Automatic and Experimental Methods to Studying Forwarding Work

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Abstract

Although forwarding has been carried out for 50 years, much is still unknown about this work. This is partly because there are numerous influential factors, and relevant data are often difficult to gather. In current forwarding productivity literature, there is generally a trade-off between representativeness and work element-specificity. Follow-up studies and standardized experiments represent the two extremes, while work observation studies are compromises. A further complication is the lack of consistent nomenclature to facilitate comparisons of findings from different studies. These issues were explored in four studies reported in this thesis.

Study I assessed the utility of standardized test paths for enhancing our understanding of the main factors influencing forwarding work, causal relationships among them, and trade-offs. Such knowledge is essential for refining future research. In Studies II and III, the utility of a forest machine manufacturer's built-in automatic follow-up datalogger was assessed. Study II focused mainly on the suitability of a standard commercial monitoring system for comparative operator-level studies. In Study III, forwarder work element-specific follow-up data were gathered in as detailedly as currently possible using an automatic system. In Study IV, the utility of sensors and dataloggers for gathering technical information on forwarder crane work was assessed. The main conclusions are summarized below.

Automated data collection has well known advantages, but such automation for forwarding work is still ongoing. Data from the forwarder's own monitoring system alone are not, currently, sufficient for unbiased work performance analysis. In addition, access to spatial data on the harvester's production is needed. Use of untapped technological potential would enable, in many cases, replacement of manual data gathering with automatic methods. However, automatic gathering of data with some important features, e.g. assortment-specificity (load-specific assortment proportions), is currently impossible. Automation enables large datasets to be gathered, but increasing the sample size beyond a certain saturation point provides no further benefits. Instead, including more factors is preferable, even at the cost of slightly smaller datasets.

Finally, various innovations and modifications to work practices could substantially improve forwarding efficiency; however, they should be evaluated cautiously, initially by theoretical analysis, to ensure resources are efficiently channelled.

Keywords: automatic recording, experiment, fuel, energy, hydraulics, fluid dynamics, mechanics, CAN-bus, haulage, forestry, non-normal data distribution.

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No pain, No gain!

Jane Fonda

Contents

List of Publications

This thesis is based on work described in the following article and manuscripts, which are referred to in the text by the corresponding Roman numerals:

I Manner J., Nordfjell T. & Lindroos O. (2013). Effects of the number of assortments and log concentration on time consumption for forwarding. *Silva Fennica* vol. 47 no. 4 article id 1030.

II Manner J., Nordfjell T. & Lindroos O. Automatic load level follow-up of forwarders' fuel and time consumption (manuscript).

III Manner J., Lindroos O., Palmroth L. & Nordfjell T. Load level forwarding work element analysis based on automatic follow-up data (manuscript).

IV Manner J., Lindroos O., Arvidsson H. & Nordfjell T. Evaluation of a new energy recycling hydraulic lift cylinder for forwarders (manuscript submitted to Croatian Journal of Forest Engineering).

Paper I is reproduced with the permission of the publisher.

The contribution of Jussi Manner to the papers included in this thesis was as follows:

I Initiated the study. Designed the study in cooperation with co-authors. Collected the data. Performed the statistical analysis and calculations. Wrote the majority of the manuscript.

II Initiated the study. Performed the statistical analysis and calculations. Wrote the majority of the manuscript. (Data were collected automatically)

III Initiated the study in cooperation with co-authors. Performed the statistical analysis and calculations. Wrote the majority of the manuscript. (Data were collected automatically)

IV Designed the study and collected the data in cooperation with co-authors. Performed the statistical analysis and calculations. Wrote the majority of the manuscript.

Abbreviations

Table 1. *Some definitions used and frequently used abbreviations*.

Abbreviation	Explanation
ANCOVA	Analysis of covariance
ANOVA	Analysis of variance
A_1	Primary piston area
A_2	Secondary piston area
A_{sp}	Standard piston area
CAN	Controller area network
CTL	Cut-to-length
DSS	Decision support systems
F_2	Secondary cylinder force
GLM	General linear model
GNSS	Global Navigation Satellite System
h	Hour
ha	Hectare
HMM	Hidden Markov Model
.hpr	Harvested production, StanForD standard
J	Joule
km	Kilometre
kPa	Kilopascal
L	Lift cylinder length
m	Metre
MAD	Median absolute deviation
m^3ob	Solid m^3 over bark
p	Pressure
p_1	Standard OR primary cylinder pressure
p_2	Secondary cylinder AND accumulator pressure
PC	Personal computer
PM	Productive machine (time), i.e. delays excluded (IUFRO 1995)
PMh	Productive machine hour
PMh_{15}	PMh with delays shorter than 15 minutes included
Productivity	Handled wood volume per unit time, e.g. m^3/PMh
r_s	Spearman's rank correlation coefficient
SD	Standard deviation
StanForD	Standard for Forest machine Data and Communication
t	Time
V	Volume
W	Work
W_1	Primary cylinder's lift work
W_2	Secondary cylinder's lift work
W_{EHLC}	EHLC's lift work
W_s	Standard cylinder's lift work
$W_{t\rightarrow t+1}$	Lift work during a given time interval from t to t+1
$W_{\text{"cylinder type"},\ t\rightarrow t+1}$	$W_{t\rightarrow t+1}$ for a given "cylinder type"
$\propto$	…is proportional to…

1 Introduction

1.1 The cut-to-length logging system

In Nordic cut-to-length (CTL) logging operations, a harvester cuts and limbs the trees, crosscuts the limbed stems into logs of different assortments, and finally piles the cut logs in assortment-specific piles. A forwarder picks up the logs in the piles, places them in its load-space and moves them to a roadside landing (thereby “extracting” them from the harvesting site). At the landing, the forwarder unloads the logs for later long-distance transport, placing them in separate assortment-specific roadside-piles. Thus, fully a mechanized CTL logging system consists of one or more harvesters and one or more forwarders.

According to data from a large follow-up study, covering 20 million m^3 of roundwood in total, by Eriksson and Lindroos (2014), overall forwarding productivity (including both thinnings and final fellings) is nearly 10 % lower than corresponding harvester productivity (weighted by handled roundwood volume). However, although forwarding consumes more time per unit of handled roundwood volume than harvester work, harvester productivity has been prioritized in CTL logging research over forwarding productivity. For instance, a steady stream of doctoral theses has been published on harvester work in recent decades (see e.g. Eliasson, 1998; Sirèn, 1998; Kariniemi, 2006; Ovaskainen, 2009; Purfürst, 2009; Palmroth, 2011; Belbo, 2011; Nuutinen, 2013), while there have been extremely few (if any) on forwarding since Gullberg (1995).

1.2 Overall forwarder design

A forwarder is a log-loading and transport machine consisting of front and rear frames with six or eight wheels. Eight-wheeled models (Figure 1) are equipped with two bogies, each attached to two pairs of wheels, while the front frame of six-wheeled models (no figure shown) has a pair of single wheels rather than a bogie. Forwarders' manoeuvrability is provided by an active articulated steering system. Moreover, a passive rotational joint enables free rotation in the torsional direction, i.e. the front and rear frames rotate independently from each other when passing obstacles. A cab, which may be rotating and/or self-levelling, is placed on the front frame. A load-space, often equipped with moveable bunks and adjustable stakes, is placed on the rear frame. The forwarder's load-bearing capacity is described as its payload (specified by the manufacturer) while the load volume capacity is given by geometric measurements.

A combustion engine delivers power both to the working and powertrain hydraulic systems, each of which includes one or more dedicated variable displacement hydraulic pumps. The working hydraulic system drives work functions such as the crane and steering, while the powertrain hydraulics (generally a so-called closed-loop system) drives a motor. However, there may be some minor differences between forwarder models. The hydraulic systems of modern forest machines are described in more detail in various publications (see e.g. Drive and Control Systems…2008).

Knuckleboom cranes, which are used on forwarders, are designed to provide large lifts and heights, partly at the cost of slow horizontal movements (Figure 1). These cranes consist of a system of hydraulic cylinders and mechanical levers, including a slewing crane pillar, pivoting mid- and outer-booms, and an extension boom (Malmberg, 1981; Gerasimov & Siounev, 1998, 2000; Virvalo & Sun, 2005). The extension's boom length affects the vertical height of the grapple, but loads are lifted and lowered mainly by changing the lift cylinder length, and to a lesser degree by changing the outer boom's cylinder length. A rotator enables unlimited rotation of the grapple. Moreover, forwarders are equipped with load-sensing hydraulic control systems that adjust the hydraulic oil pressure and flow rate according to instantaneous power requirements (e.g. Scherer *et al*., 2013).

The forwarders' drive and crane manoeuvrability are developed constantly. For instance, currently used hydrostatic mechanical power transmission may be replaced by fully hydrostatic power transmission with wheel motors and independent pendulum arms in the future (Nordfjell *et al*., 2010; Baez *et al*., 2014). In addition, bogie designs may be improved (Edlund *et al*., 2013ab), and Widéen *et al*. (2011) have designed a frame that can articulate vertically, as well as horizontally, by using two double-acting cylinders. There is also interest in automating the crane work, and certain recurrent movement patterns can already be fully or partly automated (e.g. Cranab AB, 2013; Westerberg, 2014).

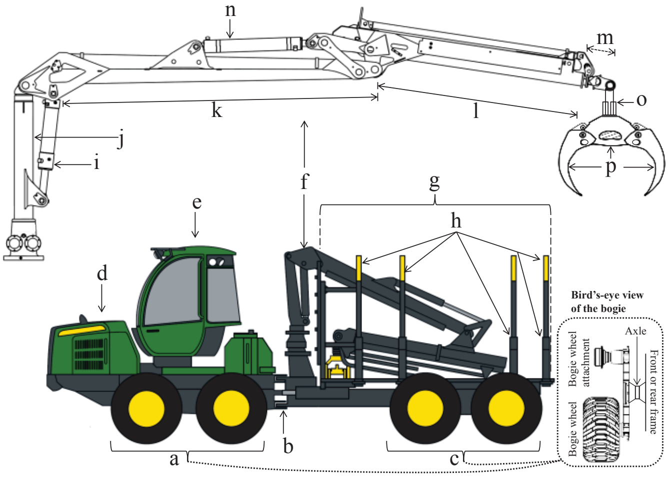

Figure 1. Sketches of an eight-wheeled forwarder showing: a) wheels attached to the front frame bogie; b) active articulated steering hinge; c) wheels attached to the rear frame bogie; d) housing for the combustion engine; e) cab; f) knuckleboom crane; g) load space; h) moveable bunks with adjustable stakes; i) lift cylinder; j) slewing crane pillar; k) pivoting mid boom; l) outer boom; m) extension boom; n) outer boom cylinder; o) rotator; p) unlimited rotatable grapple. Modified from original figures of Cranab AB, John Deere Forestry Oy, patent WO 2009040472 A1 (not included in the reference list).

1.3 Forwarding and factors affecting time consumption

1.3.1 Work elements

In work observation studies, forwarding is generally divided into separate work elements. However, the number of work elements can vary almost infinitely as no generally acknowledged nomenclature is used (cf. e.g. Kuitto *et al*., 1994; Andersson, 2015). In contrast, in long-term follow-up studies forwarding time consumption is typically analysed as whole, i.e. forwarding is not divided into work elements (see e.g. Eriksson & Lindroos, 2014). However, forwarding is usually divided into five work elements as follows: driving empty, loading, loading drive (i.e. driving events during loading), driving loaded, and unloading (including unloading drive) (see e.g. Bergstrand, 1985; Väkevä *et al*., 2001; Nurminen *et al*., 2006). Moreover, as driving and crane work can occur simultaneously, successive work elements may overlap. However, to simplify work element determination, the overlaps of successive work elements can be ignored by applying a priority rule, e.g. by setting a tyre rotation alone, or crane movement alone, as the determinant of a change of work element (see e.g. Tiernan *et al*., 2004). In addition to possible overlaps of work elements, several steering, driving and crane functions may be in use simultaneously which further increases simultaneous activity. However, overlapping intervals have been separately recorded in few (if any) forwarding work observation studies.

On average, the work elements loading, loading drive, unloading and unloading drive collectively account for 78-82 % of the forwarding time consumption when extraction distances are 200-300 m (single-way; see Section 1.3.2 for a definition of extraction distance) (Figure 2), although the time consumption for these work elements can be influenced by work planning. The transportation-only work elements (i.e. driving empty and driving loaded) jointly account for just 18-22 % of the time consumption. Time consumption for transportation-only work elements depend on the extraction distance and driving speed, which in turn are mainly determined by geophysical factors. Therefore, an operator has limited opportunities to reduce time consumption for these work elements.

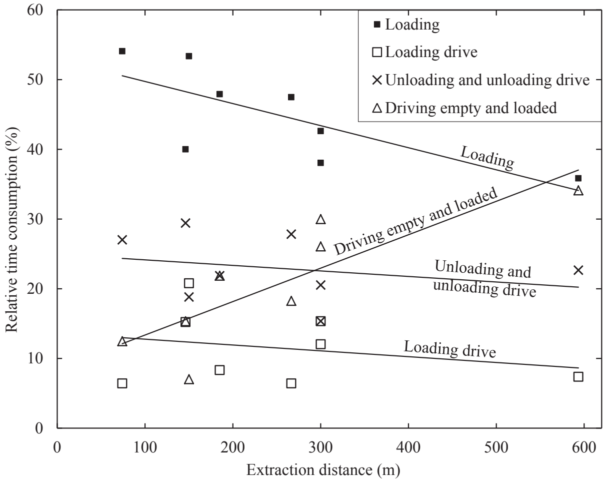

Figure 2. Relative distributions of a forwarder's productive machine (PM) time consumption versus extraction distance (single-way). Regression lines obtained from analysis of data on: forwarding after fully mechanized CTL thinning operations (Kellogg & Bettinger, 1994; McNeel & Rutherford, 1994; Hunt, 1995; Sambo, 1999; Bulley, 1999; Gullberg, 1995); forwarding using a Bruunett Mini 687F after motor-manual CTL thinning (Meek & Simard, 2000); and forwarding after both late thinning and final felling by a Valmet 646 (Poikela & Alanne, 2002). Extraction distances were calculated from data in the first five references as means of driving empty and driving loaded distances. See *Table 1* for a definition of PM time.

1.3.2 Distances

In forwarding, the total "driven distance" is often divided into several "sub-distances", as shown in *Figure 3*. For all cases except one, use of the word (driven) *distance* could be questioned, at least if distance is regarded as a numerical description of how far apart two objects are from each other (i.e. their linear separation in space). The only distance shown in *Figure 3* meeting this definition is the extraction distance since it is the shortest linear length from the centre of the harvesting site to the landing area at the roadside (see e.g. Viitala *et al*., 2004; Hakonen, 2013).

