Nuutinen collected the data. Nuutinen prepared, calculated and analyzed the data with the help of Heinonen and Väätäinen. Nuutinen and Väätäinen wrote the article, with comments from the other authors.

Study II: Nuutinen and Väätäinen planned the data collection and collected the data with the help of Prinz. Nuutinen prepared, calculated and analyzed the data with the help of Heinonen and Väätäinen. Nuutinen wrote the article, with comments from the other authors.

Study III: Laitila, Jylhä, Kärhä and Nuutinen planned the data collection. Laitila and Nuutinen collected the data. Laitila, Kärhä and Keskinen prepared, calculated and analyzed the data with the help of Nuutinen. Nuutinen wrote the article with the help of Kärhä, Laitila, Jylhä and Keskinen.

Study IV: Väätäinen planned the data collection of the experiment. Väätäinen and Nuutinen collected the data of the experiment. Kariniemi planned and collected the data of the process-data model. Palander planned, calculated and analyzed the data of the experiment. Palander and Nuutinen wrote the article, with comments from the other authors.

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1 INTRODUCTION

1.1 Time study as a tool of harvester development and research

Since the introduction of the first harvesters in the Nordic countries in the 1970s, investigations of harvester work have relied on the time study method, which is the most common work measurement technique for work studies (Figure 1). The terms time study and work measurement are often used interchangeably. However, work measurement includes all the techniques that are concerned with the evaluation of work performance (Forest Work…1995, Groover 2007). For the man at work, work measurement refers to four principal techniques (Introduction to…1992, Groover 2007): (1) time study, (2) predetermined time standards, (3) structured estimating and (4) work sampling. Respectively, for machines, work measurement may involve measuring operation time, movements and energy consumption, for instance (Forest Work…1995).

The concept of *time study* is widely used in work studies on forestry. In modern usage, as also in this thesis, time study covers all the ways in which time consumption is measured and analyzed in work situations, whether the work is accomplished by human workers or automated systems (Groover 2007). However, *time and motion study* covers a broader and more practical application, combining the time study work of Taylor and the motion study work of Gilbreth (Niebel 1988). In a time study, the amount of time consumed when performing a piece of work or its sub-phases is measured using a timekeeping device. Often, in time studies, repetitive work cycles are recorded and useless time consumption is eliminated (Introduction to…1992, Forest Work…1995, Groover 2007). A work cycle can be defined as a sequence of work phases repeated for each piece of work (Forest Work…1995). The purpose of motion study is to desribe the motions and to reduce ineffective movements by careful analysis of work motions (Niebel 1988, Forest Work…1995, Groover 2007, Palander et al. 2012). The fundamental approaches of both methods differ little, because motions take time and both ideas are uniquely interdependent (Karger and Bayha 1977). The integrated use of time and motion studies has become widely accepted, enabling researchers to achieve rational and reasonable study results (Palander et al. 2012).

Most often, work measurements for forest machines are conducted using either a time study or work sampling technique. Usually, a time study is conducted by means of continuous timing (Introduction to…1992, Groover 2007), where the clock is running continuously and the different work phases are separated from each other. The individual work phase times are obtained by successive subtractions using the cumulative time of the break points of each work phase. In this study, a work phase is a series of motion activities that constitute a work task and it is defined by limiting break points to have a unified purpose in the task (Forest Work…1995, Groover 2007). The purpose of the continuous timing is to ensure that all the time during which the performance is observed is recorded in the study. Work sampling (Niebel 1988) (= activity sampling, frequency study) is a method of finding the percentage occurrence of activities by sampling statistical random observations. The sampling method is based on probability, with the activities being counted and timed at regular intervals.

Time studies are used to determine productivity. For harvesters the most common productivity measure is labour productivity, as defined by the following ratio (Groover 2007): LPR = WU/LHI where LPR = labour productivity ratio, WU = work units of output, and LH = labour hours of input. For example, for the cutting operation of harvesters, time is regarded as a resource and the productivity ratio *product output/time input* is m^3 per working hour. Time studies are used to study factors affecting productivity, working methods and machine

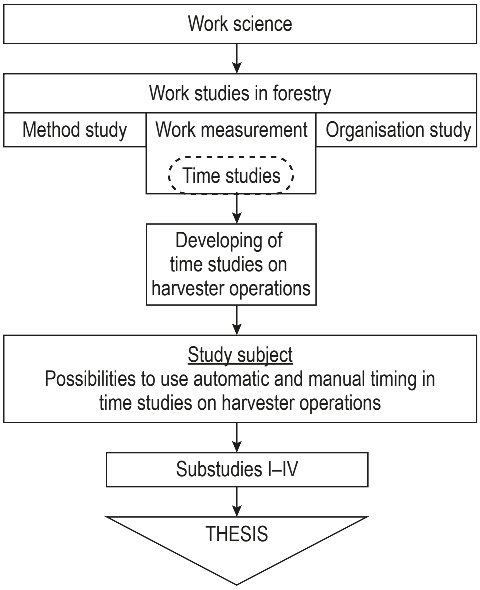


Figure 1. Flow chart describing the function of time studies for work studies and the purpose of this thesis.

technology (Björheden 1991, Harstela 1991, Introduction to…1992). As a tool for work study, time study (Figure 1) is applied to establish or improve the efficiency of forest machines (Forest Work…1995).

1.2 The development of research topics, timing techniques and study approaches in time studies on harvester operations

1.2.1 Research topics

Figure 2 describes the development of research themes in time studies on harvester operations. In the 1970s and 1980s, the main focus for harvester time studies in the Nordic countries was on testing the launched new models, because the technical development of forest machines was proceeding at a brisk clip during those decades. Most of these studies were conducted in Finland by Metsäteho and in Sweden by SkogForsk. In the 1980s, determining the piece rates for mechanical cutting also became an important task for time study (Kahala 1995).

In the 1990s single-grip harvesters started to dominate CTL (= cut-to-length method) loggings in the Nordic countries. In that decade, investigations of the cutting environment and the effectiveness of the harvester forwarder chain assumed great importance. Brunberg et al. (1989) and Brunberg (1991, 1997) defined basic productivity norms for single-grip harvesters in thinning stands. In addition, Eliasson (1998, 1999) and Lageson (1997) analyzed thinning with a single-grip harvester. The greater use of mechanical cutting in the thinning stands raised the issue of tree damages, which Siren (1998) clarified. The productivity and costs of the harvester-forwarder chain from stump to the roadside storage were investigated by the following studies: Kellog and Bettinger 1994, Kuitto et al. 1994, McNeel and Rutherford 1994, Richardson and Makkonen 1994, Landford and Stokes 1996 and Hartsough et al. 1997. Still in the 2000s, the efficiency of the whole wood procurement chain was an especially important issue; e.g. Nurminen et al. (2006) analyzed the time consumption of the mechanized

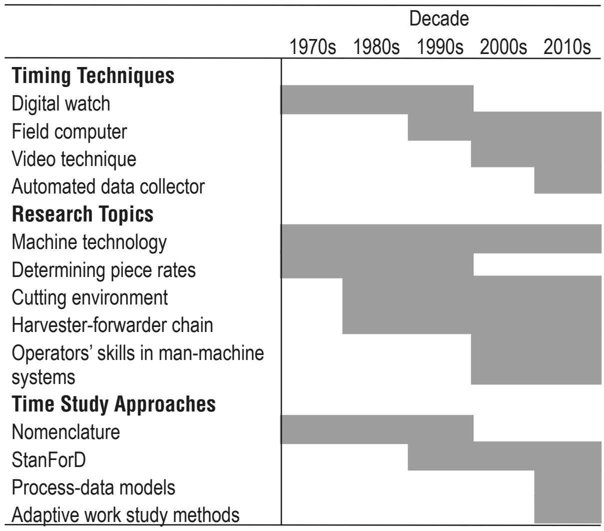


Figure 2. The development of timing techniques, research topics and time study approaches in harvester operations.

CTL harvesting system. Also Ryynänen and Rönkkö (2001) and Kärhä et al. (2004) studied the productivity and costs of thinning harvesters. In addition, the need for information has expanded: Spinelli and Visser (2008) analyzed delays in harvester operations; Spinelli and Hartsought (2000) studied mechanical cuttings in difficult terrain conditions and Poikela and Alanne (2002) and Väätäinen et al. (2006) studied the effect of timber assortments and log bunching on forwarder and harvester efficiency.

Up to 2000, the increasing efficiency of harvester operations was based on the development of mechanization and improvements in information technology. Along with machine technology development, harvester operators have shouldered new types of responsibilities in their work. Work studies in mechanical cuttings have exposed the importance of the harvester operator on overall work output (Siren 1998, Kariniemi 2006, Ovaskainen 2009, Palander et al. 2012). The reasons for the observed differences in productivity among operators were clarified by studying the importance of tacit knowledge (Väätäinen et al. 2005), cognitive abilities (Kariniemi 2006) and the working technique (Ovaskainen 2009) and work motions (Palander et al. 2012) of harvester operators.

1.2.2 Timing techniques

Timing techniques in forestry operations have evolved greatly in the past two decades, from decimal watches to the introduction of automated recorders for forest machines in the 2000s (Figure 2 and 3). At the beginning of the era of harvesters, in the 1970s and 1980s, harvester time studies were mainly conducted using decimal watches (Introduction to…1992). In the mid-1980s field computers started to replace decimal watches and paper forms in time studies, providing better possibilities for more detailed and accurate measurements of time phases (Figure 3). The advantage of an electronic field computer is that it can be used to record simultaneously the continuous cumulative working time and time consumptions of each work phase with greater accuracy and ease than a traditional decimal watch. However, decimal watches were still used until the beginning of the 1990s (Nuutinen 2005). During the 1990s, numerous time studies concerning harvesters were conducted with handheld field

Figure 3. Measuring equipment used in time studies. Left to right – decimal watch, field computer, automatic data collector of forest machines (PlusCan by Plustech Ltd.).

computers (Kellogg and Bettinger 1994, Eliasson 1998, Siren 1998), and these remained essential timing devices in the 2000s (Poikela and Alanne 2002, Kärhä et al. 2004, Puttock et al. 2005, Kariniemi 2006, Spinelli and Visser 2008, Ovaskainen 2009).

Since the 1990s, digital video cameras have been used for collecting material on harvester performance and working techniques (Väätäinen et al. 2005, Nurminen et al. 2006, Nakagawa et al. 2007). In the 2000s, it became possible to collect time study data automatically by using a harvester computer connected to CAN-bus (controller-area network) channels (Väätäinen et al. 2005, Kariniemi 2006, Tikkanen et al. 2008, Ovaskainen 2009, Nuutinen et al. 2010, Palander et al. 2012). Automated time studies for monitoring the performance of harvesters originating in cut-to-length systems have also been utilized for tree-length harvesting systems (McDonald and Fulton 2005).

The CAN-bus technique was developed and launched by Robert Bosh Corporation in 1986. It was designed specifically for automotive applications and is a multiplexed wiring system used to connect intelligent devices such as electronic control units on vehicles, allowing data to be transferred in a low-cost and reliable manner (CAN history 2011). The benefit of the CAN-bus for time studies on harvester operations is the possibility to record large amounts of time study materials with highly detailed and accurate projections of the harvester work per each processed stem.

For forest machines, Plustech Ltd developed a data collector for the automatic recording of the information flow in the CAN-bus channels. The first device recording the CAN-bus information (PlusCan data logger) (Figure 3) recorded detailed information concerning the machine operations, such as stem dimensions and time consumptions of harvester operations and movements (Peltola 2003). The successor to the PlusCan data logger, the TimberLink developed by John Deere, is a more advanced monitoring system for harvester operations that has been available as an option on all new John Deere harvesters since 2005. TimberLink is software that collects and processes the CAN-bus data about the human-machine's condition and performance (John Deere 2008a, Tikkanen et al. 2008, Nuutinen et al. 2010, Palander et al. 2012).

1.2.3 Time study approaches

Time study approaches are standards or procedures aiming to use common time study methodology and terminology (Figure 2). The first Forestry Work Study Nomenclature (Forest Work…1978) was published in 1963 and revised in 1978. It was an agreement between Denmark, Finland, Sweden and Norway worked out by the Nordic Work Study Council (NSR).

The Nomenclature aimed to improve the comparability of international time study reports (Samset 1990). The second international forest work study nomenclature was launched in 1995 (Forest Work…1995). These nomenclatures were the first steps in developing a common universal time study methodology. They contain a collective proposal of basic concepts and time phases for time measurement in forest work in order to serve as a basis for any study claiming international significance.

The only time-study standard intended specifically for forest machines is StanForD (Standard for Forest Data and Communication), which is a de facto standard for all forest machines manufactured in the Nordic countries (StanForD 2012). The first version of StanForD was published in 1987 in Sweden. In the early 1990s, Finnish researchers also joined the development of the StanForD standard (Arlinger et al. 2008, StanForD 2012). It is developed to enable analyses of the technical and organizational factors affecting forwarders and harvesters. The latest version of StanForD was issued in 2011 (Arlinger et al. 2011). In StanForD for harvesters, the main work time is divided into processing and terrain travel. Processing means functions in which the harvester head is active, primarily felling and processing the tree. Terrain travel is defined as the movement of the harvester within one specific site. During StanForD's development process, information technology has provided a number of possibilities to advance internationally common standards of time studies. To this end, heterogeneous time study methods are used for data collection in harvester work studies.

Some new time study approaches do not directly apply Nordic traditions or the StanForD standard. Spinelli et al. (2010) developed a general productivity model for the harvesters and processors used in Italy. They have proposed that general productivity models should be developed for machines instead of more accurate stand-level models for human-machine systems. In Finland, a process-data model had already been developed for this approach in 2004. It is a model of work phase classification for automatic time studies of single-grip harvesters (Kariniemi and Vartiamäki 2010). The model was developed especially to utilize harvester CAN-bus data, which in this study is referred to as the process-data. Recently, the adaptive work study method has also been developed for the stand-level approach (Palander 2012). It is actually a time and motion study approach, which uses detailed productivity and work-phase data provided by the automatic monitoring system to identify the most important work phases of work models in human-machine systems. Magagnotti and Spinelli (2012) introduced the good practice guidelines on biomass work studies. Guidelines show to the field researchers how to conduct field work and analyze the study material. The purpose of the guide was to harmonize work study methods in order to improve the comparability of work studies done in different research organizations.

1.3 The implementation system of time study on harvester operation

In Figure 4, the implementation of a harvester time study is conceptualized using Engeström's (1987) model about human activity. The activity model is a Finnish variant of the cultural-historical activity theory and developmental research. The roots of the activity theory are in Russia, where Vygotsky founded cultural-historical psychology, an important strand in the activity approach. Vygotsky's colleagues Leont'ev and Luria continued the research, seeking to understand human activities as complex, socially situated phenomena (Vygotsky 1962, Leont'ev 1981, Luria and Vygotsky 1992). The activity model of Engeström (1987) describes the actors and elements of an activity system and their interaction. The essential task of the model is to grasp the systemic whole, not just separate connections.

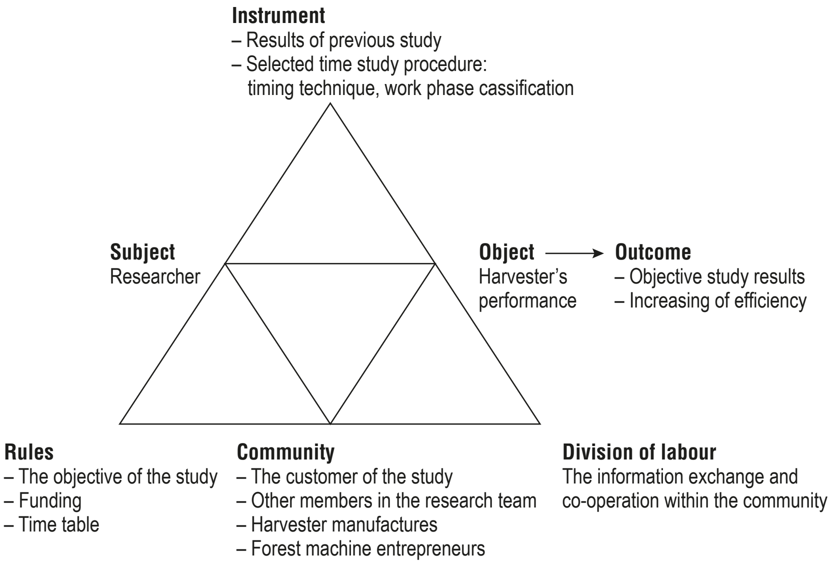


Figure 4. The model of Engeström (1987) describing the structure of a time study on harvester operations.

In the model, the subject, community and object have a bilateral interaction. Instruments are transmitters between the subject and object. Rules are transmitting between the subject and community and respectively division of labour between the object and community. In the activity system, the subject is in a key position because the activity system is analyzed from the perspective of the subject. Every activity is focused on the object that is transformed into an outcome. The outcome can be understood as the motive of the activity.

When applying the activity system model of Engeström (1987) to a harvester time study, the researcher can be considered as a *subject*. During the study, the factors influencing the harvester's performance (= *object*) are clarified. The motive of the researcher is to obtain objective study results in order to increase the efficiency of the harvester – these results are considered to be the *outcomes* of the activity. In other words, the harvester's performance during the time study is transformed into study results that can be harnessed to increase harvester efficiency. In a time study, the researcher utilizes the suitable time study techniques and methods as *instruments*. The *community* consists of the interest groups that are in some way interested in the development of the studied harvester. *Rules* are the aims, timetable and funding of the study that influence the activity of the researcher and community. *Division of labour* refers to information exchange and co-operation within the community.

