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# Impact of operational parameters on the productivity of whole tree cable yarding – a statistical analysis based on operation data

# Einfluss von Einsatzparametern auf die Produktivität bei der Seilrückung im Baumverfahren – Eine statistische Analyse auf Basis von schlagweisen betrieblichen Aufzeichnungen

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**Keywords:** cable yarding, time consumption, productivity, whole tree, yarding direction, silvicultural treatment

**Schlüsselbegriffe:** Seilrückung, Baumverfahren, Produktivität, Rückerichtung, waldbaulicher Eingriff, schlagweise betriebliche Aufzeichnung

## Zusammenfassung

In der Forstwirtschaft wird die Effizienz von Holzerntesystemen meist mittels Arbeitsstudien untersucht. Arbeitsstudien basierend auf tag- oder schlagweiser Datenerhebung sind besser geeignet, um Langzeiteffekte abzubilden und stellen eine robustere Informationsquelle aufgrund größerer Variabilität in den Einsatzbedingungen dar. In der vorliegenden Arbeit wurde der Einfluss der Einsatzparameter auf die Produktivität bei Rückung mit Seilgeräten im Baumverfahren untersucht.

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Von den Bayerischen Staatsforsten wurde die Arbeit einer Seilgerätemannschaft auf derselben Maschine (Mastseilgerät Koller K507) über einen Zeitraum von neun Jahren dokumentiert. Innerhalb von 12.852,7 h wurden bei 223 Einsätzen 271.721 Bäume mit einem Gesamtvolumen von 71.742 $m^3$ gerückt.

Das Verhältnis von Überstellungs- und Installationszeit zu reiner Seilarbeit betrug 43,1 : 56,9. In diesen Zeiten sind Unterbrechungen länger als 15 Minuten mit einem Anteil von etwa 13,5% nicht enthalten. Die Einflussgrößen Baumvolumen, Trassenlänge, Rückerichtung und waldbaulicher Eingriff zeigten signifikanten Einfluss auf den Zeitbedarf für die Seilrückung im Baumverfahren. Der Zeitbedarf pro $m^3$ sinkt mit zunehmendem Baumvolumen und steigt mit der Trassenlänge. Die Rückung bergauf ist signifikant schneller durchzuführen als jene bergab. Bei den waldbaulichen Eingriffen ist der Zeitbedarf für eine flächige Nutzung (Schlitz- und Femelschläge) geringer als wenn einzelstammweise Holz (Auslesedurchforstung) entnommen wird. Eine Sonderform mit dem höchsten Zeitbedarf sind Almfreistellungen und Schipistenerweiterungen. Das hergeleitete Modell erklärt 51,1% der Variabilität des Zeitbedarfs bei der Seilrückung im Baumverfahren aus den signifikanten Einflussparametern und hat einen Standardfehler von 0,017 h $PSH_{15}$ pro $m^3$.

## Abstract

In forestry, work studies are the most common method to investigate the efficiency of harvesting systems. Shift level or harvesting unit level studies are suited for determining long term effects and provide more robust information due to a larger variety of cases than in detailed work studies. The present study investigated the impact of operational parameters on the productivity of whole tree cable yarding, using harvesting unit level data.

The Bavarian State Forests documented cable yarding operations performed by the same crew and machine (Koller K507) over a period of nine years. During this period, 223 operations were conducted within 12,852.7 h and 271,721 trees with a total volume of 71,742 $m^3$ were yarded.

The relation between the time consumption for installation and relocation and the time consumption for extraction was 43.1 : 56.9. Delays longer than 15 minutes with a share of 13.5% are not included here. The study showed that tree volume, span length, yarding direction and silvicultural treatment had significant impact on the time consumption of whole tree cable yarding. Time consumption per $m^3$ decreased with increasing tree volume and increasing span length. Uphill yarding took significantly less time than downhill yarding. If silvicultural treatments were conducted in slit and group cut methods, time consumption was significantly smaller than in plus tree thinning. Unusual cuts, like pasture land clearings and skiing slope enlargement,

took longest. The developed model explains 51.1% of the variance of whole tree cable yarding time consumption at a standard error of 0.017 h $PSH_{15}$ per $m^3$.

## 1. Introduction

In order to investigate the performance of harvesting systems in forestry, three basic types of work studies are employed. Time studies at the cycle level conducted by a trained researcher are the most common. Shift or harvesting unit level studies strongly depend on a conscientious and motivated recorder (Olsen et al. 1998; Acuna et al. 2012), who usually is not a trained researcher. Consequently, one cannot expect the same accuracy in recordings. However, cycle level studies usually only cover short periods of work and are often subject to overestimation of the harvesting systems productivity (Pausch 2002), as they are not able to capture delay share adequately. While detailed work studies are advantageous in comparing different harvesting techniques under standardized conditions (Huber and Stampfer 2015), shift and harvesting unit level studies are more suited to determine long term effects and provide more robust information (Olsen et al. 1998, Holzleitner et al. 2011, Holzleitner et al. 2013). Additionally, study costs and effort can be reduced, as less intensive observation by a trained observer is required (Olsen et al. 1998; Acuna et al. 2012). Lately automatized recording of machine data during fully mechanized harvesting operations provides high resolution operation data. This data allows analyses dedicated to only a part of the system, such as operator (Purfürst 2009) or machine productivity and fuel consumption (Plessl 2013).