However, it is often assumed that forwarders will go around impenetrable obstacles when determining extraction distances (e.g. Femling, 2010). Occasionally the distribution of roundwood volumes on the harvesting site are also taken into account and so-called volume-weighted extraction distances are calculated to improve forwarding productivity estimates (e.g. Femling, 2010; Lindroos, 2012). Meanwhile, driving empty, loading drive, driving loaded and unloading drive distances should – in contrast to established practice and the terminology used in current forwarding literature – be called for instance *mileage*. However, to harmonize with current forwarding literature, the terminology illustrated in *Figure 3* is hereafter used throughout this thesis.

Mean reported distances for driving empty, loading drive and driving loaded (for both thinnings and final fellings) vary from 171 to 433 m, 11 to 267 m, and 122 to 414 m, respectively (e.g. Kellogg & Bettinger, 1994; McNeel & Rutherford, 1994; Poikela & Alanne, 2002; Nurminen *et al*., 2006). Moreover, the mean of the transportation-only distances [i.e. (driving empty + driving loaded)/2)] can be used as a proxy of extraction distances, although this generally results in slight overestimates (see Figure 3). Examples of extraction distances estimated from transportation-only distances include ca. 130 m for final fellings and ca. 420 m for thinnings, based on data acquired in a Finnish study by Nurminen *et al*. (2006). Other examples include estimates of ca. 150 m and 270 m for thinnings in western Oregon, USA (Kellogg & Bettinger, 1994) and selection harvests in the American Northwest Pacific Coast region (McNeel & Rutherford, 1994) respectively. Extraction distance and forwarding productivity are inversely related, thus extraction distance is used as a key factor in productivity norms for forwarding (see e.g. Kahala & Kuitto, 1986; Kuitto, 1990, 1992; MoDo Skog, 1993; Brunberg, 2004; Hakonen, 2013). The actual driven distance or "trip meter reading" per load (single-way) is longer on average than the estimated extraction distance. However, when necessary, an appropriate coefficient varying from 1.2 to 1.6 is used to estimate the actual single-way driven distance (without unloading drive) from a given extraction distance (e.g. Viitala *et al*., 2004; Hakonen, 2013).

Moreover, Tiernan *et al*. (2004) divided total driven distances by two and used a developed ratio to estimate extraction distances when modelling forwarding productivity; although for work analysis, productivity could be modelled directly using the total driven distance without such division. Alternatively, forwarding productivity can be modelled as a function of driving empty distance (see Kellogg & Bettinger, 1994), a variable similar to the extraction distance estimates described in the preceding paragraph. Finally, since there is no generally acknowledged forwarding nomenclature, "correct distance definitions" in forwarding are periodically discussed (see e.g. Lindroos, 2012).

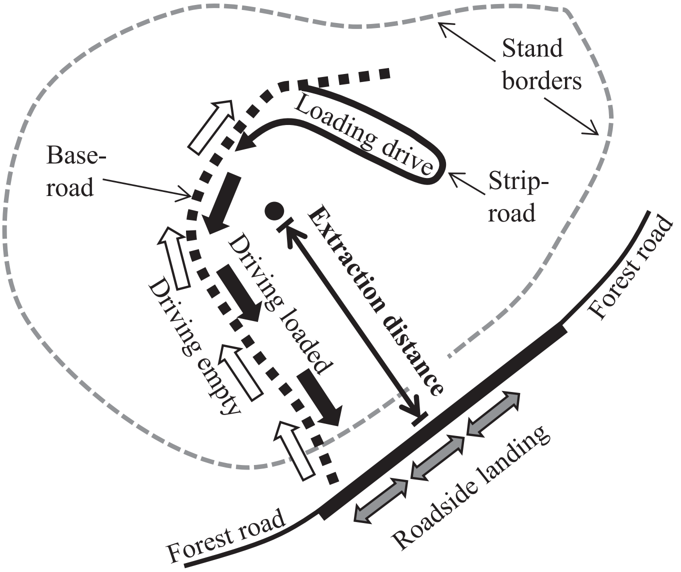

Figure 3. A plain sketch of an imaginary harvesting site. The total driven distance consists of driving empty, loading drive, driving loaded, and unloading drive distances. Essentially, driving empty and driving loaded occurred on the base-road, loading drive on the strip-road, and unloading drive at the roadside landing. The centre of the harvesting site is marked with a dot.

1.3.3 Assortments

A forwarder load can contain one or several assortments. Assortments can be further classified into major (or normal) and minor assortments depending on their proportions by volume. For instance, Bjurulf (1993) and Brunberg and Arlinger (2001) classify an assortment as a normal assortment if it accounts for more than five percent of the total volume. This proportion may refer to the total volume in a given stand or, alternatively, in a given load. Thus, there are no generally acknowledged rules for classifying assortments. Forwarding productivity depends on the number of loaded assortments, and the productivity also varies between different assortments (e.g. Bergstrand, 1985; Kellogg & Bettinger, 1994; Nurminen *et al.*, 2006; Poikela & Alanne, 2002). Numbers of assortments were found to typically range from seven to ten (3-5 saw log and 4-5 pulp wood assortments), when studying both final felling and thinning stands in Finland at the turn of the millennium (Poikela & Alanne, 2002). Nowadays, the numbers are likely to be even higher since more customer-specific log dimensions have resulted in increasing numbers of assortments at harvesting sites (see Malinen *et al.*, 2011). In a follow-up study by Kuitto *et al.* (1994), the proportion of single-assortment loads was only 14 % while proportions of 2- and 3-assortment loads were 44 and 26 %, respectively.

1.3.4 Log concentrations

Log concentration can be expressed in terms of volume per unit surface area (e.g. m^3 ha^{-1}), but from a forwarding perspective it is more commonly and accurately expressed as a volume per unit distance on the strip-road, e.g. m^3 $(100\ m)^{-1}$ (see Kahala, 1979; Kahala & Kuitto, 1986; Kuitto, 1990, 1992; Kuitto *et al.*, 1994; Väkevä *et al.*, 2001; Nurminen *et al.*, 2006; Bergstrand, 1985).

Kahala (1979) found that forwarding productivity increases as a function of log concentration, but starts to plateau beyond a threshold value. A comparison of data acquired by Kahala (1979) and in later studies by Kahala and Kuitto (1986), Kuitto (1992), Kuitto *et al.* (1994) and Brunberg (2004) indicates that forwarders' overall productivity rose between the 25 years spanned by the publications, but the relative influence of the log concentration on forwarding productivity has not changed. However, some of the increase in forwarding productivity may also have resulted from the conversion from motor-manual-cutting, which was still relatively common until the 1980s, to solely mechanized harvesting since the 1990s (as further discussed in Section 1.3.5).

Moreover, for accurate scientific work analysis, total log concentrations and forwarded log concentrations should be distinguished. Total log concentration refers to all the logs at a harvesting site, whereas forwarded log concentration refers to the load-specific log concentration, which depends on the assortment distribution at a harvesting site and assortment mixture forwarded together in a load.

1.3.5 Other factors

In motor-manual-cutting, lumberjacks piled certain assortments (the lightest logs) after crosscutting, but most logs were left where they had been felled. In contrast, single-grip harvesters pile all the logs in assortment-specific piles near the strip-road. Careless piling of logs – such as putting more than one assortment in a pile, placing piles far from strip-roads, or creating loose piles – decreases loading productivity (e.g. Kahala & Kuitto, 1986; Bjurulf, 1992; Gullberg, 1997ab; Väätäinen *et al.*, 2006). Moreover, loading productivity increases with increasing pile-size until a certain threshold. Theoretically, the optimal pile size is the product of grapple area and some coefficient (e.g. Kahala & Kuitto, 1986; Bjurulf, 1992; Gullberg, 1997ab; Väätäinen *et al.*, 2006). Presumably for the abovementioned reasons, Kuitto (1992) and Kuitto *et al.* (1994) found that forwarding productivity is notably lower after motor-manual-cutting than after fully mechanised harvesting (i.e. using a single-grip harvester). Thus, because forwarding productivity is highly dependent on log pile quality, it is unclear how much of the previously mentioned increase in forwarding productivity (Section 1.3.4) was due to improvements in forwarder technology and the conversion to solely mechanized harvesting after the 1980s.

Forwarding productivity and load size are directly proportional (e.g. Kahala, 1979; Kahala & Kuitto, 1986; Kuitto, 1990, 1992; Kuitto *et al.*, 1994; Väkevä *et al.*, 2001; Brunberg, 2004). Furthermore, terrain factors such as bearing capacity, gradient, frost, wetness and snow conditions indirectly affect forwarding productivity through their effects on driving speed (see e.g. Asserståhl, 1973; Väkevä *et al.*, 2001; Kuitto, 1990, 1992; Kuitto *et al.*, 1994). Driving empty, loading drive and driving loaded speeds vary from 51 to 61, 22 to 36 and 40 to 50 m/min, respectively. However, driving speeds do not vary between thinnings and final fellings (see e.g. Väkevä *et al.*, 2001; Nurminen *et al.*, 2006).

According to current literature, forwarders' productivity is notably higher in final fellings than in thinnings (e.g. Kuitto, 1990, 1992; Kuitto *et al.*, 1994; Väkevä *et al.*, 2001). However, few (if any) forwarding studies have isolated the effect of logging type (i.e. final felling or thinning) from that of other influential factors, e.g. forwarded log concentration. So, the difference could be partly due to other factors, e.g. lower forwarded log concentrations in thinnings. Nevertheless, factors such as the presence of residual trees may possibly slow crane work and driving speeds during the loading phase in thinnings.

Asserståhl (1973) found that effects of environmental factors are not always straightforward, as there are interactions among them, e.g. a gradient may pose a substantial obstacle if the bearing capacity is low, but not otherwise. Another example is that forwarding productivity is higher during summer than in winter for final felling, but higher in winter for thinning (e.g. Väkevä *et al.*, 2001), possibly because avoiding damage to roots of residual trees is easier when the ground is frozen.

In addition, productivity and skill levels vary substantially among forestry operators (e.g. Ovaskainen, 2009; Lindroos, 2010). Presumably such variation also applies for forwarding, but no such operator-level data on forwarding are available.

1.4 Fuel consumption during forwarding

Nordfjell *et al.* (2003) incorporated pauses in work elements and found that loading including loading drive accounts for most (40.2-62.4 %) of the total fuel consumption, followed by driving empty (19.6-22.5 %), unloading including unloading drive (10.3-18.7 %) and driving loaded (6.3-21.5 %). In addition, Nordfjell *et al.* (2003) found that mean fuel consumption varies from 5.1 to 7.2 l/load or 9.4 to 10.2 l/PMh (PMh = productive machine hour, Table 1). Published mean fuel consumption values vary from 0.62 to 0.78 l/m^3 in final fellings, and from 0.92 to 1.04 l/m^3 in thinnings (e.g. Nordfjell *et al.*, 2003; Rieppo & Örn, 2003; Brunberg, 2013). It is intuitively sound that the same factors that result in lower productivity in thinnings are also, at least partly, responsible for the higher fuel consumption in thinnings. Moreover, no information on the distribution of fuel consumption between crane work and driving has been presented in any published observational or follow-up study. Some fuel consumption measurements have been acquired for crane work and driving separately in standardized experimental conditions (see e.g. Brunberg *et al.*, 2000, 2005). However, it is not known how well the results acquired with such methodology correspond to fuel consumption in practical forwarding, so the methodology is likely more suitable for comparing the fuel-efficiency of different machines and technical applications.

The fuel consumption per load increases as a function of total driven distance (e.g. Nordfjell *et al.*, 2003, Brunberg, 2013). Moreover, according to Brunberg (2013), fuel consumption increases both with increasing payload capacity and engine power, e.g. a forwarder with a 11-14 t payload (reference power 136 kW) consumes on average 10.8 l/PMh_{15} (PMh_{15} consists of PM time and delays shorter than 15 minutes, Table 1) while a forwarder with a 15-19 t payload (reference power 176 kW) consumes on average 15.4 l/PMh_{15}. However, for fuel consumption analysis, it is also essential to know the relation between volumes of fuel consumed and forwarded roundwood volumes, e.g. l/m^3. Nevertheless, provided that the full payload capacity is used, the relationship between payload capacity and fuel consumption (l/PMh_{15}) indicates approximately similar fuel consumption per forwarded roundwood volume (l/m^3) irrespective of payload capacity.

To summarize, the total fuel consumption in forwarding is relatively well known, but the distribution of fuel consumption among the separate work elements has been studied less intensively. Moreover, forwarder fuel consumption readings vary substantially within single studies, probably due to variations in factors such as work conditions, operators, and machine models. These factors presumably affect not only absolute fuel consumption, but also the fuel consumption distribution among separate work elements, and between-study variations are even greater.

1.5 Challenges in forwarder work studies

A complete forwarding cycle, i.e. forwarding one full load, consists of moving many logs (ca 8-20 m^3 of roundwood, depending on the size of the forwarder). A complete forwarding cycle starts with driving empty and ends with unloading, and involves nearly an hour's work on average (e.g. Nurminen *et al.*, 2006). In comparison, a complete harvester work cycle involves on average less than a minute's work (felling a tree, bucking, and short machine moves; Nuutinen, 2013). Furthermore, harvester work is affected by factors which are often easy to record, so its analysis is relatively straightforward (see Nuutinen, 2013).

In summary, the large number of influential factors during forwarding research introduces high levels of complexity, and every factor (either of interest or nuisance factors) should ideally be included in analysis to minimize the risk of causal fallacy. But, due to the number and complexity of the factors involved and the long time required to collect relevant data, forwarding research is challenging. Partly for this reason, it is possible that research resources have been used to preferably study harvester work rather than forwarding. However, for the Nordic CTL logging system's overall competitiveness, forwarding research is as important as harvesting research (as discussed in Section 1.1).

1.6 Objectives

The overall objective of this thesis was to evaluate methods of studying forwarding, focusing specifically on experimental and automated data gathering. To meet this objective, four studies (designated Studies I-IV) were performed, as briefly described below.

- The objective of Study I was to analyse the effect of the number of assortments in a load, the total log concentration, and the forwarded log concentration on forwarding time consumption. For this purpose, a standardized experiment was performed to isolate effects of the studied factors, and equally important keep constant other conditions expected to affect forwarding productivity. Time study data were recorded using a handheld field computer.

- The objective in Study II was to acquire descriptive operator-level forwarding follow-up data on fuel and total time consumption in final fellings. To my knowledge, this was the first large follow-up study with one load as the unit of observation. A standard TimberLink machine monitoring system (John Deere Forestry Oy, Finland) was used for gathering and analyzing data.