1.4 Time study in the context of harvester operations development

A time study collects data about harvester performance with a view to increasing productivity (m^3/working hour) by searching for better and more effective ways to conduct the harvester's cutting (Figure 4). For that purpose the time study researcher must know when it is best to use a certain technique and then use that technique judiciously and correctly. When conducting time study at work phase level, the researcher segments the work into sub-operations (= work phases) and times each phase by means of a specialized timing device so that the work phase distribution of work time describes the operation from the perspective of the objective of the study. A good researcher should discern when work phases should be separated, what phases should be separated and for what reason. By Magagnotti and Spinelli (2012) breaking the work performance into detailed work phases gives following benefits: 1) it is possible to indicate the specific work process steps that take more time, 2) separate the effective work time from delay time, and to 3) separate functional phases that react to different work characterictics, so that more accurate models can be developed. These features of work phase classification contribute to better understand of harvester's work process dynamics.

To date, time studies on harvester operations have expanded to cover a wide range of topics, from the testing of new models to the influence on the environment, the operational efficiency of harvesting chains, operators' skills and human-machine systems. In the 2000s, the techniques employed in time studies have evolved significantly (Kariniemi 2003, 2005, Peltola 2003, McDonald and Fulton 2005, Väätäinen et al. 2005, Tikkanen et al. 2008, Ovaskainen 2009, Nuutinen et al. 2010, Palander et al. 2012), which has increased the possibilities to obtain answers to various research questions (Figure 2). However, as a result there is a need to adapt the current recommendations to these new techniques. To identify the bottlenecks of harvester operations, time study results must describe the job events as they occur. To ensure the comparability of accumulated study results, the distribution of work time – often aided by various measuring devices – should be congruent between subsequent studies. Despite the common consensus, launched protocols and continuous cooperation within the forest engineering community, there is still heterogeneity of time study approaches at the conceptual, theoretical and practical levels alike. This thesis concentrates on the use of automatic and manual timing techniques in time studies on harvester operations to increase the understanding of harvester work (Figures 1 and 4). In this thesis, manual timing involves a human being observing the harvester's performance using a handheld field computer and automatic timing in turn means recording time consumptions from the harvester's CAN-bus data using a data mining program.

1.5 Objectives of the research

The general objective of this thesis was to assess the suitabilities of automatic and manual time studies in describing the functional steps of a single-grip harvester's work process. The specific objectives of the substudies were:

1. To investigate the effect of work experience on the accuracy and variation of observers recording the operation time of harvesters. A supplementary aim was also to clarify whether measurement errors and differences between the observers affect the structure and ratio of the timings of work phases within time studies (Study I).
2. To compare the damages to sawlogs and the time and fuel consumption of stem feeding with six different steel feed rollers during the processing of stems using a single-grip harvester. A highly detailed and accurate processing and fuel consumption projection was recorded using the harvester's automated data collector at a log and stem level (Study II).
3. To define the productivity of the Fixteri II whole-tree bundler in integrated energy wood and pulpwood harvesting. In addition to that, bottlenecks of whole-tree bundling were identified for further development of the concept. Two work study researchers observed simultaneously the performance of the whole-tree bundler and timed the different work phases of cutting and bundling processes with handheld field computers (Study III).

4. To develop an automatic time study method based on a process–data model for single-grip harvesters, with inputs based on data automatically collected by the harvester's onboard computer (Study IV).

All the substudies of this thesis provide results that enable the analysis of the suitability of automatic and manual timing and thereby better understand the harvester's work and choose the most suitable time study technique depending on the research problem. The substudies are presented in chronological order, in accordance with the work process of this research. Study I clarifies the question of whether the time consumptions recorded manually by an observer using a handheld field computer are accurate and reliable enough to truly reflect the often intensive harvester work. In Study II, the research subject demands a large amount of recorded stems and logs with highly detailed and accurate processing and fuel consumption projection using the harvester's automated data collector. Study III is an example of a work study for testing a new machine innovation where the performance of the prototype was recorded manually by human beings. In Study III, two work study researchers observed the performance of the whole-tree bundler simultaneously and used handheld field computers to record the work phases of the cutting and bundling processes. The presence of two observers was required because the work process of the whole-tree bundler involved unexpected and overlapping work phases that required visual observation by a human being. Study IV described the features of work phases of automatic and manual timing. Furhermore, in Study IV, a new process-data model based on combined data of automatic and manual timing is defined.

2 MATERIALS AND METHODS

2.1 The accuracy of manually recorded time study data for harvester operation shown via simulator screen (Study I)

2.1.1 Research material and practical method

The purpose of Study I was to find out whether the time consumptions recorded by a researcher are accurate and reliable enough to truly reflect the often intensive harvester work. The time study was conducted in a TV studio, where each researcher studied 40 minutes of identical video material of simulator harvester logging (Figure 5). The video material of the thinning showed the cutting of 81 trees and also included the sound of the harvester operation. All the observers chosen for this study made a time study based on uniform instructions.

The pool of time study observers consisted of 20 novices and 10 experienced researchers. The observers were divided into three groups (10 observers/group) according to their training and experience level. Two groups consisted of students divided according to their level of practice before the time study: 15 minutes (*students 15 min*) or 30 minutes (*students 30 min*). None of the individuals in these groups had any previous time study experience. The third group consisted of forestry researchers who had previously conducted time studies in the field (*researchers*). They also were given training for 15 minutes before the experiment. Before the introductory training all the time study observers were familiarized with the work phases and the work phase definitions in the same way, and recording codes were distributed to observers a few days before the study. They recorded the work phases using Rufco-900 field computers (Figures 3 and 5) applying different number codes for the various work phases. The timing accuracy of Rufco-900 is 0.6 seconds (1 cmin).

In this study, the harvesting stages with a single-grip harvester were divided into more detailed work phases: 1) *driving forward*, 2) *extend the boom and grasp*, 3) *felling*, 4) *processing* (*delimbing and cross-cutting*), 5) *reversing*, 6) *positioning the boom forward* and 7) *pause time*. *Driving forward* and *reversing* started when the harvester started to move and ended when the harvester stopped to perform another task. *Extend the boom and grasp* started when the boom started to swing toward a tree and ended when the harvester head rested on a tree and the felling cut began. *Felling* started when the felling cut began and ended when the feeding and delimbing of the stem (*processing*) started. *Processing* consisted of delimbing and crosscutting. *Processing* ended when the operator lifted the harvester head

Figure 5. Time study laboratory and a sample picture of cutting in a harvester simulator environment from a TV screen.

to an upright position immediately after the final crosscut of the stem. *Positioning the boom forward* occurred when the operator steered the harvester head to the front of the machine before moving forward. *Pause times* were short time phases when no machine movements occurred. *Pause time* consisted mainly of work planning. In this simulation environment of a first-thinning operation there were no other work phases that occur in real harvesting, such as removal of undergrowth, gathering the logs onto piles along the strip road, and moving tops and branches.

In addition, to further analyze the observers' recorded material a division of main and complementary work phases was conducted (see Björheden 1991). Work phases 2, 3 and 4 were the main work phases repeated for each tree, while phases 1, 5, 6 and 7 were defined as complementary work phases. Generally, the complementary work phases are more difficult to identify and record compared to the main work phases; furthermore, the complementary phases where not conducted on each tree.

Time consumption data comprising of two main work phases (felling and processing) – recorded using an automated data logger (PlusCan from Plustech Ltd.) (Figure 3) – was used as reference data in this study. The definitions of the starting and ending points of the felling work phase and processing work phase were identical to the respective definitions of the manual time study. The timing accuracy of the PlusCan device is a thousandth part of a second.

2.1.2 Analysis of the research material

A comparison of all the observers was conducted based on average time consumption for the distribution of work phases in order to compare the differences in the work phase timings among the observers and their experience category. All the time consumptions of each time phase where a code was missing or an incorrect code had been entered were examined and defined as "recording with error code". In addition the measuring errors in time consumptions for all the observers were examined for the felling and processing work phases for each stem. The measuring error was counted per stem by subtracting the value (a reference value) of the automated data logger from the time value of the observer. Standard deviations and trends of measuring errors (box plots) were also counted for each observer. The average measuring error in each experience category was statistically tested with a mixed effects model with stem size as a covariant and the experience level of the observer as the random factor. The equality of the measuring errors' variances between the experience groups was pairwise tested using Levene's test (Milligen and Jonsson 1984). Also the researchers' fatigue during the time study was determined using Levene's test for each experience group. For the testing of the level of fatigue the time study was broken down into four sections of 10 minutes. The time sections were set as independent factors in the Levene's test for fatigue.

2.2 Operational efficiency and damage to sawlogs by feed rollers of the harvester head (Study II)

2.2.1 Performance study of feed rollers

Study II presented the features of harvester's time consumption projection recorded by an automated data collector. In the study six different types of steel feed rollers were tested (Figure 6): two small spike rollers (small spike 1 and small spike 2), two big spike rollers (big spike 1 and big spike 2), one roller with studs in V-angle (v-type stud), and one roller with

Figure 6. The types of the six tested feed rollers (Photo Kari Väätäinen and Heikki Tuunanen).

Table 1. The technical information of the studied feed rollers.

	Length of the spike or stud, mm			Roller's smallest diameter, mm	Acute angle of spike/ stud, degrees	Depth of spike groove, mm	Diameter of spike/ stud, mm
	Outer circle	Inner circle	Average				
Big spike 1	24	18	21	464	60	-	22
Small spike 1	14	14	14	464	60	-	16
Adaptable plate	15	15	15	470	-	4	-
Big spike 2	28	28	28	478	60	-	30
V-type stud	14	14	14	464	60/90	3.5	16
Small spike 2	14	14	14	464	60	-	16

adaptable steel plates on the ring of the roller (adaptable plate). Table 1 presents the technical information of the studied feed rollers.

The performance study of feed rollers was conducted with a John Deere 1270 D Eco III harvester (equipped with a John Deere 758 head) by two experienced operators on 12–19th March 2007 in eastern Finland in four separate clear cutting areas. The sites were approximately 50 km north-east of the city of Joensuu, near the village of Sarvinki (62°41.672´N, 30°16.289´E). The base machine and the harvester head alike are designed for second thinnings and clear cuttings (John Deere 2008b). Before the start of the study, the cylinder pressure of each feed roller type was separately adjusted to within the optimal operating levels to ensure that the functioning of each roller type was suitable for cuttings. For controlling the cylinder pressure of the rollers, the penetration of the studs of the upper rollers into the wood surface was measured and compared (Figure 7). The harvester head's upper rollers were the same during the whole study.

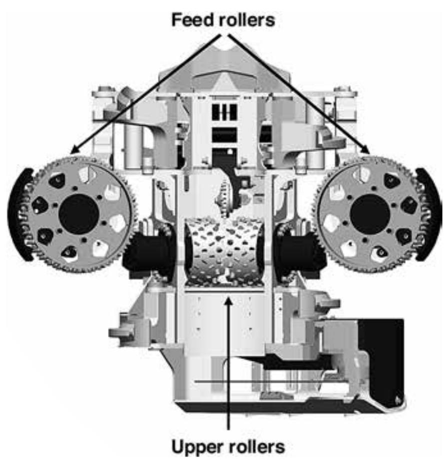


Figure 7. Harvester head of a single-grip harvester, perspective from underneath (Photo Waratah OM).

The damage caused by the feed rollers on the study logs was measured immediately after processing, before forest haulage. Because the temperature during the testing cuttings was in the range of 0 °C…+5 °C the study logs were not frozen. The proportion of tree species among the processed study stems was pine (*Pinus sylvestris*) 12%, spruce (*Picea abies*) 49% and birch (*Betula pendula*) 39%. The average mercantile stem volume of the processed stems, per studied feed roller, was in the range of 0.21–0.38 m^3. The proportion of the processed stems' mercantile volume, which was less or equal to 0.4 m^3 per roller, varied in the range of 62–81%.

2.2.2 Analysis of effective feeding time and the fuel consumption

In this study, data were collected automatically about machine functions and work phases of interest. They were feeding time during processing and fuel consumption during feeding. Processing time begins immediately after the final felling cut of the tree and ends when the operator lifts the harvester head to an upright position after the final cross-cut of the stem. Processing time includes delimbing and crosscutting of stem and pause times. Processing time and fuel consumption during processing of the 7400 studied stems were collected by using the TimberLink monitoring system of the harvester functions developed by John Deere. TimberLink has been available as an option on all new John Deere harvesters since November 2005. During the period of this study, the functions of this software comprised the collection and processing of data about the machine's condition and performance (John Deere 2008a).

For the time consumption models the working time of effective feeding was separated from the processing time. Effective feeding time excludes pause and cutting times. It represents pure feed time and enables the study and comparison of the efficiency of the rollers without the operator effect. Fuel consumption was analyzed during the processing time. Effective feeding time and fuel consumption during the processing time were modelled using roller type and log amount per stem as categorical and mercantile stem volume as covariant variables. Figures presented in the results express the predicted values of regression models. Using the models, the estimates of each roller type and tree species were calculated for three mercantile stem volumes: small stems of volume 0.05 m^3, medium stems of volume 0.35 m^3 and large stems of volume 0.65 m^3. In this study mercantile stem volume is defined as industrial timber excluding the uncommercial top of the stem. Independent modelling variables were formed so that they correlated maximally between dependent variables (effective feeding time and fuel consumption during processing time). To ensure the reliability of the models the final data to be analyzed was filtered and harmonized from the base data as follows:

– Fuel consumption per stem, which was recorded during the total processing time, was included in the modelling material only if the subtraction of the total feeding (processing) per stem and effective feeding per stem was less or equal to 2 seconds. This ensured that the fuel consumption corresponded with effective feeding time adequately.
– Stems that had more than 4 logs were excluded, because the number of these stems was insufficient for modelling.
– Spruce and pine stems were selected with a mercantile volume of under 0.8 m^3, while for birch stems those with a mercantile volume of under 0.7 m^3 were chosen. The number of bigger stems was insufficient for modelling.
– Stems whose effective feeding time and fuel consumption values deviated more than three times the standard deviation from the arithmetic average were excluded (Ranta et al. 1994).

Table 2. The number of studied stems for fuel consumption and effective feeding time.

	Fuel consumption			
	Pine	**Spruce**	**Birch**	**Total**
Big spike 1	30	298	243	571
Small spike 1	73	261	53	387
Big spike 2	142	268	125	535
Adaptable plate	5	64	25	94
Small spike 2	174	699	1050	1923
V-type stud	79	589	189	857
Total	503	2179	1685	4367
	Effective feeding time			
	Pine	**Spruce**	**Birch**	**Total**
Big spike 1	30	301	246	577
Small spike 1	73	263	54	390
Big spike 2	143	269	129	541
Adaptable plate	5	64	25	94
Small spike 2	189	713	1082	1984
V-type stud	81	593	191	865
Total	521	2203	1727	4451

The total number of analyzed stems was 4451 for effective feeding, and 4367 for fuel consumption during processing (Table 2). Effective feeding time, seconds/stem, was calculated as a sum of effective feeding time of each log. Fuel consumption, l/mercantile-m^3/stem, was calculated by using the total fuel consumption [l/h] per stem during processing and the total sum of log volume [m^3] per processed stem. The following variables of recorded TimberLink data were used in the modelling:

Stem level:

– Roller: roller type.

– Stem number.

– Total fuel consumption per mercantile stem: recorded during total processing time. [0.0 l/h].

– Tree type: the harvester operator sets the tree type code.

Log level:

– Roller type.

– Stem number.

– Log number.

– Effective feeding time: harvester head is feeding the log forward or backwards, excluding bucking and pause times. [0.000 s].

– Volume: log volume is recorded when the bucking starts. Log diameters are recorded as the rollers feed the log forward. [0.000 m^3].

2.3 Productivity of a whole-tree bundler in energy wood and pulpwood harvesting from early thinnings (Study III)

2.3.1 Fixteri II whole-tree bundler and its work process

Study III was an example of testing a new machine innovation where observers monitored the work performance and recorded the time consumption with handheld field computers. The whole-tree bundler consists of a base machine, an accumulating felling head equipped with stroke feeding and guillotine blade, and a bundling unit (Figure 8). The whole-tree bundler used in the time study was constructed using a Valmet 801 Combi harwarder as a base machine, the load space of which was replaced by the bundling unit. The whole-tree bundler was 935 cm long, and its total weight (incl. the bundling unit of 5.5 tonnes) was ca. 30 tonnes. The dimensions of the bundling unit were length 400 cm, width 195 cm, and height 270 cm.

The operation of the whole-tree bundler consists of two main processes: cutting of whole trees and compaction of whole trees into bundles (Figure 8). Firstly, the trees are felled and accumulated as a bunch of whole trees. Secondly, the bunch is fed onto the feeding table of the bundling unit, where the feed rollers pull the trees into the feeding chamber. The feeding action is assisted by the accumulating felling head, with strokes of at most 1 m. Then, the chainsaw installed at the chamber gate cuts the whole trees in the feeding chamber into

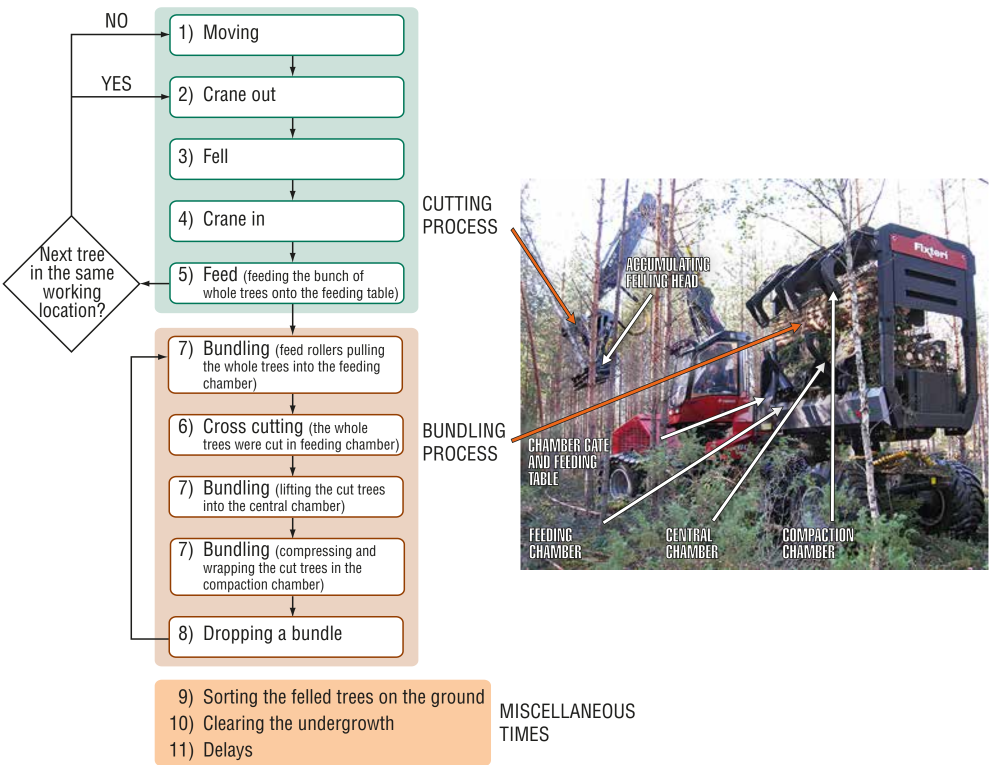


Figure 8. The Fixteri II whole-tree bundler (photo Juha Laitila) and flow chart describing the work phases for the study on time consumption in the work process of the whole-tree bundler.

lengths of 2.7 m. Next, the cut trees are lifted from the feeding chamber into the central chamber. When there are enough trees for one bundle, the sawn tree sections are lifted into the compaction chamber, where the bundle is compressed and bound together. Finally, the bundle is dropped onto the left side of the strip road. Most of the bundling process is automatic, enabling simultaneous cutting during bundling. Felling and accumulating (3 fell) is the only work phase that is repeated for each tree processed. The work phases that are repeated for each grapple bunch are as follows: crane out (2), crane in (4) and feeding the tree bunch on the feeding table (5 feed). Moving (1) and miscellaneous times (work phases 9, 10 and 11) occur while cutting, and they complement the productive working processes (see Figure 8).