However, in contrast to fully mechanized harvesting systems like harvesters and forwarders, in whole tree cable yarding operations limited data is recorded automatically. Therefore, shift or harvesting unit level data remain a useful source for work studies. In the past similar data has been utilized to determine the effect of different machine types and technological advances (Heinimann 2001), as well as silvicultural treatment types (Eriksson and Lindroos 2014) on the productivity of harvesters.

Even though alternative harvesting systems for steep terrain has emerged during the last few years (Visser and Stampfer 2015, Talbot et al. 2014), cable yarding remains the most common harvesting system for these conditions. However, cable yarding has been subject to analysis mainly at the cycle time level, and a broader analysis in terms of operation parameters impact on productivity is lacking. Lately, Lindroos and Cavalli (2016) presented a review on cable yarding productivity models published between 2000 and 2011.

The aim of the present study was to investigate the impact of operation parameters on the productivity of a whole tree cable yarding system. Both dataset size and origin were a novelty in research on cable yarding system analysis as the extensive set of harvesting unit level operation data contained data on operations conducted by the same machine and crew over several years.

## 2. Material and methods

The Bavarian State Forests systematically gathered data on working with a Koller K507 yarder over the period of April 2008 to August 2015. Within this period whole tree yarding was conducted on 223 corridors. Each corridor is subsequently referred to as its own "operation", regardless of the number of corridors at one harvesting site. The yarder's crew consisted of four people and except for the machine operator (changed in 2012), remained the same throughout the whole period.

The collected data firstly includes total working time per operation, which is further split in time consumption for installation (h), productive working time (h $PSH_{15}$; productive system hours including delays up to 15 minutes), time consumption for relocating to the next operations (h) and time consumption for repairs, refuelling and other time, e.g. briefings etc. (h), hereinafter referred to as "other time". Secondly, operation parameters are listed. Span length, the total number of yarded trees (n) and the total volume ($m^3$) are documented for each operation. Additionally, the expected productivity ($m^3$ h $PSH_{15}^{-1}$) is reported. Finally, the operations were classified by yarding direction (uphill, downhill, horizontal) and six different silvicultural treatments. While up- and downhill yarding was performed in sloped areas, horizontal yarding was conducted in swampy areas. The silvicultural treatments included plus tree thinning (TP), thinning in slit cut method (TS), regeneration felling in slit cut method (RS) and regeneration felling in group cut method (RG), unusual cuts (UC) and salvage harvesting (SH). In TP the two most important competitors of a pre-selected plus tree are removed and plus trees are spread across the whole thinning area. Contrary, in TS slit cuts of 20 m (across slope) x 10 m (downslope) are located 30 m apart along the corridor. These slits are arranged in an alternating scheme. This scheme resembles the black and white squares of a chessboard, where cable corridors form the axes of the columns. Each slit is bordered by slit-size areas of trees on the paralleling cable lines, which are bordered by cut areas down- and upslope. The same scheme is used for RS, but the slit cuts are bigger (35 m x 18 m) and located farther (35 m) apart. This method is used for commencing regeneration, while RG is used for promoting already existing regeneration. RG are group cuts of about 35 m x 35 m in size and scattered unsystematically across the operation area. UC represents operations whose intention is to create areas that will be used for other purposes than forestry (pasture areas, skiing slopes). SH includes removing of timber which has fallen either by wind, snow or bark beetle infestation. Additional parameters were calculated from the basic data. These included the share of productive working time in the total working time (utilization;%), average tree volume ($m^3$), volume per span length (span volume; $m^3$ $m^{-1}$) and productivity ($m^3$ h $PSH_{15}^{-1}$).

All analyses were carried out with the statistical software R (R Core Team 2014). The dataset was firstly explored and assessed in terms of plausibility. Then descriptive statistics, comprising of the sections time consumption, operation parameters and performance parameters were compiled. In case of work time elements were recorded as zero, and thus not existent for a certain operation, they were not included in the calculation of statistical parameters. As a consequence of only four appearances of the yarding direction "horizontal" and one appearance of the silvicultural treatment "SH", and thus likely insignificance to analysis, this data was excluded from further analysis.

Yarding direction and silvicultural treatment impact analysis constituted the second stage of analysis. In the case of the yarding direction, statistical comparison of means was conducted. Due to the larger number of different silvicultural treatments, a Tukey honest significance differences test had to be employed for the comparison of multiple means. Yarding directions and treatments were compared and depending on statistically significant differences, impact groups were formed.

