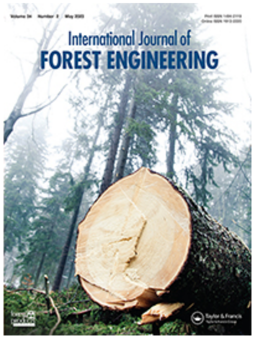

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A review on cable yarding operation performance and its assessment

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ABSTRACT
Cable yarding is a well-established practice for wood extraction in mountainous regions in most parts of the world where fully mechanized harvesting systems like harvester-forwarder combinations cannot operate due to steep terrain. Work- and time-studies are most relevant to create productivity models for cost estimation, simulation, system development or simply to compare different harvesting systems. The present work investigates 70 work studies on cable yarding operations, regarding assessment methods to establish a knowledge base on cable yarding performance models. A comprehensive literature research was performed to identify relevant studies. Information about the investigated extraction campaigns regarding site specifics, stock specifics, the utilized equipment alongside the work-study-methods, as well as the statistical approaches for model creation were collected. The data gained and the associated models were systematically analyzed to compare different yarding systems concerning their performance. A set of 98 models was selected for this purpose. Productivity of the investigated systems ranges from 1.5 m^3/PSH to 69.3 m^3/PSH with a mean value of 9.8 m^3/PSH where PSH represents the productive system hour. A meta-analysis was performed with the data that is presented in the literature found to test several hypotheses concerning the influence of different parameters on the performance of yarding systems. Various relationships are so strong that regression analysis with the meta-dataset, that is mostly containing mean values presented, results in significant correlations. The diversity in problem formulation and the corresponding diversity in methodical approaches account for limitations in comparability of performance. The consultation of guiding literature on forest work studies can promote comparability between studies.

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Cable yarding performance; productivity models; time consumption models; meta-analysis; cycle time equations; steep terrain

Introduction

Cable yarding is a widespread option for wood extraction in mountainous regions in most parts of the world. For example, in Austria where 57% of the forest-covered land has terrain slopes of more than 30%, cable-based extraction is of major importance (Nemestothy 2014). In 2021, 3.88 hm^3 solid under bark which equals 21.06% of total logging in Austria were cable yarded (BMLRT 2022). Further indicators for the importance of cable-based wood extraction are the wide manufacturer's offer for cable yarders and the number of cable yarders operatng in Europe. Wassermann (2018) identified 63 types of tower yarders from 15 European manufacturers. Spinelli et al. (2013) surveyed 1,206 Italian logging companies and described that they utilized 359 cable yarders of which 129 (36%) were tower yarders. Not only in Europe, but also in New Zealand the requirements on modern wood extraction systems promote the usage as well as the improvement of cable yarding systems (Harrill et al. 2019) that are mainly imported from the Pacific Northwest (Visser and Harrill 2017).

Cable-based wood extraction in steep terrain shows disadvantages against ground-based extraction options in regard of harvesting costs (Spinelli et al. 2015, 2017b). With respect to low or even negative profit margins in mountain forest operations the investigation of the performance shown in yarding operations is important to identify potential areas for further improvement (Varch et al. 2020).

To maximize productivity that can be understood as the ratio of output over input, scientific management aims to standardize equipment and tools, optimize the production flow and improve the labor process (Heinimann 2021). In the case of timber production, the output is the quantity of timber produced and the input can be understood as the sum of all production factors used (Kanawaty 1992).

Productivity studies often "evaluate a single production system's productive performance, characterized by system output per system time unit" (Heinimann 2021). They have a long history in the field of forest engineering and are nowadays primarily aiming at the evaluation and representation of the performance of man-machine-systems in wood extraction processes. Regarding cable yarding systems, the evaluation of efficiency, as well as the analysis of the impact of environmental features have drawn the interest of forest engineers in recent years (Cavalli 2012). The initial aim of work studies, that has been to improve processes and the effectivity of resource allocation to increase performance, shifted toward the intention to describe a system in a specific production context (Heinimann 2021).

Work studies were defined as "techniques of method study and work measurement" by the International Labor Organization

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(ILO) (FAO 1992). Kanawaty (1992) stated that a work study is typically split into two parts, namely a method study to determine the best way to fulfil a task on the one hand, and on the other hand the work measurement that includes the time and motion study (Björheden and Thompson 2000). A time study investigates a specific task regarding the elapsed time, under the assumption that the single work steps (cycle elements) are "independent of each other, resulting in strong linearity assumptions" (Heinimann 2021). In forestry, as in other branches, scientific management is aiming to gain in-depth information for process optimization. Many studies investigate wood extraction processes due to their resource intensity. On the performance of cable-based wood extraction systems Lindroos and Cavalli (2016) identified 21 scientific articles published within a timeframe of 10 years.

The detailed investigation of these systems is dangerous and expensive (Magagnotti et al. 2012). Challenges are the uniqueness of the investigated extraction operations as well as the conditions under which the measurements are done. To conduct a cycle level (CL) or an element level (EL) time study that delivers valuable results for productivity estimations, the presence of experienced researchers – often more than one – in the operational procedures is required (Björheden and Thompson 2000). To gather data for the performance assessment, the observation of a longer period and a purpose-fitting count of observed work cycles are necessary, which consequently results in a high financial effort.

Forest operations are dependent on external factors such as terrain and existing infrastructure along with grade of mechanization (Enache et al. 2016), the experience level of workers (Purfürst 2010; Ottaviani Aalmo and Talbot 2014), or the weather (Holzfeind et al. 2021). To quantify these factors, an appropriate data recording concept must be developed. The acquired data is obligated to describe the observed process transparently. Measurements must be assigned to a unit and fitted into a model that describes the process plausibly and is statistically sound.

There have been attempts to harmonize wood extraction work studies in the past decades (Bergstrand 1991; Olsen et al. 1998; Magagnotti et al. 2012) and also very recently (Heinimann 2021) by providing guidelines. Magagnotti et al. (2012) published a guideline for the operational performance of work studies in forestry without the aspiration of prescribing "how to do things" and consequently standardization, but to offer insights on various approaches that can be applied. Ackerman et al. (2014b) provides a standardized time study methodology that was developed for the South African forest industry. Heinimann (2021) aims at the development of the statistical model that describes the observed work processes and presents possible statistical approaches. Nevertheless, in the tutorial requirements on operational activities are also described, since the adequate recording of data is crucial for punctilious model development. As a foundation for common understanding, Björheden and Thompson (2000) attempted to standardize forest work study nomenclature. Often referred to in published work studies, is the Ackerman et al. (2014a) model for cost calculation for forestry equipment along with other guidelines to cost calculation principles (Miyata 1980; Woo et al. 1990; FAO 1992; Acar 1994; Brinker et al. 2002).

Nevertheless, published performance studies on cable-based wood extraction processes present very heterogenous data. The present review investigates the reasons for this heterogeneity. It analyzes selected cable logging-related work studies concerning principles that are provided by the abovementioned guiding literature. The presented productivity, efficiency, and cycle time equations are analyzed regarding their predictors and the corresponding metrics to develop an understanding for performance-influencing factors. Then a meta-dataset containing a selection of presented metrics on observed yarding operations is used to display the relationships between performance and the parameters of yarding operations.

Materials and methods

Literature review

To identify suitable literature that is providing sound data on the performance of cable yarding systems in wood extraction operations, a comprehensive literature search was conducted. In the very first step, online resources (www.google.com, www.scopus.com, www.webofscience.com) were scanned using the keywords "cable yarding" and "productivity." In the second step, the literature identified was inserted in the search box of www.researchgate.net. For each of the articles, the related research, as well as the citations and the quoted literature were scanned to identify further relevant research.

The keyword pool was expanded several times and new keywords and terms were added such as "time study," "timber harvesting," "standing skyline," "productivity analysis," "cut to length," "whole-tree yarding," "tree-length yarding" "plantation," "efficiency," "carriage" and "road spacing."

Several initially found and analyzed sources were excluded from further quantitative analysis since no suitable data for the attempt of comparing the performance of yarding activities was provided. Consequently, the review-strategy cannot be described as systematic, since a systematic review is aiming to identify and display all evidence on a topic. According to the indicators to identify the approach to literature reviews provided by Snyder (2019), the present work must be classified as a mixture of a semi-systematic review and an integrative review.

Data collection and classification

Seventy different sources that present empirical data on cable yarding performance and 98 regression models were selected for further analysis. Three peer-reviewed articles were excluded from further analysis since they are presented in Korean language (Cho et al. 2015; 2016b; Choi et al. 2018).

To bring the extracted information from the literature reviewed to an order that allows for further analysis, a spreadsheet was used to gather numeric information on the observed yarding operations. The spreadsheet contains general information about the source, such as the name(s) of the author(s), the year it was published in, the purpose of the research and the country it originated from.

Relevant information regarding the time study, the model development and the performance assessment were collected. Information about the explanatory value of the models (e.g. R-squared), the scope in which it was created (e.g. number of valid observations), the applied timing method, the duration of observation and the observed productivity were also collected. In addition, the time-study-data was gathered comprising the means of cycle times, the definition of the cycle time elements and the average time spent on each cycle time element or work step, as well as observed delay times.

Descriptions provided of the yarding operation were extracted, including the yarding equipment (mainline pull, carriage capacity), the yarding corridor metrics (slope, yarding distance, lateral distance), as well as load data (mean piece size, mean volume per cycle, number of yarded logs), the extraction method and the yarding direction. Parameters that describe the stand such as the management system, the tree species composition, the stand density and the growing stock (volume per hectare), average DBH and average tree height were collected. The applied silvicultural treatment, its intensity, the harvested volume and the felling method were recorded. In datasets where clear cut (CC) was the treatment, the intensity was set to 100%.

Analysis of statistical models

To develop an understanding for the performance influencing parameters within cable yarding operations 98 statistical models, originating from 35 different sources, were analyzed regarding the independent variables and dependent variables. A collection of regression models were selected since they evaluate performance shown in yarding activities directly[1]. Models for the performance shown in single work cycle elements that are presented in the literature reviewed were not considered in this list (e.g., Spinelli et al. 2017a, 2021). In Cadei et al. (2021) a model for energy efficiency is presented that is not further analyzed in this paper.

Quantitative analysis

Seventy-four datasets were examined from the literature reviewed to describe the observed yarding operations and their performance. These datasets were selected for their consistency regarding the presented data. In terms of study design three categories are identified. Cycle level (CL) as well as elemental level (EL) studies are considered, but only work cycle-based statistical models are considered for quantitative analysis. Shift level (SL) studies were excluded, because they do not provide detailed information on specific yarding operations. Studies that present data in any other than the metric system were also excluded (Huyler and LeDoux 1997; Largo 2004; Hartley and Han 2007).