- The objective of Study III was to analyze forwarder work elements in final fellings using a dataset of unprecedented quantity and a resolution with one load as the unit of observation. The data were acquired from a TimberLink system and analysed in cooperation with the supplier, John Deere Forestry Oy (Finland), which enabled exceptionally detailed work element documentation.

- The objective of Study IV was to evaluate the energy saving capacity of a new hydraulic lift cylinder (EHLC), and to document its technical strengths, weaknesses, and development potential. In addition, the study illustrated how the forwarder crane's energy, force, and effect requirements during lift work can be determined by mounting sensors temporarily on the crane and connecting them to a datalogger to automatically record the data.

However, more specific aims were to increase our knowledge of the strengths and weaknesses of methodologies for gathering data on forwarder machinery and work that could be used in rigorous scientific analysis. Study I assessed the utility of standardized test paths for enhancing our understanding of the main factors influencing forwarding work, causal relationships among them, and their trade-offs. Such knowledge is essential for refining future research. In Studies II and III, the utility of a forest machine manufacturer's built-in automatic follow-up datalogger was assessed. Study II focused mainly on the suitability of a standard commercial monitoring system for comparative operator-level studies. In study III, forwarder work element-specific follow-up data were gathered in as much detail as currently technically possible using an automatic system. The methodology used in Studies II and III determined both machine and crane movements based on controller area network (CAN)-bus messages, and (in contrast to Study IV) no additional sensors were used. In Study IV, the utility of third-party research instruments (sensors) and dataloggers for gathering technical information on forwarder crane work was assessed. In addition, the functionality of innovative forwarder machinery in a standardized experimental environment was evaluated.

Since the main objectives of the PhD project were to improve understanding of methodologies for gathering and analyzing forwarding data, the *Material and methods* (chapter 2) and *Discussion* (chapter 4) sections cover large proportions of the text in this thesis. Results from each study are addressed only briefly (chapter 3) and study-specific conclusions are included in the respective result-sections. Moreover, for study-specific discussions, readers are advised to read corresponding papers (designated Papers I-IV).

1.7 Conceptual framework

Abundant, high quality data are crucial for analyzing work, which in turn is crucial for improving productivity. In this context, the primary objectives of Studies I-IV were to determine the *optimal ways to do things* in forwarder work and machinery science (Figure 4). However, because forest technology research is an applied science and closely connected to industry, equally important objectives were to determine how the limited research resources available for forwarder work science and machinery can be used most efficiently (*the optimal things to do*). Advances in the understanding of *optimal* *things to do* and *optimal ways to do things* should help efforts to plan efficient forwarder-related research in the future. Moreover, the study-specific results of this PhD project are not going to fill “acute knowledge gaps” (Figure 4), but will provide some basic knowledge, and this thesis should be seen as a description of pioneering work and a discussion of the outlined issues.

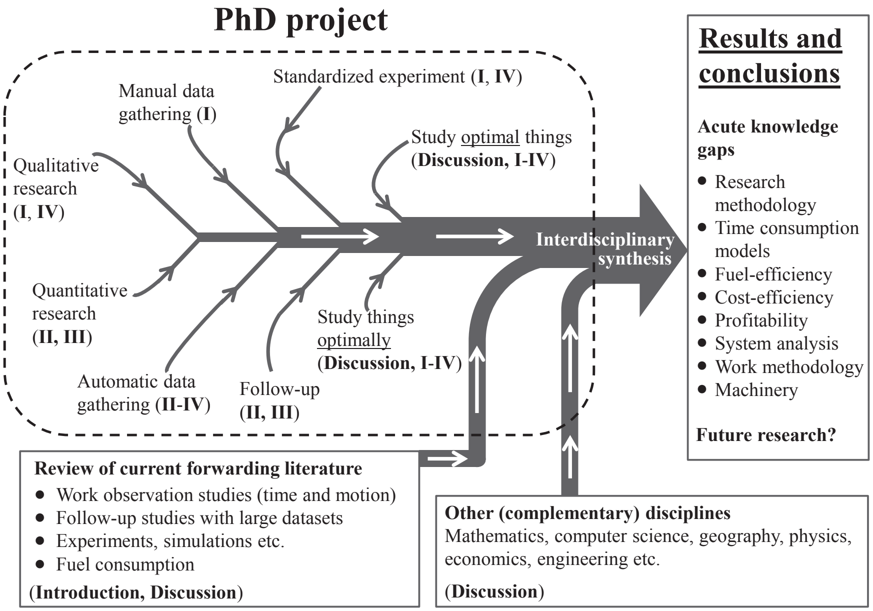

Figure 4. Conceptual framework of the thesis and underlying Studies (I-IV).

2 Materials and Methods

2.1 Standardized field experiment on forwarding (Study I)

In this experiment two factors were varied: the number of assortments (1, 2, 3 or 5) in a load and total log concentration [6.4, 19.2 or 32.0 solid m^3 over bark (m^3ob) per 100 m of strip-road]. Each of eight treatments was replicated three times, with randomised application of treatments during observations. The treatments resulted in six forwarded log concentrations – 1.3, 3.8, 6.4, 7.7, 11.5 or 19.2 m^3ob $(100\ m)^{-1}$ – which were used as a derived factor (see description of analysis below). Calculations of the total log concentration were always based on the presence of equal volumes of all five assortments, irrespective of the number of assortments in a load.

The field experiment was carried out using a standardized test path (Figure 5), representing a strip-road section at a site mimicking a final felling site with no residual trees and good driving conditions. The radius of the test path was about 20 m and the circumference was 125 m. The driving direction was counter-clockwise. The roadside-piles were pre-filled up to 1.5 m from the ground level to correspond to average unloading conditions, i.e. a half full roadside-pile. Each roadside-pile was 9.5 m long and they were placed side by side.

Along the path, there were fixed positions for standard-sized piles (see below). The total log concentration was manipulated by varying the predetermined distance between the piles. To facilitate loading studies, the experimental path was circular so the forwarder never had to reverse. Distances longer than the path circumference were created by having the operator drive multiple laps and pick piles in a predetermined order.

Before the study, ca. 600 logs of *Pinus sylvestris* pulpwood were divided randomly into five groups and colour-marked to represent assortments. Within assortments, four logs constituted a pile with an average volume of 0.26 m^3ob

(SD 0.02). One full load consisted of 30 piles and an average load size was ca. 8 m^3ob.

Forwarding was divided into the work elements loading, loading drive, unloading and unloading drive (driving empty and driving loaded were not included in the study). After a load was completed, a second operator picked up logs from the roadside-piles at the landing and distributed them to the test path to form the next load.

Work elements were defined so that they could not overlap. The work elements loading or loading drive and unloading or unloading drive were differentiated based on tyre rotation. When the tyres were not rotating, the work element was defined as loading or unloading, and when the tyres were rotating the work element was defined as loading drive or unloading drive.

In addition to the work elements, loading and unloading components were observed and used as dependent variables. The time consumption for loading stop, loading crane cycle, unloading stop, unloading crane cycle and driven distance between the first and the last loaded pile in a load was recorded. In addition, numbers of loading stops, unloading stops, piles per loading stop, loading crane cycles per stop, unloading crane cycles per stop and unloading crane cycles per load were used as dependent variables. The number of observations for loading and unloading components varied from 1 to 30 per load (for more detailed information see Paper I). Sorting work was included in the ongoing crane cycle. A preceding crane cycle ended simultaneously with a new one starting.

In this study, the operator had to comply with a set of specific instructions. The work elements were not allowed to be carried out simultaneously, i.e. no crane work was allowed during the driving tasks. At the landing, logs were unloaded onto one side of the road only. Unloading of several assortments at one time i.e. stop between two roadside-piles to unload two assortments simultaneously, was not allowed. However, assortments could be sorted in any possible way.

An eight-wheeled mid-sized forwarder (Valmet 860.1, Komatsu Forest AB), with a maximum payload of 14 000 kg and standard load-space, was used during the study. The 20 year-old male operator in the experiment had one year working experience with forwarders after graduating from three years of vocational training to become a forest machine operator. The field study took place in mid-Sweden, close to the municipality of Rättvik between the 17th and 20th of August 2010. The whole field study was filmed and the time study was carried out afterwards by snap-back timing, based on the film material. Time consumption was measured in PM time.

Effects of factors on dependent variables were analysed by Analysis of Variance (ANOVA) and Analysis of Covariance (ANCOVA). When 1- and 3-assortment loads were compared, over total log concentrations, the design was balanced and enabled two-way ANOVA. Due to the practical limitations of enabling a fully balanced design for all levels of factors, a two-way ANOVA was complemented with one-way ANOVAs that included additional numbers of assortments in a load (2 or 5) at selected total log concentrations [(19.2 or 6.4 m^3ob (100 m)$^{-1}$], respectively. When the two-way ANOVA showed significant main effects of both factors, the effect of forwarded log concentration was analyzed by entering it as a covariate into the one-way ANOVA of the number of assortments in a load, resulting in an ANCOVA model. The models were simplified by pooling data when no significant main and interaction effects were detected. General linear model (GLM) procedures in Minitab 16 (Minitab Ltd.) were used for running the ANOVA models and analyzing pairwise differences (with Tukey's simultaneous test of means). The normality assumption was evaluated by the Anderson-Darling test, and the threshold level of significance was set to 5 %.

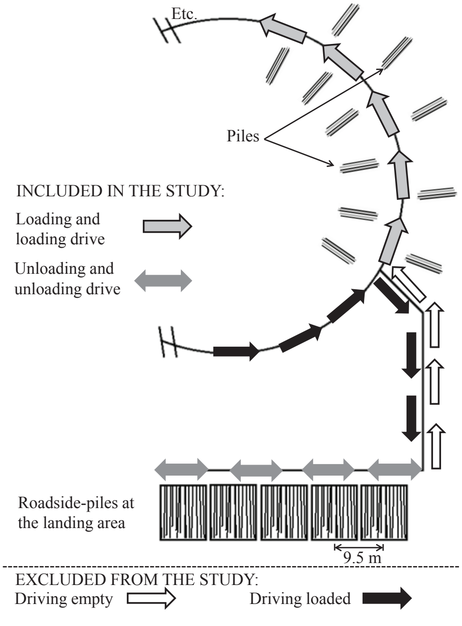

Figure 5. The standardized circular test path defined by an imaginary log distribution. Each pile and roadside-pile contained only one of the five assortments.

2.2 Forwarder work studies with automatic data gathering (Studies II & III)

For Studies II and III follow-up datasets were gathered automatically with the TimberLink machine monitoring system for forwarders, hereafter “TimberLink”.

TimberLink differentiates loading and unloading crane cycles from each other based on Hidden Markov Model (HMM) decoding by the Viterbi algorithm. In practice this means that TimberLink identifies the crane cycle type (i.e. loading or unloading crane cycle) from the combination of grapple position and opening-closing information, while (for instance) possibly available crane-scale information is not used. For example, during the boom-out and boom-in phases of a loading crane cycle the grapple is assumed to be opened and closed, respectively. Similarly, during the boom-out and boom-in phases of an unloading crane cycle the grapple is assumed to be closed and opened, respectively. However, although forwarder crane work is cyclic it also includes exceptions and variations. Therefore, the probabilistic classification algorithm Viterbi is applied to determine the most likely crane cycle type (i.e. loading or unloading) based on the CAN-bus control signals generated by the operator. The algorithm decodes the most likely sequence of hidden states, i.e. fuzzy crane cycle parts, which in turn enables recognition of a complete crane cycle.

Differentiation of loading and unloading crane cycles is crucial because it also enables the recognition of work elements in general (Figure 6). Loading starts simultaneously with the first loading crane cycle, and ends simultaneously with the last loading crane cycle. Similarly, unloading starts simultaneously with the first unloading crane cycle, and ends simultaneously with the last unloading crane cycle.

An ongoing crane cycle, loading or unloading, ends and a new one starts simultaneously when the boom is conclusively removed from the load space after opening the grapple. Here, “conclusively” means after possible sorting work in the load space (which is included in the ongoing crane cycle) has finished.

TimberLink extracts the crane work PM time directly from the CAN-bus, i.e. HMMs are not applied for this. However, not all crane work PM time is recognized as a crane cycle (loading or unloading), but even in such cases it is included in loading or unloading crane work PM time.

Driving events between the first and last loading crane cycles are defined as loading drive and, similarly, driving events between the first and last unloading crane cycles are defined as unloading drive. Driving between the last unloading crane cycle and the first loading crane cycle is defined as driving empty, and similarly, driving between the last loading crane cycle and the first unloading crane cycle is defined as driving loaded. Generally preparation time that may occur between a driving event and crane work, i.e. neither drive nor crane work, is included in “other time”.

Driving pauses (when speed = 0) are excluded from all speed observations and speed is measured only when it is nonzero (speed > 0). However, driving pauses are included in the total driving empty time and total driving loaded time (although they are excluded from the respective PM times). Moreover, driving pauses are excluded from the loading drive time and unloading drive time, which are given as PM time.

Total time, i.e. engine time, includes all time when the engine is running (Figure 7). “Other time” includes interruptions and micro-pauses whenever the engine is running. Forwarding a full load always includes at least six loading and six unloading crane cycles. If this condition of a full load is not fulfilled, a load in question will be defined as an incomplete load. All the observations of work involved in forwarding an incomplete load or loads will be moved to the next load or load(s) until the condition of a full load is fulfilled. Crane work and driving can overlap and no priority rule is applied. More detailed descriptions of work element definitions in TimberLink are presented in Paper III.

In the data gathering phases of Studies II and III, two brand new, large (21.8 tonnes) John Deere 1910E forwarders with 19 ton payload capacity were used. The first was operated by six operators and the second by three operators, giving nine operators in total. The follow-up data were collected during the final felling of stands located in the province of Dalarna, mid-Sweden. However, neither stand-specific characteristics nor forwarded volumes are available. The data were automatically gathered during the normal work and the operators were not aware of the ongoing follow-up study. The operators’ forwarder work experience varied from a few up to more than 20 years.

In Study II, the logging operations with the first forwarder took place from 8.2.2011 to 9.10.2013 (7506 loads), and with the second forwarder from 23.3.2011 to 13.6.2013 (7823 loads). The TimberLink database was transferred from both forwarders to a PC with the TimberLinkOffice-Plus programme installed (TimberLink-Office 2.5.4). The dataset included all variables that could be extracted in text-format from the standard commercial version of TimberLinkOffice-Plus, with one load as the unit of observation. In addition, supplemental fuel consumption readings from the TimberLinkOffice-Plus standard data were derived to make the analyses more complete.

In Study III, the logging operations with the first forwarder took place from 23.3.2011 to 13.6.2013 (6040 loads), and with the second forwarder from

15.10.2012 to 9.10.2013 (2828 loads). Instead of using standard TimberLink datasets, which only include a few time and motion variables, more detailed data were used in Study III (Table 2). TimberLink databases from the machines used in the study were delivered to John Deere Forestry Oy Finland for further processing, using the newest versions of TimberLink's algorithms, which were not in commercial use at the time of writing this thesis.