2.3.2 Productivity study

The time study was carried out in Central Finland in September 2009. The data were collected from 28 time study plots located in two separate stands (62º 5.114’N, 26º 40.534’E and 62º 2.846’N, 28º 53.345’E). The plots represented 35–40-year-old Scots pine (*Pinus sylvestris*) first-thinning stands located on mineral soils. The average breast height diameter ($d_{1.3}$) of cut trees in the plots was in the range of 6–11 cm, the average height ranged from 7.1 to 11.3 m and the average stem volume of whole trees from 18 to 77 dm^3. Each time study plot was 50 + x m long and 20 m wide, and included four circular stand data plots 50 m^2 in size, located as illustrated by Jylhä and Laitila (2007). In the productivity study, the last bundle was finished even if this meant passing the plot’s end point. This extra length (x m) of the time study plot was added to the initial plot length (50 m + x m).

Stand data from the circular plots were collected as reported by Jylhä and Laitila (2007). Mean plot-wise whole-tree volumes and the numbers of removed trees per hectare were needed when constructing the time consumption models. Whole-tree volumes for each tree were obtained by summing stem volumes and volumes of living crown. Stem volumes were computed using the models of Laasasenaho (1982). Volumes of living branches and foliage were based on the dry mass functions of Repola et al. (2007). Dry branch masses were divided into branch wood and branch bark as in Kärkkäinen (1976). The dry masses of the branch components were converted into volumes using the basic densities reported by Gislerud (1974) and Kärkkäinen (1976).

Each bundle produced during the time study was numbered and thereafter forwarded to the roadside storage, where they were scaled separately during unloading with a Ponsse Load Optimizer crane scale. The mean plot-wise solid volumes of the whole-tree bundles were derived from the mean plot-wise green mass of the bundles and the mean green density of the bundles produced in the time study, based on the hydrostatic sampling described by Kärhä et al. (2009). The length and moisture content of the bundles were also recorded. In total, 454 bundles were weighed by the crane scale, and 123 bundles were included in the hydrostatic sampling. The output of the whole-tree bundler was recorded as the number of bundles per time study plot per effective working hour (E_0, excluding delay times) and m^3 per effective working hour (m^3/E_0).

Two work study researchers observed the performance of the whole-tree bundler simultaneously and recorded the work phases of the cutting and bundling processes (Figure 8) with Rufco-900 fieldwork computers (Figure 3). The working time was recorded applying a continuous timing method where a clock runs continuously and the times for different work phases are separated from each other by numeric codes (e.g. Harstela, 1991). The presence of two observers was required because of the simultaneity of some phases of the cutting and bundling processes (Figure 8). The bundler operator had eight years’ experience of driving forest machines and almost four years' experience of operating the whole-tree bundler. He was also the inventor and developer of the whole-tree bundler. The harvester operator has been stated to be the most important factor of productivity (Siren 1998, Väätäinen et al. 2005, Kariniemi 2006, Ovaskainen 2009). Since only one experienced operator was used in the performance study of this study, the comparison between productivity differences in different working conditions was more reliable that in the case of several operators.

The first observer (Researcher I) recorded the whole working process (Figure 8) by focusing especially on tree cutting, with the working time divided as follows:

1. Moving
2. Crane out (moving and positioning the harvester head to fell a tree)
3. Fell (cutting and accumulating trees; the number and size of trees in each grapple bunch were recorded)
4. Crane in (transferring the bunch of trees to the bundle unit)
5. Feed (feeding the bunch into the bundle unit)
6. Cross-cutting (whole trees were cut in the feeding chamber)
7. Bundling (bundling operations in the feeding, central and compaction chambers)
8. Dropping a bundle (the bound bundle was dropped onto the strip road)
9. Sorting the felled trees on the ground
10. Clearing undergrowth
11. Delays (the cause was recorded).

Researcher II concentrated on recording the relative proportions of the different work phases making up the entire work process (Figure 8). The simultaneous time consumption for different phases of the work process was also measured, in which case the working time of the whole-tree bundler was divided as follows:

– Moving
– Grapple time (total time of cutting trees and accumulating grapple bunch)
– Crane in (moving the bunch of trees to the bundle unit)
– Cross-cutting the trees in the bundle unit
– Cutting of trees (= crane movements) simultaneously with cross-cutting the whole trees in the feeding chamber
– Cutting of trees (= crane movements) simultaneously with bundling the cut whole trees in the central and compaction chambers
– Moving simultaneously with bundling
– Bundling
– Dropping the bundle onto the strip road
– Clearing undergrowth
– Delays (the cause was recorded).

In total, 5482 trees (95–332 per time study plot) accumulated in 1905 grapple bunches (31–114 per time study plot) were harvested in the time study. The time consumption recorded by researcher I was used when constructing the productivity models. When he recorded the entire working process, the crane functions had the highest priority, and the moving and bundling phases were the next in priority, respectively.

2.3.3 Modelling of time consumption

According to the observations of researcher I, the time consumption model of the whole-tree bundling was combined into three main work phases: moving, cutting and bundle processing (see Figure 8).

– Moving (1) is the time period when the bundler moves from one working location to another. It begins when the tracks are rolling and ends when the boom starts to move towards a tree in order to fell it.
– The work phase of cutting includes boom movements when cutting the trees and bringing them to the bundling unit. It includes moving and positioning the harvester head around a standing tree (2 crane out), cutting and accumulating trees (3 fell), moving the bunch of trees to the bundling unit (4 crane in) and feeding the bunch into the bundling unit (5 feed).
– The work phase of bundle processing includes cutting the whole trees in the bundling unit (6 cross-cutting), compressing and wrapping the bunch of trees (7 bundling) and dropping the bound bundle onto the strip road (8 dropping a bundle).

The time consumption models were formulated applying regression analysis. The different transformations and curve types were tested in order to achieve symmetrical residuals for the regression models and in order to ensure the statistical significance of the coefficients. The regression analysis was carried out using the SAS statistical package.

2.4 An automatic time study method for recording work phase times during timber harvesting (Study IV)

2.4.1 Process-data model

The main problem faced in automatic recording for time studies on harvester work is the large amounts of time study materials per each processed stem, which must be reorganized systematically. The purpose of Study IV was to develop an automatic time study method that uses a process-data model in order to increase understanding of automatic time studies.

A model of work phase classification for automatic time studies of single-grip harvesters was developed in 2004 (Kariniemi and Vartiamäki 2010). It is a process-data model in which pause times are considered in addition to the effective work time. The process-data model was developed especially to utilize the CAN-bus data of a harvester, which in this study is referred to as the process data. Process data includes detailed information about harvester operations such as stem dimensions, time consumption of harvester work, machine movements and fuel consumption.

The process-data model is based on the ideal work cycle of a single-grip harvester wherein the work phases follow regularly repeating steps (Figure 9). For defining the process-data model, time study material was recorded from Ponsse, Timberjack and Valmet harvesters (one harvester per each manufacturer), The experiments of the study were conducted on June 2004 in south and middle Finland. For the experiments one time study plot consisting of 200 stems for each harvester was chosen from clear-cutting stands. In the study, the structure of automatic time study data of each harvester type was clarified in order to develop the harmonized process-data model. The time study material included automatic recordings of automated data

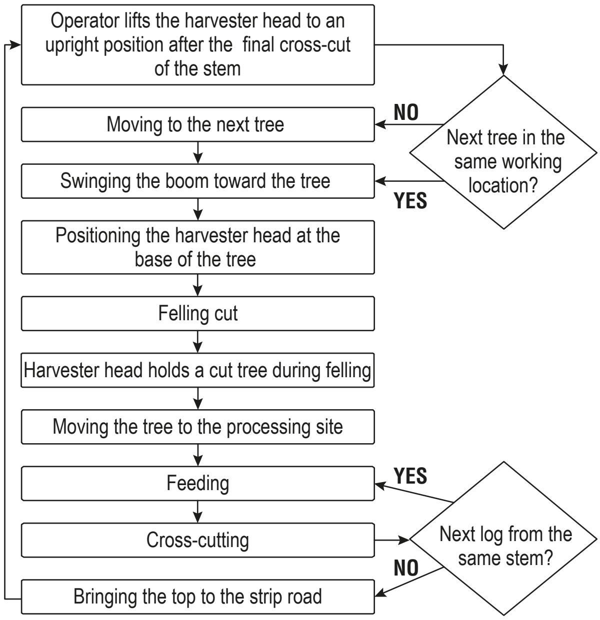


Figure 9. The ideal work cycle of a single-grip harvester.

collector and manual recordings taken by a Husky-Hunter handheld field computer for each stem. Furthermore, the experiments were recorded by video camera. The video material was used for the re-examination of each harvesters' work performance, and as reference data to confirm the accuracy and reliability of automatic and manual recordings. The proportions of tree species of the processed study stems were: Scots pine (*Pinus sylvesteris*) 11%, Norway spruce (*Picea abies*) 63% and Birch 26% (*Betula pendula*). The average mercantile stem volume of the processed stems was 0.446 m^3 (Kariniemi 2012). The structure of the process-data model is described in Figure 10.

The model consists of three hierarchical levels: the level 1 work phases in the hierarchy, the work cycle elements within these phases (level 2 phases), and the components of these work cycle elements (level 3 phases). The total work time for each processed tree equals the combined time consumption of the level 1 work phases. In levels 2 and 3, the level 1 work phases are subdivided into smaller work cycle elements, and the time consumption of each level 1 work phase equals the sum of the work cycle elements at lower levels of the hierarchy. In the original model, all work phases are considered to be separate, which means that the time consumptions do not overlap.

In level 1 of the hierarchy, the work phases are grasping the stem, felling, and processing. Tables 3 and 4 define the start and end points of the level 1 work phases and their work cycle elements. The time consumption during grasping the stem is calculated as an average value for the processed trees at each "working location" or in each stand, whereas felling and processing times are recorded for each tree. Kariniemi (2006) has described the working location: "The working location is an ideal area limited to the reach of the boom, within which it is possible to work as a single entity, provided that the operator is skilled enough".

In level 2, the level 1 work phases are subdivided into five shorter work cycle elements and four pauses. Tables 3 and 4 provide details of the level 2 time elements. If positioning

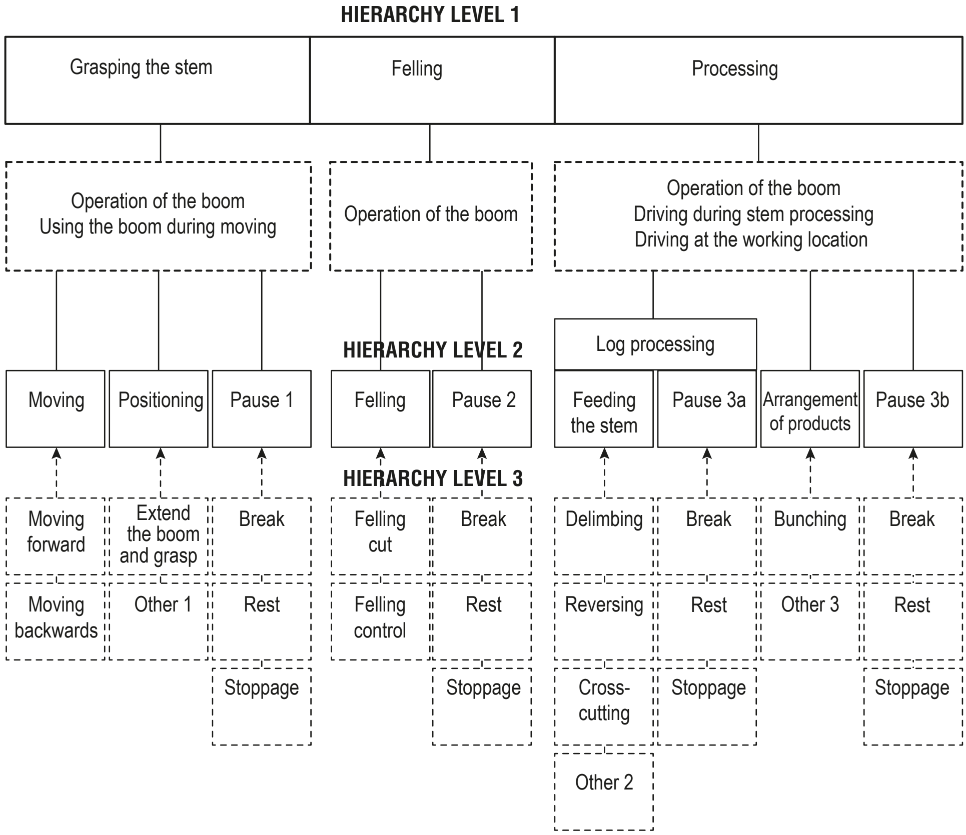


Figure 10. Flow chart for process-data model describing the relationships between the different work phases in harvester work (Kariniemi and Vartiamäki 2010).

occurs while the harvester is moving, the whole working time is registered as part of the moving phase. During the grasping the stem phase, when the boom or the harvester head are motionless due to reasons such as work planning by the operator or a machine breakdown, the time is included in the pause 1 phase. Felling is split into felling and pause 2. Felling starts when the felling cut begins and ends when the stem feeding starts. Pause 2 is defined as a time phase during which the machine, boom, and harvester head are motionless. Processing is divided into feeding the stem, pause 3a, arrangement of the products, and pause 3b. The processing time of each log is split into feeding the stem and pause 3a. Feeding the stem starts when the stem begins moving through the harvester head and ends when the feeding of the log stops. Pause 3a is the time phase during log processing when the machine, the boom, and the harvester head are motionless. Arrangement of the products includes operation of the boom and harvester head and pause 3b is the time phase without any harvester operations. Arrangement of the products and pause 3b occur immediately after the processing of each log.

In level 3 of the hierarchy, the moving phase in level 2 is divided into forward and backward movements. The positioning work phase equals the sum of the extend the boom and grasp phase and the “other 1” phase. Extend the boom and grasp begins when the boom starts to swing towards a tree and ends when the harvester head is resting against a tree. Other

1 includes phases for clearing undergrowth and for arrangement of the products around a tree to be felled or repositioning the head to avoid an obstacle such as a large rock that prevents the head from reaching the tree. The felling phase includes the felling cut and felling control phases. Felling cut means the cut that fells a standing tree, whereas felling control means moving the felled tree to the position where it will be processed. The feeding the stem work phase is broken down into four phases: delimbing, reversing, cross-cutting, and “other 2”. During delimbing, the branches are removed by feeding the stem through the harvester head while the harvester head is moving forwards. Reversing occurs when the harvester head is moving backward along the stem. Cross-cutting includes time consumption during the cross-cut that produces each log. Other 2 includes work not involving delimbing or cross-cutting, such as piling logs. The arrangement of the products phase is split into bunching and “other 3” phases. Bunching includes moving the stem to the most convenient position for cross-cutting so that the logs will form a single pile. Other 3 includes sorting the logs after the feeding the stem phase and moving tops and branches. The pause 1, pause 2, pause 3a, and pause 3b phases are split into shorter phases based on their duration: “break” for a pause ≤ 3 sec, “rest” for a pause longer than 3 sec but shorter than 30 sec, and “stoppage” for a pause ≥ 30 sec.

2.4.2 Challenges to automatic timing using the process-data model

However, unforeseen situations deviating from “normal” work procedures (Figure 9) can occur during the work, which can lead to difficulties in identifying the harvester operations, especially when using the automatic recording of time data. It is important to ensure that all human–machine operations can be included in the right work phases and that all work time is recorded in the effective work. Thus the reasons for the possible unsuitability of the automatic recordings for the process-data model should be clarified. Unforeseen situations that can confuse the automatic recording of effective time consumption are described for each level 1 work phase (see Figure 10) below:

1. Grasping the stem: Automatic recording can record removal of undergrowth correctly into the work phase when the harvester head is swung towards the tree and the tree is removed by fell cut. It is also possible that the removal of undergrowth is conducted by pressing or dragging the tree using the harvester head without a felling cut. In these cases the operations are not registered correctly. Also a pre-felled tree can cause confusion for time consumption in grasping the stem and stem felling because the felling cut is made beforehand. If the tree to be felled is too branchy, the butt of the tree must be delimbed before the felling cut. This operation should be included in grasping the stem because it is preparation for felling.
2. Stem felling: When the felling cut of a tree with an oversized diameter has to be repeated several times the tree has as many durations of felling cuts. It is also possible to fell several trees consecutively and then process them, which does not follow the ideal work cycle. After the felling cut and before stem feeding, the damage to the butt of the tree must be removed by sawing off a short piece, and this operation should be included in the stem processing work phase.
3. Stem processing: Several operations that might occur during stem processing can confuse the division of time consumption. The stem can break during felling whereupon a small piece must be cut from the first log. Furthermore a twig-tree must be separated into two stems by a new felling cut. During cross-cutting the first cut might not suffice, leading to several cutting times. In a case where the top of a stem or a whole undergrowth tree is fed

through the harvester head and the diameter is too small for a mercantile log the wrong work time is recorded into stem processing, because there is no output (m^3). Sometimes stem feeding is conducted by using only boom movement without using feed rollers whereupon the feeding time and the length of the stem cannot be recorded. The ending point of stem processing has two alternatives: 1) the final cross-cut of the stem or 2) the harvester head is lifted into an upright position – which is a matter of collective agreement.