Not all datasets provided all data explicitly. For example, Picchio et al. (2020) did not present the average cycle volume and load volume, respectively. Yet, it can be calculated from mean piece count per yarding cycle and the average tree volume, since the information is provided that whole trees (WT) were extracted. Furthermore, the relation of productive time, scheduled time and the utilization rate as well as the relation between total cycle time, delay-free cycle time and the utilization rate were used to fill data gaps.

The dataset originating from Acuna et al. (2011) was excluded since it is incomparable due to the research question. Furthermore the presented data in Huber and Stampfer (2015) is not suitable for a comparison due to the study layout. Talbot et al. (2015) used the data from the same observations that were used in Talbot et al. (2014), which led to exclusion. In Haynes and Visser (2001), as well as in Abeyratne (2021) output quantification was presented as mass. Conversion to volume was not possible because of unknown densities. Consequently the datasets were excluded.

The created meta-dataset underwent a simple statistical analysis approach using descriptive statistics, plots and multiple linear regression, testing the effect of possibly influencing variables. If present in the meta-dataset, nominal and ordinal-scaled variables were converted to factors, while the cardinal scaled variables were treated as numeric variables. All statistical analysis steps were done within the software package R (R Core Team 2022) using the libraries “ggplot2” (Wickham 2016), “readxl” (Wickham and Bryan 2022) and “openxlsx” (Schauberger and Walker 2021). The application of mean comparison tests like Tukey’s honestly significant difference test were not considered due to the heterogeneity in the dataset and many missing values within individual records. Moreover, a deeper statistical analysis was not within the scope of this particular review.

Results

Purpose of reviewed studies

From an engineering perspective, 14 study purposes were identified from within the dataset. Of course, studies can have multiple purposes at once. Thereafter multipurpose studies have been assigned to multiple purpose categories. However, with 56 most of the studies looked at single system performance, followed by yarder comparison with eight and yarding direction with six records (Figure 1a). Looking at silvicultural treatments or environment in which operations have been carried out, most studies were done in clear cuts with 19, followed by thinning operations (10), salvage logging (7) and selective cut (7, Figure 1b).

In detail, possible reasons to conduct studies were the assessment of single new (Talbot et al. 2013; Proto et al. 2016) or established (Ozturk and Senturk 2006, 2016; Ozturk and Demir 2007) yarding equipment under specific conditions as well as the direct comparison of two comparable machines or systems under same or similar conditions (Spinelli et al. 2009, 2017a; Varch et al. 2020). The effect of new technology like partial automation is investigated (Spinelli et al. 2020). Furthermore, the training and learning curve effect along with the level of qualification and experience of workers were investigated (Ottaviani Aalmo and Talbot 2014; Hoffmann et al. 2016a). Performance was evaluated for optimal road spacing purposes (Ghaffariyan et al. 2009b). Also the influence of various silvicultural treatments (Renzie and Han 2001, 2008; Hoffmann et al. 2016b; Erber et al. 2017), different operational parameters such as the yarding direction (Spinelli et al. 2015; Lee et al. 2018), or the extraction method (Cho et al. 2019; Han and Han 2020) were surveyed. Aspects of ergonomic

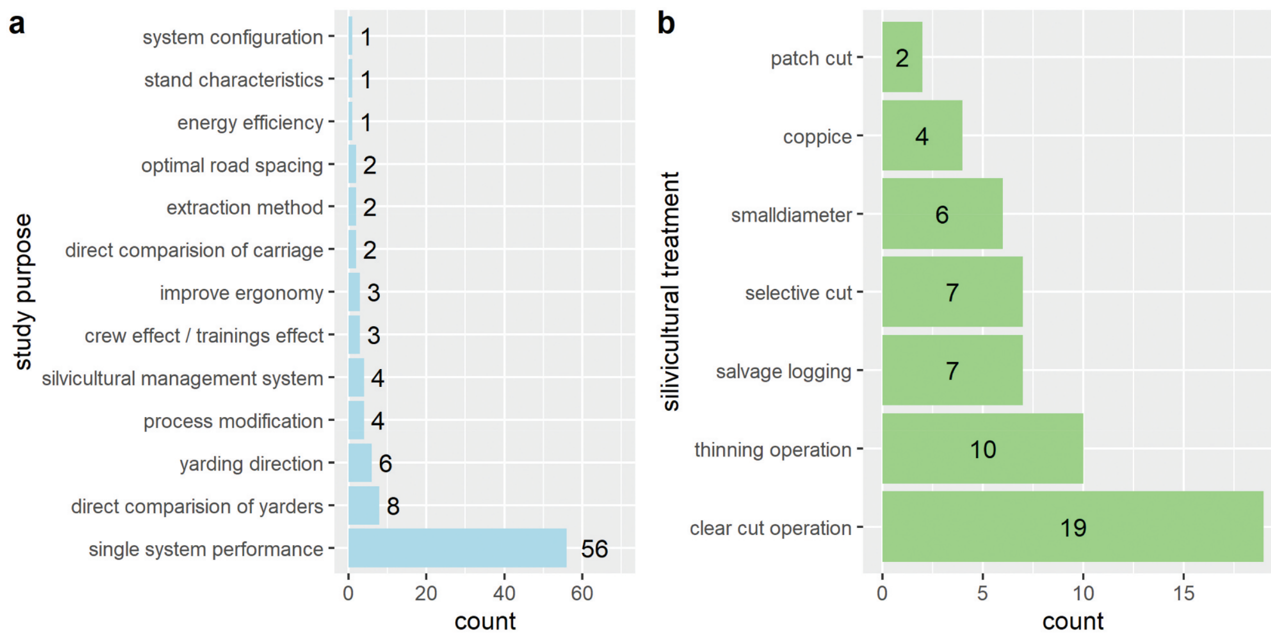

Figure 1. Number of cable yarding performance studies categorized by (a) engineering perspective and (b) the kind of silvicultural treatment applied or stand conditions.

improvement such as the usage of radio-controlled chokers (Leitner 2009; Stampfer et al. 2010; Devlin and Klvac 2014) or the possibilities of indulgent silvicultural treatment for especially sensitive environments (Schweier and Ludowicy 2020; Shoshyn et al. 2022) are motives to investigate cable yarding operations as a part of the wood supply chain. Table 1 provides a description of the purposes of the reviewed studies.

Cost calculation

Besides the performance evaluation of the applied extraction systems, many studies evaluate the cost of the observed operation by applying cost calculation-principles that can be found in the literature. Regarding the literature reviewed, costs were calculated in 40 (57%) of the 70 studies (Table 1). In 10 studies (14%), the cost was calculated according to Ackerman et al. (2014a). Brinker et al.'s (2002) principle was used five times (7%). Miyata (1980) is referred to in 12 studies (17%) and the FAO (1992) is referred to three times (4%). Woo et al. (1990) and Acar (1994) are referred to once. Four studies refer to more than one source for cost calculation (Macri et al. 2016; Jeong et al. 2017; Cho et al. 2018; Han and Han 2020). In one study (Renzie and Han 2008), the Forest Engineering Research Institute of Canada's (FERIC) standard costing method was applied. Eleven studies (16%) present a cost calculation without mentioning a reference for the applied method.

Timing and data collection method

The timing methods "cumulative timing" (Eroğlu et al. 2009) and "snap back timing," (Ozturk 2009; Hoffmann et al. 2015, 2016a, 2016b) were presented in Björheden and Thompson (2000), along with "selective timing." They were referred to in the literature regarding timing methods also with altering nomenclature "continuous timing" (Munteanu et al. 2019) or "continuous time recording" (Spinelli et al. 2017a). The reviewed performance studies furthermore applied "repetition timing" (Ozturk and Senturk 2006; Ozturk and Demir 2007; Senturk et al. 2007; Zimbalatti and Proto 2009, 2010; Proto and Zimbaletti 2015; Macri et al. 2016; Proto et al. 2016) and "repetitive multimoment timing" (Tunay and Melemez 2003), as manual timing methods. In several studies, handheld computers with time-study data logger software were used, (Daxner 1998; Haynes and Visser 2001; Hartley and Han 2007; Ghaffariyan et al. 2009a; Pierzchała 2010; Stampfer et al. 2010; Ottaviani Aalmo and Talbot 2014; Huber and Stampfer 2015). Acuna et al. (2011) chose a different approach and applied video analysis for timing purposes (Table 1). As recent works show, advances in sensor technology might support automated timing in cable yarding operations in the future (Gallo et al. 2013, 2021; Pierzchała et al. 2018; Varch et al. 2022).

Study design

Observational studies, also named descriptive studies, are used to describe a system under specific conditions. They are the simplest of work study designs and typically carried out to learn about a specific yarding system under non-variable conditions. Per definition, the system-describing variables are neither affected nor controlled by the investigator (Ackerman et al. 2014b). The comparability to other observational studies is limited since results may differ as soon as conditions vary slightly (Lindroos and Cavalli 2016). Among the literature reviewed, 17 sources (24%) present observational studies without model development (Zimbalatti and Proto 2009; Cho et al. 2016a; Choi et al. 2018) (Table 1). For instance the work of Zimbalatti and Proto (2010) investigates roundwood extraction in Calabria, South Italy by a Greifenberg TG 1100 cable yarder.

Table 1. List of examined literature with reference, country of origin, the determined study scope (EL: element level, CL: cycle level, SL: shift level), study design determined, the purpose of the study or the targeted goals, the applied statistical analysis methods and tools, information about cost-calculation and the timing and data collection method.