In the statistical analysis presented in Study II, three-way nested ANOVA was used to analyze effects of the factors machine, operator, and work element on the dependent variables (Eq. 1):

$$y_{ijkl} = \mu + \alpha_i + \beta_{j(i)} + \gamma_k + (\alpha\gamma)_{ik} + (\beta\gamma)_{j(i)k} + \varepsilon_{l(ijk)} \qquad (1)$$

where y_{ijkl} is the dependent variable, μ is the grand mean, α_i is the fixed effect of machine, $\beta_{j(i)}$ is the fixed effect of operator (which is nested with the machine), γ_k is the fixed effect of work element, $(\alpha\gamma)_{ik}$ is the fixed interaction between machine and work element, $(\beta\gamma)_{j(i)k}$ is the fixed interaction between operator and work element, and $\varepsilon_{l(ijk)}$ is the random error term assuming normal and independent distribution. Moreover, when operators were compared within a single work element, the factor work element was removed from the three-way nested ANOVA, resulting in a nested ANOVA.

To obtain general overall results, data for each variable recorded during work by all nine operators were also pooled. One-way ANOVAs or t-tests were used to determine factor's effects from the pooled data collected in Study II, and all the data collected in study III.

In both Studies II and III data distributions were examined by ocular inspection of residual plots and histograms. If the distributions appeared to be non-normal the data were transformed to meet ANOVA requirements. GLM procedures were used to run the ANOVA models, and analyse pairwise differences with Tukey's simultaneous test of means (setting the threshold level of significance to 5 %).

Statistical analyses were performed using the programs Minitab 17 (Minitab Ltd.) and RStudio version 3.0.1 (The R Foundation for Statistical Computing). See Papers II and III for more detailed descriptions of these analyses.

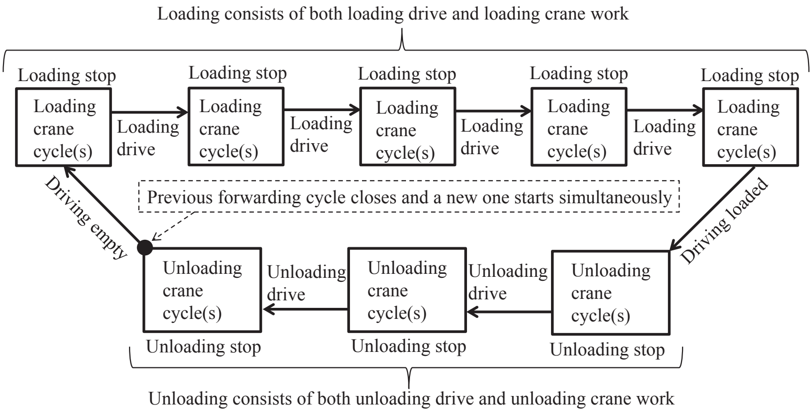

Figure 6. Work element determination in TimberLink.

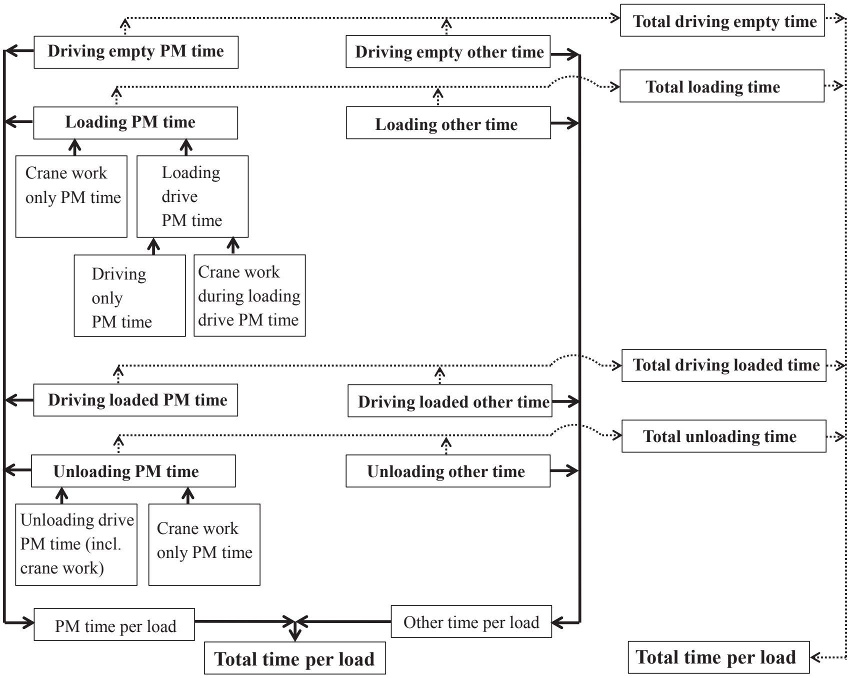

Figure 7. Two alternative ways to derive a total time per load: keeping PM time and other time separated (thicker contiguous flow line); or pooling PM and total time for each of four work elements (thinner dotted flow line).

Table 2. *Variables included in Studies II and III. "Yes" = included in study; "No" = not included in study; for "Overall" see footnote. In Study II data were analysed operator-wise while operator-specific data were not available for Study III. The unit of observation was one load with one exception*(1.

Main work element	Sub -work element, sort	II	III
Driving empty	Total time, minutes/load	No	Yes
	PM time, minutes/load	No	Yes
	Other time, minutes/load	No	Yes
	Driven distance, m/load	No	Yes
	Average drive speed, km/h	Yes	Yes
	Fuel consumption, l/h	Overall(1(2	No
Loading	Total time, minutes/load	No	Yes
	PM time, minutes/load	No	Yes
	Other time, minutes/load	No	Yes
	Crane work only PM time, minutes/load	No	Yes
	Driving only PM time(a, minutes/load	No	Yes
	Simult. crane work and drive time(b, minutes/load	No	Yes
	Loading drive PM time$^{=a+b)}$, minutes/load	No	Yes
	Driven distance, m/load	No	Yes
	Average drive speed, km/h	Yes	Yes
	Number of loading crane cycles, cycles/load	No	Yes
	Average loading crane cycle time, seconds/cycle	yes	Yes
	Fuel consumption (including loading drive), l/h	Overall(1(2	No
Driving loaded	Total time, minutes/load	No	Yes
	PM time, minutes/load	No	Yes
	Other time, minutes/load	No	Yes
	Driven distance, m/load	No	Yes
	Average drive speed, km/h	Yes	Yes
	Fuel consumption, l/h	Overall(1(2	No
Unloading	Total time, minutes/load	No	Yes
	PM time, minutes/load	No	Yes
	Other time, minutes/load	No	Yes
	Crane work only PM time, minutes/load	No	Yes
	Unloading drive PM time(3, minutes/load	No	Yes
	Driven distance, m/load	No	Yes
	Number of unloading cycle, cycles/load	No	Yes
	Average unloading crane cycle time, seconds/cycle	Yes	Yes
	Fuel consumption (including unloading drive), l/h	Overall(1(2	No
Total time(c, minutes/load		Yes	Yes
PM time, minutes/load		No	Yes
Other time, minutes/load		No	Yes
Total driven distance(d, m/load		Yes	Yes
Fuel consumption for driving only(e, l/load		Yes	No
Fuel consumption for crane work only(f, l/load		Yes	No
Fuel consumption for simultaneous crane work and driving(g, l/load		Yes	No
Fuel consumption for other time(h, l/load		Yes	No
Total fuel consumption$^{=e+f+g+h}$, l/load		Yes	No
Fuel consumption for PM time$^{=e+f+g}$, l/load		Yes	No
Total fuel consumption per total driven distance$^{=(e+f+g+h)/d}$, l/km		Yes(2	No
Fuel consumption during the PM time per total driven distance$^{=(e+f+g)/d}$, l/km		Yes(2	No
Total fuel consumption per total time$^{=(e+f+g+h)/c}$, l/h		Yes(2	No

1)Machine-specific overall mean for the whole study period (i.e. no load-specific data available).

2)Included only in Paper II (i.e. excluded from the thesis).

3)May also include simultaneous crane work.

2.3 The energy-efficient hydraulic lift cylinder (EHLC) (Study IV)

The EHLC has a secondary cylinder built into its piston rod, to store potential energy from lowering the boom in the form of pressurized hydraulic oil in an accumulator and using the stored energy in the next boom lift (Figure 8). As the accumulator is pressurized, the product of secondary cylinder pressure (p_2) and secondary piston area (A_2) creates a secondary cylinder force (F_2). As the secondary piston thrusts the primary cylinder head continuously with a F_2 that depends on p_2, it creates an assisting force during boom lifts and a braking force during boom lowering. During boom lifting, the accumulator discharges and p_2 decreases, while a boom lowering charges the accumulator and increases p_2. Thus, F_2 decreases the EHLC's need for external energy inputs. Some losses in p_2 are likely to occur, e.g. due to oil leakage from the secondary to the primary cylinder. If p_1 exceeds p_2 the check-valve opens and the accumulator will be charged from the hydraulic circuit system (Figure 8). Therefore, higher pressure must be maintained in the accumulator and secondary cylinder than in the primary cylinder to obtain an assisting force during a boom lift. Occasional pressure spikes in the hydraulic circuit pass oil through the check-valve and load the accumulator. Thus, occasional pressure spikes that always occur in ordinary hydraulic systems (Manring, 2005), and hence occasional transient check-valve openings, make essential contributions to the EHLC's functionality because they maintain a higher p_2 than p_1 during boom lifts, and compensate for leakage (see the $p_{2\ \mathrm{reference}}$ curve in Figure 9). In addition, the secondary cylinder's lift work (W_2) increases with increasing p_2, which in turn decreases the need of external energy inputs. Thus, check-valve openings caused by occasional pressure spikes should not be confused with "malfunction" of the EHLC, i.e. regularly opened check-valve. Given that $A_2/A_{sp} \approx 0.066$ and $p_1 \leq p_2$ during the entire boom lift, the theoretical minimum energy saving is ca 6.6 % (Figure 8). Technical principles and claims for a flawlessly functioning EHLC mounted on a forwarder crane are described in more detail in Paper IV and the WIPO Patent WO/2011/075034.

Test settings included mechanical restriction of the crane reach at 5.7 m. Moreover, during the experiment, the boom was lifted and lowered by actuating the lift cylinder's directional control valve by use of a joystick. Three settings for the valve's response to the joystick actuations were used, resulting in different directional control valve opening speeds for the same joystick movement, and hence different acceleration and boom speeds, designated "slow", "medium" and "fast". A boom lift with valve setting "slow" was followed by a boom lowering with valve setting "slow" and so on. The experiment took place between the 11th and 13th of July 2011 in Umeå, Northern Sweden and the operator was a 31-year-old male with no previous experience of work with heavy machinery.

The moveable secondary piston will move in the direction of the lower pressure at any given time, since both of the secondary piston's ends have the same area (Figure 8). By closing and opening certain valves in the hydraulic system the accumulator can be overridden, the secondary piston moved inside the primary piston rod, and the EHLC can function as a standard hydraulic lift cylinder (standard cylinder), providing a reference cylinder for comparisons of energy use (Figure 8). Hence, the succeeding lift work will be conducted with assistance from the accumulator, provided that $p_1<p_2$, otherwise the piston will function as a conventional piston. A general model for determining lift work during a given time interval ($W_{t\rightarrow t+1}$) (Eq. 2) was used as a starting point for calculating the work performed by the two compared cylinders.

$$W_{t\rightarrow t+1} = 0.5 \times (p_t + p_{t+1}) \times A_{piston} \times (L_{t+1} - L_t) \qquad (2)$$

Here: p is the cylinder pressure at time t or t+1, A_{piston} is a piston area, and L is the cylinder length at time t or t+1. The work conducted during a given boom lift was calculated by dividing the lift into 10^5 time intervals per second and summing the work for all time intervals.

The standard cylinder's lift work during time interval from t to t+1 ($W_{s,\, t\rightarrow t+1}$) was calculated according to Eq. 2 with p_1 (i.e. the pressure observations retrieved from load cell$_1$, Figure 8) as pressure and A_{sp} as piston area (Figure 8). Calculation of EHLC's lift work in a technically perfect state ($W_{EHLC,\, t\rightarrow t+1}$) was based on p_1 and A_1 as piston area (Figure 8). However, the EHLC might not work perfectly, for instance if p_1 exceeds p_2 during part of a lift.

In this study, the part of a lift where $p_1<p_2$ is referred to as the EHLC's "successful lift phase" (p_2 curve in Figure 9: $t_1\rightarrow t_2$), because during this phase the EHLC is theoretically capable of contributing to the lift with recovery energy. Similarly, the "unsuccessful life phase" refers to the part of the lift after which $p_1>p_2$ for the first time and the EHLC will not be able to contribute to reductions in energy use (p_2 curve in Figure 9: $t_2\rightarrow t_3$).

Lift work calculations for the EHLC's successful lift phase were identical to those for flawless functioning of the EHLC. However, work calculations for EHLC's unsuccessful lift phase varied depending on whether p_1 or p_2 was highest. For time intervals with $p_1>p_2$, the EHLC was assumed to function as a standard cylinder and work was determined correspondingly ($W_{s,\, t\rightarrow t+1}$). For time intervals with $p_1<p_2$ during the unsuccessful lift phase, the EHLC's work was determined as the sums of $W_{EHLC,\, t\rightarrow t+1}$ and the secondary cylinder's lift

work ($W_{2,\, t\rightarrow t+1}$), given that EHLC functionality was regained via loading from the hydraulic circuit during the lift (consuming energy), rather than from use of the recovered potential energy. $W_{2,\, t\rightarrow t+1}$ was calculated according to Eq. 2 with p_2 as pressure and A_2 as the piston area (Figure 8). The energy savings for the EHLC's successful lift phase were determined as the secondary cylinder's proportion of the EHLC's total work during the successful lift phase, which in turn was determined as the sum of the primary and secondary cylinder work.

The statistical analysis only included boom lifts, as boom lowerings were excluded. ANCOVA was used to evaluate effects of three fixed factors (lift cylinder model, payload, and valve setting) on two dependent variables: total work per lift and the initial p_1, retrieved from a load $cell_1$ (Figure 8). The cylinder model factor had two levels (EHLC and standard cylinder), the payload factor had three levels (0, 264 and 513 kg), and valve setting factor had three levels (slow, medium and fast). In total, this resulted in 18 treatments, which were each replicated several times ($15 \leq n \leq 57$).