2.4.3 Materials and methods for the adjustment of the process-data model

Case study

In Study IV, the results of the work phase analysis and the adjustment of the process-data model are based on the study materials collected in a previous time study (Väätäinen et al. 2005), wherein automatic and manual timing were examined in a case study. Automatic timing was conducted using a data logger as a recording device. Manual timing was conducted by a human being as an observer using a handheld field computer.

The experiments of the case study were conducted by a Timberjack 1070 C single grip harvester equipped with Timbermatic 300 measurement and information system in November and December 2002 in north-eastern Finland. For the study, six professional harvester operators were chosen. Theis cutting experience on a Timberjack single grip harvester varied from 2 to 10 years (operator A, B. C, D, E and F had 2, 10, 6, 10, 3 and 10 years of experience, respectively). The variability of the harvesting conditions in the study stands was minimised: the terrain of the stand had to be flat and the tree size, structure of tree species and stem density had to be as even as possible. Time study plots of 45 or 60 minutes of effective operating time were assigned to all operators. Six time study plots from the two first thinning stands and respectively three time study plots from one clear-cutting stand were selected for each operator. The total amount of harvested commercial stems in the thinning stands was 3298 and in clear-cut stands 705. In Scots pine (*Pinus sylvesteris*) dominated first thinning stands the average initial stem size was 0.126 m^3 and in Norway spruce (*Picea abies*) dominated clear-cut stand 0.530 m^3 respectively.

In the case study, the operators' performance was simultaneously observed and timed manually by a field computer and automatically by a PlusCan data logger for each processed tree. The PlusCan data logger recorded detailed information of the harvester operations, such as stem dimensions and time consumptions of harvester functions and movements. Two experienced researchers conducted the manual timing. For the manual timing continious timing method was used in which work phases were recorded using a Rufco-900 fieldwork computer. The time consumption was measured with an accuracy of a tenth of a second by the field computer and data logger alike. The study included also operators' work tehnique observation and eye focusing –study.

The adjustment of the process-data model

To modify the original process-data model (Figure 10) three tests were performed using principal component analysis. In the analysis, six time study plots from two first thinning stands of the case study (Väätäinen et al. 2005) were used for each operator. To identify the allocations of the work phases within an improved process-data model the final data to be analyzed was filtered and harmonized from the base data. In the tests, the work phases of the harvester's work for a total of 1776 stems were analysed. The tests included the following research questions:

Test 1) How does the process-data model describe the automatically recorded time phases?

Test 2) Which time phases that were recorded manually can be added into the original process-data model?

Test 3) What aspects of the process-data model should be improved based on the answers to research questions 1 and 2?

In the first test, automatic recording followed the steps of the work cycle without including the pause work phases that are included in the process–data model in Figure 10, and the definitions of the work phases are described in Table 4. The test concentrated to examine the activities during the processing phase. The level 1 work phases were grasping the stem, felling, and processing. Total processing time included driving, sawing, and boom use. Simultaneous driving and using the boom during processing were also included in the total processing time.

In the second manual recording test, the observer followed the steps of the work cycle presented in Figure 11. Test 2 examined all three level 1 work phases (gripping the stem, felling and processing). The definitions of these work phases are presented in Table 3. The extend the boom and grasp, felling, felling and bunching, and processing phases were defined as the main work phases repeated for each tree. Bringing the top to the strip road was also main work phase because it's duration was focused on the processed trees, although it was not conducted on all trees. The moving forward, moving backward, clearing, bunching logs, piling of slash, and positioning the boom forward phases were complementary work phases that were not conducted on each processed tree. In the manual time study, the time for each of these work phases was recorded separately.

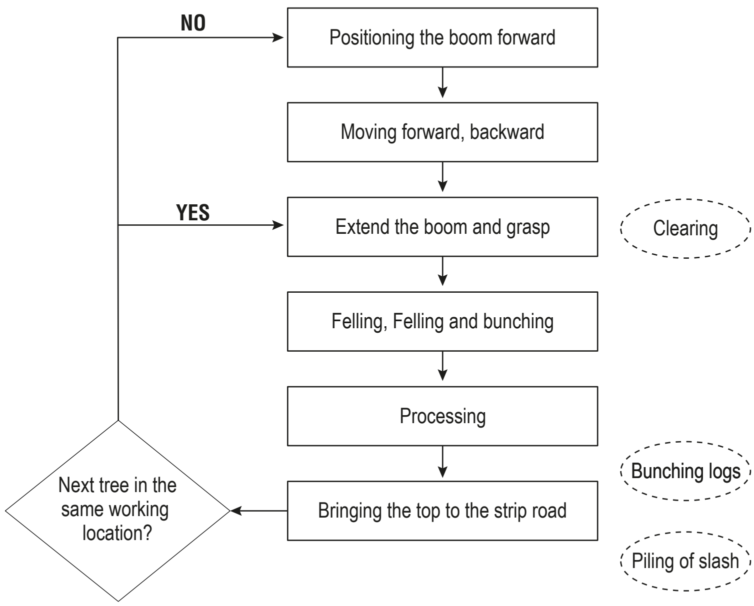


Figure 11. Flow chart for work phases describing the manually recorded work cycle.

Table 3. Divisions of time phases used for manual recording.

Work phase	Definition
Moving forward	Begins when the harvester starts to move forward and ends when the harvester stops; was recorded when the harvester was driving, but not when the harvester was in motion during the felling or processing work phases.
Extend the boom and grasp	Starts when the boom began to swing toward a tree and ends when the chain saw began the felling cut; thus, this phase also includes positioning the harvester head at the base of the tree.
Felling	Starts when the felling cut begins and ends when the feeding and delimbing of the stem starts. Felling included the duration of boom movement while the head was holding a cut tree in order to move it to a processing site at a maximum distance of 3 m from the base of the tree.
Felling and bunching	This phase included the duration of felling the tree and moving the felled tree to a processing site located more than 3 m from the base of the tree.
Processing (delimbing and cross-cutting*)*	Started when the stem feeding began and ended when the operator lifted the harvester head to an upright position after the final cross-cut through the stem.
Clearing/ Clearing and positioning/ Clearing and felling	Removal of undergrowth and unmerchantable trees from around standing trees that must be felled. Clearing = total time consumption of clearing, Clearing and positioning = time consumption for boom movements of clearing, Clearing and felling = time consumption for felling cut of clearing.
Bunching logs	Gathering the logs into piles along the strip road.
Piling of slash	This work phase was recorded whenever slash was piled as a separate work phase (i.e., not as part of the processing phase).
Bringing the top to the strip road	Bringing unmerchantable tops of stems to the strip road after the final cut to produce the last log.
Moving backward	Begins when the harvester starts to move backward and ends when the harvester stops; was recorded when the harvester was driving, but not when the harvester was in motion during the felling or processing work phases.
Positioning the boom forward	This phase occurred when the operator moved the harvester head to the front of the machine before moving forward.

Table 4. Divisions of time phases used for automatic recording.

Work phase	Definition
Grasping the stem	Starts when the harvester or boom start to move and ends when the felling cut begins.
Felling	Begins when the felling cut starts and ends when the stem feeding starts.
Sawing during felling	Duration of the felling cut during felling.
Processing	Time from the start of feeding of the first log to ejection of the final log from the head.
Driving during processing	Harvester movement during the processing work phase.
Sawing during processing	Total time for cross-cutting the stem into logs.
Using the boom during felling and processing	Using the boom during the felling and processing phases but excluding moving.
Simultaneous driving and using the boom during processing	Using the boom at the same time as processing and moving.

The third test examined all three level 1 work phases (grasping the stem, felling, and processing) in the original process-data model. In the test 3 the automatic (test one) and manual timing (test two) data were combined to develop an improved process–data model of the harvester's work.

In the tests, principal component analysis was used to adjust the process-data model. This approach was used to reduce the variation contained in the measured variables into principal components that were not correlated with each other but that explained as much as possible of the overall variation. The principal components were linear expressions used to explain both the overall and individual variation. The three tests produced results that shed light on the research questions and examined all level 1 work phases of the process-data model.

Principal-component analysis calculates the values of the principal components from a correlation matrix. This calculation gives every variable a weight that reveals its position within and its impact on the overall work cycle. The component is also given an eigenvalue, which represents the relative proportion of the overall variation that a component can explain. For the analysis solutions that included components with an eigenvalue greater than 1 (Kaiser 1960) were chosen. This analysis used the Varimax rotation provided by the SPSS-X software (SPSS 1988) to minimise the number of variables with high loadings (i.e., high weights) for each factor, and thereby simplify interpretation of the factors.

3 RESULTS

3.1 The accuracy of manually recorded time study data for harvester operation shown via simulator screen (Study I)

3.1.1 The frequency of recorded work phases

The total number of recorded main work phases per observer did not clearly differ between each experience group; *students 15 min* recorded an average of 241 main work phases, *students 30 min* 241 phases and *researchers* 243 phases. In other words, the students failed to record two phases whereas the researchers managed to record all the main work phases during the recording period, on average. Furthermore, the number of main work phases in different time intervals for each group was similar.

However, there were clear differences between the experience groups when recording the complementary work phases. The total number of recorded complementary work phases per observer averaged 98 phases for the *researchers*, 93 phases for *students 30 min* and only 82 phases for *students 15 min*. *Students 15 min* recorded complementary work phases of 2 seconds and shorter (average 7.1 phases per observer), which was 44% less than the value of *researchers* (12.7). With phases of 4 seconds and shorter *students 15 min* averaged 35.3 complementary phases and *researchers* 53.9, which equalled a difference of 35% (Figure 12).

The major differences for complementary work phases were in reversing and positioning the boom forward. These differences were mainly in the short timings; in the reversing work phase of 4 seconds and shorter timings *students 15 min* recorded 42% less than *researchers* and in the positioning the boom forward work phase 53% less. Straight after the timing study the observers were asked which work phase they felt to be the most difficult to record; the responses were, in order of difficulty, positioning the boom forward and reversing. The observers made few error recordings by incorrect coding during the time study. On average, *students 15 min* made about 5 error recordings each, *students 30 min* 3 and *researchers* 1 error recording each during the study.

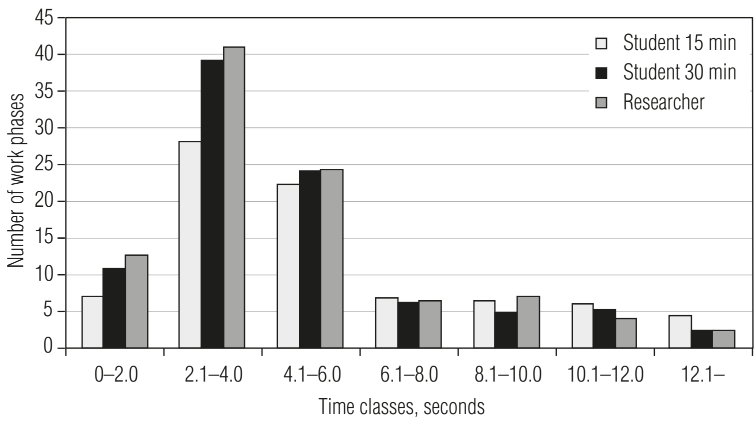


Figure 12. The frequency of recorded complementary work phases per observer between experience groups in time consumption classes during the 40 min time study.

3.1.2 The differences in structuring of work phases of observers

The average work phase timings between each group did not differ significantly (Figure 13). The biggest difference in the group averages was found in the timing of pause times (0.5 seconds/stem). However, the recordings of individual observers differed remarkably in many work phases. For example, in the main work phases, the ranges of observers' average timings were 7.6–11.6 seconds in extend the boom and grasp, 4.8–6.3 seconds in felling and 7.7–10.0 seconds in processing, and the maximum time difference was at its highest in the extend the boom and grasp work phase (34% difference).

The 95% confidence level of the individual observers' average recordings revealed significant variation between individual timings (Figure 13). It was notable that the confidence level decreased when experience level increased in most of the work phases. Furthermore, the confidence levels were surprisingly high in all the experience groups, especially in the extend the boom and grasp work phase.

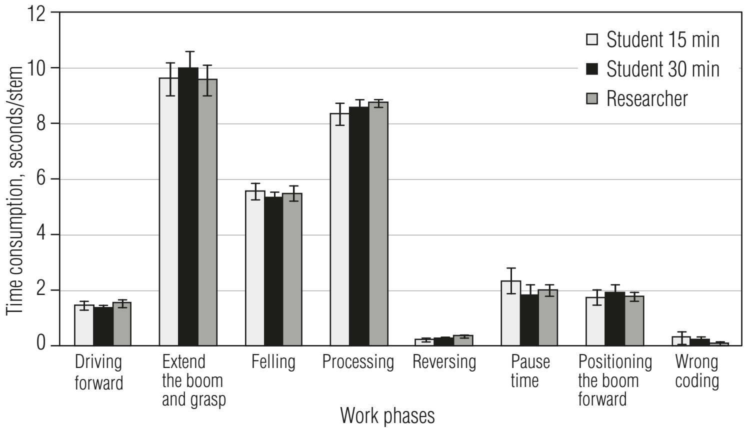


Figure 13. Average time consumption structure of work phases of observers among experience groups in the 40-minute time study. Line segments identify the 95% confidence levels of observers' average timing values in each experience group.

3.1.3 Measuring accuracy within experience groups

The comparison of the observers' recorded data and the PlusCan data logger's reference data revealed the observers' actual timing errors for both the felling and processing work phases for each measured stem. The reference value per stem, on average, was 5.75 seconds for felling and 9.10 seconds for processing. In the processing work phase 62% of the *researchers'* timing errors were within the error interval of ±0.5 seconds, while the value for *students 15 min* was 33% and for *students 30 min* 47%. The largest error average for an observer in the felling work phase was found in the group of *students 15 min*, where the difference was 17% less than the reference value. In the processing work phase the largest difference for an observer was 15% less than the reference value (in the group of *students 15 min*).

The experience level had no statistically significant influence on the measuring error averages of the observers in either the felling or processing work phases, when analyzing the influence with the mixed effects model (Tables 5 and 6). The significance values of the test for the effect of experience were 0.526 in felling and 0.215 in processing.

Table 5. The mixed effects model table for testing the influence of experience level on the average measuring errors of observers in the felling work phase. Dependent Variable: measuring error of felling.

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	Hypothesis	4.12	1	4.112	1.059	0.305
	Error	557.159	143.482	3.883(a)		
Work experience	Hypothesis	7.981	2	3.991	0.657	0.526
	Error	163.920	27	6.071(b)		
Stem value	Hypothesis	2.296	1	2.296	0.752	0.386
	Error	6688.240	2189	3.055(c)		
Work experience * researcher	Hypothesis	163.920	27	6.071	1.987	0.002
	Error	6688.240	2189	3.055(c)		

a) 0.274 MS(work experience * researcher) + 0.726 MS(Error)
b) MS(work experience * researcher)
c) MS(Error)

Table 6. The mixed effects model table for testing the influence of experience level on the average measuring errors of observers in the processing work phase. Dependent Variable: measuring error of processing.

Source		Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	Hypothesis	91.131	1	91.131	13.913	0.001
	Error	287.795	43.937	6.550(a)		
Work experience	Hypothesis	61.380	2	30.690	1.629	0.215
	Error	508.674	27	18.840(b)		
Stem value	Hypothesis	3.139	1	3.139	1.611	0.204
	Error	4674.293	2399	1.948(c)		
Work experience * researcher	Hypothesis	508.674	27	18.840	9.669	0.000
	Error	4674.293	2399	1.948(c)		

a) 0.272 MS(work experience * researcher) + 0.728 MS(Error)
b) MS(work experience * researcher)
c) MS(Error)

There were significant differences in the variances of observers' measurement errors between the groups of students and researchers (Table 7). In the case of felling, there was no significant difference in error variances between *students 15 min* vs. *students 30 min*, whereas the difference of error variance was significant for *students 15 min* vs. *researchers* and *students 30 min* vs. *researchers*. In the processing work phase the experience level had a statistically significant influence on error variances for all experience groups (Table 5).

Figure 14 presents the box-plot charts of the distribution of measurement errors for all experience groups in the felling and processing work phases. Unlike felling, in processing a clear reduction can be seen in the measurement error deviation when increasing the experience level. In the felling work phase, the average measurement error was very close to zero for all experience groups. In processing, the average measurement error for the *students 15 min* was –0.63 seconds, for the *students 30 min* –0.41 seconds and for the *researchers* –0.24 seconds. In processing, the standard deviations were 2.01 seconds for the students 15 min and 0.81 seconds for the *researchers*.

The observers' fatigue during the time study did not have any effect on the measurement error on the basis of the analysis of the research data, and also the error codes recorded by the observers had a minor effect on the measurement accuracy (Nuutinen 2005). Furthermore,

Table 7. The significance for the equality of the measuring error variances between experience groups. Work phases: felling and processing. Compared experience groups: 1 = student 15 min, 2 = student 30 min, 3 = researcher.