Reference	Country	Scope	Study design	Purpose of the study	Statistical methods	Cost calculation	Timing and data collection method
Abeyratne 2021	New Zealand	EL	Observational/ model	Productivity and cycle time of yarding system	Multiple regression analysis		
Acuna et al. 2011	Australia	EL	Observational/ model	Productivity and cycle time of a combination of swing yarder and feller buncher in steep terrain	Multiple linear regression		Video record analysis
Aruga et al. 2019	Japan	EL	Observational/ model	Comparison between different age classes	Regression analysis	Done	
Baek et al. 2020	Korea	CL	Observational/ model	Productivity and cost of two cable yarders, comparison of the productivity efficiency of two yarder types	Regression analysis, 2/3 of data for model generation, 1/3 of data for validation, sensitivity analysis	Brinker et al. 2002	
Baldini et al. 2003	Italy	EL	Observational/ model	Productivity	Regression	Done	
Cadei et al. 2021	Italy	EL	Observational/ model for energy efficiency, not for performance	Energy efficiency of yarding system	Linear regression analysis, linear mixed effect models		
Campbell et al. 2016	New Zealand/ Austria	EL	Observational/ model	Productivity	Linear regression techniques, Shapiro–Wilk test for normalization		
Cavalli and Lubello 2006	Italy	CL	Observational	Productivity and cost of yarding system			
Cho et al. 2016a	Korea	CL	Observational	Productivity and operational cost of yarding system	Regression model, sensitivity analysis for each element	Miyata 1980	Continuous chronometry
Cho et al. 2018	Korea	CL	Observational/ model	Productivity and cost of yarding system	Regression analysis (70% generation/ 30% validation), sensitivity analysis	Brinker et al. 2002, Miyata 1980	
Cho et al. 2019	Korea	CL	Experimental	Comparison between two extraction systems (productivity and cost) CTL (ground based) vs FT (cable-based)		KWF	
Chung et al. 2022	USA	CL	Observational/ model	Productivity and cost, effect of pre-bunching	Multiple least-squares linear regression analysis	Miyata 1980	
Daxner 1998	Austria	EL	Observational/ model	Productivity and efficiency of carriage "WOODLINER"	Stepwise multiple linear regression, ANCOVA	FAO 1992	Time study software Latschbacher
Devlin and Klvac 2014	Ireland	EL	Observational	Productivity and cost of yarding systems and radio-controlled choker		Miyata 1980	
Eker et al. 2001a	Turkey	EL	Observational/ model	Productivity and time consumption	Regression analysis		
Engelbrecht et al. 2017	Malaysia	SL & CL	Observational/ model	Productivity of grapple yarding system	Normalized data, ANCOVA, Tukey–Kramer test, χ^2 test, regression analysis, Scheffe´s test		
Erber et al. 2017	Germany	SL	Observational/ model	Impact analysis of yarding direction and silvicultural treatment, time consumption model	Regression analysis		
Eroğlu et al. 2009	Turkey	EL	Observational	Time consumption			Cumulative time measurement[8]7F
Evanson et al. 2017	New Zealand	EL	Observational	Productivity		Done	
Ghaffariyan et al. 2009a[9]	Austria	CL	Observational/ model	Productivity	Balancing data, stepwise regression, correlation testing	Done	Time study software
Ghaffariyan et al. 2009b	Austria	CL	Observational/ model	Optimal road spacing	Multiple regression		
Ghaffariyan et al. 2010	Austria	CL	Observational/ model	Optimal road spacing	Multiple regression	Done	

(*Continued*)

Table 1. (Continued).

Reference	Country	Scope	Study design	Purpose of the study	Statistical methods	Cost calculation	Timing and data collection method
Han and Han2020	USA	EL	Observational/ model	Comparison between extraction methods (FT vs TL)	Stepwise regression, normality tests, residual plot, Durbin–Watson test, forward selection method, matrix plots, variation inflation factors (VIF), Pearson correlation, Mallows' CP values, 70% model building, 30% testing (paired *t*-test)	Brinker et al. 2002, Miyata 1980	
Hartley and Han 2007	USA	EL	Observational/ model	Comparison of management systems	Regression model	Miyata 1980	Time study data logger program
Haynes and Visser 2001	USA	EL	Observational/ model	Effect of professional training on productivity	Single and multiple regression		Time study data logger program
Hoffmann et al. 2015	China	EL	Observational/ model	Performance of yarding system	Regression analysis	FAO 1992	Snap back
Hoffmann et al. 2016a	China	EL	Observational/ model	Performance of start up cable yarding crew	Stepwise multiple regression		Snap back
Hoffmann et al. 2016b	China	EL	Observational/ model	Comparison of two management systems clear cut (FT) vs selective cut (TL)	Stepwise multiple regression	Ackerman et al. 2014a	Snap back
Huber and Stampfer 2015	Austria	EL	Experimental/ model	Effect of topping trees on efficiency	Multiple regression, aggregation of separate sub models on main cycle elements		Time study data logger program
Huyler and LeDoux 1997	USA	EL	Observational/ model	Cycle time	Regression analysis		Continuous timing
Jeong et al. 2017	Korea	EL	Observational	Productivity and cost		Brinker et al. 2002, Miyata 1980, Woo et al. 1990	
Largo 2004	USA	EL	Observational/ model	Productivity and cost of yarding system	Multiple regression analysis	Miyata 1980	
Lee et al. 2018	Korea	EL	Observational/ model	Productivity and cost	Sensitivity analysis, least square regression, 70% model building, 30% test	Brinker et al. 2002	
Lee and Lee 2021	Korea	CL	Observational/ model	Productivity and cost	Homogeneity tested by Bartlett's K^2 method, ANOVA + ANCOVA, paired *t*-test	Miyata 1980	
Leitner 2009	Austria	EL	Experimental/ model	Efficiency and ergonomic benefit of Ludwig RC Choker	Multiple linear regression, ANCOVA	Done	
Macri et al. 2016	Italy	EL	Observational/ model	Productivity and cost	Regression model	Ackerman et al. 2014a; Miyata 1980	Repetition timing
Munteanu et al. 2017	Romania	EL	Observational/ model	Time consumption	Regression analysis		
Munteanu et al. 2019	Romania	EL	Observational/ model	Time consumption, productivity, cost	Correlation analysis, regression model, normality check by Q-Q plot, stepwise backward regression, fitting by least-squares multiple linear regression technique	Ackerman et al. 2014a	Continuous chronometry
Ottaviani Aalmo and Talbot 2014	Norway	EL	Observational/ model	Time consumption	Linear mixed regression, intercorrelation testing		Time study data logger program
Ozturk 2009	Turkey	EL	Observational/ model	Time consumption, productivity	Regression model, sensitivity analysis		Snap back
Ozturk and Aykut 2003	Turkey	EL	Observational	Productivity and time consumption			
Ozturk and Demir 2007	Turkey	EL	Observational/ model	Time consumption, productivity	Multiple regression, sensitivity analysis		Repetition timing
Ozturk and Senturk 2006	Turkey	EL	Observational/ model	Productivity, cost	Linear regression model, Durbin–Watson test for autocorrelation between the independent variables		Repetition timing
Ozturk and Senturk 2016	Turkey	EL	Observational/ model	Productivity	Regression model, Durbin–Watson test for autocorrelation between the independent variables		
Picchio et al. 2020	Italy	EL	Observational/ model	Comparative analysis of two cable yarder operations	Multivariate ANOVA	Miyata 1980	
Pierzchała 2010	Austria	EL	Observational/ model	Productivity of long cable system	Multiple regression, collinearity analysis, residual analysis	FAO 1992	Time study software Latschbacher

(*Continued*)

Table 1. (Continued).

Reference	Country	Scope	Study design	Purpose of the study	Statistical methods	Cost calculation	Timing and data collection method
Proto and Zimbaletti 2015	Italy	EL	Observational	Productivity and cost		Done	Repetition timing
Proto et al. 2016	Czech Republic	EL	Observational/ model	Productivity and costs of the system; differences between uphill and downhill	Regression model	Done	Repetition timing
Renzie and Han 2008	Canada	SL & CL	Observational	Productivity and cost of alternative silvicultural systems/treatments		Forest Engineering Research Institute of Canada's FERIC standard costing methods	
Schweier et al. 2020	Germany	SL	Observational/ model	Productivity and cost	Regression analysis, ANOVA, Cook's distance, mean value comparisons	Done	
Senturk et al. 2007	Turkey	EL	Observational/ model	Productivity and cost of Koller K300	Regression analysis	Done	Repetition timing
Shepherd and Visser 2021	New Zealand	EL	Observational	Productivity of Koller K602h			
Shoshyn et al. 2022	Belarus Republic	EL	Observational/ model	Performance of cable yarder under swampy conditions	Regression analysis	Done	
Spinelli et al. 2009	Italy	EL	Observational/ model	Productivity and cost	Regression techniques	Miyata 1980	
Spinelli et al. 2015	Italy	EL	Observational/ model	Productivity, comparison between uphill and downhill	Stepwise regression techniques		
Spinelli et al. 2017a	Italy	EL	Observational/ model	Productivity and cost, comparison between two carriage types	ANOVA, square root transformations for normalizing, Levene's test, χ^2 test, multiple linear regression	Ackerman et al. 2014a	Continuous time recording
Spinelli et al. 2020	Italy	EL	Experimental/ model	Productivity and cost, effect of partly automation	ANOVA, Tukey–Kramer test, Kruskal–Wallis non-parametric test, Scheffe's test, multiple linear regression	Ackerman et al. 2014a	
Spinelli et al. 2021	Italy	EL	Experimental/ model	Productivity, time consumption and cost, effect of yarding technique: single hitch vs double hitch	Mann–Whitney test, multiple linear regressionanalysis, residual analysis	Ackerman et al. 2014a	
Stampfer et al. 2010	Austria	EL	Observational/ model	Efficiency and ergonomic benefit of Ludwig RC Choker	Regression analysis, correlation analysis, ANOVA, residual analysis		Time study software Latschbacher EG 20
Stoilov 2019	Romania	EL	Observational/ model	Productivity and cycle time of yarding system	Regression analysis, exclusion of outliners, correlation analysis		
Stoilov 2021	Bulgaria	El	Observational/ model	Productivity and cost of yarding system	Regression analysis	Ackerman et al. 2014a	
Stoilov et al. 2021	Bulgaria	El	Observational/ model	Productivity and cost of yarding system in salvage operation	Least squares multiple linear regression, exclusion of outliners, correlation analysis	Ackerman et al. 2014a	
Talbot et al. 2013	Norway	EL	Observational/ model	Productivity of fully integrated yarding system	Multiple linear regression		
Talbot et al. 2015	Norway	CL	Observational/ model	Effect of disintegration of an integrated yarding system	Elaborate testing, regression methods	Ackerman et al. 2014a	
Torgersen and Lisland 2002	Norway	EL	Observational	Productivity of yarding system			
Tunay and Melemez 2003	Turkey	EL	Observational/ model	Productivity and cost	Regression techniques	Acar 1994	Repetitive (multimoment) timing
Varch et al. 2020	Austria	EL	Observational/ model	Efficiency and cost, comparison between two carriage types	Regression analysis, correlation analysis, ANOVA	Ackerman et al. 2014a	
Zimbalatti and Proto 2009	Italy	EL	Observational	Productivity, comparison between three yarder types			Repetition timing
Zimbalatti and Proto 2010	Italy	EL	Observational	Productivity			Repetition timing

In contrast to observational studies where no factorial treatment takes place, an experimental study design often offers better insight into the performance of wood extraction systems. The possibility to control independent variables not only allows for control of variation, but also adds complexity to the study design, especially if more than one factor is affecting the dependent variable. Experimental designs compare various factors to identify an effect and its cause. This requires a prior investigation whether there are interaction effects between two factors (Ackerman et al. 2014b). An example for an experimental study is the work of Cho et al. (2019) who compared the performance of two integrated harvesting systems in South Korea. Regarding the literature reviewed, this can be considered as an exception, since the rest of the studies present a statistical model (modeling studies) or had been classified as observational studies (Table 1).