Finally, a model for the time consumption of yarding was developed. The time consumption per unit of output (h $PSH_{15}$ $m^{-3}$) was formulated through the application of regression analysis, where the tree volume, yarding direction, span length and silvicultural treatment were included into the explanatory dataset. Productivity ($m^3$ h $PSH_{15}^{-1}$) was calculated subsequently as the reverse of the time consumption per output. The valid range of the model was established by the $5^{th}$ and $95^{th}$ quantile of the explanatory variables.

# 3. Results

## 3.1. Descriptive statistics

### 3.1.1.Time consumption

The total duration of the operations was 12,852.7 h. During 55 of 223 operations, no time for relocation to the next corridor was recorded, which implies that harvesting was conducted on 55 separate harvesting units. In 32 of 187 operations no time for other time was recorded. The share of productive time in the total time consumption (utilization) was 58.1% and the share of delays yarding operation (time excluding installation and relocation) was 13.5%. Statistical parameters for the time consumption elements are presented in Table 1.

*Table 1: Statistical parameters of the operations time consumption elements. If time con-sumption elements did not exist for a certain operation, they were not included in the calculation of the statistical parameters, which is indicated by the smaller sample size (n).*

Tabelle 1: Statistische Kennzahlen des Zeitbedarfs. Kamen einzelne Elemente bei einem Einsatz nicht vor, wurden sie in die Berechnung nicht einbezogen, was sich in einer geringeren Anzahl (n) ausdrückt.

| parameter | unit | n | mean | sd | median | min | max |
|---|---|---|---|---|---|---|---|
| productive time | h $PSH_{15}$ | 223 | 33.2 | 19.1 | 29.0 | 3.0 | 160.0 |
| relocation time | h | 168 | 1.6 | 0.9 | 1.0 | 0.5 | 5.5 |
| other time | h | 191 | 7.5 | 7.9 | 5.0 | 0.5 | 47.0 |
| installation time | h | 223 | 16.3 | 7.2 | 15.0 | 1.0 | 60.0 |
| total time | h | 223 | 57.0 | 28.6 | 52.0 | 4.0 | 257.0 |

### 3.1.2. Operational parameters

More uphill (140) than downhill operations (79) were conducted, while horizontal yarding occurred only four times. RS (103 operations) and TS (70 operations) were the most frequent silvicultural treatments (Table 2).

*Table 2: Study layout. Distribution of yarding direction and silvicultural treatment types.*

Tabelle 2: Versuchslayout. Verteilung der Rückerichtung und der waldbaulichen Eingriffsarten.

| parameter | uphill yarding | downhill yarding | horizontal yarding | sum |
|---|---|---|---|---|
| **TP** | 9 | 12 | 0 | **21** |
| **TS** | 48 | 22 | 0 | **70** |
| **RS** | 65 | 37 | 1 | **103** |
| **RG** | 5 | 6 | 0 | **18** |
| **UC** | 5 | 2 | 3 | **11** |
| **SH** | 1 | 0 | 0 | **1** |
| **Sum** | **140** | **79** | **4** | **223** |

In total 271,721 trees with a cumulative volume of 71,742 $m^3$ were yarded during 223 operations. On average, the total volume per operation was 321.7 $m^3$ and the average total number of trees 1,218. Average tree volume, based on average tree volume per operation was 0.29 $m^3$ and 0.26 $m^3$ if weighed by total volume per operation. The average span length was 330 m. Consequently, the average span volume was 1.07 $m^3$ $m^{-1}$ (Table 3).

*Table 3: Descriptive statistics of operation parameters.*

Tabelle 3: Deskriptive Statistik der Einsatzparameter.

| parameter | unit | mean | sd | median | min | max |
|---|---|---|---|---|---|---|
| total volume | $m^3$ | 321.7 | 168.2 | 300.0 | 30.0 | 1.002.0 |
| total trees | n | 1.218 | 776 | 1.052 | 150 | 6.326 |
| tree volume | $m^3$ | 0.29 | 0.11 | 0.27 | 0.14 | 0.79 |
| span length | m | 330 | 141 | 300 | 90 | 800 |
| span volume | $m^3$ $m^{-1}$ | 1.07 | 0.50 | 0.98 | 0.27 | 3.60 |

### 3.1.3. Productivity

Average actual productivity (10.1 $m^3$ h $PSH_{15}^{-1}$) slightly surpassed the planned expected productivity of 9.9 $m^3$ h $PSH_{15}^{-1}$. Planned productivity is the average productivity the Bavarian State Forests expect for this type of machine and it is based on long-term records.