In addition to the dependent variables mentioned above, the EHLC was also evaluated separately to address its functionality (i.e. without comparison between cylinder models). For such analyses all the cylinder model-related terms were removed from the three-way ANCOVA, resulting in a two-way ANCOVA where the dependent variables analysed were related to pressure in the primary and secondary cylinders as well as work and time during the successful lift phase.

Both the two and three-factorial models included all possible interaction effects between factors. The continuous variables initial and final cylinder length, stroke length and lift time of each boom lift were used as covariates if they significantly contributed to the model, they were considered logical and would not be confounded with treatment effects. To avoid a rank deficiency, the initial and final cylinder lengths were prioritized over the stroke length. The stroke length's effect was tested only if the initial or final cylinder length had no effect.

As in Study I, GLM procedures were used to run the ANOVA and ANCOVA models and analyze pairwise differences (with Tukey's simultaneous test of means). The normality assumption was evaluated by the Anderson-Darling test, and the threshold level of significance was set to 5 %. Differences in initial cylinder pressures within the EHLC were tested for deviation from zero using a one-sample t-test. The critical level of significance was set to 5 %. Minitab 16 (Minitab Ltd.) was used for all these analyses.

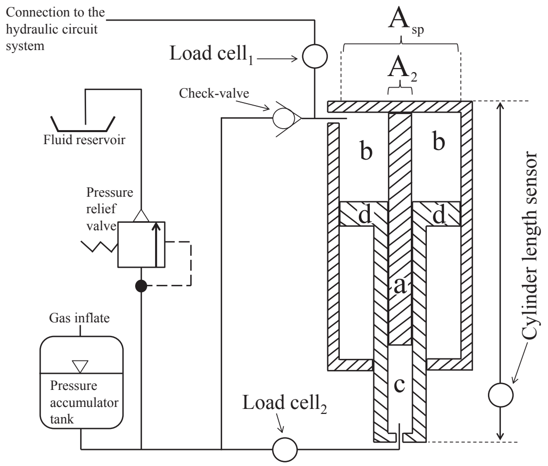

Figure 8. Thordab AB's patented "Energy-efficient hydraulic lift cylinder" (EHLC) with a pressure accumulator tank (accumulator), and a movable secondary piston (a) which divides the cylinder system into primary (b) and secondary cylinders (c). c is housed inside the primary piston rod (d) and connected to the accumulator. When the EHLC functions as a standard cylinder, a is inside d. Primary piston area (A_1=11370 mm^2) is a quotient of the standard piston area (A_{sp}=12174 mm^2) and secondary piston area (A_2=804 mm^2). Load cell$_1$ measured the pressure in the standard or primary cylinder (p_1), while load cell$_2$ measured the secondary cylinder and accumulator pressure (p_2).

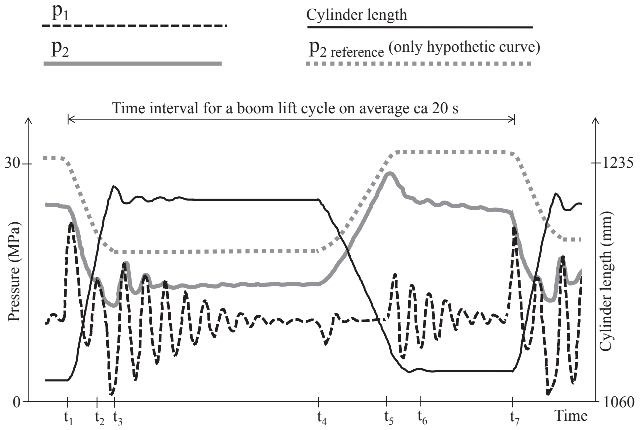

Figure 9. Example of observed pressures and cylinder lengths as functions of time for one whole EHLC boom lift cycle ($t_1 \rightarrow t_7$) with the valve setting "medium" and payload of 0 kg. Boom lift, as well as the successful lift phase, starts at time t_1. The successful lift phase ends at t_2 when the secondary cylinder pressure (p_2) exceeds the primary cylinder pressure (p_1) for the first time. Boom lowering, as well as charging of the accumulator, starts at t_4. During $t_5 \rightarrow t_6$, p_2 drops rapidly because the pressure relief valve opens and oil flows to the oil reservoir (Figure 8). At t_7, a new lift starts. A hypothetical p_2 curve ($p_{2\ \mathrm{reference}}$) for a flawlessly functioning EHLC is also shown. All the curves, except $p_{2\ \mathrm{reference}}$, are based on real experiment observations.

3 Results

3.1 Standardized forwarding field experiment (Study I)

Effects of total log concentration and assortments on work elements

ANOVA showed that the factors total log concentration and number of assortments in a load had significant main effects on the total time consumption per load, i.e. pooled time consumption for the four studied work elements. The total time consumption tended to decrease with increasing total log concentrations, and increase with increases in the number of assortments in a load. Significant interaction was detected, showing that the factors' effects generally (but not always) varied between compared treatments.

ANOVA also showed that loading drive time consumption decreased significantly with increases in both total log concentrations and number of assortments in a load. Significant interaction was detected, showing that the factors' effects generally (but not always) varied between compared treatments. The time consumed by loading, unloading and unloading drive significantly increased with increases in the number of assortments in a load whereas total log concentration had no significant effect in this respect.

Effects of total log concentration and assortments on loading components

ANOVA also showed that neither total log concentration nor the number of assortments in a load significantly affected the loading drive time consumption per unit driven distance. However, they had significant main effects on all the other analyzed loading components except two (the number of piles per crane cycle and loading crane cycle time consumption, for which probabilities of effects were just outside the set level for significance, at $p \geq 0.054$). Significant interaction was detected, showing that the factors' effects generally (but not always) varied between compared treatments. The number of stops per load generally, but not always, decreased with increasing total log concentration and with increases in the number of assortments in a load. Time consumption for loading stop, as well as numbers of piles, loading crane cycles, and piles gathered per crane cycle, all increased with increases in total log concentration.

Effect of the number of assortments at equal forwarded log concentration

Forwarded log concentration varies depending on the number of assortments in a load. Thus, the main effect of the number of assortments in a load might be confounded with this variation in forwarded log concentration. However, ANCOVA showed that at equal forwarded log concentration, time consumption per loading stop increased significantly with increasing number of assortments in a load, while the number of assortments in a load had no significant effect on the loading drive time consumption, number of loading stops per load, the number of piles loaded per stop or the number of crane cycles per stop. The number of loading stops per load decreased significantly as a function of forwarded log concentration, whereas loading drive time consumption, time consumption per loading stop, the number of piles loaded per stop and the number of crane cycles per loading stop increased significantly as a function of forwarded log concentration.

Effect of the number of assortments on unloading components

ANOVA showed that unloading components were significantly affected only by the number of assortments in a load. The total log concentration had no significant effect and there were no interactions between the main effects. Therefore, unloading data were pooled within the number of assortments in a load. Effects of number of assortments on the unloading components were not always linear, but increases in the number generally had either negative or positive effects, depending on the dependent variable. For more detailed information see Paper I.

Forwarded log concentration

The forwarded log concentration was found to most strongly influence forwarding time consumption. The finding was considered more important than the actual time consumption values observed and presented in the study (see Paper I for more detailed results). That finding is intuitively reasonable because the forwarded log concentration is the product of two hierarchical decisions regarding the assortments bucked when harvesting the trees and the assortment mixture in each load. Thus, although forwarding work is a seemingly simple task, it is necessary to acknowledge that it is a complex problem which requires a high level of human decision-making for efficiency.

Thus, the most time-efficient number of assortments in a load depended on assortment-specific log concentrations. At low log concentrations (both forwarded and total), even small changes strongly influenced the forwarding time consumption, whereas the time consumption was almost constant at higher log concentrations.

3.2 Forwarder work studies with automatic data recording (Studies II & III)

Central tendencies and dispersions of the variables included in both Studies II and III (total time consumption, total driven distance, speeds and crane cycle times; Table 2) were nearly identical (cf. Table 3: operators pooled, Tables 4 & 5). Observations of all variables were lognormally distributed except speed and the number of unloading crane cycles, which were normally distributed (complete data not shown). In both studies, there were high levels of dispersion in recorded variables.

There was also substantial dispersion on operator-level (Table 3). For instance, the shortest individual total median driven distance was 14 % below the overall median, while the longest individual median distance was 36 % above the overall median. Similarly, the shortest individual median time was 20 % below the overall median, while the longest median individual time was 23 % above the overall median. The dispersions were approximately of the same magnitude, in terms of percentiles, for both overall medians and individual operator data.

Loading, unloading, driving empty and driving loaded PM time accounted for, on average, ca. 46, 19, 9 and 8 % of total forwarding time consumption respectively, while other time accounted for the remaining ca. 14 % (based on means, Table 4). Moreover, simultaneous crane work and driving occurred during 6.7 % of the loading PM time (based on means, Table 4). Transportation-only distances collectively accounted for 56.2 %, while loading and unloading drive distances accounted for 39.5 % of the total driven distance (based on means, Table 5). In addition, 4.3 % of the total driven distance could not be classified.

Fuel consumption values for all tested individual work elements significantly differed (Table 6: operators pooled). Typically, driving-only accounted for most (ca. 50 %) of the total fuel consumption per load, followed by crane-work-only (ca. 40 %), simultaneous crane work and driving (ca. 5 %), and other time (slightly over 2 %), based on medians (Table 6: operators pooled). Findings for individual operators were in line with the findings for the pooled data, with three exceptions. For operators 3, 6 and 7, the fuel consumption values for driving-only and crane-work-only were not significantly different (Table 6).

Table 3. *Speed during driving, time consumption for loading and unloading crane cycles, total time and total driven distance per load. Rows 1-9 represent an operator which in turn is nested with one of two machines. Means are followed by standard deviation (SD) in parentheses, while medians are followed by fifth and 95th percentiles (perc.) in brackets. The unit of observation is one load.*

			Speed [km/h]$^{(1}$			Time consumption per crane cycle [second/cycle]$^{(2}$		Total driven distance per load [m]$^{(3}$	Total time consumption per load [minutes]$^{(4}$
			Driving empty	Loading drive	Driving loaded	Loading	Unloading		
Ma.	Op.	n	Mean, SD	Mean, SD	Mean, SD	Median, perc., stat.	Median, perc., stat.	Median, perc., stat.	Median, perc., stat.
1	1	3441-3638	2.9^{A} (1.1)	1.8^{B} (0.6)	2.4^{CDE} (0.8)	26.6 [21.7; 33.4] a	24.6 [19.3; 31.9] b	638 [216; 1702] AB	50.1 [22.6; 88.7] *a*
1	2	801-899	3.7^{F} (1.2)	2.2^{G} (0.6)	2.8^{A} (0.9)	23.8 [19.6; 30.6] cd	22.6 [18.2; 30.1] e	805 [245; 1723] C	47.8 [22.9; 80.3] *a*
1	3	795-841	3.4^{H} (1.0)	2.3^{CDE} (0.6)	2.7^{I} (0.8)	21.8 [17.8; 27.2] f	25.2 [17.9; 36.9] gb	635 [210; 1452] BD	41.4 [18.6; 77.7] *b*
1	4	238-256	3.4^{H} (1.0)	2.2^{EG} (0.6)	2.6^{IJ} (0.7)	30.7 [24.9; 37.8] h	24.7 [19.5; 33.5] gbc	909 [286; 1877] C	52.9 [23.3; 93.8] *a*
1	5	939-1225	3.1^{KL} (1.1)	2.1^{G} (0.8)	2.4^{JCD} (0.9)	24.7 [19.3; 39.4] g	23.3 [18.0; 33.2] d	803 [288; 1974] C	49.1 [27.1; 86.8] *a*
1	6	628-647	3.3^{H} (1.1)	2.1^{G} (0.5)	2.8^{AM} (0.9)	28.6 [22.4; 36.2] i	24.5 [18.9; 33.6] bc	645 [215; 1615] AB	48.1 [20.2; 86.3] *ac*
2	7	852-985	3.2^{K} (1.0)	2.4^{JC} (0.7)	3.0^{LO} (0.9)	26.7 [19.7; 42.0] j	27.8 [20.2; 42.8] i	579 [171; 1405] D	43.3 [19.2; 93.9] *c*
2	8	3573-3978	3.2^{K} (1.0)	2.3^{DE} (0.6)	2.9^{OA} (0.8)	20.0 [16.4; 25.5] l	20.5 [15.8; 27.6] k	652 [165; 1732] B	39.4 [16.8; 76.9] *b*
2	9	2438-2860	3.8^{P} (0.9)	2.7^{MI} (0.6)	3.4^{H} (0.9)	21.8 [17.7; 27.0] f	20.6 [15.8; 27.9] k	690 [198; 1695] A	34.3 [16.9; 64.4] *d*
Op. pooled		13705-15329	3.3^{A} (1.1)	2.2^{B} (0.7)	2.8^{C} (0.9)	23.2 [17.6; 33.4] A	22.6 [16.8; 32.4] B	670 [200; 1709]	43.1 [18.9; 81.7]

1)The data were normally distributed. 2) 3) 4)The data were lognormally distributed and transformed to meet analysis of variance (ANOVA) requirements.

Op. 1-9:
1)27 Means in total that do not share a superscript uppercase letter are significantly different (three-way nested ANOVA with Tukey test, $p<0.05$).
2)18 groups in total that do not share a lowercase letter are significantly different (three-way nested ANOVA with Tukey test, $p<0.05$).
3)9 groups in total that do not share an uppercase letter are significantly different (nested ANOVA with Tukey test, $p<0.05$).
4)9 groups in total that do not share a lowercase italic letter are significantly different (nested ANOVA with Tukey test, $p<0.05$).

Op. pooled:
1)3 means in total that do not share a superscript uppercase italic letter are significantly different (one-way ANOVA with Tukey test, $p<0.001$).
2)2 groups in total that do not share an uppercase letter are significantly different (one-sample t-test, $p<0.001$, data met statistical requirements).

2)3)4)Note: pairwise differences concern groups – not medians. Means of transformed observations used in ANOVA are not shown.