The literature reviewed first and foremost (69%) presents examples for models created from observational studies, what consequently classifies them as modeling studies as Ackerman et al. (2014b) understand them. Experimental studies that provide statistical models (Leitner 2009; Huber and Stampfer 2015; Spinelli et al. 2020, 2021) are rare (6%) because the experimental character of harvesting related work studies must be scrutinized since the possibility to fully control the system state variables under real world conditions is mostly not given (Heinimann 2021). An example for this kind of experimental design is the work of Stampfer et al. (2010), who investigated the efficiency and ergonomic benefits of radio-controlled chokers in cable yarding operations, applying a monofactorial block design study layout. The statistical models were obtained by regression techniques, whereby various regression techniques were applied. Statistical testing and data processing are not very homogeneous. The listing of applied techniques (Table 1) includes analysis of variance (ANOVA), linear and multiple regression modeling, multiple comparison tests, correlation analysis, and others.

Scope of work studies

The scope of work studies is defined by the level of interest that is investigated (Ackerman et al. 2014b). For Heinimann (2021) the process of scoping is divided into three considerable aspects. At first the investigated production system must be described by a decisive response, its state, the input and the describing nuisance variables. Second, the system boundaries need to be set by defining where input enters and output exits the system. For most of the reviewed production systems, the standing tree is the boundary when input begins. On the other hand, the logged piece of wood, ready for further transportation at the forest road is the boundary where output exits the system. The third aspect of scoping is the definition of the observational unit, that also allows for classification. According to Magagnotti et al. (2012) and Heinimann (2021) this can be (1) the work cycle, (2) the shift or (3) the cutting unit. Work or cycle elements that were investigated in a lot of cable yarding-related productivity studies are a subset of a work cycle. Contrary to this, Ackerman et al. (2014b) accounted for them as an own class. In their definitions, the cutting unit level (UL) is not presented. Instead, the plot level (PL) study is defined.

Shift and cutting unit level

Shift level (SL) studies are beneficial when the productivity of a system should be assessed for a long period of time like in follow-up studies or for general monitoring. Ackerman et al. (2014b) suggest the recording of (1) shift start and end time, (2) record of crew working, (3) production in appropriate unit, (4) job type, (5) delays and causes of delays and (6) fuel consumption. The presence of a trained researcher is not necessarily required since there is only one data record needed per shift. For example, a supervising operator can record the required data on a prepared datasheet (Engelbrecht et al. 2017). This results in low study costs. The benefit of reduced effort can be compromised by the fact that the data quality strongly depends on the motivation of the recorder to support the study (Erber et al. 2017). The recorder needs to understand his role for the success of the study (Ackerman et al. 2014b). Some of this data possibly is automatically recorded by onboard data loggers (Varch et al. 2022) or recorded by the owner of the machine (Schweier et al. 2020), but for cable yarding operations data quality and density is mostly not as good as for fully mechanized harvesting systems. For both types, SL and UL, the system input is measured in units of productive time and the output is measured in units of mass or volume (Heinimann 2021). Regarding the reviewed literature four studies (5%) are classified as SL studies.

Cycle level studies

A completed work cycle is the most apparent observational unit that can be investigated regarding cable yarding performance studies (Heinimann 2021). Depending on the objective and the investigated process it can be conducted manually or by applying automatized data-gathering (Ackerman et al. 2014b). This requires equipment that is set appropriately to record the desired data. The input of the production system is measured in units of time, whereas the output is recorded in mass or volume units (Heinimann 2021). Advantages of CL studies are that they examine the variability in work processes and allow for delay information. Ackerman et al. (2014b) do not recommend the application of CL studies for the evaluation of wood extraction processes. They are work-intensive and expensive (Heinimann 2021), but do not provide information about the single work elements. Regarding the literature reviewed, 13 studies (18%) are classified as CL studies.

Element level studies

A work cycle can be divided into a subset of individual functional steps, the work elements (Magagnotti et al. 2012). The work element as an observational unit provides detailed data describing the investigated process in much higher resolution, what allows for deeper analysis and a better understanding. Traditionally EL studies are conducted manually with a stopwatch and clipboard, but recently broadly available technologies promote the possibility of the application of modern timing methods. For example, Varch et al. (2020) used time-study software (RC 5, version 1) on a handheld computer (Algiz 7) for their study on recuperating carriages. Furthermore, video record analysis is a modern possibility for timing that is applied in performance studies observing fully mechanized harvesting systems (Holzleitner et al. 2018, 2019; Holzleitner and Kanzian 2022). Regarding the reviewed cable yarding performance studies, only Acuna et al. (2011) used video record analysis for timing purposes.

The input to EL studies is measured in time units. The output is measured in units of volume or mass. In most of the reviewed EL studies, the values of single elements are summed at the end, so the output can be correlated with a completed work cycle in addition to the information gained about the single work elements. Regarding the literature reviewed, 54 (77%) studies are classified as EL studies.

Review of statistical models

Independent variables

According to Heinimann et al. (2001), the influencing parameters for the performance of a cable yarding systems are the stem volume, yarding distance, lateral yarding distance, bunching strategy, and the yarder type and the extraction method. Independent variables are required to describe these parameters quantitatively. The 98 reviewed models include 3.94 independent variables on average (mode = 3, range: 1 to 7) (Table 2). Seventy-five of the 98 models (77%) use the yarding distance (yard.dist), which is the distance the extracted wood moves along the cable-line as input. In most of the studies it is referred as "yarding distance," (e.g., Ghaffariyan et al. 2009b), but occasionally is referred as "extraction distance," (e.g., Picchio et al. 2020), "transportation distance" (Senturk et al. 2007), or "hauling distance" (Talbot et al. 2013). Three models instead use the "span length" (Erber et al. 2017) or "line length" (Engelbrecht et al. 2017) as an input variable.

Sixty-four models (65%) use the lateral yarding distance (lat. dist) as an independent variable, the nomenclature is heterogenous regarding the denotation of the load movement from the stand to the cable corridor. For example, Baek et al. (2020) referred to it as "lateral distance," Campbell et al. (2016) used the term "lateral haul distance." Spinelli et al. (2015) called it "lateral yarding distance." Ozturk (2009) refers to it as "lateral bunching distance," Ozturk and Senturk (2016) as "lateral dragging."

In 23 of the reviewed models (23%) the average slope of the cable corridor is considered as an input variable, either recorded as terrain slope or as the cable line slope. Three models (3%) consider the yarding direction (yard.dir) as an influencing factor.

The payload size is strongly affecting productivity according to the piece-volume-principle. Therefore, payload quantification is crucial for the development of productivity models. Thirty-four of the models (35%) use the load volume per cycle (vol.cycle) as an input variable, (e.g., Lee and Lee 2021). Twenty-two models (22%) use the piece count per cycle (n. cycle) (e.g., Hartley and Han 2007). Nine models (9%) use the tree volume (tree.vol) as an input variable (e.g., Stampfer et al. 2010) and 12 of the reviewed models (12%) use the piece size as an input variable (e.g., Varch et al. 2020).

The harvesting intensity (e.g., Ghaffariyan et al. 2009a) is considered in 12 of the 98 models (12%) and the residual vegetation (e.g., Ozturk and Senturk 2006) in seven (7%). The effect of silvicultural treatment (silv.treat) is an independent factor in two of the models (2%) (e.g., Erber et al. 2017). The log presentation (Hoffmann et al. 2016b) in one (1%).

Twenty-seven of the reviewed models (28%) moreover explain the influence of parameters that are specific to their research question or special conditions that probably have an influence on the performance. For example, the investigation of the benefits of radio-controlled (rc) chokers (Leitner 2009; Stampfer et al. 2010; Campbell et al. 2016) is demanding the incorporation of a corresponding variable representing if rc-choker are used or not (dummy.choker) in the model. In the past these variables often have been named dummy variables to be included in regression analysis. Nowadays they are usually named factors. Spinelli et al. (2017) investigated the effect of a motorized carriage and introduced a corresponding dummy variable (dummy.motorized) in their model.

The time that is required for the completion of single cycle elements is employed as an input variable for five models (5%) (e.g. Ozturk and Senturk 2006). In all these five models that originate from the same region, the total cycle time is the dependent variable.

Dependent variables

The performance-describing dependent variable is the productivity in most cases, which is the yarded volume in relation to the spent time, or the efficiency, which is the time spent in relation to the yarded volume or the cycle time, representing the time needed to complete one whole yarding cycle. Cycle time can be assessed as delay free cycle time or as total cycle time (cycle time including delays). Table 2 shows that in the literature reviewed the productivity is referred as "productivity" (e.g., Pierzchała 2010; Acuna et al. 2011; Spinelli et al. 2015), as "net productivity" (e.g., Baldini et al. 2003; Engelbrecht et al. 2017), as "production rate" (e.g., Campbell et al. 2016), as "yarding productivity" (e.g., Daxner 1998; Cho et al. 2018), or "total time productivity" (Shoshyn et al. 2022). The unit of productivity is in all but one of the reviewed models m^3/PMH[2] or m^3/PSH[3] as presented in Table 2. Haynes and Visser (2001) used t/PMH. Productivity is employed as a dependent variable 32 times (32%) regarding the selected models.

The efficiency was referred as "efficiency" (e.g., Leitner 2009; Stampfer et al. 2010), or "yarding efficiency" (Varch et al. 2020) and was employed four times (4%) as an independent variable. Delay free cycle time was referred as such in the reviewed publications presenting statistical models, except in (Talbot et al. 2013), where the "effective time for yarding" was assessed. The cycle time including delays was referred as "total cycle time" (Tunay and Melemez 2003; Ozturk and Demir 2007; Ozturk 2009; Hoffmann et al. 2015, 2016b; Proto et al. 2016; Spinelli et al. 2017a), or as "cycle time" (Huyler and

Table 2. Description of reviewed statistical models from various sources analyzed regarding dependent and independent variables. PSH = productive system hour

Number	Reference	Dependent variable	Dependent variable unit	Independent variables	Number of independent variables	R^2	Adj. R^2	Number of valid observations	Model's *p*-value
1	Abeyratne 2021	Cycle time	min	yard.dist	1	0.5		353	
2	Abeyratne 2021	Cycle time	min	yard.dist	1	0.1		431	
3	Abeyratne 2021	Cycle time	min	yard.dist	1	0.44		246	
4	Abeyratne 2021	Cycle time	min	yard.dist	1	0.6		1030	
5	Abeyratne 2021	Cycle time	min	n.cycle yard.dist	2	0.6		1030	
6	Acuna et al. 2011	Productivity	m^3/PMH	yard.dist n.cycle dummy.bunch	3	0.62		184	0
7	Baek et al. 2020	Delay free cycle time	sec	vol.cycle yard.dist lat.dist n.cycle	4	0.5934		346	<0.01
8	Baek et al. 2020	Delay free cycle time	sec	vol.cycle yard.dist lat.dist n.cycle	4	0.4813		244	<0.01
9	Baldini et al. 2003	Net productivity	m^3/PMH	yard.dist	1	0.739		70	
10	Baldini et al. 2003	Net productivity	m^3/PMH	yard.dist	1	0.8518		66	
11	Baldini et al. 2003	Net productivity	m^3/PMH	yard.dist	1	0.678		155	
12	Baldini et al. 2003	Net productivity	m^3/PMH	yard.dist	1	0.6026		114	
13	Baldini et al. 2003	Net productivity	m^3/PMH	yard.dist	1	0.7066		95	
14	Campbell et al. 2016	Production rate	m^3/PMH	n.cycle piece.size yard.dist	3	0.68		177	
15	Campbell et al. 2016	Production rate	m^3/PMH	vol.cycle	1	0.71		97	
16	Campbell et al. 2016	Production rate	m^3/PMH	n.cycle piece.size lat.dist	3	0.74		45	
17	Campbell et al. 2016	Production rate	m^3/PMH	vol.cycle dummy.chokerset yard.dist	3	0.29		239	
18	Cho et al. 2018	Yarding productivity	m^3/PMH	lat.dist yard.dist tree.vol	3	0.75		230	<0.001
19	Chung et al. 2022	Delay free cycle time	sec	yard.dist lat.dist n.cycle	3		0,47	293	<0.001
20	Chung et al. 2022	Delay free cycle time	sec	yard.dist	1		0,53	195	<0.001
21	Daxner 1998	Yarding productivity	m^3/PSH_0	yard.dist lat.dist piece.size	3	0.618		369	
22	Engelbrecht et al. 2017	Net productivity	m^3/PMH	piece.size line.length n.cycle stack.dist dummy.yarder dummy.team	7		0.501	42,927	<0.0001

(*Continued*)

Table 2. (Continued).