## 3.2. Impact analysis

### 3.2.1. Yarding direction

Productivity and utilization were significantly larger if yarding was conducted uphill. Except for the element "installation time" time consumption elements did not differ significantly. On average, installation took about three hours less in uphill yarding than in downhill yarding, even though span lengths were considerably shorter in downhill yarding. Statistical comparison showed that for the same span lengths, installation takes significantly longer (0.06 h vs. 0.05 h, $p=2 \times 10^{-5}$) if a downhill configuration is installed. No significant difference could be observed at the total time consumption level. The number of yarded trees was smaller in downhill yarding, but was not statistically significant. No significant differences could be observed for the span volume and tree volume parameters (Table 4).

*Table 4: Impact of yarding direction on operation parameters of whole tree cable yarding (5% significance level). Treatments with different superscripts differ significantly.*

Tabelle 4: Einfluss der Rückerichtung auf Einsatzparameter bei der Seilrückung im Baumverfahren (5% Irrtumswahrscheinlichkeit). Mit verschiedenen Buchstaben gekennzeichnete Rückerichtungen unterscheiden sich signifikant.

| parameter | unit | downhill yarding | uphill yarding |
|---|---|---|---|
| productivity | $m^3\ h\ PSH_{15}^{-1}$ | $9.6 \pm 2.4^{a}$ | $10.4 \pm 2.2^{b}$ |
| utilization | % | $53.5 \pm 10.7^{a}$ | $58.6 \pm 10.3^{b}$ |
| productive time | $h\ PSH_{15}$ | $30.5 \pm 15.5^{a}$ | $33.1 \pm 17.3^{a}$ |
| relocation time | h | $1.5 \pm 0.8^{a}$ | $1.6 \pm 0.9^{a}$ |
| other time | h | $7.4 \pm 7.9^{a}$ | $7.3 \pm 7.6^{a}$ |
| installation time | h | $18.0 \pm 6.8^{a}$ | $15.0 \pm 6.2^{b}$ |
| total time | h | $55.9 \pm 24.6^{a}$ | $56.4 \pm 26.4^{a}$ |
| span length | m | $306.6 \pm 134.4^{a}$ | $341.7 \pm 140.2^{a}$ |
| total volume | $m^3$ | $280.3 \pm 141.3^{a}$ | $334.0 \pm 162.9^{b}$ |
| span volume | $m^3\ m^{-1}$ | $1.1 \pm 0.5^{a}$ | $1.0 \pm 0.5^{a}$ |
| tree volume | $m^3$ | $0.3 \pm 0.1^{a}$ | $0.3 \pm 0.1^{a}$ |
| total trees | n | $1087 \pm 596^{a}$ | $1227 \pm 703^{a}$ |

### 3.2.2. Silvicultural treatment

As a consequence of the larger number of levels of the factor silvicultural treatments, analysis was more complex than the analysis of yarding direction. In the case of productivity, three different levels could be established. Productivity in TP and UC (level 1) was significantly lower than in TS (level 2), while productivity in RS and RG (level 3) was significantly larger than in all other treatments. In contrast to that, utilization was highest in UC. It did not differ significantly from RG, but did differ significantly from TP, TS and RS. Productive time did only differ significantly between TS, which was the shortest treatment, and UC, which was the longest treatment. Neither a significant difference for all other time elements nor a significant difference in span length could be observed. Total volume per operation was significantly larger in RG than in TP and RS. Additionally, span volume in RG was significantly larger than in all other treatments. Tree volume in RS was significantly larger than in TP and TS. The total number of trees harvested in RG and UC was significantly larger than in the other treatment types (Table 5).

*Table 5: Impact of silvicultural treatment on operation parameters of whole tree cable yarding (5% significance level). Treatments with different superscripts differ significantly.*

Tabelle 5: Einfluss des waldbaulichen Eingriffs auf Einsatzparameter bei der Seilrückung im Baumverfahren (5% Irrtumswahrscheinlichkeit). Mit verschiedenen Buchstaben gekennzeichnete Eingriffsarten unterscheiden sich signifikant.