	Compared pairs (based on Mean)											
	1–2				1–3				2–3			
	Df1	Df2	Levene Statistic	Sig	Df1	Df2	Levene Statistic	Sig	Df1	Df2	Levene Statistic	Sig
Felling	1	1478	0.862	0.353	1	1478	9.963	0.002	1	1478	5.072	0.024
Processing	1	1618	7.331	0.007	1	1618	47.457	0.000	1	1618	37.063	0.000

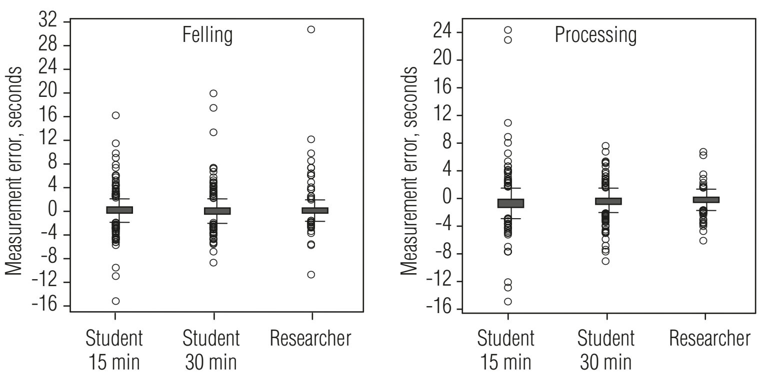


Figure 14. The box-plot charts of measurement errors in the felling and processing work phases in each experience group. Measurement error = measurement value recorded by observers – a value recorded by PlusCan data logger.

the effects of age, sex, playing of computer games and use of computer on measurement error were examined. The results found that these factors did not influence the results either (Nuutinen 2005).

3.2 Operational efficiency and damage to sawlogs by feed rollers of the harvester head (Study II)

3.2.1 Effective feeding time and fuel consumption

One purpose of Study II was to test the feeding time during processing and fuel consumption during feeding when using six different steel feed rollers. To this end, a highly detailed and accurate processing and fuel consumption projection was recorded using the harvester's automated data collector at a log and stem level.

Effective feeding time
The following model (Equation 1) was estimated for the natural logarithm of effective feeding time of each tree species:

$$\begin{aligned}\ln(\text{Effective feeding time}) &= \text{Intercept} + \text{Roller}_i + \text{Logs per stem}_j \\ &+ b_1 * \ln(\text{Mercantile stem volume}) + b_{2j} * \text{Logs per stem}_j * \ln(\text{Mercantile stem volume}) \\ &+ b_{3i} * \text{Roller}_i * \ln(\text{Mercantile stem volume}) + \varepsilon, \qquad (1)\end{aligned}$$

where

ln(Effective feeding time)	= natural logarithm of the effective feeding time
Roller_i	= roller type, i = 1, 2, 3, 4, 5, 6
Logs per stem_j	= the number of logs per stem, j = 1, 2, 3, 4
ln(Mercantile stem volume)	= natural logarithm of the mercantile stem volume
ε	= residual term.

It was assumed that the residuals are independent and normally distributed and their variance is homogenous. The statistical coefficients of Equation 1 are presented in Table 8.

Example regarding the combination of the estimated effective feeding time using Equation 1:

Roller	= big spike 2, Logs per stem = 3, Tree species = spruce
Mercantile stem volume	= 0.35 m^3
ln(Mercantile stem volume)	= -1.0498
ln(Effective feeding time)	= 2.363 + 0.028 +(-0.134) + [0.245 + 0.025 + 0.010] * -1.0498 = 1.9631
exp(1.9631)	= 7.12 seconds/stem

Figure 15 shows the estimated effective feeding time of spruce and birch. Due to the insufficient amount of data for pine (Table 2), estimated values of feeding time (Figure 15) and fuel consumption (Figure 16) per stem were not presented. Effective feeding time was mostly dependent on mercantile stem volume and secondly on the amount of logs per stem. The effective feeding times of pine and spruce did not differ significantly from each other; the average time consumption for the smallest one-log stems of 0.03 m^3 was less than 2 seconds, while for the biggest four-log stems of 0.8 m^3 it was 9–11 seconds per stem. For birch the estimated value of effective feeding time was clearly the longest, up to 13 seconds for the biggest four-log stems of 0.7 m^3 (Figure 15). For small stems of 0.05 m^3, when the amount of logs increased from 1 to 2, the effective feeding time increased the most, by about 60%. For

Table 8. Statistical information of the regression model (Equation 1) for effective feeding time, sec/stem. Dependent variable: natural logarithm of the effective feeding time. Independents: roller type and log amount per stem as categorical and natural logarithm of the mercantile stem volume as covariant variables. B = Regression coefficient. Sig. = significance for the coefficient or an effect.

Parameter	Pine			Birch			Spruce		
	N=521, R^2=0.919			N=1727, R^2=0.876			N=2203, R^2=0.905		
	B	Std. Error	Sig.	B	Std. Error	Sig.	B	Std. Error	Sig.
Intercept	2.397	0.038	0.000	2.694	0.049	0.000	2.363	0.026	0.000
Roller			0.322			0.000			0.001
[Roller=Big spike 1]	-0.072	0.066	0.274	-0.232	0.055	0.000	0.064	0.028	0.021
[Roller=Small spike 1]	0.042	0.048	0.382	-0.032	0.077	0.679	-0.018	0.033	0.577
[Roller=Big spike 2]	0.057	0.043	0.189	0.054	0.055	0.325	0.028	0.034	0.411
[Roller=Adaptable plate]	0.070	0.123	0.569	0.136	0.142	0.336	0.145	0.060	0.015
[Roller=Small spike 2]	0.057	0.048	0.242	-0.094	0.042	0.024	0.079	0.024	0.001
[Roller=V-type stud]	0[a]			0[a]			0[a]		
logs per stem			0.000			0.000			0.000
[logs per stem=1]	-1.323	0.134	0.000	-1.213	0.070	0.000	-0.907	0.061	0.000
[logs per stem=2]	-0.495	0.082	0.000	-0.725	0.063	0.000	-0.549	0.051	0.000
[logs per stem=3]	-0.138	0.052	0.008	-0.266	0.058	0.000	-0.134	0.038	0.000
[logs per stem=4]	0[a]			0[a]			0[a]		
ln(Mercantile stem volume)	0.265	0.032	0.000	0.418	0.037	0.000	0.245	0.019	0.000
*logs per stem * ln(Mercantile stem volume)*			0.000			0.000			0.000
[logs per stem=1] * ln(Mercantile stem volume)	-0.170	0.043	0.000	-0.193	0.040	0.000	-0.052	0.023	0.026
[logs per stem=2] * ln(Mercantile stem volume)	-0.071	0.039	0.069	-0.187	0.040	0.000	-0.077	0.025	0.002
[logs per stem=3] * ln(Mercantile stem volume)	-0.001	0.038	0.988	-0.104	0.041	0.010	0.025	0.025	0.330
[logs per stem=4] * ln(Mercantile stem volume)	0[a]			0[a]			0[a]		
*Roller * ln(Mercantile stem volume)*			0.225			0.000			0.000
[Roller=Big spike 1] * ln(Mercantile stem volume)	-0.017	0.034	0.619	-0.083	0.021	0.000	0.039	0.011	0.001
[Roller=Small spike 1] * ln(Mercantile stem volume)	0.023	0.031	0.468	-0.057	0.035	0.100	-0.002	0.013	0.862
[Roller=Big spike 2] * ln(Mercantile stem volume)	0.024	0.027	0.375	0.001	0.024	0.977	0.010	0.013	0.457
[Roller=Adaptable plate] * ln(Mercantile stem volume)	0.203	0.171	0.236	0.106	0.110	0.334	0.090	0.035	0.010
[Roller=Small spike 2] * ln(Mercantile stem volume)	0.040	0.026	0.126	-0.023	0.018	0.194	0.051	0.009	0.000
[Roller=V-type stud] * ln(Mercantile stem volume)	0[a]			0[a]			0[a]		

[a] This parameter is set to zero because it is redundant.

big birch stems of 0.65 m^3, when the amount of logs increased from 3 to 4, the increase was 25%, while for spruce the increase was 16% and for pine 15%.

The maximum difference between feed rollers in terms of effective feeding time, when comparing the minimum value to maximum value, was greatest in the case of birch: for small stems 29%, for medium stems 19% and for large stems 24%. For spruce, the difference was smallest and varied between 6–11%. The feed rollers also had a statistically significant influence on the effective feeding time averages of the rollers for birch and spruce (Table 8).

The effective feeding time differences between feed rollers will have a significant influence on the total cutting time: for medium stems, of mercantile volume 0.35 m^3, the range of differences between the maximum and minimum of the estimated effective feeding time per roller was 6–19%, which would increase the effective time consumption of cutting by 1–3%.

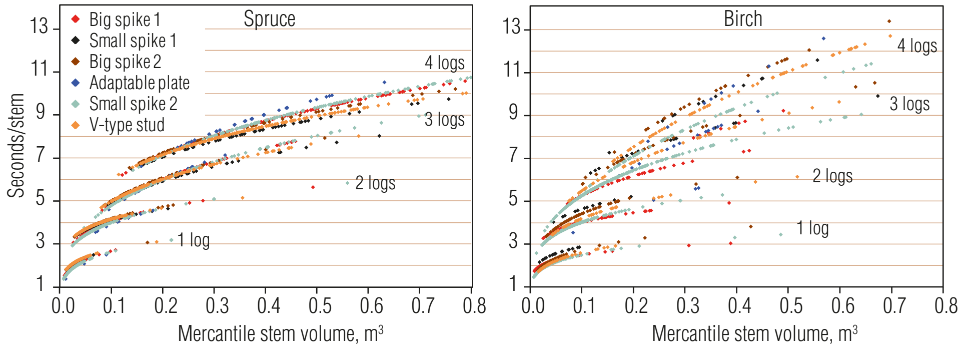


Figure 15. Estimated effective feeding time of spruce and birch (Equation 1).

Fuel consumption during processing

The following model (Equation 2) was estimated for the natural logarithm of fuel consumption during processing of each tree species:

$$\ln(\text{Fuel consumption during processing}) = \text{Intercept} + \text{Roller}_i + \text{Logs per stem}_j + b_1 * \ln(\text{Mercantile stem volume}) + b_{2j} * \text{Logs per stem}_j * \ln(\text{Mercantile stem volume}) + b_{3i} * \text{Roller}_i * \ln(\text{Mercantile stem volume}) + \varepsilon, \quad (2)$$

where

ln(Fuel consumption during processing) = natural logarithm of the fuel consumption during processing,
Roller_i = roller type, i = 1, 2, 3, 4, 5, 6
Logs per stem_j = the number of logs per stem, j = 1, 2, 3, 4
ln(Mercantile stem volume) = natural logarithm of the mercantile stem volume
ε = residual term.

It was assumed that the residuals are independent and normally distributed and their variance is homogenous. The statistical coefficients of Equation 2 are presented in Table 9.

Example regarding the combination of the estimated fuel consumption during processing using Equation 2:

Roller = big spike 2, Logs per stem = 3, Tree species: spruce
Mercantile stem volume = 0.35 m^3
ln(Mercantile stem volume) = -1.0498
ln(Fuel consumption during processing) = -2.438 + 0.071 +(-0.103) + [-0.665 + 0.034 + 0.023] · -1.0498 = -1.8317
exp(-1.8317) = 0.16 l/m^3

Figure 16 shows the estimated fuel consumption during processing of spruce and birch. Fuel consumption per processed stem was in the range of 0.1–0.6 l/m^3 depending on the mercantile stem volume. Fuel consumption of pine, birch and spruce starts to increase rapidly when the stem volume decreases under 0.2 m^3/stem. Birch had the highest fuel consumption level.

Table 9. Statistical information of regression model 2 for fuel consumption during processing, l/m³. Dependent variable: natural logarithm of the fuel consumption during processing. Independent variables: roller type and log amount per stem as fixed factors and natural logarithm of the mercantile stem volume as covariant. B = Regression coefficient. Sig. = significance for the coefficient or an effect.

Parameter	Pine N=503, R^2=0.913			Birch N=1685, R^2=0.830			Spruce N=2179, R^2=0.880		
	B	Std. Error	Sig.	B	Std. Error	Sig.	B	Std. Error	Sig.
Intercept	-2.491	0.040	0.000	-2.170	0.053	0.000	-2.438	0.027	0.000
Roller			0.472			0.014			0.088
[Roller=Big spike 1]	0.033	0.071	0.638	-0.111	0.059	0.059	0.001	0.029	0.975
[Roller=Small spike 1]	0.078	0.052	0.131	0.019	0.083	0.819	-0.021	0.034	0.535
[Roller=Big spike 2]	0.085	0.047	0.067	0.098	0.059	0.098	0.071	0.035	0.044
[Roller=Adaptable plate]	0.063	0.130	0.630	0.156	0.151	0.302	0.105	0.062	0.092
[Roller=Small spike 2]	0.090	0.052	0.086	-0.066	0.045	0.146	0.034	0.025	0.167
[Roller=V-type stud]	0[a]			0[a]			0[a]		
logs per stem			0.000			0.000			0.000
[logs per stem=1]	-1.316	0.143	0.000	-1.204	0.075	0.000	-0.869	0.064	0.000
[logs per stem=2]	-0.479	0.091	0.000	-0.633	0.069	0.000	-0.419	0.055	0.000
[logs per stem=3]	-0.135	0.056	0.016	-0.244	0.062	0.000	-0.103	0.040	0.010
[logs per stem=4]	0[a]			0[a]			0[a]		
ln(Mercantile stem volume)	-0.671	0.034	0.000	-0.488	0.040	0.000	-0.665	0.020	0.000
*logs per stem * ln(Mercantile stem volume)*			0.000			0.000			0.003
[logs per stem=1] * ln(Mercantile stem volume)	-0.189	0.046	0.000	-0.242	0.044	0.000	-0.055	0.024	0.025
[logs per stem=2] * ln(Mercantile stem volume)	-0.062	0.042	0.144	-0.186	0.044	0.000	-0.027	0.026	0.305
[logs per stem=3] * ln(Mercantile stem volume)	0.004	0.040	0.912	-0.113	0.044	0.011	0.034	0.027	0.198
[logs per stem=4] * ln(Mercantile stem volume)	0[a]			0[a]			0[a]		
*Roller * ln(Mercantile stem volume)*			0.029			0.277			0.000
[Roller=Big spike 1] * ln(Mercantile stem volume)	0.044	0.037	0.230	-0.017	0.023	0.451	0.028	0.012	0.017
[Roller=Small spike 1] * ln(Mercantile stem volume)	0.047	0.034	0.165	-0.012	0.038	0.753	0.000	0.013	0.997
[Roller=Big spike 2] * ln(Mercantile stem volume)	0.039	0.030	0.188	0.024	0.026	0.342	0.023	0.014	0.100
[Roller=Adaptable plate] * ln(Mercantile stem volume)	0.138	0.181	0.448	0.127	0.117	0.279	0.076	0.036	0.035
[Roller=Small spike 2] * ln(Mercantile stem volume)	0.088	0.029	0.002	0.015	0.019	0.440	0.053	0.009	0.000
[Roller=V-type stud] * ln(Mercantile stem volume)	0[a]			0[a]			0[a]		

[a] This parameter is set to zero because it is redundant.

The number of processed logs led to the greatest increase in fuel consumption per m³ in the case of the smallest stems. For small stems of 0.05 m³, when the number of logs increased from 1 to 2, the fuel consumption during processing increased at most by about 50%. For large birch stems of 0.65 m³, when the amount of logs increased from 3 to 4, the fuel consumption increase was 25%, while it was 13% for spruce and 15% for pine. There were significant differences also between the maximum and minimum fuel consumptions of the feed rollers' estimated consumption levels. Most of the time, fuel consumption increased simultaneously with the increase in effective feeding time: the slowest rollers had the highest fuel consumption. The maximum differences between the fuel consumption of the feed rollers, when comparing the minimum value to maximum value, were found for birch with a range of 15–25%, depending on the mercantile stem volume. The respective differences for pine were 6–30% and for spruce 7–12%. The feed rollers only had a statistically significant influence on the fuel consumption averages of the rollers during processing in the case of birch (Table 9).

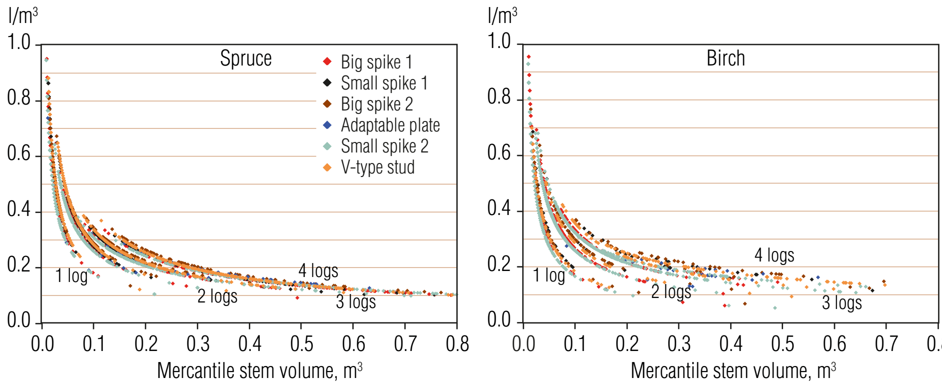


Figure 16. Estimated fuel consumption during processing of spruce and birch (Equation 2).

3.3 Productivity of a whole-tree bundler in energy wood and pulpwood harvesting from early thinnings (Study III)

In Study III, the productivity level and the performance characteristics of the second version of the whole-tree bundler (Fixteri II) were defined on the basis of the observations of two researchers, which they recorded by handheld field computers.

3.3.1 Distribution of effective work time

The division of the effective time into work phases was based on the observations of the second researcher (Figure 17). The proportion of the grapple work phase was 19%. The crane in work phase constituted 11% of the total E_0, while cross-cutting of the trees took 16% of the E_0. The combined proportion of bundling and dropping the bundle work phases was 13%, and moving took 5% of the E_0. Cutting (crane movements) simultaneously with the bundling phases took 21% of the E_0. The proportion of cutting simultaneously with cross-cutting the trees in the bundle unit was 13% and that of simultaneous moving and bundling was 2%.