Table 4. *Forwarding time consumption (minutes/load). Total time consumption consists of productive machine (PM) time and other time. Means are followed by SD in parentheses, while medians are followed by median absolute deviation (MAD) in brackets. In addition 5th, 25th, 75th and 95th percentiles are given to provide a general understanding of the distribution of observations for each time element. The unit of observation is one load and unit of analysis is a minute per load. The number of observation varied from 8555 to 8868.*

			Percentiles			
Time element	Mean, SD	Median, MAD	5th	25th	75th	95th
Total driving empty time	7.0 (7.7)	5.2 [3.2]	0.3	2.5	9.1	19.1
Driving empty PM time	4.3 (3.6)	3.5 [2.1]	0.2	1.7	5.9	11.1
Driving empty other time	2.3 (5.8)	0.5 [0.5]	0.0	0.1	2.3	9.3
Total loading time	22.9 (16.0)	19.9 [6.6]	8.5	19.9	27.6	45.5
Loading PM time	21.0 (11.8)	18.8 [6.1]	8.2	13.4	25.9	40.0
Loading other time	1.9 (7.3)	0.5 [0.4]	0.1	0.2	1.4	7.7
Crane work only PM time	14.3 (7.2)	13.0 [3.7]	6.0	9.7	17.4	26.2
Simultaneous crane work and driving(a	1.4 (1.5)	0.9 [0.6]	0.1	0.4	1.9	4.2
Driving only PM time(b	5.3 (5.0)	4.2 [2.2]	0.7	2.3	6.8	13.2
Loading drive PM time=a+b)	6.7 (5.7)	5.6 [2.7]	1.1	3.1	8.7	16.0
Total driving loaded time	4.8 (4.2)	3.7 [2.2]	0.5	1.8	6.5	12.7
Driving loaded PM time	3.8 (3.6)	2.8 [1.9]	0.1	1.2	5.3	11.1
Driving loaded other time	0.6 (1.6)	0.3 [0.2]	0.0	0.1	0.6	2.0
Total unloading time	10.2 (9.9)	8.2 [2.5]	3.7	6.0	11.3	23.0
Unloading PM time	8.8 (5.8)	7.5 [2.2]	3.5	5.6	10.2	18.8
Unloading other time	1.4 (6.2)	0.3 [0.3]	0.0	0.1	1.1	4.7
Crane work only PM time	7.4 (3.8)	6.8 [1.7]	3.2	5.2	8.8	13.4
Unloading drive PM time(1	1.4 (2.8)	0.5 [0.4]	0.0	0.2	1.5	6.1
Total time per load	45.8 (24.1)	42.1 [11.8]	19.1	31.0	55.3	84.5
PM time per load	39.3 (17.4)	36.8 [10.1]	17.3	27.5	48.2	68.2
Other time per load	6.5 (11.9)	3.4 [2.2]	0.6	1.6	7.1	21.6

1) May also include simultaneous crane work.

For more detailed work element definitions see *Figure 7*.

Table 5. *Some descriptive forwarder work variables followed by corresponding units. Means are followed by SD in parentheses, while medians are followed by MAD in brackets. In addition 5th, 25th, 75th and 95th percentiles are given. The unit of observation is one load.*

Variable	Sort	Mean, SD	Median, MAD	Percentiles			
				5th	25th	75th	95th
Driving empty distance	m/load	256.0 (234)	199.4 [129.3]	4.9	90.6	358.1	702.1
Loading drive distance	m/load	236.8 (255.3)	183.0 [91.0]	37.3	102.5	289.3	596.1
Driving loaded distance	m/load	182.0 (172)	134.8 [95.7]	3.1	52.4	262.4	524.2
Unloading drive distance	m/load	71.4 (166.4)	18.6 [17.2]	0.0	4.3	72.4	305.4
Extraction distance(1	m/load	219.0 (177.5)	173.9 [99.8]	24.8	87.6	302.1	578.6
Total driven distance	m/load	779.8 (518.5)	666.2 [275.0]	197.2	425.5	1006.8	1720.2
Driving empty speed(2	km/h	3.4^{a} (1.0)	3.3 [0.5]	1.8	2.8	3.9	5.1
Loading drive speed	km/h	2.1^{b} (0.5)	2.0 [0.3]	1.3	1.7	2.4	3.0
Driving loaded speed	km/h	2.9^{c} (0.8)	2.8 [0.5]	1.6	2.4	3.4	4.4
Loading crane cycle numbers(3	cycles/load	34.9^{a} (12.0)	34.0 [7.0]	17.0	27.0	42.0	56.0
Unloading crane cycle numbers	cycles/load	16.7^{b} (5.9)	16.0 [3.0]	9.0	13.0	20.0	25.0
Loading crane cycle time	s/cycle	23.7 (5.2)	22.5 [2.8]	17.6	20.2	26.2	33.3
Unloading crane cycle time	s/cycle	23.4 (5.3)	22.5 [3.0]	16.9	19.8	25.9	33.0
Proportion of crane work during loading drive PM time	%	22.1 (16.3)	18.3 [9.1]	3.1	10.4	29.8	53.8

1)Extraction distance = (driving empty distance + driving loaded distance)/2

2)Different superscript letters within variable sort indicate significant differences ($p<0.001$, one-way ANOVA with Tukey test, n=8868).

3)Different superscript letters within variable sort indicate significant differences ($p<0.001$, paired t-test, n=8868). Differences between the pairs were normally distributed.

Table 6. *Fuel consumption (litre/load) given in medians with fifth and 95th percentiles (perc.) in brackets. PM fuel consumption does not include consumption during other time. Rows 1-9 represent an operator (Op.) which in turn is nested with one of two machines (Ma.). The original data were lognormally distributed and transformed before performing the statistical tests (stat.). The unit of observation is one load.*

			Individual work elements(1				Aggregated work elements	
			Driving only	Simultaneous crane work and driving	Crane work only	Other time	PM fuel consumption(2	Total fuel consumption(3
Ma.	Op.	n	Median, perc., stat.	Median, perc., stat.	Median, perc., stat.	Median, perc., stat.	Median, perc., stat.	Median, perc., stat.
1	1	3638	4.1 [1.3; 10.2] ab	0.5 [0.1; 1.4] c	3.6 [1.7; 5.4] de	0.1 [0.0; 0.8] f	8.5 [3.7; 15.6] A	8.7 [3.8; 16.2] *a*
1	2	899	5.2 [1.5; 10.7] gh	0.5 [0.1; 1.3] c	3.8 [2.2; 5.5] bdij	0.2 [0.0; 1.2] k	9.7 [4.5; 15.9] B	10.1 [4.6;16.6] *bc*
1	3	841	4.2 [1.4; 9.2] abij	0.2 [0.0; 0.4] lm	3.7 [1.8; 5.6] deij	0.1 [0.0; 1.1] fl	8.1 [3.8; 13.7] AC	8.4 [3.8; 14.5] *ade*
1	4	256	5.5 [1.6; 10.9] gn	0.6 [0.2; 1.3] c	4.1 [2.3; 5.7] abdhij	0.1 [0.0; 0.7] flm	10.4 [4.5; 16.7] B	10.6 [4.6; 17.3] *b*
1	5	1225	5.2 [2.0; 11.9] g	0.2 [0.0; 0.7] o	3.5 [2.1; 5.2] dej	0.2 [0.0; 0.7] kp	9.2 [4.6; 16.5] BD	9.4 [4.8; 16.8] *bc*
1	6	647	4.2 [1.4; 10.2] abi	0.4 [0.1; 1.1] q	4.2 [2.0; 6.5] abij	0.2 [0.0; 1.0] kop	8.9 [4.0; 16.2] D	9.2 [4.1; 17.2] *c*
2	7	985	3.4 [1.1; 7.7] er	0.1 [0.0; 0.4] s	3.2 [1.5; 6.0] er	0.2 [0.0; 0.9] kop	7.0 [2.9; 12.5] E	7.2 [3.0; 13.3] *f*
2	8	3978	4.0 [0.9; 10.1] ij	0.4 [0.1; 1.2] t	3.2 [1.6; 5.1] t	0.2 [0.0; 0.9] op	7.8 [3.0; 14.9] C	8.1 [3.1; 15.5] *e*
2	9	2860	4.4 [1.3; 10.2] an	0.3 [0.1; 0.8] u	3.1 [1.7; 5.1] r	0.1 [0.0; 0.7] m	8.0 [3.7; 14.9] A	8.3 [3.8; 15.3] *d*
Op. pooled		15329	4.2 [1.2; 10.3] *A*	0.4 [0.0; 1.1] *B*	3.4 [1.7; 5,4] *C*	0.2 [0.0; 0.9] *D*	8.3 [3.6; 15.4]	8.5 [3.7; 15.9]

The data were lognormally distributed and transformed to meet ANOVA requirements.

Op. 1-9: 1)36 groups in total that do not share a lowercase letter are significantly different (three-way nested ANOVA with Tukey test, $p<0.05$).

2)9 groups in total that do not share an uppercase letter are significantly different (one-way ANOVA with Tukey test, $p<0.05$).

3)9 groups in total that do not share a lowercase italic letter are significantly different (one-way ANOVA with Tukey test, $p<0.05$).

Op. pooled: 1)Four groups in total that do not share an uppercase italic letter are significantly different (one-way ANOVA with Tukey test, $p<0.001$).

Note: pairwise differences concern groups – not medians. Means of transformed observations used in ANOVA are not shown.

3.3 Energy-efficient hydraulic lift cylinder (EHLC) (Study IV)

The EHLC's overall functionality during the experiment

The EHLC's functionality depends on p_2 exceeding p_1 (Figure 8). However, this never occurred during a full boom lift, only during various intervals of the first part of the boom lift, i.e. "successful lift phases". With valve settings "medium" and "fast", p_2 exceeded p_1 at the beginning of a lift (Figure 9: t_1). During this "successful lift phase" (Figure 9: $t_1 \rightarrow t_2$), the accumulator contributed recovered energy from the preceding lift. Meanwhile, during the rest of the lift (Figure 9: $t_2 \rightarrow t_3$), no potential energy was recovered as the accumulator was re-loaded from the hydraulic circuit (consuming energy) rather than using recovered potential energy.

During the next boom lowering, the accumulator was loaded as $p_1 < p_2$ (Figure 9: $t_4 \rightarrow t_5$). When p_2 exceeded approximately 30 MPa, the accumulator stopped charging, indicating that the pressure relief valve was released at that pressure (Figure 9: $t_5 \rightarrow t_6$).

EHLC's successful lift phase

With the valve setting "slow", the initial p_1 was already significantly higher than p_2, thereby eliminating the possibilities of energy recovery even before starting to lift the boom. Consequently, only data obtained with the valve settings "medium" and "fast" were further analysed.

During the successful lift phase, with the valve settings "medium" and "fast", EHLC saved 7.0-9.4 % of energy. This energy-saving percentage increased significantly with decreasing payload. However, the practical energy savings were minor since the successful lift phase covered only 0.3-17.7 % of the total stroke length for all the tested treatments with one exception (52.3 % when lifting 0 kg with the valve setting "medium").

Comparison of the EHLC and standard cylinder

In three out of nine cases, the initial p_1 was significantly lower for the EHLC than for the standard cylinder, while in the other six cases there was no significant difference in this respect. Moreover, when evaluating a full boom lift, the EHLC functioned best when payloads of 513 and 0 kg were lifted with the valve setting "medium". Under these conditions, a lift with the EHLC consumed significantly (2.1-3.2 %) less energy than a lift with the standard cylinder. However, for a full lift of 264 kg with the valve setting "fast", the EHLC consumed significantly more energy (17.8 %) than the standard cylinder.

Evaluation of the EHLC

The results showed that the EHLC did not work as expected, at least partly because of internal oil leakage between the primary and secondary cylinders. The leakage was most pronounced with the valve setting “slow” because the volume of leaked oil increased with increasing time, and “slow” resulted in the longest complete crane cycles. However, the leakage was notable even under conditions providing the best EHLC performance (lifting 0 kg with the valve setting “medium”). An example of leakage from the secondary cylinder is shown in *Figure 9*; here, the leakage was responsible for the decline in p_2 during the time interval $t_6 \rightarrow t_7$ (when the pressure relief valve was closed, see Figures 8 & 9).

Moreover, the EHLC’s accumulator gas volume was too small in relation to the changes in the secondary cylinder oil volume during the boom liftings and lowerings. This is also apparent in *Figure 9*, as p_2 decreases sharply as a function of cylinder length during lift period $t_1 \rightarrow t_2$, and correspondingly increases rapidly during lowering until the pressure relief valve opens ($t_4 \rightarrow t_5$). According to Boyle’s law, increasing the accumulator gas volume would solve this problem as it would stabilize p_2 or reduce its peak-to-peak amplitude. The main problem here is not that the maximum p_2 is too low (it is already regulated by the pressure relief valve, as previously described) but that p_2 decreases rapidly to a low level.

4 Discussion

There is a clear tendency to automate the gathering of work performance data for CTL logging operations. Reasons for this trend, and hindrances, are discussed in *Section 4.1*. Differences between automatically (Studies II & III) and manually (previous literature) gathered forwarding follow-up and work-observation datasets are discussed in *Section 4.2*. Issues such as possible sources of observation error, dealing with possible observation errors, and potential for improving the reliability of automatically gathered forwarding performance data are discussed in *Section 4.3*. Alternative methodologies for determining fuel consumption in forwarders are reviewed in *Section 4.4*. Alternative data gathering and research methodologies for forwarder work and machinery are reviewed in *Section 4.5*. Gaps in forwarding research and some possible development pathways for the future are scrutinized in *Section 4.6*. Finally, conclusions from the studies are summarized in *Section 4.7*.

4.1 From manual to automated data gathering in CTL logging operations

Traditionally, forest work data were collected manually, e.g. by using stop watches and notebooks, and subsequently handheld field computers, in field studies. Because manual data collection is labour intensive, the resulting datasets are often small, due in large part to financial limitations (e.g. Kellogg & Bettinger, 1994; McNeel & Rutherford, 1994; Gullberg, 1995; Tufts, 1997; Tiernan *et al*., 2004; Mederski, 2006; Nurminen *et al*., 2006; Stankić, 2012). Therefore, in recent decades there has been a shift to automatic data gathering in harvester work research, and manual data gathering now has only a minor supplementary role (Nuutinen, 2013). Automated data gathering for harvester work has become effortless since StanForD harvester files alone include highly detailed automatically gathered production and work performance data, which are easily available for every user through an onboard PC computer (see Arlinger *et al*., 2012; Möller *et al*., 2013). Basically, the measurement and bucking system that was initially required for optimized stem bucking currently also enables the recognition of harvester work elements in detail for work monitoring purposes. Moreover, information from the StanForD files can be coupled to CAN-bus data, thereby further increasing the number of work element variables that can be accessed.

In contrast to harvester work research, the automation of data gathering in forwarding research is an ongoing and incomplete process. Datasets for forwarding time consumption are still collected mainly manually using handheld field computers in time and motion studies, i.e. work observation methodology (see e.g. Kellogg & Bettinger, 1994; McNeel & Rutherford, 1994; Gullberg, 1995; Tufts, 1997; Tiernan *et al*., 2004; Mederski, 2006; Nurminen *et al*., 2006; Paper I). Information from GNSS dataloggers is being used in some studies of both forwarder and skidder work (e.g. Taylor *et al*., 2001; Cordero *et al*., 2006; Strandgard & Mitchell, 2015; Spinelli *et al*., 2015). However, the sparse forwarding follow-up studies are mostly based on records extracted from forest companies' own information systems (see e.g. Holzleitner *et al.,* 2011; Eriksson & Lindroos, 2014). Such follow-up studies are representative, but the accuracy of recordings varies as many essential parts are generally reported by the operators themselves. In contrast, forwarding datasets with well-documented variables can be obtained from standardized experiments (e.g. Study I), which facilitate straightforward isolation of factors' effects, but generate small datasets with questionable generalisability.