| parameter | unit | TP | TS | RS | RG | UC |
|---|---|---|---|---|---|---|
| productivity | $m^3\ h\ PSH_{15}^{-1}$ | $7.6 \pm 1.2^{a}$ | $9.9 \pm 2.1^{b}$ | $10.8 \pm 2.0^{c}$ | $11.5 \pm 2.8^{c}$ | $7.5 \pm 1.3^{a}$ |
| utilization | % | $56.3 \pm 9.4^{a}$ | $57.1 \pm 10.0^{a}$ | $54.8 \pm 11.0^{a}$ | $61.2 \pm 9.1^{a,b}$ | $71.1 \pm 9.6^{b}$ |
| productive time | h $PSH_{15}$ | $35.0 \pm 14.6^{a,b}$ | $32.7 \pm 14.6^{a}$ | $28.8 \pm 16.3^{a}$ | $38.1 \pm 20.9^{a,b}$ | $51.0 \pm 20.2^{b}$ |
| relocation time | h | $1.3 \pm 0.7^{a}$ | $1.5 \pm 0.9^{a}$ | $1.6 \pm 0.8^{a}$ | $1.8 \pm 1.2^{a}$ | $1.9 \pm 1.2^{a}$ |
| other time | h | $9.9 \pm 9.5^{a}$ | $7.4 \pm 7.5^{a}$ | $6.8 \pm 6.3^{a}$ | $9.0 \pm 12.7^{a}$ | $2.5 \pm 1.4^{a}$ |
| installation time | h | $18.4 \pm 6.4^{a}$ | $16.5 \pm 6.0^{a}$ | $15.5 \pm 6.7^{a}$ | $15.1 \pm 8.4^{a}$ | $15.1 \pm 3.3^{a}$ |
| total time | h | $67.5 \pm 30.4^{a}$ | $56.7 \pm 21.7^{a}$ | $51.4 \pm 24.5^{a}$ | $62.7 \pm 36.3^{a}$ | $70.2 \pm 19.5^{a}$ |
| span length | m | $337.1 \pm 162.0^{a}$ | $353.3 \pm 111.3^{a}$ | $316.7 \pm 143.2^{a}$ | $263.9 \pm 169.4^{a}$ | $407.1 \pm 105.8^{a}$ |
| total volume | $m^3$ | $258.1 \pm 101.9^{a}$ | $317.0 \pm 138.8^{a,b}$ | $301.4 \pm 154.9^{a}$ | $422.5 \pm 241.3^{b}$ | $373.6 \pm 128.0^{a,b}$ |
| span volume | $m^3\ m^{-1}$ | $0.83 \pm 0.36^{a}$ | $0.98 \pm 0.39^{a}$ | $1.03 \pm 0.44^{a}$ | $1.70 \pm 0.61^{b}$ | $0.91 \pm 0.13^{a}$ |
| tree volume | $m^3$ | $0.25 \pm 0.09^{a}$ | $0.29 \pm 0.09^{a,b}$ | $0.32 \pm 0.13^{b}$ | $0.25 \pm 0.11^{a,b}$ | $0.19 \pm 0.03^{a}$ |
| total trees | n | $1114 \pm 538^{a}$ | $1175 \pm 505^{a}$ | $1024 \pm 613^{a}$ | $1804 \pm 1025^{b}$ | $1986 \pm 775^{b}$ |

### 3.3. Time consumption model

Model development showed that average tree volume, yarding direction, span length and silvicultural treatment had a significant influence on the variability of time consumption in whole tree yarding operations. In total, 51.1% of the variance could be explained by these explanatory variables. Respective standard error was 0.017 h $PSH_{15}$ per $m^3$. Valid range of the models was established by the $5^{th}$ and $95^{th}$ quantiles of the average tree volume, which were 0.16 $m^3$ and 0.49 $m^3$ respectively, and the span lengths which were 140 m and 560 m, respectively. Estimation can be carried out for all analysed types of silvicultural treatments (TP, TS, RS, RG, UC) and yarding directions (up- and downhill). Comparison with observations showed that the mean deviation from the derived curves was $8.57 \times 10^{-19}$ h $PSH_{15} \pm 0.02$ h $PSH_{15}$).

$$\textit{time consumption } [h\ PSH_{15}\ m^{-3}] = a + b \times \textit{tree volume}^{-0.9} + c \times \textit{yarding direction} + d \times \textit{span length} + e \times \textit{silvicultural treatment} \quad \text{Eq. 1}$$

*Table 6: Coefficients and statistical parameters for the time consumption model.*

Tabelle 6: Koeffizienten und statistische Kennzahlen des Zeitbedarfsmodells.

| Parameter | ID | coefficient | standard error | t-value | p-value |
|---|---|---|---|---|---|
| intercept | a | $8.887 \times 10^{-2}$ | $6.529 \times 10^{-3}$ | 13.61 | $< 2.000 \times 10^{-16}$ |
| tree volume [m³] | b | $1.116 \times 10^{-2}$ | $1.210 \times 10^{-3}$ | 9.22 | $< 2.000 \times 10^{-16}$ |
| yarding direction | c | | | | |
| | downhill | 0.000 | | | |
| | uphill | $-7.043 \times 10^{-3}$ | $2.469 \times 10^{-3}$ | -2.85 | $4.800 \times 10^{-3}$ |
| span length [m] | d | $1.970 \times 10^{-5}$ | $8.670 \times 10^{-6}$ | 2.27 | $2.420 \times 10^{-2}$ |
| silvicultural treat-ment | e | | | | |
| | TP, UC | 0.000 | | | |
| | TS | $-2.323 \times 10^{-2}$ | $4.345 \times 10^{-3}$ | -5.35 | $2.331 \times 10^{-7}$ |
| | RS | $-2.900 \times 10^{-2}$ | $4.243 \times 10^{-3}$ | -6.83 | $8.800 \times 10^{-11}$ |
| | RG | $-3.965 \times 10^{-2}$ | $5.585 \times 10^{-3}$ | -7.10 | $1.900 \times 10^{-11}$ |