Number	Reference	Dependent variable	Dependent variable unit	Independent variables	Number of independent variables	R^2	Adj. R^2	Number of valid observations	Model's *p*-value
				top.vol					
23	Erber et al. 2017	Time consumption	PSH_{15}/m^3	tree.vol yard.dir line.length silv.treat	4	0.511		223	
24	Ghaffariyan et al. 2009a	Delay free cycle time	min	yard.dist lat.dist slope tree.vol intensity road.space	6	0.9	0.899	1554	0.05
25	Ghaffariyan et al. 2009a	Delay free cycle time	min	yard.dist lat.dist slope piece.size intensity	5	0.886	0.885	958	0.05
26	Ghaffariyan et al. 2009a	Delay free cycle time	min	yard.dist lat.dist slope piece.size intensity	5	0.889	0.888	541	0.05
27	Ghaffariyan et al. 2009b	Delay free cycle time	min	yard.dist lat.dist vol.cycle tree.vol stand.density slope	6	0.934	0.933	591	0.05
28	Ghaffariyan et al. 2010	Delay free cycle time	min	yard.dist lat.dist intensity yard.dir slope vol.cycle	6	0.894	0.893	752	0.05
29	Han and Han 2020	Delay free cycle time	min	lat.dist yard.dist	2	0.37		156	<0.05
30	Han and Han 2020	Delay free cycle time	min	lat.dist yard.dist	2	0.78		121	<0.05
31	Hartley and Han 2007	Delay free cycle time	min	yard.dist lat.dist n.cycle	3	0.42		301	
32	Hartley and Han 2007	Delay free cycle time	min	yard.dist lat.dist n.cycle	3	0.29		115	
33	Hartley and Han 2007	Delay free cycle time	min	yard.dist lat.dist n.cycle dummy.graple	4	0.36		346	
34	Hartley and Han 2007	Delay free cycle time	min	yard.dist	3	0.25		126	

(*Continued*)

Table 2. (Continued).

Number	Reference	Dependent variable	Dependent variable unit	Independent variables	Number of independent variables	R^2	Adj. R^2	Number of valid observations	Model's p-value
				lat.dist n.cycle					
35	Hartley and Han 2007	Delay free cycle time	min	dummy.silv.treat	1	0.48		860	
36	Haynes and Visser 2001	Productivity	t/PMH	yard.dist n.cycle piece.size dummy.train	4	0.7			
37	Hoffmann et al. 2015	Total cycle time	min	yard.dist lat.dist slope veg n.cycle vol.cycle dummy.manage	7	0.46		145	<0.001
38	Hoffmann et al. 2016a	Cycle time	min	yard.dist lat.dist slope veg off-set.slope	5	0.61		170	<0.001
39	Hoffmann et al. 2016a	Cycle time	min	yard.dist lat.dist slope veg	4	0.36		81	<0.001
40	Hoffmann et al. 2016a	Cycle time	min	yard.dist lat.dist slope veg log.vol n.cycle	6	0.66		216	<0.001
41	Hoffmann et al. 2016a	Cycle time	min	yard.dist n.cycle lat.dist veg	4	0.41		159	<0.001
42	Hoffmann et al. 2016b	Total cycle time	min	yard.dist lat.dist veg log.presentation n.cycle	5	0.43		88	<0.001
43	Hoffmann et al. 2016b	Total cycle time	min	yard.dist lat.dist log.presentation n.cycle	4	0.43		89	<0.001
44	Hoffmann et al. 2016b	Total cycle time	min	yard.dist lat.dist veg log.presentation	4	0.53			<0.001
45	Huyler and LeDoux 1997	Cycle time	min	yard.dist lat.dist tree.vol	4	0.67		80	

(*Continued*)

Table 2. (Continued).

Number	Reference	Dependent variable	Dependent variable unit	Independent variables	Number of independent variables	R^2	Adj. R^2	Number of valid observations	Model's *p*-value
				vol.cycle					
46	Largo 2004	Delay free cycle time	min	yard.dist lat.dist	2	0.28		218	<0.05
47	Largo 2004	Delay free cycle time	min	yard.dist lat.dist	2	0.21		237	<0.05
48	Lee et al. 2018	Delay free cycle time	sec	yard.dist	1	0.58		101	0.00
49	Lee et al. 2018	Delay free cycle time	sec	large.end.diameter yard.dist lat.dist	3	0.54		56	0.00
50	Lee and Lee 2021	Delay free cycle time	min	yard.dist lat.dist vol.cycle	3		0.531	343	<0.01
51	Lee and Lee 2021	Delay free cycle time	min	yard.dist lat.dist vol.cycle	3		0.65	92	<0.01
52	Leitner 2009	Efficiency	min/m³	tree.vol dummy.choker	2	0.774	0.773	936	0.000
53	Leitner 2009	Efficiency	min/m³	tree.vol yard.dist dummy.choker	3	0.816	0.814	270	0.000
54	Macri et al. 2016	Total yarding cycle time	min	yard.dist lat.dist slope vol.cycle	4	0.71		70	
55	Macri et al. 2016	Total yarding cycle time	min	lat.dist yard.dist slope vol.cycle	4	0.73		70	
56	Munteanu et al. 2017	Cycle time	sec	lat.dist slope	2		0.22	316	
57	Munteanu et al. 2019	Cycle time	sec	yard.dist lat.dist lat.slope	3	0.57		558	<0.001
58	Ozturk 2009	Total cycle time	min	yard.dist lat.dist cycle.time.elements	4			75	
59	Ozturk and Demir 2007	Total cycle time	min	cycle.time.elements	6	0.995		80	
60	Ozturk and Senturk 2006	Total time	min	yard.dist lat.dist vol.cycle cycle.time.elements	6				
61	Ozturk and Senturk 2016	Yarding time	min	yard.dist vol.cycle lat.dist	3		0.807	30	
62	Picchio et al. 2020	Extraction time	min	vol.cycle yard.dist	2		0.859	3485	<0.001

(*Continued*)

Table 2. (Continued).

Number	Reference	Dependent variable	Dependent variable unit	Independent variables	Number of independent variables	R^2	Adj. R^2	Number of valid observations	Model's *p*-value
63	Picchio et al. 2020	Extraction time	min	vol.cycle	2		0.934	3416	<0.001
				yard.dist					
64	Pierzchala 2010	Productivity	m^3/PSH_{15}	yard.dist	4	0.66		228	
				lat.dist					
				piece.size					
				n.cycle					
65	Proto et al. 2016	Total cycle time	min	yard.dist	3	0.44		100	0.001
				lat.dist					
				vol.cycle					
				dummy.yard.dir					
66	Senturk et al. 2007	Delay free cycle time	min	yard.dist	4	0.8			
				lat.dist					
				vol.cycle					
				timber.number					
67	Senturk et al. 2007	Delay free cycle time	min	yard.dist	4	0.7			
				lat.dist					
				vol.cycle					
				timber.number					
68	Senturk et al. 2007	Delay free cycle time	min	yard.dist	4	0.64			
				lat.dist					
				vol.cycle					
				timber.number[10]					
69	Shoshyn et al. 2022	Productivity	m^3	yard.dist	6				
				lat.dist					
				stocking					
				vol.cycle					
				piece.size					
				n.cycle					
70	Spinelli et al. 2015	Productivity	m^3/h	yard.dist	4	0.39		171	
				lat.dist					
				n.cycle					
				piece.size					
71	Spinelli et al. 2015	Productivity	m^3/h	yard.dist	3	0.66		137	
				lat.dist					
				piece.size					
72	Spinelli et al. 2015	Productivity	m^3/h	yard.dist	3	0.42		308	
				lat.dist					
				piece.size					
73	Spinelli et al. 2017	Total cycle time[11]	sec	yard.dist	2		0.461	83	<0.05
				dummy.motorized					
74	Spinelli et al. 2020	Productivity	m^3/PMH	yard.dist	2 (+1)	0.163		280	<0.05
				dummy.auto					
75	Stampfer et al. 2010	efficiency	min	tree.vol	2	0.77		936	
				dummy.choker					
76	Stoilov 2019	Delay free cycle time	min	lat.dist	3 (+3)	0.774		90	<0.05
				yard.dist					
				slope					
77	Stoilov 2019	Cycle time	min	lat.dist	2 (+5)	0.54		90	<0.05

(*Continued*)

Table 2. (Continued).