Studies II and III were the first forwarding studies based on fully automatically gathered follow-up datasets with work-element specificity and one load as the unit of observation. An obstacle in the automation of forwarding data gathering is that forwarding has substantially different characteristics from harvester work, and automatically gathering work-element data is substantially more complex. A forwarder's CAN-bus data provide access to relevant information regarding (for example) the forwarder's steering, speed, and crane use, but not essential indications of whether the machine is loading or unloading. This is because essential links between control signals and work elements are missing, even separating forwarding into separate loads is impossible. Therefore, some supplemental methodology that provides additional information is required, for example application of classification and probabilistic algorithms to the control signals (Studies II & III.

In addition to providing larger datasets, automated data gathering also has other advantages. For example, attaching automated dataloggers to the CAN-bus enables researchers to collect much more precise data regarding all work elements than traditional time studies based on visual observation of logging operations (e.g. Väätäinen *et al.*, 2003; Palander *et al.*, 2013). The discrepancies between manually and automatically recorded durations are generally small for the main work elements, but it is difficult for human observers to recognize minor work elements or details (Väätäinen *et al.*, 2003). Inexperienced observers especially tend to miss short work cycles and details (Nuutinen *et al.*, 2008). Thus, there is a risk of variations in human observers' skills affecting the results, and furthermore, complicating comparisons of different studies. Moreover, the automation of data gathering presumably decreases the risk of observer-effects, i.e. the risk that observed individuals change their behaviour when monitored, assuming that the observed individuals are not aware of them being studied (see e.g. Mayo, 1933; Vöry, 1954). Essentially, most differences between manually and automatically gathered work-observation datasets apply to all kinds of focal work, not only CTL logging. In addition, forest-work datasets may also be combinations of manually and automatically collected data (see e.g. Purfürst, 2010; Strandgard *et al.*, 2013). Indeed, according to Väätäinen *et al.* (2003), such combinations provide the best results. This is an intuitively sound finding since numerous variables (e.g. quality of bucked logs, damage to remaining trees and environmental factors) should also be taken into account when analysing productivity in many cases, but recording them automatically is challenging or impossible (see Sirèn, 1998).

4.2 Manually and automatically gathered forwarding datasets

Results of Studies II and III were intuitively logical and consistent with previous findings based on manually gathered data (see discussions in Papers II & III). There are no other large-scale follow-up datasets on forwarding with one load as the unit of observation, but the observed log-normal distributions are consistent with data presented by Eriksson and Lindroos (2014) from a study with one stand as the unit of observation. Moreover, positively skewed datasets are generally very common in natural and technical sciences, for instance from harvester work (see e.g. Palmroth, 2011; Purfürst & Erler, 2011).

However, some minor differences between the automatically and manually collected data were found (see discussions in Papers II & III), which to some extent may have originated from TimberLink's rigid work cycle definition. For instance, if a forwarder operator picks up “an extra pile” clearly after a particular loading drive phase, a human observer may ignore the “extra pile” when determining driving phases. In contrast, TimberLink distinguishes different driving phases systematically according to the given rules, which may lead to relatively longer loading and relatively shorter driving loaded phases. For the driving empty phase, the relative effects are opposite since TimberLink recognizes a loading drive as starting from the pick-up of the first pile, regardless of its proximity to the landing area. TimberLink might also, depending on terrain conditions, slightly overestimate driving distances and speeds due to wheel slip (see e.g. Ringdahl, 2012). However, a measurement is always just an approximation, and this applies also for manual recording.

Moreover, dangling the grapple inside or outside load-space, without actively actuating it, is not classified as crane work by TimberLink. This classification is applied even if the grapple is holding a log, while a human observer could consider this case as simultaneous crane-work and driving. A human observer is not capable of recording the shortest micro-pauses as accurately as automatic dataloggers (see e.g. Väätäinen *et al*., 2003; Nuutinen *et al*., 2008). Consequently, the proportion of “other time” in the TimberLink dataset was higher than corresponding proportions presented in previously published, manually gathered, forwarding datasets (cf. Kuitto *et al*., 1994; Väkevä *et al*., 2001; Table 4).

In conclusion, TimberLink’s rigid work cycle definition can mostly be considered a strength rather than a weakness as it has largely beneficial consequences, but it should be taken into consideration when analyzing data. Furthermore, the rules for defining work elements are changeable, thus the above comments may not remain valid in the near future. Finally, although this discussion only directly concerns TimberLink, the principal methodological differences between manual and automatic data gathering are universal.

4.3 Potential and limitations of automatically gathered forwarding datasets

In Studies II and III, large automatically gathered follow-up datasets with one load as the unit of observation were used for the first time in forwarding work analysis. In addition to the abovementioned differences from manually gathered datasets (see Section 4.2), the datasets analyzed in both studies included sporadic numbers of unexpectedly extreme observations. This was possibly, for some of cases, due to use of the Viterbi classification algorithm. The algorithm is reportedly robust for classifying clearly cyclic work such as harvester work (see Palmroth, 2011). Forwarding of a single-assortment load can also be considered cyclic in this context, with minor exceptions such as an occasional pile accumulation within a loading crane cycle. However, other parts of forwarding work are non-cyclic, such as the unloading of loads that contain several assortments (which involves much assortment sorting leading to both unloading and loading crane cycles), thereby generating complex control signals (see Paper I).

Hence, the non-normal data in Studies II and III included a minor number of outliers, which may have resulted from failure of work element determination, most intuitively when handling loads containing several assortments. However, the data were not filtered, since it was not known if outliers were measurement errors or extreme observations and (thus) possibly essential parts of forwarding work. However, the transformation effectively normalized the data distributions, thus the outliers' effects on the ANOVA results were minor or non-existent (see Papers II & III for regression analyses). Moreover, medians can be considered more robust to outliers than arithmetic means (see Tables 3-6), or alternatively use of geometric means is a common and robust measure of central tendencies in back-transformed lognormal data. However, if a unit of observation was a stand – instead of a forwarder load as in Studies II and III – designating the range of plausible observations would be easier since reasonable observation ranges are often well known. For instance, Eriksson and Lindroos (2014) removed all the stands from their large forwarding follow-up dataset which did not comply with given conditions. Moreover, as relative dispersion in data intuitively decreases with increases in the unit of observation's magnitude, stand-level variation should be more moderate than load-level variation.

Developing the automated data gathering technology is likely to be a sounder alternative than trying to find an algorithm for outlier removal, at least on load-level. For instance, GNSS-based applications or use of crane-scale information could open new possibilities for improving the reliability of automatically gathered forwarding datasets. When a loaded grapple (i.e. additional mass) is moved to the load-space and an unloaded grapple (i.e. no additional mass) is moved from the load-space, the forwarder is probably loading. Similarly, when an unloaded grapple is moved to the load-space, and a loaded grapple is moved from the load-space, the forwarder is probably unloading. There are also other possibilities for distinguishing work elements. For instance, when the crane is in use at a roadside landing area, the forwarder is probably unloading; and when it is in use at a harvesting site, the forwarder is probably loading (see Figure 3). Some promising results of using GNSS for work element recognition have already been reported (see e.g. Strandgard &

Mitchell, 2015). Indeed, crane cycle recognition could be greatly refined by using a combination of technological options such as classification algorithms, GNSS, and scale information. The capability to differentiate loading and unloading crane work is essential because it also enables recognition of other work elements as explained in *Section 2.2*.

With use of crane-scale data, the handled log volumes could be approximated (by lifted weight) even for each crane cycle. However, scale data do not provide any automatic assortment information. Even if automated forwarding data gathering is currently impossible with load-wise assortment-specificity, there is still untapped technical potential. Modern harvesters produce .hpr files which include volume and assortment data for each harvested log (e.g. Jönsson *et al.,* 2011; Möller *et al.,* 2013). In addition, .hpr files include log-wise coordinates of the harvester's cab at the time when each log was cut. Thus, .hpr files enable 2-dimensional maps of assortment volumes via the geographical position of the harvester's cab. Access to such spatial data enables more unbiased comparisons in forwarding research.

Meanwhile, upgrading the automatic forwarding data gathering to assortment-specificity would require more accurate spatial data of on-ground logs and forwarder grapple positioning than is currently possible (see e.g. Lindroos *et al*., 2015). Alternatively, during unloading, load-wise assortment proportions might be derived, from the following three data sources: 1) crane-scale data; 2) CAN-bus and spatial data on forwarder grapple use; 3) spatial data on roadside-piles at the landing. But again, the accuracy of today's spatial data brings the feasibility of this methodology into question. Instead, the use of Radio-Frequency Identification (RFID) might be technically more achievable (see e.g. Gjerdrum, 2009; Picchi *et al*., 2015). In this alternative method, harvesters equip each log with a tag that includes assortment and volume data. The forwarder then, along with the ordinary work, automatically reads the tags and saves the necessary data for the later use.

Moreover, when analysing productivity, there are numerous variables that often should be taken into account but which can be difficult to record automatically. Examples of these variables include work quality, damage to remaining trees, and environmental factors (see e.g. Sirèn, 1998).

4.4 Fuel consumption estimation

Essentially, the design principles that apply to forwarding time consumption studies also apply to forwarding fuel consumption studies. Follow-up studies provide large and representative datasets, often including data related to several machine models, but no work-element-specific fuel consumption readings or load-wise information (see e.g. Rieppo & Örn, 2003; Holzleitner *et al*., 2011). In contrast, standardized experiments provide detailed work-element-specific fuel consumption readings, but (in addition to limited representativeness) it is uncertain how well the experimental design corresponds to real-life working conditions (see e.g. Brunberg *et al*., 2000, 2005). In this respect, work observation studies are a compromise (see e.g. Nordfjell *et al*., 2003), providing fuel consumption readings for the main work elements and data reflecting ordinary work, but they have limited representativeness due to the relatively small number of studied loads.

In addition to the abovementioned alternative study designs, there are also several technological options for determining volumes of consumed fuel. Traditionally, forwarders' fuel consumption has been measured using a mass flow meter, or gravimetrically using a portable fuel tank coupled to the forwarder's fuel system (see e.g. Nordfjell *et al*., 2003; Rieppo & Örn, 2003; Brunberg *et al*., 2005; Jönsson & Löfroth, 2007). Mass flow meters can be mounted on the machines to report volumes of fuel consumed or on roadside reservoir tanks to report fuel refill volumes as described for instance by Nordfjell *et al*. (2003) and Rieppo and Örn (2003), respectively. Generally, such approaches are direct methods of measuring fuel consumption because the volume or weight of fuel consumed is measured *per se*. Alternatively, fuel consumption readings can be derived mathematically from CAN-bus messages of modern forwarders. These provide indirect estimates (rather than measurements *per se*) of fuel consumption based on a function (see e.g. Paper II). All modern forwarders are equipped with a user interface, i.e. an onboard computer, which provides "nearly continuous" fuel consumption readings, based on indirect measurements, for monitoring purposes. However, the specificity of fuel consumption readings varies among manufacturers (cf. e.g. John Deere Forestry Oy, 2015; Komatsu AB, 2015; Ponsse Oyj, 2015).

For research on forest machine work, access to the "nearly continuous" fuel flow volumes is a strength of deriving data from the CAN-bus messages. It enables separate determination of fuel consumption even for the most minor work elements, along with the ordinary work. In contrast, current scientifically acknowledged methodology provides at most fuel consumption readings for the four main forwarder work elements (Nordfjell *et al*., 2003).

However, deriving fuel consumption readings from a forwarder's CAN-bus messages is not rigorously verified methodology, for several obvious reasons. Firstly, such verification should be done for each machine model separately, as machines' technical specifications differ, and ideally tests should be performed in various work conditions. Secondly, providing a reference value for "nearly continuous" fuel consumption readings derived from CAN-bus messages is difficult with certified (direct measurement) instruments.

Numerous verification tests have been done on CAN-bus dataloggers mounted on various machines including trucks, agricultural tractors, and forwarders. Deriving fuel consumption readings from CAN-bus messages is reportedly useful for determining overall average fuel consumption data for long-term follow-up purposes (e.g. Surcel & Michaelsen, 2009; Čupera & Sedlák, 2011; Roy & Hamilton, 2012). However, the accuracy of short-term readings under varying working conditions, such as in forwarding, is unknown (see discussion in Paper II).

To summarize, the accuracy of onboard computers' fuel consumption readings is not scientifically verified and they include some uncertainty. However, they have clear advantages over traditional direct measurements in many cases, and indirect measurement is often the only option for short work elements.

4.5 Do things optimally – choices of study methods

Generally, in the absence of variations in other factors such as operators or alternative work methods, establishing causality is not usually a problem when work elements alone are compared. In such cases, it is not even assumed that work conditions are constant, on levels of factors of interest, when formulating questions. Indeed, the variations in work conditions are the factors of interest, at least to some extent. For instance, the data presented in Tables 3 and 6 allow comparisons of observations of work performed either by a single operator, or pooled observations of work performed by all operators. Work by different operators should be compared cautiously, due to the risk of causal fallacy. It is unclear how much (and what parts) of variation in data are due to differences between operators, and how much is due to nuisance factors associated with work conditions. Moreover, the risk of questionable causality often arises in regression analyses. For instance, in Studies II and III, factors other than driven distances could have influenced the time and fuel consumption predictions. Strictly, due to the risk of questionable causality, it could only be concluded that the time and fuel consumption readings for the work elements and driven distances were associated (see Papers II & III).

However, productivity improvement often also requires the ability to compare operators or alternative work techniques. A powerful option to isolate effects of the studied factors is to apply standardized experimental design (see Studies I & IV), but such a design also has drawbacks. It is uncertain how well a particular experimental design corresponds to real-life working conditions because work has to be standardized to a limited set of conditions in order to minimise effects of possible nuisance factors. In addition, as no real work is accomplished during the data gathering, sample sizes tend be small due to financial limitations, which limits representativeness even more. Moreover, in productivity-oriented follow-up studies, the measurements are typically given in volume terms, e.g. m^3/PMh. Data from the forest company's information system enables forwarding productivity analysis with stand as the unit of observation (see e.g. Eriksson & Lindroos, 2014), and crane-scale data (which is already provided by optional equipment in many forwarder models) enables productivity analysis with forwarder load as the unit of observation.