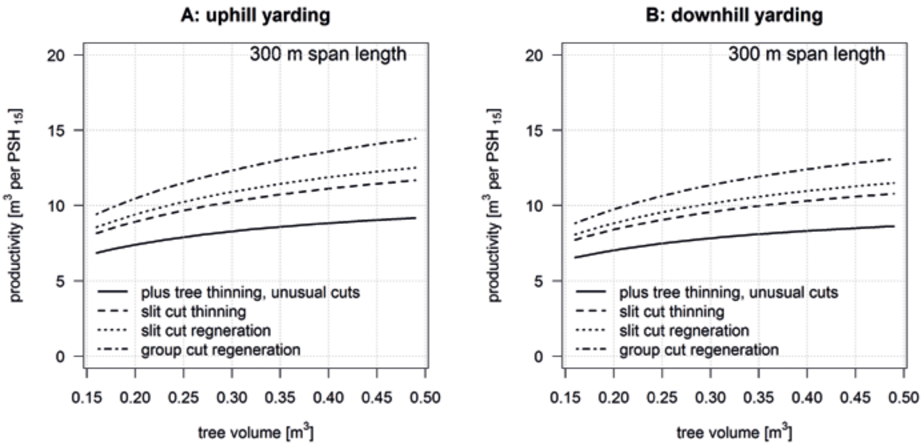


*Figure 1: Productivity of a yarding with a Koller K507 dependent on tree volume, yarding direction and silvicultural treatment at a span length of 300 m.*

Abbildung 1: Produktivität der Seilrückung mit einem Koller K507 in Abhängigkeit von Baumvolumen, Rückerichtung und waldbaulichem Eingriff bei einer Trassenlänge von 300 m.

## 4. Discussion

The focus of this study was to determine the effect of yarding direction and silvicultural treatment on the operational performance and to develop a time consumption model for whole tree cable yarding. Analysis was based on a harvesting unit level dataset of whole tree cable yarding operations, comprising of 223 operations, carried out by the same crew and the same machine over a period of more than eight years.

Considerable time is required for rigging a cable corridor. The results of the present study show that installation takes significantly longer if a downhill configuration is installed. The same effect was observed by Stampfer et al. (2006), who associated this effect to the required installation of a haul-back line in this configuration. Silvicultural treatments did not have an effect on the installation time consumption. It can be assumed that the type of treatment does not matter and installation time consumption is affected by factors like terrain relief and required number of intermediate supports (Stampfer et al. 2006).

The operation of the tower yarder was delayed by other activities, including repair or refuelling. The average delay share of 13.5% is smaller than the results (35.0%) of Huyler and LeDoux (1997) for a Koller K300 operation studied in the United States and within the range of results (10% to 22% and 30% to 44%) from Spinelli et al. (2010 and 2015), although in later study these percentages were attributed to the short study duration.

Overall productivity was within reasonable limits and in line with other results for comparable types of machines (Limbeck-Lilienau 2002, Viertler 2003, Holzleitner and Stampfer 2005, Eggenberger 2005, Stampfer et al. 2010). For the presented data, no general rule can be deduced regarding the reason for a certain productivity level. Evidently, productivity was significantly higher in uphill yarding, an effect similarly observed by Ghaffariyan et al. (2009). The authors assigned this effect to the speed of yarding. While there is no need to use brakes in uphill yarding, in downhill yarding braking could be necessary to avoid damage to remaining trees along the corridor by the dangling load. Loscheck (2009) observed the same when yarding small diameter trees downhill and therefore proposed to yard trees fixed at their tops and not at the bottom end. Contrary to these findings, Limbeck-Lilienau (2002) and Spinelli et al. (2015) could not observe any difference in productivity or in the amount of residual stand damage . However, as the present study includes a much larger number of operations than in any former, it can be assumed that its results are more reliable, even though the results are identical in most cases. Comparative studies of silvicultural treatment impact on productivity are rare. Gridling (2000), who studied the extraction of stems by helicopter, is one of the few examples in literature. In this study, productivity of extraction was significantly higher if stems were forwarded from sites where clear-cutting was conducted, than from sites where regeneration felling was carried out in group cut method. Spinelli and Magagnotti (2011) compared harvesting costs for both maturity cuts and thinning operations in spruce stands. It showed that yarding productivity in TS is much lower than in RG and costs for the former are 16% higher.

In the present study, productivity was lowest in UC and TP, and highest in RS and RG. Low productivity of TP can be explained by the need to manoeuver the harvested trees between the remaining trees. UC operations were performed with the clear-cut method, so one would eventually expect a larger productivity. In many cases, the span also crossed non-woodland areas, which consequently increased the average yarding distance for an individual tree. RS treatments yarding distances were on average about 50 m longer than in the RG treatment. This effect was balanced by the larger tree volume in RS (0.32 $m^3$ vs. 0.25 $m^3$) and further indicated by an outstandingly larger span volume of RG (1.70 $m^3$ $m^{-1}$ vs. 1.03 $m^3$ $m^{-1}$). Both in RS and RG treatments a larger amount of trees was felled within a small area. As such it can be assumed that concentration effects also contributed to the overall performance.