Number	Reference	Dependent variable	Dependent variable unit	Independent variables	Number of independent variables	R^2	Adj. R^2	Number of valid observations	Model's *p*-value
				yard.dist slope vol.cycle					
78	Stoilov 2019	Productivity	m^3/PMH	lat.dist yard.dist slope vol.cycle	4(+2)	0.95		90	<0.05
79	Stoilov 2019	Productivity	m^3/SMH	yard.dist slope vol.cycle	3(+4)	0.74		90	<0.05
80	Stoilov 2021	Delay free cycle time	sec	lat.dist slope	2	0.49	0.46	90	<0.05
81	Stoilov 2021	Cycle time	sec	yard.dist slope	2	0.20	0.15	90	<0.05
82	Stoilov 2021	Productivity	m^3/PMH	vol.cycle lat.dist slope	3	0.45	0.42	90	<0.05
83	Stoilov 2021	Productivity	m^3/SMH	vol.cycle slope	2	0.31	0.27	90	<0.05
84	Stoilov et al. 2021	Delay free cycle time	sec	yard.dist lat.dist slope dummy.damage	4		0.54	90	<0.05
85	Stoilov et al. 2021	Delay free cycle time	sec	lat.dist	1		0.87	30	<0.05
86	Stoilov et al. 2021	Delay free cycle time	sec	lat.dist	1		0.67	30	<0.05
87	Stoilov et al. 2021	Delay free cycle time	sec	lat.dist	1		0.20	30	<0.05
88	Stoilov et al. 2021	Productivity	m^3/PMH	yard.dist lat.dist vol.cycle	3		0.73	90	
89	Stoilov et al. 2021	Productivity	m^3/PMH	lat.dist vol.cycle	2		0.84	30	<0.05
90	Stoilov et al. 2021	Productivity	m^3/PMH	lat.dist vol.cycle	2		0.62	30	<0.05
91	Stoilov et al. 2021	Productivity	m^3/PMH	lat.dist vol.cycle	2		0.57	30	<0.05
92	Stoilov et al. 2021	Productivity	m^3/SMH	vol.cycle	1		0.50	90	<0.05
93	Stoilov et al. 2021	Productivity	m^3/SMH	vol.cycle	1		0.54	30	<0.05
94	Stoilov et al. 2021	Productivity	m^3/SMH	lat.dist vol.cycle	2		0.62	30	<0.05
95	Stoilov et al. 2021	Productivity	m^3/SMH	lat.dist vol.cycle	2		0.57	30	<0.05
96	Talbot et al. 2013	Effective time for yarding	sec	yard.dist lat.dist n.cycle	3	0.56	0.55	149	<0.001
97	Tunay and Melemez 2003	Total cycle time	sec	cycle.time.elements	1	0.94		40	0.1
98	Varch et al. 2020	Yarding efficiency	PSH_0/m^3	yard.dist lat.dist tree.vol	3		0.6	305	<0.001

LeDoux 1997; Hoffmann et al. 2016a; Munteanu et al. 2017, 2019), as "yarding time" (Ozturk and Senturk 2016), as "total time" (Ozturk and Senturk 2006), or "extraction time" (Picchio et al. 2020). Regarding the reviewed models, the total cycle time and delay free cycle time were employed as a dependent variable 30 (31%) and 32 (33%) times, respectively. Erber et al. (2017) used the time consumption with PSH_{15}/m^3 as output to their model. Nearly all investigated sources provide the productivity (mostly in m^3/PMH without any further specifications) of the investigated yarding operation, at least in addition to their model output.

Model characteristics

The R-squared value (R^2) also known as the coefficient of determination is a measure of how good the generated model fits the data. A coefficient of determination of 0.87 means that the model can explain 87% of the variation in the data and is often understood as an indicator for the model's quality. The adjusted R-squared value (adj. R^2) accounts for the overfitting due to the additional inserted predictors. When the adj. R^2 is higher than R^2, it indicates that the addition of an input variable increased the explanatory value of the model. Regarding the 98 selected models, for 73 (75%) models a R-squared value is presented. For 35 models (36%) an adjusted R^2 value is presented.

The p-value indicates the probability that the null hypothesis is true, or in other words the smaller the p-value, the more likely it is (based on the data) that the predictors are affecting the response variable. For 58 models (59%) a p-value is presented.[4]

For 90 models (92%) the number of valid observations is presented. A valid observation is a complete and uncompromised data record that is used for model fitting. This is, for example, all data that was gathered on one complete yarding cycle in the case of EL or CL studies. In case of SL studies, the number of shifts represents the sample size. Since the SL studies are often conducted over long periods and include data from many harvesting operations, the results are considered to be more robust (Erber et al. 2017).

Data acquisition

As previously described, quantitative data is recorded during work studies to identify performance-influencing parameters in production systems. Heinimann (2021) presented a list of metrics for system inputs and outputs that are relevant and praxis orientated for forest work studies. The input to a yarding production system is subdivided in the production factors, the objects to be yarded and the operational inputs (energy). Output is the product (yarded timber) and the emissions.[5] The object to be yarded is, in most of the reviewed studies, the felled tree. However, there are studies observing cut-to-length operations with preprocessed logs (Hoffmann et al. 2015; Lee et al. 2018).

Only a few studies present a reference for the load volume determination. Firstly Smalian's formula, (e.g., Hoffmann et al. 2016a; Cho et al. 2016a) and secondly Huber's formula (e.g., Zimbalatti and Proto 2009; Proto et al. 2016) are mentioned. Spinelli et al. (2015) noted that the volume was determined from mid diameter and length in a cut-to-length yarding operation. In the literature reviewed there are only a few examples (e.g., Schweier and Ludowicy 2020) that specify the volume of the yarded timber by indicating the voluminal consideration of bark (m^3_{ub}/m^3_{ob}).[6]

Previous attempts for harmonization of forest work studies (Ackerman et al. 2014b) and its nomenclature (Björheden and Thompson 2000) presented a detailed time concept for forest work studies containing 28 time classes. Heinimann (2021) followed with an adapted, and with respect to practicability simplified, classification that contains five time classes. Most of the examined models are represented by this concept. An exception are the models, 69, 70, and 71 (Spinelli et al. 2015) that link the extracted volume to hours without further specifications (m^3/h) and model 68 (Shoshyn et al. 2022), where the extracted volume is not linked to a time unit.

The abbreviation "PMH_0" describes the production time in multiple regards. It indicates that the recorded time was productive time that was spent by a machine and was recorded in hours. The subscript figure "0" indicates that all delays are excluded (e.g., Ghaffariyan et al. 2009b; Hoffmann et al. 2016a). The subscript figure "15" in the abbreviation "PMH_{15}" means that short delays under 15 minutes are included (e.g., Varch et al. 2020).

The typical yarder-specific work cycle elements and delays were described by Ackerman et al. (2014b) together with a proposal for break points. Break points in time study context are happenings that mark the transition from one work step (cycle element) to the next work step. For example, this can be the beginning of carriage movement, which separates the cycle elements "Mainline in" and "Carriage in." Within the literature reviewed work cycle elements nomenclature is inconsistent and break points were set differently in a broad variety. For example, the element "Carriage out" is often referred as "outhaul" (Ghaffariyan et al. 2009b) or "outhaul empty" (Ozturk 2009). In some cases specifications were made e.g. "outhaul and position" (Evanson et al. 2017). For this cycle element, the break points are relatively homogenous among the studies and were at least formulated similar to Ackerman et al.'s (2014b) definition. In most cases they are defined by the start and the end of the carriage movement along the cable line.

In contrast, the cycle time elements "Mainline out" and "Mainline in" are not universally descriptive for all yarding operations. The usage of those terms implicates the utilization of a yarding system where the carriage is clamped, and the hook mechanism is attached to the mainline itself. Motorized slack pulling carriages and self-propelled carriages carry hoist ropes for load attachment. Therefore, nomenclature is adapted, the term "lateral out" describes this work element accurately. In various studies, the work phase is described as "hook descent" (Zimbalatti and Proto 2009), or "release of mainline" (Ghaffariyan et al. 2009b). Evanson et al. (2017) referred to the "walk in, lower and pull rope," a description of the choker setters' activity and the movement made by the rope or the hook.

The start of the "choker setting" (Ghaffariyan et al. 2010), "choking" (Jeong et al. 2017), "choke" (Talbot et al. 2013) or "hook-up" (Hoffmann et al. 2016b) cycle element is in most cases marked by the arrival of the choker setter with the hook at the load, or when the choker setter starts to attach the first piece of wood (Devlin and Klvac 2014). It ends when the choker setter is in the clear and gives the sign, respectively (Baek et al. 2020).

The "mainline in" or "lateral in" time element starts when the "hooking," "choker setting" ends. In most sources the starting break point is marked by the end of the previous cycle time element (e.g., Pierzchała 2010), or when the load is starting to move toward the carriage (Eroğlu et al. 2009). The diversity in nomenclature is, analog to the described nomenclature diversity for "mainline out," a product of diversity in utilized systems.

There are several examples for studies, where the tasks and activities of the three previously discussed cycle elements were aggregated to one data record (e.g., Hoffmann et al. 2015; Campbell et al. 2016; Chung et al. 2022). Furthermore there are examples for studies where the hook-pulling and the hooking were aggregated, but the pulling of the load to the carriage was timed separately (Ozturk and Aykut 2003; Tunay and Melemez 2003).

"Carriage return" has, analog to "carriage out" homogenous definitions regarding breakpoints. Starting and ending is mostly associated with the beginning and ending of carriage movement along the cable line. However, nomenclature is very heterogenous. It is referred to as "inhaul" (e.g., Ghaffariyan et al. 2009b), as "travel of loaded carriage" (Ozturk and Senturk 2016), or "carriage in" (Hartley and Han 2007).

Lee and Lee (2021) and Spinelli et al. (2015) aggregated the "lateral in" or "mainline in" and "inhaul" or "carriage in" work steps to "carriage in." Eker et al. (2001) as well as Lee et al. (2018) chose the same approach but referred to "pulling loaded carriage" and "in-haul," respectively.

"De-choking" as described by Ackerman et al. (2014b) is not referred to as such in the literature reviewed. Used terms are: "unhook" (Baek et al. 2020), "load release" (Ghaffariyan et al. 2009b), "unchoking" (Picchio et al. 2020), "unload" (Spinelli et al. 2015), or "carriage unloading" (Zimbalatti and Proto 2010). Break points are in most cases defined by the non-movement of the carriage at the landing site.

Some authors oriented themselves on previously conducted performance studies regarding cycle element definitions. Baek et al. (2020) and Proto et al. (2016) referred to Huyler and LeDoux (1997). It has to be noted that not every source provides a definition of break points (e.g., Baldini et al. 2003). Contrary to Ackerman et al.'s (2014b) delay categorization, delays are mostly categorized as operational delays, mechanical delays or personal delays (Pierzchała 2010; Hoffmann et al. 2015; Cho et al. 2016a). Investigation of delays is, depending on the research question and the investigated system, not always requested and detailed information on delay time is mostly not presented.

Quantitative meta-data analysis

The average productivity for all 75 datasets is 9.8 m^3/PSH_{15}, whereby uphill operations are more productive with 10.2 m^3/PSH_{15} compared to downhill with 8.5 m^3/PSH_{15} (Table 3). However, a large variation can be observed in the dataset, because productivity ranges from 2.1 m^3/PSH_{15} (q.05) to 26.1 m^3/PSH_{15} (q.95) if looking at the quantiles. Even though mean uphill production rates are higher compared to downhill, this is not the case if the median (q.50) is calculated for the subsets uphill and downhill resulting in values of 6.4 m^3/PSH_{15} versus 9.1 m^3/PSH_{15}. Assuming that load volumes per cycle behave in line with production rates, delay free cycle times should show the same difference between uphill and downhill yarding resulting in lower median delay free cycle times. Nevertheless, a downhill yarding cycle takes 37% longer with 8.2 min/cycle then the median cycle time for uphill yarding of 6.0 min/cycle (Table 3).