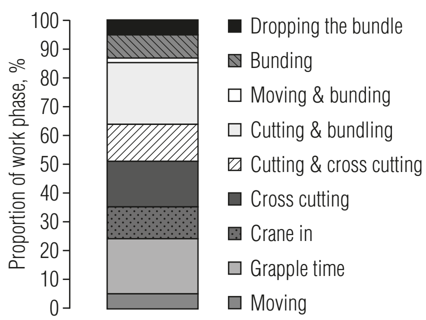


Figure 17. The average structure of work phases of effective (E_0) working time for the whole-tree bundler.

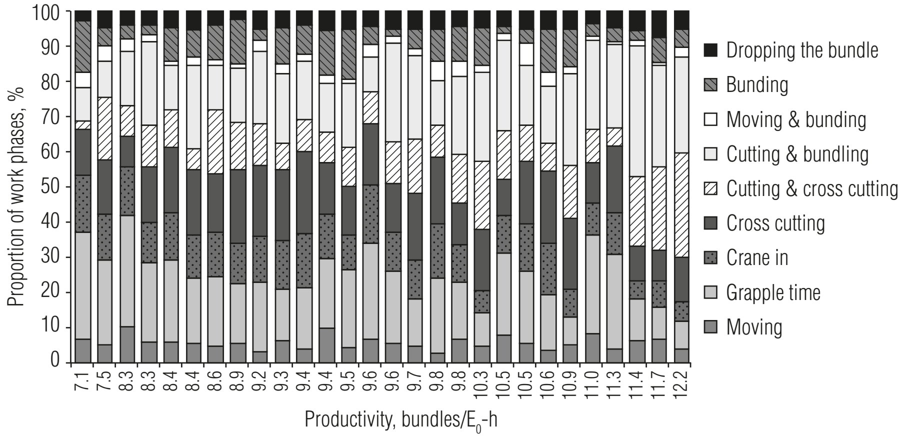


Figure 18. Time study plot of the relative time consumption for the work phases in whole-tree bundling.

The work phases that took place simultaneously accounted on average for 35% of the total E_0. An increase in the proportion of overlapping functions increased productivity as shown in Figure 18. When the proportion of overlapping work phases was lowest (16%), the productivity was at the minimum level (7 bundles per E_0-h). The highest productivity, 12 bundles per effective working hour, was reached when simultaneous functions peaked at 60% (Figure 18).

3.3.2 The time consumption models for whole-tree bundling

According to the observations of researcher I, the time consumption model of the whole-tree bundling was constructed as follows:

Moving
Moving time was dependent on the density of tree removal (Eq. 3). The moving time per processed tree decreased when the density of tree removal increased. In such cases it was possible to cut more trees from one working location:

$$t_1 = 0.074+3130.29 * 1/x \quad (3)$$

where

t_1 = moving between working locations, s/tree
x = the average density of removal, trees/ha
$r^2 = 0.46$

Cutting
The consumption of time for cutting (Eq. 4) was predicted based on the average volume of removal by plot:

$$t_2 = 1.044 * \ln(v - 4.999) + 9.027 * e^{0.007*v} \quad 4)$$

where

t_2 = the consumption of time for cutting, s/tree
v = the average volume of removed trees, dm^3
$r^2 = 0.51$

Bundle processing
The time consumption in bundle processing was modelled using the average volume of removal by plot as the independent variable (Eq. 5). The processing time per bundle increased as a function of the removal volume. When processing the smallest whole trees, it was possible to feed even two full grapple loads into the feeding chamber at the same time. On the other hand, tall trees had to be fed into the bundle unit one by one, resulting in an increase in the cross-cutting time:

$$t_3 = 0.154 * \ln(v - 4.999) + 3.227 * e^{0.022*v} \quad (5)$$

where

t_3 = the consumption of time for bundle processing, s/tree
v = the average volume of removed trees, dm3
$r^2 = 0.65$

The time consumption in the bundle processing work phase was dependent on the number of trees accumulated in the bundle. The number of trees per processed bundle was dependent on the average volume of the removed whole trees (Eq. 6):

$$n = 48.593 - 9.246 * \ln(v) \quad (6)$$

where

n = the number of processed whole trees per one bundle
v = the average volume of removed whole trees, dm^3
$r^2 = 0.64$

Total time consumption of whole-tree bundling
The total effective time per bundle was obtained by adding up the time consumptions of the work phases as follows (Eq. 7):

$$t_{tot} = (t_1 + t_2 + t_3) * n \quad (7)$$

where

t_{tot} = the total effective time consumption, s/bundle
t_1 = moving, s/tree
t_2 = cutting, s/tree
t_3 = bundle processing, s/tree
n = the number of whole trees per bundle

3.3.3 The model for bundle volume

The *solid content of the bundles* increased in line with the increase in the volume of removed whole trees. The bundle volume was therefore dependent on the average volume of cutting removal (Eq. 8, Figure 19):

$$v_b = 0.644 - (4.299 * 1/v) \tag{8}$$

where

v_b = the solid volume of the whole-tree bundle, m^3
v = the average volume of removed whole trees, dm^3
$r^2 = 0.37$

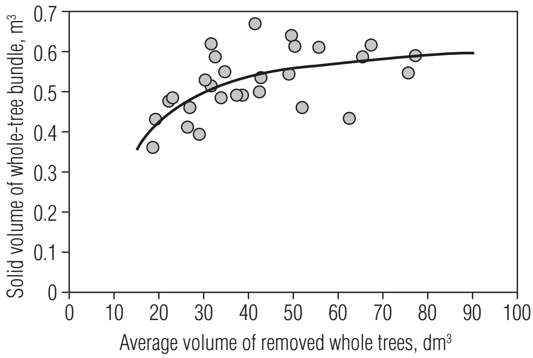


Figure 19. Size of a whole-tree bundle as a function of the average volume of removed whole trees by plot.

3.3.4 Productivity of whole-tree bundling

The effective time consumption was converted to E_0-h/m^3 productivity applying Equation 9. An increase in the average volume and the density of the removal increased the productivity of whole-tree bundling. When the average removal density was 1 000 trees per hectare and the volume of removal averaged 20 dm^3, the productivity of whole-tree bundling was 3.4 m^3/E_0-h and with an average removal of 75 dm^3 it was 6.1 m^3/E_0-h. When the density of removal rose to 3 000 trees per hectare, the productivities were 3.8 m^3/E_0-h and 6.4 m^3/E_0-h, respectively (Figure 20).

$$p_e = 3600 * (v_b/t_{tot}) \tag{9}$$

where

p_e = the effective hour productivity, m^3/E_0-h
v_b = the solid volume of a bundle, m^3
t_{tot} = the total effective time consumption for bundle harvesting, s/bundle

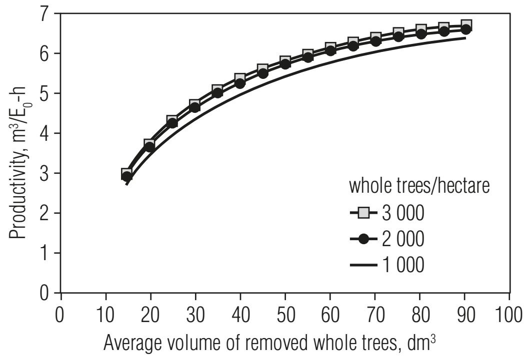
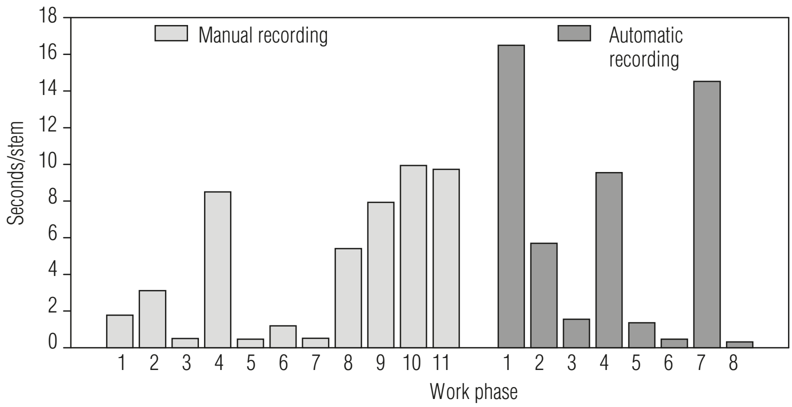


Figure 20. Productivity of whole-tree bundling as a function of the average volume of removed whole trees.

3.4 An automatic time study method for recording work phase times during timber harvesting (Study IV)

Figure 21 shows the recorded average time consumption structure of work phases of harvester's effective cutting time for automatic and manual recording in the case study (Väätäinen et al. 2005). The definitions of the work phases are described in Table 3 and 4.



Manual recording
1. Positioning the boom forward
2. Moving forward
3. Moving backward
4. Extend the boom and grasp
5. Clearing
6. Clearing and positioning
7. Clearing and felling
8. Felling
9. Felling and bunching
10. Processing (cross-cutting and delimbing)
11. Bringing the top to the strip road

Automatic recording
1. Grasping the stem
2. Felling
3. Sawing during felling
4. Processing
5. Sawing during processing
6. Driving during processing
7. Using the boom during felling and processing
8. Simultaneous driving and using the boom during processing

Figure 21. The average time consumption structure of work phases of harvester's effective cutting time for automatic and manual recording.

3.4.1 Automatically recorded time consumptions

In the first test, the work phases of the conventional process–data model (Figure 10) were examined, how they describe the automatically recorded work phases. Table 10 summarizes the principal components of these work phases in the improved process–data model. The overall work components in the actual automatic recording of the case study can be divided into grasping the stem, manual processing, and automatic processing. The principal components of automatic recording explained 71.2% of the overall variation (Table 10). The grasping the stem work component had only one separate work phase -grasping the stem- (see the definition in Table 4). This work phase was equivalent to the grasping the stem level 1 work phase of the original process-data model.

The manual and automatic processing components were not congruent with the level 1 work phases of the original process–data model (grasping the stem, felling, and processing). In addition, these work components included overlapping work phases: driving during processing, using the boom during felling and processing, and simultaneous driving and using the boom during processing.

The manual processing component was split into driving during processing, simultaneous driving and using the boom during processing, and felling. The work phases of the manual stem processing component occur due to the operator's decision making during the work, when the operator also decide the speed and the duration of the function (for example driving or moving the boom). The felling phase within the manual processing component was equivalent to the felling phase in the original process–data model. The simultaneous driving and using the boom during processing, and the driving during processing phases within the manual

Table 10. Results of the principal-components analysis of timber harvesting phases with automatic recording. A Varimax rotation with Kaiser normalization was used in the principal-components analysis (weights of less than 0.3 have been replaced with a weight of 0). The highest weightings are presented in boldface for each main component.

Variable	Component I	Component II	Component III	Communalities
Grasping the stem	0	0	**0.925**	0.859
Driving during processing	**0.924**	0	0	0.874
Using the boom during felling and processing	0.568	**0.651**	0	0.795
Simultaneous driving and using the boom during processing	**0.905**	0	0	0.826
Felling	**0.661**	0	0	0.528
Sawing during felling	0	**0.498**	-0.373	0.397
Sawing during processing	0	**0.813**	0	0.667
Processing	0	**0.859**	0	0.753
Eigenvalue	2.4	2.1	1.1	Total of components I to III
Proportion of the variation explained (%)	36.2	21.5	13.5	71.2

Interpretation of the principal components:
I Manual processing
II Automatic processing
III Grasping the stem

processing component were important variables in this analysis. However, these phases were not defined in the hierarchy level 3 of the original model because they included overlapping functions.

The automatic processing component was split into processing, using the boom during felling and processing, sawing during processing, and sawing during felling. The automatic stem processing component refers to the part of the semi-automatic work process, were the operator just makes harvester's function to be activated (for example stem feeding). The sawing during processing phase was equivalent to the cross-cutting phase in the original model. The using the boom during felling and processing phase occurs during the bunching level 3 phase of the original process-data model. However, the using the boom during felling and processing phase did not fit into the original model because it included time consumptions of simultaneous machine operations. Furthermore, the work phase overlapped with the manual processing component. The sawing during felling was equivalent to the felling cut phase of the original model, and it overlapped both the automatic processing and the grasping the stem components.

3.4.2 Manually recorded time consumptions

In the second test, the manually recorded components of time consumption were examined to determine whether they could be added in the original process–data model. Table 11 summarizes the principal components of these work phases. The components of manual recording explained 58.9% of the overall variation (Table 11). The level 1 work phases in the original model (grasping the stem, felling, and processing) were congruent with three of the components revealed in the manual recording (grasping the stem, felling and prosessing). However, clearing was revealed as an important additional work component. In the clearing component the principal-component analysis included clearing, clearing and positioning, and clearing and felling work phases of the manual recording (definitions of these work phases in Table 3). In level 2 of the original model, the moving and positioning phases included the same operations observed in the manual recording: moving forward and moving backward, and extend the boom and grasp. At the same level, the felling phase included the felling phase and the felling and bunching (> 3 m) phase. The processing level 1 phase in the original model included same operations revealed by the manual recording (cross-cutting and delimbing).

In the original model (Figure 10), the extend the boom and grasp phase in level 3 and the positioning phase in level 2 diverged from the positioning the boom forward phase of the manual recording (Figure 11, Table 3). This is because the positioning phase in the original model only includes boom movements to fell a tree, whereas in the manual recording, the positioning the boom forward phase was recorded separately when the operator steered the harvester head to the front of the machine before moving to the next working location. The principal-component analyses included this phase in the grasping the stem component (Table 11).

Table 11. Results of the principal-components analysis of timber harvesting with manual recordings. A Varimax rotation with Kaiser normalization was used in the principal-components analysis (weights of less than 0.2 have been replaced with a weight of 0). The highest weightings are presented in boldface for each main component.

	Component				
Variable	**I**	**II**	**III**	**IV**	**Communalities**
Moving forward	0	0	**0.788**	0	0.664
Extend the boom and grasp	0	0	0	**0.781**	0.615
Felling	0	**-0.921**	0	0	0.866
Cross-cutting and delimbing	0	0	0	**0.723**	0.539
Clearing	**.0765**	0	0	0	0.628
Bringing the top to the strip road	0	0	0	0.205	0.058
Moving backward	0	0	**0.612**	0	0.394
Positioning the boom forward	0	0	**0.752**	0	0.589
Felling and bunching (> 3 m)	0	**0.910**	0	0	0.862
Clearing and positioning	**0.862**	0	0	0	0.766
Clearing and felling	**0.708**	0	0	0	0.505
Eigenvalue	1.8	1.7	1.6	1.2	Total of components I to IV
Proportion of the variation explained (%)	17.1	15.6	14.7	11.5	58.9

Interpretation of the principal components:
I Clearing
II Felling
III Grasping the stem
IV Processing

3.4.3 Process-data model

In the third test, the changes required to improve the original process–data model based on the answers to research questions 1 and 2 were investigated. The potential work phases that could improve the model were identified by means of principal-components analysis (Table 12), which allowed to combine the important work phases from the manual and automatic recordings. The main work components were automatic processing, manual processing, clearing, grasping the stem, felling, positioning and arrangement of the products. These components of automatic and manual recording explained 72.8% of the overall variation (Table 12). The level 1 phases in the original model (grasping the stem, felling, and processing) were congruent with the main work components –grasping the stem, felling, and automatic processing- revealed by the principal-components analysis. The analysis revealed manual processing, clearing, positioning, and arrangement of the products as additional components.

In level 1 of the original model, the grasping the stem work phase included the extend the boom and grasp (manually recorded; M, hereafter), moving forward (M), and moving backward (M) phases. The positioning the boom forward (M) phase occurs before the harvester starts to move to the next working location. This phase could not be incorporated in the original model because the definition of positioning in the model only includes boom movements to fell a tree. In the improved model, it was included in the grasping the stem component. The bringing the top to the strip road (M) phase could be included inputted into the Other 2 phase under in level 3 of the original model. In the improved model, this work phase was under the arrangement of the products work component. Furthermore, the extend the boom and grasp the stem (M) work phase was included in the positioning work component.

Table 12. Results of the principal-components analysis of timber harvesting with both manual and automatic recording. Automatic recording is indicated with an "A" and manual recording is indicated with an "M". A Varimax rotation with Kaiser normalization was used in the principal-components analysis (weights of less than 0.3 have been replaced with a weight of 0). The highest weightings are presented in boldface for each main component.