In Studies II and III, there was generally substantial dispersion in the data. However, due to the large datasets, there was sufficient statistical power to detect significant relationships among the variables in both the ANOVA and regression analyses (see Papers II & III). No significant between-operator differences were detected in some cases, especially for the variable with the smallest numbers of observations (number of forwarded loads). However, considering the number of means compared (see Tables 3 & 6), such cases were rare; and in many cases, sample sizes could probably be reduced without excessively reducing the statistical power.

Data gathering cannot be automated for all factors affecting forwarding, so additional arrangements are required for gathering comprehensive datasets. In practice, downsizing the dataset (or sample sizes) could potentially enable inclusion of more factors, thereby increasing statistical power by reducing unexplained variation. Moreover, sample sizes could be reduced without excessively impairing descriptive statistics. The observations of work by operators with the smallest sample sizes provided comprehensive understanding of the data distributions; at least the distributions did not change systematically with increased sample size (Tables 3 & 6). In addition, although the dataset used in Study II (n=15329) was nearly twice as large as the one used in Study III (n=8868), the patterns and dispersions of data regarding total time consumption and total driven distance were practically identical (cf. Table 3: operators pooled; Tables 4 & 5).

In Study IV, the feasibility and utility of using third-party research instruments (sensors) and data collectors to gather high-resolution technical information on forwarder crane work was assessed. The sensors were found to be capable of recording changes in cylinder length and pressure with time "nearly continuously" (10^5 Hz frequency), enabling e.g. the determinations of lift force, energy, and power. Moreover, sensor technology had already been successfully used to record forestry crane movements before Study IV. For instance, Purfürst and Erler (2006) used acceleration sensors to record harvester head positions. Moreover, GNSS technology has been used to determine main forwarding work elements (see e.g. Strandgard & Mitchell, 2015; Spinelli *et al.,* 2015). Thus, the use of third-party research instruments is a feasible data gathering option if the required information is not accessible from the forwarder's onboard data system.

Thus, only two types of methodologies, standardized experiment (Studies I & IV) and follow-up (Studies II & III), were essentially used in this PhD project (Figure 4). However, in practice, the methodologies used in Studies I and IV differed notably from each other. Study I was a conventional field experiment while Study IV was performed at a machine testing station (SMP, Umeå, Sweden) which enabled exceptionally comprehensive control over the test and nuisance factors. Other methods for evaluating machinery innovations or technical aspects that were not applied include simulations (see e.g. Lindroos *et al*., 2008; Jundén *et al*., 2013; Ersson *et al*., 2014) and theoretical reasoning (see e.g. Gerasimov & Siounev 1998, 2000; Lin *et al*., 2013).

The EHLC could have been assessed through theoretical reasoning, for instance by determining W_2 computationally from the initial cylinder length (L_i) to final cylinder length (L_f) as a force integral based on Boyle's law, $p \propto V^{-1}$ (Eq. 3). However, such an approach also requires determination of the parameters of Eq. 3, the constants $V_{acc,\,ref}$ and $p_{2,\,ref}$ (the accumulator gas volume and pressure at a given reference cylinder length L_{ref}, respectively). Parameters presented here were derived by regression analysis (not shown) of data acquired from experiments with the EHLC under the treatment that created on average the highest initial p_2 (i.e. payload, 513 kg; valve setting, "medium", see Paper IV). Alternatively, some intuitively sound target values (i.e. pursued values) could be used as parameters if no measured data were available. For example, the EHLC's average initial cylinder length (1066 mm) under the focal treatment was entered as L_{ref} into Eq. 3, and if $L_{ref} = 1066$ mm, then $V_{acc,\,ref} = 117$ cm^3 and $p_{2,\,ref} = 24377$ kPa. Finally, to ensure that calculated values were representative for a typical boom lift during the experiment, the standard cylinder's overall average initial and final cylinder lengths (1084 and 1216 mm) during the experiment were entered as L_i and L_f. A_2 was provided by the EHLC's manufacturer.

$$W_{2,\,L_i \rightarrow L_f} = \int_{L_i}^{L_f} \frac{V_{acc,\,ref} \times p_{2,\,ref} \times A_2}{V_{acc,\,ref} + A_2 \times (L_x - L_{ref})} \, dL_x \qquad (3)$$

Hence, according to Eq. 3, the calculated W_2 for a full boom lift (i.e. from the cylinder length 1084 mm to 1216 mm) is ca 1.7 kJ. As the overall average W_s of one full boom lift in the entire experiment was ca 24 kJ, the calculated energy saving with EHLC for a full boom lift would be ca. 7 %. Moreover, if $V_{acc, ref}$ was doubled to 234 cm^3, W_2 would be ca 2.0 kJ, providing an energy saving of ca. 8 %. However, most importantly, the risk for p_1 and p_2 intersecting would be notably smaller. More substantial energy savings can be gained by increasing A_2. If A_2 was doubled, in addition to doubling $V_{acc, ref}$, W_2 would be ca. 3.4 kJ, providing an energy saving of 14 % for a full boom lift. However, the calculations include an assumption, that the EHLC could still create the same $p_{2, ref}$ (i.e. 24377 kPa) at a given L_{ref} (i.e. 1066 mm).

Thus, the methodology applied in Study IV could not determine the energy saving potential for the EHLC's full boom lift due to the (unexpected) intersection of p_1 and p_2, but at least a rough estimate could be obtained through theoretical reasoning (Eq. 3). This shows that in an early prototype phase, even such a simple calculation can provide essential indications whether the focal innovation has enough potential to warrant further development, or if it is better to invest development resources elsewhere.

New inventions and prototypes can also be successfully studied by observational field studies (e.g. Lindroos *et al.*, 2008; Laine & Rantala, 2013) and simulations (Lindroos *et al.*, 2008; Jundén *et al.*, 2013; Ersson *et al.*, 2014). The EHLC could have been evaluated by simulations too (see ITH, 2011). Moreover, energy savings for the EHLC's successful lift phase – or if the EHLC functions flawlessly, for the whole boom lift – could be evaluated by a field study. Most simply, all the factors (and covariates) used in the experiment could be removed, and only W_2's proportion of the total work (i.e. W_1+W_2) could be determined (see Section 2.3). However, as a trade-off for simplicity, such an approach would not obtain technical information regarding the EHLC that is essential for documenting and solving its technical problems. A more advanced observational study design, i.e. inclusion of factor(s) as in Study IV, would require the use of a crane-scale (for recording the log weight for each crane cycle) and crane joint sensors to enable unbiased between-treatment comparisons.

In summary, only two types of methodologies, standardized experiment and follow-up, were used in Studies I-IV (Figure 4). However, there are other data gathering and research methodologies like theoretical reasoning, simulation, and observational time and motion studies. The use of untapped technical potential would in many cases enable long-term follow-up studies based on automated data gathering to replace conventional experiments and observational studies.

4.6 Doing optimal things in future studies

As noted in the *Introduction*, a forwarder is both a loading and a driving machine. By improving its driveability, both ride comfort (ergonomic quality) and bearing capacity can be increased (see e.g. Edlund, 2012). That in turn also enables higher driving speeds during forwarding and (hence) improves productivity. However, on forest terrain, driving speeds cannot be increased indefinitely due to obstacles. Therefore, other steps are also needed to increase productivity; for instance, the automation of some crane work functions (Westerberg, 2014), as also mentioned in the *Introduction*.

Choosing the optimal work method or improving working manoeuvres is an essential part of productivity improvement. Productivity improvement can be also a combination of new technical innovations and improved working manoeuvres. In Study I, single-assortment loads were found to be the most productive alternative in most cases (Paper I). However, multi-assortment loads have more potential for improving productivity. They have a major advantage in short driving times, and a major current disadvantage in long crane work times, but new technological innovations such as the "assortment grapple" (Skogforsk Nyheter 2014) could have the potential to address this problem. In addition, assortments which are planned to be forwarded in the same load should be placed in near-by piles at the landing to avoid unnecessary unloading drive and to facilitate sorting.

In order to channel resources optimally, criticality is an essential criterion in product development, especially for innovations in early phases. For instance, preliminary approximations have already shown that the energy savings provided by the EHLC will be minor and lower than those provided by similar products (See Paper IV). Moreover, it is questionable how much the EHLC could reduce forwarders' fuel consumption. It does not directly enable the use of less powerful, i.e. less fuel consuming, combustion engines because driving (the work element with the highest power requirement) sets the minimum requirement for engine power (see Löfgren, 1999; Edlund, 2012; Papers II & IV). Thus, the EHLC's potential applications seems primarily to be in hydraulic lift devices where the top engine power is used for lift work, which is not the case in forwarders. In conclusion, resources should be channelled to improve powertrain efficiency rather than to decrease the need for lift energy (see e.g. Edlund, 2012; Swedish Energy Agency, 2014).

An important consideration in this context is as follows: in capital-intensive businesses, maximising productivity is generally a sound option because minimizing single variable cost (e.g. fuel costs) has relatively minor effects on overall profitability. Furthermore, training can potentially help efforts to either maximize productivity or minimize fuel consumption. Notably, several studies have shown that bus drivers' fuel and time consumption (less delays) can be reduced by training (e.g. af Wåhlberg, 2007; Vlassenroot *et al.*, 2007; Zarkadoula *et al.*, 2007). Forestry work is carried out in a complex and highly variable environment (e.g. Vöry, 1954; Samset, 1990, 1992) and there is large variation in performance between operators (e.g. Reichel, 1999; Lindroos, 2010; Purfürst, 2009). Thus, due to the complexity of forestry work, training could have even higher potential in forestry than in the bus traffic sector where the drivers follow given routes. Some promising training results have already been reported for forwarding (e.g. Jönsson & Löfroth, 2007). However, some studies have shown that realising training potential in real-life is challenging as newly-trained drivers tend to revert to old habits and routines (e.g. Beusen *et al.*, 2009), although a monitoring system that provides continuous real-time feedback about drivers' habits may improve the duration of training results (Wåhlberg, 2007). In addition, a monitoring system enables comparisons between operators (bench-marking). For instance, comparing follow-up data from highly productive operators and rookies could be useful in training. The onboard computers of modern forest machines already have some monitoring ability, but the specificity level varies notably among manufacturers (c.f. e.g. John Deere Forestry Oy, 2015; Komatsu AB, 2015; Ponsse Oyj, 2015). Furthermore, the challenges that must be addressed in forwarder work studies (see Section 1.5) must also be addressed during monitoring because automated data gathering is an essential part of work monitoring systems. Thus, in summary, the complex work environment both partly creates the need for monitoring systems and makes unbiased work evaluation challenging.

Every forwarder load must be planned, in terms of route and assortment combination, in order to minimize the total time consumed by forwarding in a given stand. The hierarchical decision-making process involved is complex, so a computer-based decision support system would also be beneficial (see e.g. Väätäinen *et al.*, 2012; Ylimäki *et al.*, 2012). Programmes for the purpose have been created in recent decades, but none have been commercially successful to date (see e.g. Carlsson *et al.*, 1998; Westerlund, 1998; Carlsson & Rönnqvist, 1999; Carlsson *et al.*, 1999; Flisberg *et al.*, 2007). A common problem is over-simplification as these programs lack the capacity to address key issues of real-life decision-making, such as optimal assortment combinations to be forwarded together in the same load. Decision support systems (DSS) should provide a list from the first to the last load to be forwarded. For each load, a suggestion for the route and piles to be picked-up should be provided. However, adaptive (re-)optimization capacities are also needed, due to the risk that given load suggestions cannot be followed perfectly. Required spatial data for the harvested assortment volumes are available via .hpr files as explained in *Section 4.3*. DSS would, as byproduct, also enable automatic forwarding follow-up data gathering with load-wise assortment-specificity since each load suggestion includes detailed data on assortment volumes. This assumes, naturally, that the given load suggestions can also be followed in reality, at least sufficiently.

Ideally, to minimize forwarding time consumption, harvester operators should have a computer-based aid to plan the base- and strip-road networks. The complex DSS required by this aid should be developed through interdisciplinary cooperation between forest scientists, computer scientists, mathematicians, and practical foresters.

4.7 Summary and Conclusions

A generally acknowledged nomenclature for forwarding is needed for effective use of research resources. As definitions and terminology vary among studies, synthesising findings from different studies is complex. Efforts to standardise nomenclature could be initiated by the leading forest engineering journals, and conducted by a representative group of the most influential forwarding researchers to reach the required consensus across the discipline. Preferably, automatic data gathering should also be standardized over all machine manufactures. For instance, standardized production reporting has been practiced in Nordic CTL-logging operations already for decades (Skogforsk, 2007).

To enhance forwarder productivity, there is a need to elucidate the complex decision-making involved in forwarding. Such research should focus on improving automated data gathering because representative well-documented follow-up data are essential for unbiased scientific work studies, e.g. forwarding system analysis. Also, improving work methodology is essential for increasing overall productivity and competitiveness, and substantially more important for international competitiveness than increasing fuel- and energy-efficiency.

The optimal study methodology is case-specific. In early-phase evaluations of innovations, straightforward theoretical reasoning should be applied, and more research resources should be approved only if such evaluations yield promising results.

Development of automated data gathering enables the replacement of conventional experimental and observational study datasets with more representative follow-up datasets with good work element-specificity. However, data from the forwarder's own work monitoring system is often insufficient for unbiased analysis, and access to spatial data on the harvester's production (i.e. .hpr files) is needed. Access to such data sources is not likely to enable load-wise comparisons but it could enable (for example) stand-wise comparisons with one forwarder load as the unit of observation.

Automated data gathering is based on systematic rules. Hence, in contrast to most manual data collection, nuisance factors such as the observer's skills do not affect the results. In addition, automated data gathering decreases the risk of the observer-effect, provided that the operators are not aware of an ongoing follow-up study.

Automation provides easy access to large datasets but increasing the sample size beyond a certain saturation point provides no further benefit. Instead, including more factors could be a sound option, even at the cost of a slightly smaller sample sizes.

Medians and geometric means are more robust to outliers than currently used arithmetic means. The use of medians or geometric means as a measure of central tendency should also be considered in forwarding follow-up and monitoring (systems) that use automatically gathered datasets.

The potential of GNSS applications and/or crane-scale data has not been fully exploited, especially in combination with CAN-bus data, which could greatly improve the reliability of automatic forwarding data gathering. However, gathering some highly desirable information automatically with assortment-specificity (indications of load-specific assortment proportions) is not currently possible.

To summarize, there is a trade-off in current forwarding literature between representativeness and work element-specificity. Follow-up studies and standardized experiments represent the two extremes, while work observation studies are a compromise with intermediate representativeness and work element-specificity. However, in many cases, use of untapped technological potential would enable replacement of conventional observational studies, and even experiments, with automatic data gathering.

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