While productivity and cycle times might attract the most research first, conditions under which the studies have been carried out provide a deeper insight into the different operations (Table 4). Yarding distance reportedly ranges from 44 to 372 m (q.05, q.95) with a median of 134 m. A noticeable difference between uphill and downhill yarding can not be detected. Mean volume of wood transported per cylce is 1.09 m^3, but can reach up to 5.97 m^3/cycle. However, 90% of the studies report cycle volumes between 0.20 and 2.38 m^3 with a median of 0.80 m^3/cycle. However, comparing the median of the studies on downhill operations against uphill unveils a higher volume per cycle with 0.99 m^3 for downhill versus 0.75 m^3 for uphill yarding (Table 4). This explains the difference observed in productivity mentioned above and points out that higher cycle times can be outweighed through higher volumes to achive desireable productivity.

The extraction method may influence yarding productivity and delay free cycle time regarding the investigated datasets. For cut-to-length (CTL), tree length (TL) and wholetree (WT) the median productivity is 6.0, 4.1 and 10.1 m^3/PSH_{15}, respectively (Figure 2a). For WT operations 90% of the studies indicate a productivity between 2.0 and 27.9 m^3/PSH_{15}. Delay free cycle time does not differ much between CTL and WT, as for both groups the gross of the studies (90%) report values between approx. 3.5 and 15 min. TL seems to have lower cycle times across the studies, but only 13 sources dealt with TL operations (Figure 2b).

Table 3. Descriptive statistics on meta-dataset extracted from literature for productivity and delay free cycle time for the whole dataset (overall) and the subsets based on yarding direction (uphill, downhill). Missing entries are excluded resulting in a different number of records (n). SD = standard deviation, min = minimum, q.05 = 5% percentile, q.50 = 50% percentile, q.95 = 95% percentile, max = maximum.

variable	productivity			cycle time		
unit	m^3/PSH_{15}			min		
subset	Overall	uphill	downhill	overall	uphill	downhill
mean	9.8	10.2	8.5	7.4	7.1	8.6
sd	9.5	10.7	4.0	3.8	3.4	4.7
min	1.5	1.5	1.7	3.2	3.6	3.2
q.05	2.1	2.4	1.9	3.6	3.9	3.2
q.50	7.1	6.4	9.1	6.0	5.6	8.2
q.95	26.1	27.1	13.3	14.9	14.8	16.0
max	67.3	67.3	13.3	21.0	18.4	21.0
n	74	56	18	70	53	17

To prove if the well-known piece-volume principle may be present in the meta-dataset as well, productivity was plotted against average volume per cycle. A clear trend can be observed indicating a positive correlation between both (Figure 3a). Furthermore, the extraction method might have an impact and shows a trend as well, respectively. However, this seems not to be the case for the meta-dataset. Average yarding distance could impact productivity as well. As shown in Figure 3b, there might be a trend that with increasing average yarding distance the productivity may drop. However, further analysis will be done, applying regression methods to prove if the trend can be confirmed. It has to be noted that one data record is excluded because it shows extremly high production rates with 67.3 m^3/PSH_{15}. Furthermore, not all records contain yarding distance, which limits the available records for the regression analysis to 63.

Based on the 63 records, using values for productivity, average cycle volume (vol.cycle), average yarding distance (yard.dist) and extraction method (extr.meth), linear regression modeling was done with following model as starting point (Eq. 1). β_i represents the estimates within the model. After a first pass with inclusion of all mentioned independent variables, it can be seen that extraction method did not pass the $p \leq 0.05$ level set to be included in the final model (Model 1, Table 5). Removing extraction method from the model caused only a minor drop in model performance from $R^2 = 0.716$ to $R^2 = 0.715$. The same is true for the AIC (Akaike's Information Criterion) which did not change due to the exclusion (Model 2, Table 5). With an R^2 of 0.715 more than 71% of the variation of productivity within the meta-dataset can be explained by cycle volume and yarding distance, which is quite high in the context of forest operations productivity modeling.

$$productivity = \beta_0 + \beta_1 vol.cycle + \beta_2 yard.dist + \beta_3 extr.meth \quad (1)$$

Discussion

Classification

The variation in study methodology is very wide, since every extraction operation is unique due to specific site and operational conditions. Research is mostly done on real forest operations that are mostly executed by commercial harvesting companies. Kanawaty (1992) stated that a work study is typically split into a method study and the work measurement. Cable yarding work studies often do not include the method study, since the responsible decision maker's evaluation of the site and operational conditions, as well as their experience in cable yarding activities, are defining "how the task is fulfilled." At least the interest in an economically justifiable operation and the responsibility for a safe operation are requiring that in most cases. Consequently, researchers can often only adapt their research methods to those conditions. Nevertheless, the assumption can be made that experienced decision makers in harvesting enterprises come at least close to the one best way to perform the task when planning the extraction operation.

Researchers observe the operation and cannot influence the work processes. Therefore, the studies have no experimental character as defined by Ackerman et al. (2014b) and must be classified as observational studies. It can be argued that Varch et al. (2020) conducted an experimental study, using a mono factorial random study design. Since each of the investigated carriages were utilized in a separate cable line where the average slope and the average yarding distance were altering, a classification as an observational study is possible. Two systems were investigated under similar conditions, their performances were described and compared afterward. Other studies, where two or more pieces of yarding gear are compared to each other (e.g., Zimbalatti and Proto 2009; Spinelli et al. 2017a; Varch et al. 2020), are classified as observational studies in the present work for the same reason. However, categorization is difficult due to the specificity of studies and requires consideration of details in study design and differential diagnosis between the evaluation techniques presented.

Comparability of evaluated performance

The quantitative comparability of work studies originating from different studies that were conducted by different authors is very limited and requires great care and attention to the specifications of the studies (Lindroos and Cavalli 2016). Authors with experience in conducting a performance evaluation have preferences on research methods that are based on their experience. They will consequently choose a similar

Table 4. Descriptive statistics of the conditions provided by the studies reviewed on cable yarding operations and performance. (n = number of records, SD = standard deviation, min = minimum, q.05 = 5% percentile, q.50 = 50% percentile, q.95 = 95% percentile, max = maximum).

variable	yarding distance			volume / cycle			slope		
unit	m			m^3			%		
subset	overall	uphill	downhill	overall	uphill	downhill	overall	uphill	downhill
mean	154	152	161	1.09	1.10	1.06	53.9	55.6	46.7
sd	113	114	113	0.89	0.97	0.63	13.7	13.0	14.9
min	41	41	50	0.17	0.19	0.17	17.5	27.0	17.5
q.05	44	43	50	0.20	0.30	0.20	32.1	33.7	23.1
q.50	134	130	140	0.80	0.75	0.99	55.0	59.0	47.5
q.95	372	312	358	2.38	2.56	1.94	72.2	74.2	65.5
max	729	729	400	5.97	5.97	2.13	78.0	78.0	70.0
n	72	54	18	68	50	18	55	45	10

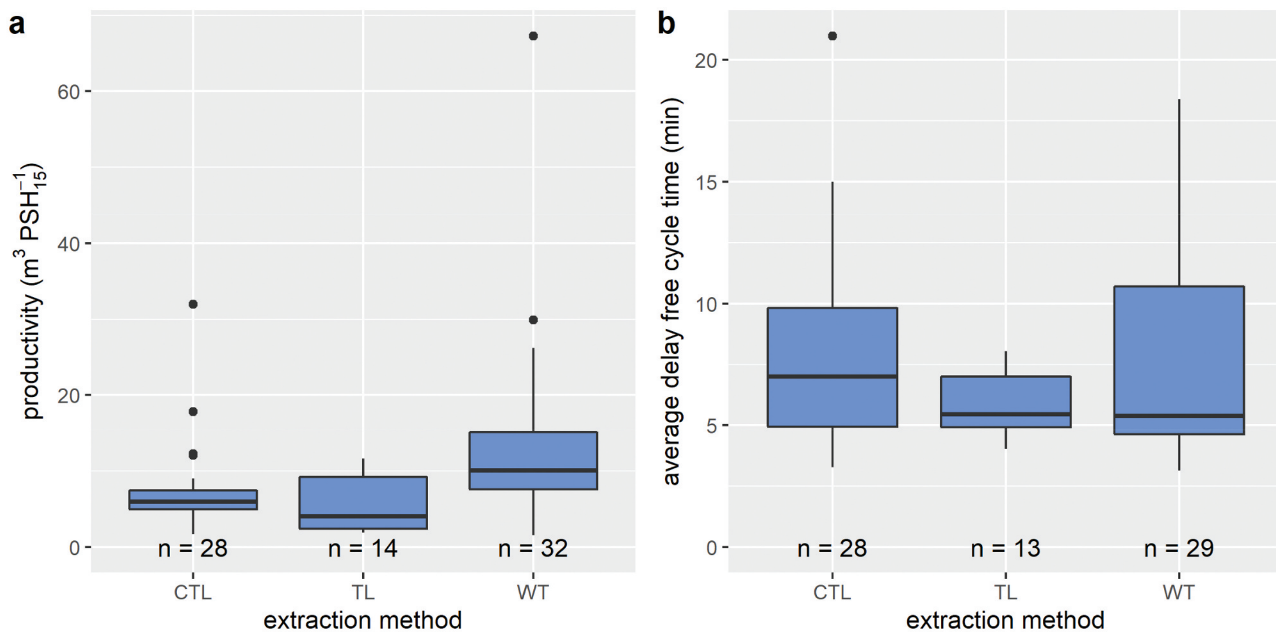

Figure 2. Boxplots expressing the (a) productivity and (b) delay free cycle time range by extraction method for cut-to-length (CTL), whole tree (WT) and tree length (TL) extraction.