Variables	Component							Communalities
	I	II	III	IV	V	VI	VII	
Moving forward, M	0	0	0	**0.793**	0	0	0	0.690
Extend the boom and grasp, M	0	0	0	0	0	**0.814**	0	0.699
Felling, M	0	0	0	0	**-0.950**	0	0	0.942
Cross-cutting and delimbing, M	**0.917**	0	0	0	0	0	0	0.849
Clearing, M	0	0	**0.714**	0	0	0	0	0.591
Bringing the top to the strip road, M	0	0	0	0	0	0	**0.977**	0.960
Moving backward, M	0	0	0	**0.540**	0	0	0	0.350
Positioning the boom forward, M	0	0	0	**0.649**	0	0	0	0.590
Felling and bunching (> 3 m), M	0	0.415	0	0	0.834	0	0	0.928
Clearing and positioning, M	0	0	**0.792**	0	0	0	0	0.682
Clearing and felling, M	0	0	**0.750**	0	0	0	0	0.587
Grasping the stem, A	0	0	0	**0.762**	0	0.397	0	0.812
Driving during processing, A	0	**0.897**	0	0	0	0	0	0.873
Using the boom during felling and processing, A	**0.575**	0.504	0.495	0	0	0	0	0.855
Simultaneous driving and using the boom during processing, A	0	**0.896**	0	0	0	0	0	0.834
Felling, A	0	**0.639**	0	0	0	0.502	0	0.685
Sawing during felling, A	0	0	**0.475**	0	0	0.313	0	0.421
Sawing during processing, A	**0.795**	0	0	0	0	0	0	0.636
Processing, A	**0.910**	0	0	0	0	0	0	0.843
Eigenvalue	2.8	2.5	2.3	2.1	1.7	1.5	1.1	Total of components I to VII
Proportion of the variation explained (%)	14.7	13.3	12.1	10.9	8.8	7.7	5.3	72.8

Interpretation of the principal components:
I Automatic processing
II Manual processing
III Clearing
IV Grasping the stem
V Felling
VI Positioning
VII Arrangement of the products

In the improved model, the felling component included the felling (M) work phase and the felling and bunching (M) work phase. On the other hand, the felling (A) phase was included in the manual processing component. The sawing during felling phase (A) was included in the felling cut phase of the original model, but in the improved model, it was included in the clearing component (Table 12). These results indicate different timing allocation between the manual and automatic recordings (see Tables 10 and 11). In the original model, the manually recorded clearing phase was included in the Other 1 phase. This was possible because in the model, the total grasping the stem time is usually calculated as the average value for the stems at each working location or for the whole stand. In the improved model, clearing

(M), clearing and positioning (M), and clearing and felling (M) were included in the clearing component. These results indicate a different hierarchical structure between the original and improved model. The improved model includes three hierarchy levels of work phases. The seven principal components are located in the highest level. The second level consists of work phases of automatic and manual recording, which time consumptions do not overlap. The third level includes overlapping work phases, which were recorded automatically (Table. 12).

In the improved model, the automatic and manual processing components systematically replace the processing level 1 phase of the original model. Therefore, the driving during processing (A) phase was included in the manual processing component and the sawing during processing (A) phase was included in the automatic processing component. Furthermore, the using the boom during felling and processing (A) was in the improved model in the automatic processing component, and simultaneous driving and using the boom during processing in the manual processing component.

4 DISCUSSION

The general objective of this thesis was to define the suitabilities of automatic and manual time study techniques to get a structured description of the functions of a harvester's work performance and thereby increase the understanding of a harvester's work process. This is most important when investigating factors affecting work productivity and collecting bases for cost calculations, payment of salaries and simulation studies. Time studies are often used to select the most suitable technology or working methods for forest operations. The time study method should be focused according to each study. Prior to the collecting of time study material the reliability of the selected timing technique should be always controlled beforehand.

Work studies in forestry are an important branch of work science (see Figure 1) and are applied to improve the productivity of harvester work. Ovaskainen (2009) states that the productivity of harvester work is based on three main factors: forest, harvester and operator. Time studies can be used to determine the influence of all these factors on increases in efficiency.

When the researcher is implementing the time study the selected timing technique and distribution of work time are important instruments in order to produce relevant time study results (see Figure 4). Without useful and reliable study data it is not possible to get answers to the research questions. Automatic timing collects the time consumptions of each work phase from the information flow in the harvester's CAN-bus channels while manual timing with a handheld field computer is based on the observer's visual monitoring.

Based on the results of Studies I-IV the usabilities of automatic and manual timing techniques and the process-data model are discussed from the following perspectives: 1) the distribution of work time, 2) stem and log level information, 3) other information in addition to working time, 4) accuracy and reliability of the measuring technique, 5) generalization of study results and 6) efficiency of recording. The results of Studies II and IV discuss the features of automatic recording in chapter 4.1. In chapter 4.2, the possibilities for manual timing are analyzed through Studies I, III and IV. The process-data model presented in Study IV is discussed in chapter 4.3. In chapter 4.4, the results of this thesis are compressed into three statements. Chapter 4.5 assesses this thesis and finally the directions for future research are presented in chapter 4.6.

4.1 Automatic recording

Based on the results of Studies II and IV there is no doubt that automatic recording enables the collection of larger amounts of time study materials with lower costs than visual observation using a handheld field computer. In Study II, the TimberLink monitoring system enabled the collection of a highly detailed and accurate processing and fuel consumption projection with six different steel feed rollers and 7400 studied stems in six field days. After filtering and harmonizing the base data to ensure the reliability of the time and fuel consumption models the final data consisted of 4451 stems for effective feeding, and 4367 stems for fuel consumption (see Table 2). The time study material of Study II was large enough to reveal the importance of improving the cost and energy efficiency of the harvester's stem feeding work phase. Furthermore in Study II, the data was sufficient to determine the differences between the studied feed rollers in fuel consumption and feeding speed. The automatic time study method for recording timber harvesting work – developed in Study IV – enables the recording of the most important work phases from large amounts of time study materials.

These results are in accordance with the conclusions made by Palander et al. (2012), who automatically recorded over fifty work study variables and used computerized data mining to select the most important work conditions and work phases. Also in the study of Kariniemi (2006), substantial amounts of time study materials were collected by digital data gathering. The base data of the study consisted of 13 harvester operators working in 69 study stands in which removal amounted to 3217 m^3 and 24773 stems.

Automatic recording enables the analysis of highly detailed and overlapping harvester functions at the stem and log level. In the experiment of Study IV, the performance levels of six harvester operators were observed and timed for each processed tree using automatic and manual timing. When conducting the manual time study using a handheld field computer, the time per each work phase was recorded separately (see Figure 11 and Table 3). For example, for the stem processing work phase, manual timing was accurate enough to produce the time consumption, excluding pause times per each processed stem. To obtain a more detailed projection of the stem processing work phase, automatic timing was necessary. Automatic timing enabled splitting the processing time of each stem into smaller subphases. Moreover, automatic timing enabled the measurement of work phases that can overlap to varying degrees, such as the work phase simultaneous driving and using the boom during processing (Table 4) and the work phase using the boom during felling and processing (Table 10). In the studies of Väätäinen et al. (2003), Väätäinen et al. (2005), Kariniemi (2006) and Ovaskainen (2009) the overlapping durations of simultaneous operations were important indicators for the operators' performance levels and motor-sensory abilities. The overlapping operations could also be used for identifying the human factors that influence the performance of a human-machine system (Palander et al. 2012). Therefore, in the future the proportion of simultaneous and overlapping functions should be taken more carefully into account.

Using automatic recording the impact of the cutting environment on productivity can be explained. Väätäinen et al. (2005) recorded the grasping the stem work phase using the PlusCan data logger (Study IV). The work phase included boom movements in order to fell a tree and harvester moving between working locations (Table 4), which can be used to describe the effect of working conditions. For example, the duration of grasping the stem per processed tree increases when the terrain is difficult to move on or when the density of removed trees is low.

Automatic recording makes it possible to exclude the operator effect from the harvester's time consumption; e.g. in Study II, using the TimberLink software the effective feeding time was split from the time consumption of total stem processing. Effective feeding is the pure feeding time excluding pause and cutting times. In Study II, the effective feeding time was used to study and compare the efficiency of the feed rollers without the operator effect. This was necessary due to the well-known fact that the operator, machine and environment have a substantial influence on the general work output, particularly in mechanized loggings (Väätäinen et al. 2005, Kariniemi 2006, Ovaskainen 2009, Palander 2012). Excluding the operator effect using the automatic recording technique is possible only for such work phases were the operator just make the function activated, like stem feeding. However, this is not possible for such operations like driving or moving the boom, where operator also decide the speed of the function.

Automatic recording offers more possibilities for multidisciplinary research, which improves productivity, machine development, ergonomics and education of operators: Studies II and IV were examples where the time consumptions of automatic timing were combined with work time information on other machine functions at the stem and log level. The time study data of Study IV recorded by the PlusCan data logger included the dimensions, volumes and time consumptions of each processed stem. This gave the possibility to compare each subphase of the processing work phase in different stem sizes between the operators. Furthermore in Study IV, the stem-level timings of manual and automatic recording were combined in the same matrix with the stem dimensions measured by automatic recording. In this case the time study material of manual recording – which also included operators' working technique observations – strengthened the results of automatic timing. In Study II, the TimberLink monitoring system recorded processing time, fuel consumption and volumes and dimensions for each stem and log. This data was used to study the influence of the feed rollers on the feeding speed and energy efficiency of the stem processing work phase.

There are also a number of other studies that have utilized automatic recording to combine time consumptions with other information: Tikkanen et al. (2008) measured a harvester's fuel consumption during processing by TimberLink whereas McDonald and Fulton (2005) recorded GPS information on moving distances and working locations during grasping the stem. Also soil bearability indicators have been measured and combined with the working location and time (Asikainen et al. 2011). Furthermore, some experiments have shown that process data can provide useful feedback in operator training or to support the operators in decision making concerning stem processing during work cycles (Palmroth 2011, Palander et al. 2012).

The repeatability of automatic timing increases the possibility to obtain more generalized study results. In Study II, the experiment could be repeated by recording the time and fuel consumption projection of the studied feed rollers using the TimberLink software. Using the same study method with different stem dimensions, tree species proportions and harvester types would give more generalized results about the feed roller effect. Study IV confirmed that repeating the experiment with automatic recording using the adjusted process-data model is a highly promising means of improving data recoding accuracy (Table 12).

The unforeseen situations presented in Study IV deviating from "normal" work procedures (see Figure 9) can lead to difficulties in identifying the machine operations, especially when using the automatic recording of time data. In Study I, a video technique was used to test the accuracy and reliability of the PlusCan data logger for the felling and processing work phases. The test revealed that if the felling cut of a tree with an oversized diameter has to be repeated several times, this will lead to confusion during the timing of the felling work phase. Furthermore the current automatic recording technique cannot detect the causes of delays; however, the operator can input a numeric code for each delay type during the work.

The calibration of automatic recording equipment, likewise in manual recording, is important to control the reliability of recorded study material. One way to test the accuracy of timing equipment is to record the right reference values for the durations of work phases by video recording. For example, in Study I, the videorecording test revealed systematic measuring error in durations of felling work phase of automatic recording. Furthermore, Rieppo and Örn (2003) tested fuel consumptions of 20 forwarders and 14 single-grip harvesters by a fuel consumption gauge, and also by manual measurement of the filled fuel volumes. The study aimed to develop the fuel consumption measuring technique of forest machines and timber trucks.

As recent advanced studies have suggested, the entire data collection phase, including the transfer of data for further analysis, can be automated using tools such as TimberLink (Kariniemi 2006, Palander et al. 2012). This strength of automatic timing increases the possibilities of work studies. An automatic time study is an effective means of recording large amounts of materials to obtain a comprehensive picture of the work . Highly detailed projection of harvester work enabling the recording of remarkably short and overlapping work phases combined with other information offers a multidimensional picture of harvester work. This is necessary for technical machine development and to achieve a better understanding of the structure of human-machine work. However, there are still unexpected situations that can confuse automatic time study projection.

4.2 Manual recording

The results of Studies III and IV revealed that a human being was able to observe visually and flexibly and record some unexpected operations at the logging site that could not be detected by automatic timing. These harvester functions often occur in situations and conditions on the logging site that deviate from the normal work cycle (see Figure 9) and as such cannot be registered automatically, as was also noted by Peltola 2003 and Väätäinen et al. 2003. Study III was an example of testing a new prototype – a bundle harvester – where manual recording was necessary to define the productivity of the prototype and to identify the bottlenecks of the whole work process. First of all, no automated data recording technique was available for the bundle harvester. Traditional observing and recording by field computer or video recording were the possible alternatives to collect the time study material. Recording by field computer proved to be the only feasible timing technique because the video could not capture all the harvester functions.

In the field experiment of Study III the presence of two observers was necessary because the boom movements of the bundle harvester overlapped with the moving and bundling work phases and respectively moving could occur simultaneously with bundling (Figure 8). Both observers are professional work study researchers and have several years' work experience on time studies on mechanical logging (Nuutinen et al. 2008). Another researcher (researcher I) concentrated on recording the work cycles for the time consumption models of bundle harvesting. For constructing the parameters for the time consumption models it was necessary for researcher I to record regularly repeated cycle-phases without overlapping functions (Olsen et al. 1998, Spinelli et al. 2010). When researcher I recorded the working process, the crane functions had the highest priority, and the moving and bundling work phases were next in priority, respectively. In other words, during crane functions (work phases crane out (2), fell (3), crane in (4) and feed (5)), the other simultaneous functions were not recorded. By following this priority in the time study the time consumption model of cutting (Equation 4) predicted the real crane cycle time. Respectively Cuchet et al. (2004) and Röser et al. (2012) took the same approach as in Study III. They devised a priority list of work phases based on their study goals, attributing the time spent on two concurrent functions to one of them. However, in some cases one single observer can appropriately code the most frequent combinations of overlapping functions and then record them just as any other separate work phases.

The second important aim for Study III, in addition to defining the productivity, was to identify the bottlenecks of whole-tree bundling for further machine development. For that reason it was vital for the researchers to monitor the work performance and have discussions with the operator during the experiment to get a visual picture of the work performance. To interpret the time study results the researchers studied carefully the work cycles in order to plan the work phase classification for the time study. In order to find the essential reasons in explaining the increase in productivity between the prototypes Fixteri I and II it was necessary for the same researchers to act as observers in both time studies.

When a bundle harvester is performing its work, certain functions occurred that deviated from the regularly repeating work cycle (Study III). In order to be recorded correctly, these functions had to be visually observed by a human being. These work phases were: sorting the felled trees on the ground (9), clearing the undergrowth (10) and delays (11) (Figure 8). Furthermore, the recording of the fell work phase (3) would not be possible without the presence of a researcher. During the fell work phase, researcher I recorded the time consumption of cutting and accumulating each tree, and the number of cut trees in each grapple bunch.

However, it is a common situation that time and motion studies are conducted for new machine concepts and prototypes without automatic recording possibility. Also in these cases a highly detailed projection of machine work would be occasionally important to develop the technology and working methods. For that purpose video-recording can be used. For example, Väätäinen et al. (2005) conducted micro-motional time and motion study by recording harvester operators' eye focusing during cutting using a helmet video-camera. However, especially in thinning stands video camera can not catch all the harvester's functions because the standing trees are diminishing the visibilty. Furhermore during the experiments of Väätäinen et al. (2005) the operators were asked questions in real time about their working technique and these results were combined with the video-recording observations. Technically it is possible to use extra data loggers mounted to harvester which register for example boom movements but in some cases this can be a matter of too high costs.

Study IV presented functions deviating from the harvester's "normal" so-called ideal cutting cycle (Figure 9) where observation by a human being is still needed. Mostly these situations are harvester functions caused by an exceptional cutting environment: dense undergrowth that must be removed around a standing tree that has to be felled, branchy trees that need extra delimbing before the felling cut, trees with an oversized diameter requiring several felling cuts or stem damage that must be removed with a short cut. However, by means of recent data mining techniques such exceptional work phases can also be recognized based on additional data processing, e.g. recognizing the crane position, movement segments, etc.

The important finding of Study I was that the accuracy of manual timing is considerably limited when recording stem-level durations that include remarkably short operations in the case of observers of all experience levels. For example, the most experienced researchers' measurement error per stem in the processing work phase was -0.2443 seconds on average (Figure 14), which can be explained by factors such as reaction time, interpretation of time phases and level of accuracy, all of which are personal characteristics. Furthermore, in the processing work phase 62% of the experienced researchers' timing errors were within the error interval ±0.5 seconds. This means that 38% of the error interval was greater than ±0.5 seconds per stem.

If such differences can be revealed in the restricted and uniform conditions used in Study I, it can be assumed that these variations are more significant out in the field. For example, Väätäinen et al. (2003) compared manual time study data recorded by field computer to automated data logger recordings in a time study of a single-grip harvester operating in an actual forest. The average manual measurement error per stem in the processing work phase increased by 0.367 seconds (2.5 times) per stem compared to Study I. These differences should be taken into account when planning the use of different data collection methods.

The results of Study I concerning the timing capability of a human being indicate that especially stem level work phases of short duration – maximum 3-5 seconds – are difficult to record by field computers. Also the recording of complementary work phases (like reversing and positioning the boom forward) whose duration is 4 seconds and shorter was too inaccurate, especially for inexperienced observers, despite the careful training before the time study (Figure 12). Also for the experienced researchers the rate of measuring errors of more than 0.5 seconds was significant. If such short elements are to be analyzed, especially at the stem and log level, automated data collection should be used.

The results of Study I indicate that observers' skills and experience seem to affect measurement accuracy in manual time studies and thereby the derived results in the case of intensive time studies on harvester operations. The results revealed that time studies made by the experienced researchers were more reliable. The variance of measurement error was smaller for researchers than inexperienced students. However, there was wide variation in accuracy between observers in all experience groups studied. Not only among students, but also among professional researchers, observers had systematic differences in the actual moments of recording. In Study III, measuring of overlapping operations with a handheld field computer proved to be a challenging task because the simultaneity of different time operations required the presence of two observers. Therefore, the observers should receive detailed training and gain practical experience of timing different work phases in forest operations.

It must be noted that safety while performing a time study is the most important consideration, as in all work. Harvester manufacturers define the safe area as being 75 m from the harvester during the work. During manual time study the observers must often stay (especially in thinning stands) inside the risk zone to be able to record the harvester's functions. This involves a risk of serious accidents for the observer, e.g. a 'chain bullet' shot by the broken chain saw of the harvester.

The presence of a researcher has been required to detect unexpected working situations on the logging site. The visual and flexible observation of a human being will probably still be needed in the future because including visual observations recorded manually in the results of automatic timing improves the reliability of the analysis and interpretation of results. However, a manual time study can no longer produce enough detailed and diverse information for the development of harvesters and their work methods.

4.3 Adjusted process-data model

The most important finding of this thesis is for cut-to-length systems, the adjusted version of the process-data model of Kariniemi and Vartiamäki (2010) (Figure 10). The new model for harvesterwork is presented in Figure 22. The proposed model is based on the principal components analysis of Study IV (Table 12), which combines the work phases from the automatic and manual timings of the case study. The results revealed that the components of combined data provided by automatic and manual timing explained the proportion of 72.8% of the overall variation. The new model consists of main work components (level 1), work phases (level 2) and overlapping work phases (level 3) which are defined in Table 13. The level two work phases are recorded separately, which means that the time consumptions do not overlap. The level three overlapping work phases include time consumptions of simultaneous machine operations. In the model, the level one main work components are build up from the durations of the work phases in level two and three. The main work components are identical to the main work components of the principal components analysis of Study IV (Table 12). The model is independent of the timing technique and its hierarchic structure enables the model to be adjusted depending on the theme of research. In the model, the positioning main work component can be recorded separately or it can be included into the the grasping the stem main work component. The main work components of the model are valid only for automatic and manual timings of Study IV. For that reason for advanced work study techniques it is necessary to adjust the process-data model to local work conditions using the automatic time study method of Study IV (Table 12).