The developed model for estimating the time consumption of yarding whole trees under different conditions provides reasonable results. As most other models for estimating cable yarding time consumption, it includes stand and operation related variables. While tree (whole tree yarding) or piece volume (cut to length system) and yarding distance are common explanatory variables, datasets can further contain variables like lateral yarding occurrence or distance, slope, harvesting season or pre-concentration operations (Daxner 1998, Heinimann et al. 1998, Stampfer 2002, Viertler 2003, Eggenberger 2005, Pierzchala 2011). Even though defined as possible explanatory variable (Limbeck-Lilienau 2002, Eggenberger 2005, Stampfer and Holzleitner 2005, Ghaffariyan et al. 2009), yarding direction usually hadno significant influence on the productivity, except in Ghaffariyan et al. (2009) and the present study.

Time consumption models in cable yarding are mostly based on a small number of yarding cycles and usually include only one type of silvicultural treatment. Even in cases in which data from a larger number of operations could be gathered (Holzleitner and Stampfer 2005, Ghaffariyan et al. 2009), data originated from at least three different machines or crews. Consequently, to get long-term data of one crew and machine is unlikely and its value must not be underestimated, even though one may criticize slight imbalances in terms of yarding direction and silvicultural treatment case distribution. However, data largely free from the unquantifiable influence of different crew and machine characteristics is much more likely to provide more robust results on performance factors like yarding direction and silvicultural treatment.

## 5. Conclusion

The effect of yarding direction and silvicultural treatment on the operational efficiency in whole tree cable yarding was studied and a time consumption model was developed. Downhill yarding was found to be less advantageous, as installation takes significantly more time. Likewise, productivity is significantly lower if yarding is conducted in downhill configuration. Overall productivity increase, whenever a silvicultural treatment (like slit and group cut method) inhabits concentration effects (a larger number of trees is felled within a small area). Contrary, treatments (like plus tree thinning, clear-cut-like types) where the whole operation area is affected and harvested trees are spread widely, are less productive. The developed model provides reasonable estimates for time consumption during yarding of whole trees. The study database includes a very large number of operations carried out by the same crew and machine during a period of almost nine years which is a unique feature in the scientific literature on cable yarding operations.

## References

Acuna, M., Bigot, M., Guerra, S., Hartsough, B., Kanzian, C., Kärhä, K., Lindroos, O., Magagnotti, N., Roux, S., Spinelli, R., Talbot, B., Tolosana, E. & Zormaier, F. (2012). Good practice guidelines for biomass production studies. Sesto Fiorentino, Italy: CNR IVALSA. 50 p. http://www.forestenergy.org/pages/cost-action-fp0902/good-practice-guidelines.

Olsen, E. D., Hossain, M. M., & Miller, M. E. (1998). Statistical comparison of methods used in harvesting work studies. Corvallis, OR, College of Forestry, Forest Research Laboratory, Oregon State University, United States. 45 p.

Daxner, P. (1998). Produktivität und Effizienz des selbstfahrenden Laufwagens „Woodliner" [Productivity and Efficiency of the self-propelled carriage „Woodliner"]. Master-thesis. Institut für Forsttechnik , Universität für Bodenkultur. 71 p.

Eggenberger, M. (2005). Optimierung und Einsatz moderner Holzerntesysteme im Gebirgswald [Optimization and utilization of modern harvesting systems in mountain forests]. Department Umweltwissenschaften , Eidgenössische Technische Hochschule Zürich. 71 p.

Eriksson, M., Lindroos, O. (2014). Productivity of harvesters and forwarders in CTL operations in northern Sweden based on large followup datasets. International Journal of Forest Engineering, 25(3): 179-200.

Ghaffariyan, M. R., Stampfer, K., Sessions, J. (2009). Production equations for tower yarders in Austria. International Journal of Forest Engineering 20 (1): 17-21

Gridling, H., Stampfer, K. (2000). Holzrückung mit dem Helikopter K-Max [Forwarding of timber by the helicopter K-Max]. Österreichische Forstzeitung (Arbeit im Wald) 111 (5): 4-5.

Heinimann, H.R., Visser, R., Stampfer, K. (1998). Harvester-cable yarder system evaluation on slopes - a Central European study in thinning operations. In COFE (Council on Forest Engineering) Proceedings „Harvesting logistics: from woods to markets", ed. Schiess P. and Krogstad F., 41-46. Portland, OR, 20-23 July.