In Study IV, the automatic time study method recorded the durations of using the boom during felling and processing, driving during processing and simultaneous driving and using

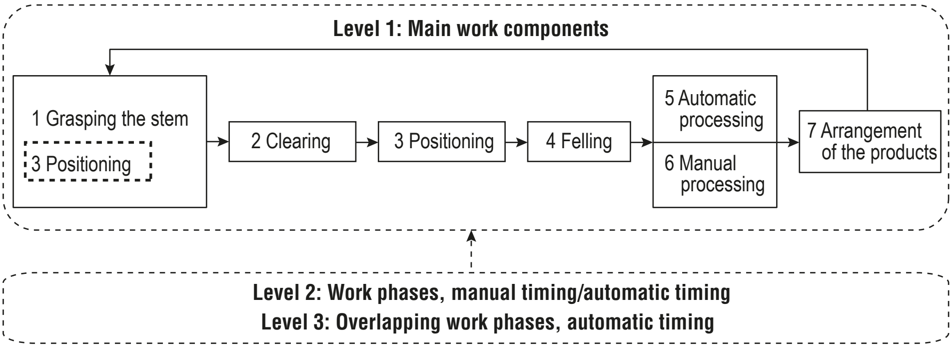


Figure 22. Flow chart for adjusted process-data model describing the relationships between the different time phases in harvesterwork.

the boom during processing (Table 4). The overlapping operations of these work phases could not be included in the original process-data model. A reason for this was that the work phases of the process-data model are constructed separately for use in modelling studies (Olsen et al. 1998, Spinelli et al. 2010) aimed at determining the relationships between time consumption and work condition parameters, which require the work cycle in the time study to be constructed of regularly repeating cycle-phases without overlapping subphases. It is a challenge to produce time consumption information in a consistent format using different data collecting techniques . The new process-data model is based on a more systematic and clear hierarchical structure of the work phases, which can account for both separate and overlapping work phases (Tables 12 and 13).

An advantage of the adjusted process-data model is that it enables the combinations of the information obtained using automatic and manual recording. One concrete theme is the analysis of delays, which are recognized as being one of the major factors that limit productivity and are, therefore, an integral part of most time studies (e.g. Spinelli and Visser 2008). Using the division of work time in accordance with the original process-data model (Figure 10), pause times can be recorded by a handheld field computer and these results can then be combined into an adjusted process-data model as new work phases. It must be noted that the use of this data mining and manipulation process can compromise the accuracy of the data. Results may be biased by additional data. Furthermore, automatically recorded pause time work phases can be assigned to the hierarchy of the adjusted process-data model. It is also possible to calculate times for the combined work phase by increasing the pause work phase to an effective work phase. In time studies, pause times are often eliminated as useless time consumption (Introduction to… 1992, Forest Work…1995, Groover 2007). However, it is important to consider these work phases in order to understand the harvester operators' abilities (Hidaka et al. 2006, Kariniemi 2006).

As Table 12 shows, the duration of using the boom during felling and processing indicated the existence of overlapping and simultaneous work phases. This finding also confirms the results of Väätäinen et al. (2005), Kariniemi (2006) and Ovaskainen (2009). In these studies the overlapping durations of simultaneous work phases were important indicators for explaining the operators' performance levels and motor-sensory abilities. The simultaneous work phases could also be used for identifying the human factors that influence the performance of a human-machine system (Palander et al. 2012). Therefore, in the future the proportion of simultaneous

Table 13. Divisions and definitions of time phases used adjusted in process-data model.

	1 Grasping the stem	2 Clearing	3 Positioning	4 Felling	5 Automatic processing	6 Manual processing	7 Arrangement of the products
Level 1: Main work components	Moving between working locations and using the boom. Start: final cross-cut of the previous stem. End: felling cut of the next tree or clearing begins.	Removal of undergrowth from around standing trees that must be felled. Start: boom starts to swing toward undergrowth. End: head is ready for next merchantable tree.	Boom movements in order to fell a tree. Can be included also into *Grasping the stem*. Start: boom starts to swing toward a tree to be felled. End: felling cut of a tree begins.	Start: felling cut begins. End: stem processing starts.	Includes semi-automatic functions, were the operator makes harvester's function to be activated. Start: stem feeding starts. End: ejection of the final log.	Operator decides speed and duration of harvester's function. Start: stem feeding starts. End: ejection of the final log.	Bunching and sorting logs, and moving tops and branches. Start: boom starts to move. End: head is ready for next tree.
Level 2: Work phases, manual timing	**Moving forward**	**Clearing**	**Extend the boom and grasp**	**Felling**	**Processing (cross-cutting and delimbing)**		**Bringing the top to the strip road**
	Start: harvester starts to move End: harvester stops.	Total time consumption for the removal of undergrowth. Start: boom starts to move. End: head is ready for next tree.	Start: boom starts to swing toward a tree to be felled. End: felling cut of a tree begins.	Felling the tree and moving the tree maximum 3 m from the base of the tree. Start: felling cut begins. End: stem processing starts.	Start: stem feeding starts. End: ejection of the final log.		Bringing unmercantable tops of stems to the strip road. Start: final cross-cut of the last log. End: head is ready for next tree.
	Moving backward	**Clearing and positioning**		**Felling and bunching**			
	Start: harvester starts to move. End: harvester stops.	Includes boom movements for the removal of undergrowth. Start: boom starts to move. End: felling cut of unmerchantable tree begins.		Felling the tree and moving the tree more than 3 m from the base of the tree. Start: felling cut begins. End: stem processing starts.			
	Positioning the boom forward	**Clearing and felling**					
	Moving the head to the front of the harvester. Start: final cross-cut of the previous stem. End: havester starts to move to the next working location.	Includes felling cut for the removal of undergrowth. Start: felling cut of unmerchantable tree begins. End: head is ready for next tree.					

Table 13. Continued.

	1 Grasping the stem	2 Clearing	3 Positioning	4 Felling	5 Automatic processing	6 Manual processing	7 Arrangement of the products
Level 2: Work phases, automatic timing	**Grasping the stem**			**Felling**	**Processing**		
	Start: final cross-cut of the previous stem. End: felling cut of the next tree begins.			Start: felling cut begins. End: stem processing starts.	Start: stem feeding starts. End: ejection of the final log.		
				Sawing during felling	**Sawing during processing**		
				Start: felling cut begins. End: felling cut ends.	Total time consumption for cross-cutting the stem into logs. Start: cross-cutting begins. End: cross- cutting ends.		
Level 3: Overlapping work phases, automatic timing					**Using the boom during felling and processing**	**Driving during processing**	
					Using the boom during the felling and processing phases but excluding moving.	Harvester movement during the processing work phase.	
						Simultaneous driving and using the boom during processing	
						Using the boom at the same time as processing and moving.	

work phases should be taken more carefully into account. However, measuring simultaneous phases with a handheld field computer is a challenging task because the simultaneity of different operations often requires the presence of two of more observers (Nuutinen et al. 2011). In this respect, an adjusted process data model makes it possible to conduct a highly detailed work cycle projection and increases the possibility to better understand the structure of human-machine work.

The rapid evolution of information technology can generate local adaptations of the process-data models in individual stands. If various time study methods can no longer be relied on to arrive at a mutual understanding, the adoption of the adjusted time study protocol (Figure 22) would prevent misunderstandings, both at the conceptual-theoretical and practical levels. It would also facilitate the production of internationally more comparable work-study reports. These suggestions are in accordance with recent methodological experiences gained from the adaptive control of a human-machine system in a study by Palander et al. (2012). The advantage of the adjusted process-data model is that it can be adapted to human-machine systems depending on the study subject or measuring technique.

4.4 Conclusion

The main goal of this thesis was to assess the suitabilities of automatic and manual time study in describing the functional steps of a single-grip harvester's work process. The results of Studies I-IV can be summarized in the following statements:

Firstly, the results of this thesis confirmed that in order to meet the challenges of harvesters' and operators' development the biggest potential of time studies lies in process data-based recording. The reason for this is that harvesters will continue to be automated further in the future. Also, computer-based systems that support the operator's work are already today an essential part of the productive wood procurement chain. Automatically recorded time study materials are accurate and large and the division of their work phases is highly detailed. Automatic timing enables the recording of overlapping durations of simultaneous work phases. Furthermore, the time consumptions of the work phases of automatic timing can be combined with information on various machine and operator functions at the stem and log level. This is necessary for technical machine development and to improve the understanding of the structure of human-machine work. However it must be remembered that automatic timing is not always possible, especially with new harvester types, although the technical development is rabidly moving in that direction.

Secondly, the measuring accuracy of manual timing is limited, especially in intensive time studies. However, there is still a need for manual time studies when measuring new work processes. This is especially true in short studies with quite limited data as well as in fairly varying circumstances, where the presence of an observer is required to detect unexpected working situations on the logging site. Furthermore, automatic time studies may also be too expensive for these experiments. The presence of the observer during the experiment yields a visual and practical overview of work performance, which decreases the risk of systematic errors in time study data. Also the reliability of automatic recording increases if the views of the observer about the work performance are compared with the interpretation of the results of automatic timing.

Thirdly, based on combined data (automatic and manual recordings) a new process-data model of single-grip harvester work was identified, which enables the combination of the data collected by automatic and manual recording. The benefit of this method for time studies of cut-to-length harvester work is the possibility to record the most important work phases from large amounts of time study materials with highly detailed and accurate projection of the harvester work per each processed stem. The new process-data model is superior, because it records work phases that overlap to varying degrees. Using the adjusted process-data model, including visual observations recorded manually in the results of automatic timing improves the reliability and the analysis of results.

4.5 Assessment of the research

This thesis described the features of automatic and manual time study techniques as a tool of work studies in forestry. The overall purpose was that this would help researchers to select the right recording method for each time study and to promote the use of common collective methods in time studies. Studies I and IV had features of experimental studies. Study I demonstrated the variability inherent in manual time studies; Study II highlighted the potential of automated time studies; Study III showed the inherent problem with functional overlapping; Study IV drew the conclusions, after directly comparing automated and manual time study.

In Study I, the number of observers was sufficient in order to explore the influence of an observer's work experience on measurement accuracy. The number of cut trees was adequate to investigate the actual objectives of this study. However, the length of the measured video material could have been longer, at least 2 hours, to reveal how the observer's fatigue affects timing accuracy. The accuracy and reliability of the PlusCan data logger were tested and confirmed by means of a video technique using a timing accuracy of a hundredth part of a second.

The strength of Study I was that it was a laboratory-based experiment. Study I stressed the teaching and demonstration of work phase definitions and divisions before the study started. Additionally, the harvester simulator environment made it easier to detect the transition moments of time phases during the time study. The simulated thinning operation also involved sound, which was important in detecting certain elements (breaks, etc.). Thus, the stable and unique study environment of the studio made is easier to use identical study materials for all observers and control for other factors that may influence the timing than if the study had been conducted in the field. Although Study I was conducted in a studio environment, the results can to some extent be generalized to apply to real-time study practices.

Study II was an example of how automatic recording can promote technical development and reveal the importance of a single work phase to the whole work process. Study II described well how study material recorded by TimberLink made it possible to carry out a deep analysis of the stem processing work phase and to produce useful information for the technical development of feed rollers. The TimberLink material also included several other variables describing the processing work phase that were not used in the analysis of Study II: idle times and crane times during processing, indicating the working technique of the operator; the acceleration time at the beginning of stem feeding, which explains the feeding properties of the rollers; and also the feeding pressures of each roller, which could be combined with the feeding time. In Study II, automatic recording was able to produce results from the feeding speed and fuel consumptions at the stem and log level with different stem sizes and tree species. These results proved that the features of feed rollers have a significant influence on the total productivity and energy efficiency of harvester cutting. Study II focused only on a small part of the extensive and detailed data flow in CAN-bus channels; however, it was a good example of how automatic recording can give important suggestions for developing single functions.

In Study III, the visual observation of two researchers and manual recording by handheld field computers gave a description of the work performance of the bundle harvester as a whole. During the experiment researchers interfaced with the bundle harvester operator, discussing the work performance and the technique of the machine, thereby strengthening and enriching the conclusions made on the basis of the time study results. The study brought to light the unexpected situations and conditions on the logging site that are best recorded manually by field computer. Study III also highlighted the importance of a skilled time study observer (Nuutinen et al. 2008).

Study IV has the features of an experimental study where the main focus is to find common characteristics, models and new theoretical ideas, methods and concepts by comparing alternatives under similar work conditions. In an experimental study strategy, tests are used as a means of researching different phenomena (Eisenhard 1989, 1991, Dyer and Wilkings 1991). Experimental studies can be repeated and typically examine the interplay of defined variables in order to provide as complete an understanding of an event or situation as possible. A good research hypothesis and questions are integral elements when conducting experimental research because they steer the process of collecting study material, producing results, making synthesis and writing the study report (Dyer and Wilkins 1991). In Study IV, the experiment involved automatic and manual recording of data in a harvester time study. The PlusCan data logger represented automatic recording, and the visual observation of a human being using a handheld field computer represented manual recording. The process-data model was included in the automatic recording because it was developed especially for automatic timing.

In Study IV, the performance of a man-machine system (operator – single-grip harvester) was recorded in parallel using automatic and manual recording techniques. This provided a fruitful possibility to compare the information value of both techniques. Statistical methods (principal-components analysis) were successfully used in the analysis. The analysis produced seven statistically significant main work components. For example, the main work component clearing indicates the dense undergrowth in the thinning stands of the experiment that must be removed from around standing trees that must be felled (Figure 22, Table 12 and 13). Palander et al. (2012) stated that the inputs from working environment and from displays inside the harvester reflects the operator's decisions which are translated into work phases during the work. The experiment of Study IV does not offer the possibility for statistical generalization. However, this is not the purpose of the experimental study strategy, as Stake (2005) has stated. The experimental study strategy applied in Study IV was to describe the potential features of automatic and manual timing in order to reach a better understanding of harvester work. Nevertheless, analytic generalization is possible by using an experimental study strategy (Dyer and Wilkins 1991), which means that new concepts, methods and theories can be tested under similar work conditions. This means that the features of automatic and manual timing of the studies by Väätäinen et al. (2005) and Kariniemi and Vartiamäki (2010) could be repeated.

4.6 Future research

The quality of time consumption material gathered for projection of harvester work depends on the information demand of the users. The future research questions raised from this thesis are based on the overall goal of time studies, that is, to increase the productivity of harvester work (Figure 1).

The work phases of the process-data model (Figure 10) of Kariniemi and Vartiamäki (2010) were defined using actual field data for the dominant harvester models. Furthermore, in Study IV of this thesis, the adjusted process-data model (Figure 22, Table 12 and 13) was developed based on a large field study carried out by Väätäinen et al. (2005) wherein the time consumptions of each tree were recorded automatically and manually by handheld field computer under the same work conditions. Adjusting the process-data model to improve data recording accuracy has great potential in forest work, but this must be confirmed through additional work studies in different work conditions. For further development of the process-data model, more detailed harvester functions call for experience, such as when developing the semiautomation of boom movements (Löfgren 2004, 2006, 2009).

The process-data model could be further adjusted using the experimental study strategy applied in Study IV. The experiment could involve fuel consumption and location information combined with the time consumption. In a case where fuel consumption would be included in the process-data model, an important development target is that the fuel consumption should be assigned to each work phase, providing information about the influence of each work phase on total cost- and energy-efficiency. Furthermore, the process data includes information about the harvester's location in the stand during the work (McDonald and Fulton 2005). For the process-data model, important information includes the moving distances between the working locations and the coordinates of the working locations and processed trees.

The development of sensor, data transfer and information technology have enabled the automatic monitoring of machine functions and operating environment: e.g. the features of the tree stand and terrain monitored by the harvester (Väätäinen et al. 2012), which could be combined with the work phases of the process-data model. Furthermore, these features could be utilized on a large scale to clarify the working technique of experienced operators. For example in Finland, in the next ten years, the lack of experienced harvester operators calls for knowledge about consideration and planning in mechanical cutting (Penttinen et al. 2011). Increasing efficiency has made harvester operators' work very intensive, requiring them to make a large number of complex decisions during the work. Väätäinen et al. (2005), Kariniemi (2006), Ovaskainen (2009) and Palander (2012) have showed that the importance of consideration and planning in mechanical harvesting has increased.

Unforeseen situations deviating from the normal work procedure (Figure 9) can confuse the timing of automatic recording in particular. Also, different data collecting techniques pose a challenge in terms of producing time consumption information in the same format. These questions should be clarified so that all work time is uniformly registered in the right work phase. In cost action project FP0902 (Magagnotti and Spinelli 2012), harmonizing of standard measurements has been noted to be important for forest biomass research.

Study I was conducted in a laboratory environment, which leads to the question of whether the researcher's recorded time consumptions are accurate and reliable enough when recording out in the field. Observing done by a human being will always be subjective. This thesis has given proofs that it is at the same time an advantage and disadvantage. Further research about the observer's recording ability in an actual time study environment should be made. For example, using the method of Study I, a group of time study researchers should conduct a timing of harvester work at the same time in the forest. Timing should last long enough to obtain adequate repetitions of the time phases. This will allow the influence of the researcher's fatigue to be included. Furthermore, other factors influencing measurement accuracy, such as climatic conditions and visual obstructions, should be included.

The process-data model is based on digital data gathering. The results of Study IV revealed that the combined use of manual and automatic recording can produce fruitful results. For that reason, manual recording using the process-data model calls for practical experiences that should be investigated in a real harvester time study.

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