Heinimann, H. R. (2001). Productivity of a cut-to-length harvester family - an analysis based on operation data. 2001 Council on Forest Engineering (COFE) Conference Proceedings: "Appalachian Hardwoods: Managing Change" Snowshoe, July 15-18, 2001. 7 p.

Holzleitner, F., Stampfer, K. (2005). Seilrückung im Baumverfahren - Eine Analyse [An analysis of whole tree cable yarding]. Wald und Holz 11, 48-51

Holzleitner, F., Kanzian, C., Höller, N. (2013). Monitoring the chipping and transportation of wood fuels with a fleet management system. Silva Fennica Vol. 47(1) article id: 899. 11 p.

Holzleitner, F; Stampfer, K; Visser, R. (2011). Utilization rates and cost factors in timber harvesting based on long-term machine data. Croatian Journal of Forest Engineering 32(2): 501-508.

Huber, C., Stampfer, K. (2015). Efficiency of topping trees in cable yarding operations. Croatian Journal of Forest Engineering 36(2): 185-194.

Huyler, N., LeDoux, C. (1997). Cycle-time equation for the Koller K300 cable yarder operating on steep slopes in the Northeast. Res. Pap. NE-705, USDA Forest Service, Northeastern Forest Experiment Station 4 p.

Limbeck-Lilienau, B. (2002). Hochmechanisierte Holzernte mit schräger Seiltrasse [Highly mechanized diagonal cable corridor harvesting]. Master-thesis. Institut für Forsttechnik , Universität für Bodenkultur. 59 p.

Lindroos, O., Cavalli, R. (2016). Cable yarding productivity models: a systematic review over the period 2000-2011. International Journal of Forest Engineering 27(2): 79-94.

Loschek, J. (2009). Oberhalb der Forststrassen - Bergabseilung von Schwachholz [Above the forest roads - downhill yarding of small dimension trees]. Wald und Holz 6, 4-6.

Pausch, R. (2002). A system approach for the analysis of interrelationships between forest structure, Work volume and cost of stand establishment, stand tending and harvesting operations in forest districts of northern and eastern Bavaria. PhD-thesis. Lehrstuhl für Forstliche Arbeitswissenschaft und Angewandte Informatik, Technische Universität München. 325 p.

Pierzchała, M. (2011). Development of a productivity model for long distance cable yarding. Master-thesis. Institut für Forsttechnik , Universität für Bodenkultur. 67 p.

Plessl, W. (2013). Maschinendatenbasiertes Produktivitäts- und Treibstoffverbrauchsmodell für Harvester [Machine data based model for productivty and fuel consumption for harvesters]. Master-thesis. Institut für Forsttechnik , Universität für Bodenkultur. 39 p.

Purfürst, F.T. (2009). Der Einfluss des Menschen auf die Leistung von Harvestersystemen. [The operator's influence on harvester productivity]. PhD-thesis. Institut für Forstnutzung u. Forsttechnik, Technische Universität Dresden, Germany. 307 p.

Spinelli R., Magagnotti, N., Lombardini, C. (2010). Performance, capability and cost of small-scale cable yarding technology. Small-scale Forestry 9: 123-135

Spinelli R., Magagnotti N. (2011). The effects of introducing modern technology on the financial, labour and energy performance of forest operations in the Italian Alps. Forest Policy and Economics 13: 520-524.

Spinelli R., Magagnotti N., Visser R. (2015). Productivity models for cable yarding in Alpine forests. European Journal of Forest Engineering 1 (1): 9-14.

Stampfer, K. (2002). Optimierung von Holzerntesystemen im Gebirge [Optimization of timber harvesting systems in mountainous regions]. Habilitation-thesis. Institut für Forsttechnik, Universität für Bodenkultur. 101 p.

Stampfer, K., Limbeck-Lilienau, B., Kanzian, C., Viertler, K. (2003). Baumverfahren im Seilgelände - Verfahrensbeispiele [Whole tree cable yarding - case studies]. Kooperationsplattform Forst-Platte-Papier. 26 p.

Stampfer, K., Visser, R., Kanzian, C. (2006). Cable corridor installation times for European yarders. International Journal of Forest Engineering, 17(2): 71-77.

Stampfer, K., Leitner, T., Visser, R. (2010). Efficiency and ergonomic benefits of using radio controlled chokers in cable yarding. Croatian Journal of Forest Engineering 31(1): 1-9.

Talbot, B., Ottaviani, G., Stampfer K. (2014). Productivity analysis of an un-guyed integrated yarder-processor with running skyline. Croatian Journal of Forest Engineering 35(2): 201-210.

Viertler, K. (2003). Baumverfahren im Seilgelände in schwächeren Baumdimensionen [Whole tree yarding of small dimension trees]. Master-thesis. Institut für Forsttechnik , Universität für Bodenkultur. 45 p.

Visser, R., Stampfer, K. (2015). Expanding ground-based harvesting onto steep terrain: A review. Croatian Journal of Forest Engineering 36(2): 321-331.