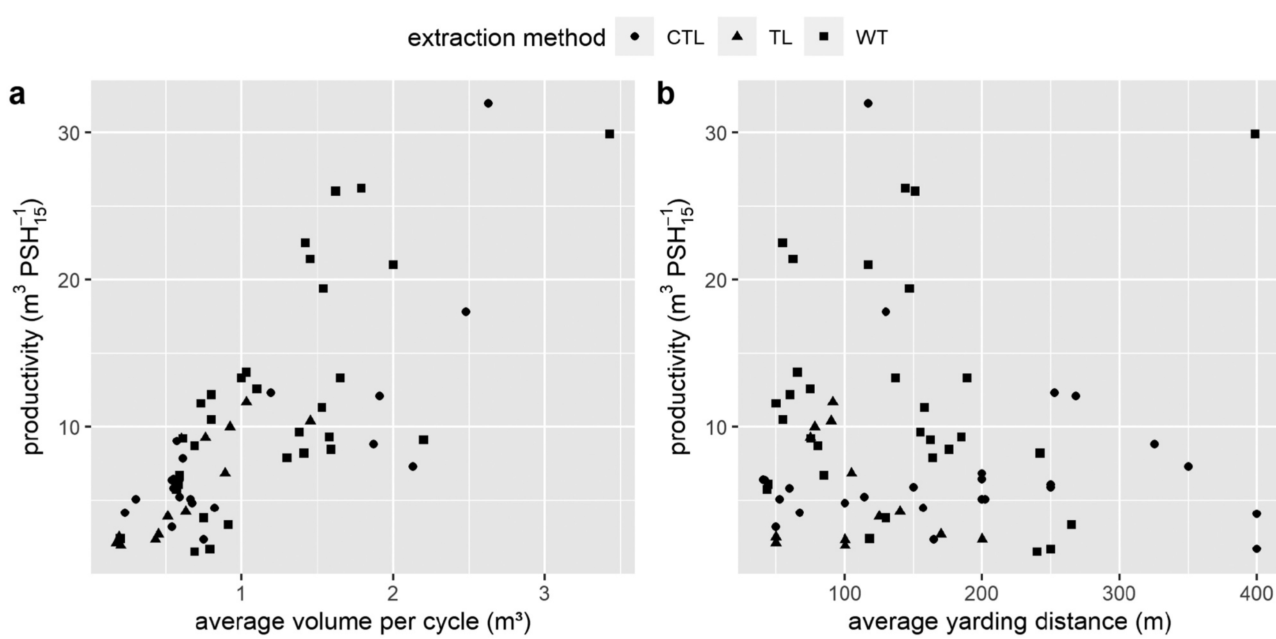

Figure 3. Yarding productivity by extraction method for (a) average cycle volume and (b) average yarding distance.

approach, with modifications to adapt to the actual study goals and conditions.

The variety of utilized yarding systems and the resulting variety in problem formulation require a corresponding variety of study layouts, as every research question requires the contemplation of a constitutive indicator. To achieve that, adaption of the investigation methods to particular conditions is mandatory. Consequently, the evaluated and presented data are not homogeneous and are inconsistent concerning data structure, density, and quality.

Regarding performance studies and especially regarding cable yarding time studies, the break point definition is crucial for comparability. The above displayed heterogeneity in break point definition, primarily between the cycle elements that take place in the stand (mainline out or lateral out, hooking or choking, mainline in or lateral in), makes a comparison between studies at the elemental level very difficult. The recording of corresponding elemental times often requires the presence of a researcher in the stand near the felling site. This is dangerous and especially in steep terrain inconvenient, but it is crucial to gain a deeper understanding of the yarding process. Ackerman et al.'s (2014b) suggestion for break point definitions provides reproducible measurements. An application of these

Table 5. Linear regression models for the combined assessment of the predictors average cycle volume (vol.cycle) and average yarding distance (yard.dist) and extraction method (extr.meth). Model 1 includes all independent variables, whereas in Model 2 extr.meth was excluded, because it did not pass the minimum *p*-value of 0.05 to be included. (CI = confidence interval of the estimates, AIC = Akaike's Information Criterion, p-values ≤ 0.05 marked in bold).

	Model 1			Model 2		
Predictors	Estimates (βi)	CI	*p*	Estimates (βi)	CI	*p*
(Intercept)	2.87	0.29 to 5.44	**0.030**	3.45	1.45 to 5.44	**0.001**
vol.cycle	10.18	8.40 to 11.97	**<0.001**	10.52	8.83 to 12.21	**<0.001**
yard.dist	−0.04	−0.05 to −0.02	**<0.001**	−0.04	−0.05 to −0.02	**<0.001**
extr.meth (TL)	0.20	−2.61 to 3.00	0.888			
extr.meth (WT)	1.51	−0.73 to 3.74	0.183			
Observations		63			63	
R^2/R^2 adjusted		0.734/0.716			0.725/0.715	
AIC		353.086			351.329	

definitions should be considered when conducting a time study on cable yarding operations.

Alongside break point definition, the aggregation of cycle elements is also relevant in regard to comparability. As described, in several studies the cycle elements were aggregated in various configurations. This affects the resolution of the study and is a further aspect to be considered when comparing results of various studies.

The heterogeneity in cycle time element nomenclature is less problematic for comparability. It is not relevant, whether the movement of the load toward the cable line is referred to as "lateral in" or "mainline in." This variation in nomenclature accrues from the attempt to describe the investigated system correctly. The term "mainline out" is specific for yarding systems which spool out the mainline for load attachment and does not describe a system in which a carriage is carrying a hoist rope on an extra drum. It can be argued that the term "lateral out or in" is including those configurations as well, since it describes the direction of the movement, lateral to the yarding direction. Still, living skyline systems are excluded, in which the load is not moved laterally to the cable corridor, but tangentially toward the yarder (Talbot et al. 2013). Nevertheless, a common understanding can be promoted by a common language, which underlines the value of Björheden and Thompson's (2000) effort to harmonize nomenclature and allows for the suggestion to use the most inclusive nomenclature.

Quantification of performance

To provide the best possible information on the evaluated performance, it is necessary to provide the productivity in a specific format, e.g. m^3_{ub}/PSH_{15} (volume measured under bark, investigation of a system during productive time, short delays under 15 min included). As presented in Table 2 most of the literature reviewed is not providing data in this format. While the indicator for short delay consideration is presented in most of the productivity models the indicator for bark consideration is not presented among the models reviewed. Among the literature presented on cable yarding performance (see Table 1), the indicator is presented rarely (e.g., Schweier and Ludowicy 2020). In the section "Quantitative meta-data analysis" all productivity information is presented as m^3/PSH_{15} regardless of the original declaration from the source. Analog to productivity, also for efficiency (e.g. PSH_{15}/m^3_{ub}) the indicators are valuable.

The usage of PSH instead of PMH in yarding operations should be considered. Heinimann (2021) argued that also in cases were only one machine is observed, the observational unit is a system consisting of the utilized machine and its operator. In the case of yarding operations, the system consists of the yarder – including operator – and the choker setters. Most of the observed operations from the literature reviewed employ a crew of four workers (mean = 3.7, range: 2 to 8), that supports this approach since every one of them is a performance-influencing element of the investigated system.

For time as input or output, the problem of unit selection does not arise, since time is always measured in seconds, minutes, hours, etc. in forest work studies and conversion is simple. However, the usage of centi-minutes has benefits and can be recommended, since it is easier to imagine the extent of e.g. 3.41 min than the extent of 205 s.

The usage of any other than the metric system in load quantification (Huyler and LeDoux 1997; Largo 2004; Hartley and Han 2007) should be avoided, to allow the work to be put into context internationally. It needs to be stressed that the exact and complete documentation of the recorded data, including entities, is crucial for comparability and also to meet scientific standards since reproducibility is a key requirement (Heinimann 2021). Currently, a comprehensive protocol providing support to researchers for how the data should be presented does not exist. From the authors' experience data might have been collected and sits on the media, but during writing of the reports and publications the reporting of basic figures often gets lost due to the complexity of productivity studies and the specific research questions one tries to answer.

Data acquisition

The application of action cameras on heavy machinery to record the working process for later analysis on screen was only done by Acuna et al. (2011) regarding the reviewed cable logging studies. However, it is a successfully used method for the investigation of fully mechanized extraction systems (e.g., Niemistö et al. 2012; Holzleitner et al. 2018, 2019; Holzleitner and Kanzian 2022) where all relevant work steps can be observed by one camera. The application in cable yarding studies may not be as beneficial since single work elements are carried out in different locations and one single camera cannot film all relevant processes. Nevertheless, further evaluation of this possible application should be considered. A configuration with multiple cameras with synchronized clocks could deliver valuable insights, especially if one camera is installed in the carriage, facing downward to record the activities in the stand.

The recording of the span length instead of the average yarding distance occurs primarily in SL studies (Erber et al. 2017; Evanson et al. 2017), which seems to be conclusive considering the absence of research personnel during the operation. The span length is one record per installed line, while the average yarding distance is obtained from records taken in cycle frequency. That could be considered too much of an effort by the person who is responsible for data recording and could be a source of errors. This is one of the factors that define the differences in resolution between SL and CL, or even EL studies. However, the usage of data loggers tracking the carriage position and movements (Gallo et al. 2013, 2021; Pierzchała et al. 2018), multiple cameras, and CAN-Bus (Central Area Network) loggers (Varch et al. 2022) might be further exploited in the future. These technologies might reduce manual field work for researchers. The downside will be the complexity and costs added in study preparation, and moreover in post-processing of all data streams collected to get meaningful results. Beside costs and complexity Pierzchała et al. (2018) could determine 78% of the cycle elements correctly for cable yarding operations. Gallo et al. (2021) were able to identify 97.6% of the defined cycle elements using GNSS records, processed with self-developed algorithms. Pan et al. (2022) could classify 94% of the work elements within feller-buncher operations with a low cost camera. These promising results illustrate the potential of digital time assessment methods.

The altering approaches in payload size quantification probably accrue from operation-specific considerations. Due to safety concerns, it is not recommended to measure the processed logs in the landing area of an integrated yarding system, where a boom with an attached processor is operating. The quantification method must be fitted to the conditions of the single work investigation. This results in a variety of different payload size information formats. Nevertheless, with respect to performance comparability this would be less of a problem, if a method description allows for reproducibility under consideration of the relationship between piece volume, piece count and cycle volume as described in the section "Quantitative meta-data analysis." Compared to automatic timing of work cycle elements, the automation of payload size measurement has not been covered by the literature the authors are aware of. However, to successfully carry out sensor-based productivity studies both timing and payload measurement must be done simultaneously. For integrated systems having the cable yarder and processor on the same platform, researchers could probably extract volumes from the processor's protocol and link it to the corresponding time records of the yarder. However, for other systems accurate automatic volume and payload measurements which can be linked to individual work cycles might not be possible in the near future, respectively.

Selection of independent variables

The selection of the tested independent variables is, along with practicability considerations regarding data acquisition, also driven by "forest common sense" like the piece-volume principle and experience of researchers. For instance, Lee and Lee (2021) follow Schweier and Ludowicy (2020) and Baek et al. (2020) with the selection of predictors. For specific research questions concerning the influence of factors like radio-controlled chokers (Leitner 2009; Stampfer et al. 2010) or motorized carriages (Spinelli et al. 2017a), specific dummy variables were introduced.

Limitations of comparability

As already stated, the quantitative comparison of the evaluated performance from different sources is limited. Different yarding conditions result in different effective factors. Moreover, factors with great influence on one investigated system may be not present, or at least not significantly influencing the performance in another system.

An example of that is the residual vegetation that may influence the performance during the cycle elements "mainline in" or "lateral in." In a study where a clearcut operation is observed, there will not be any residual stand left that could affect performance but eventually there are big rocks lying around which increase terrain ruggedness and cause a similar effect. In the first case the ruggedness can be quantified on a cardinal scale by reporting the harvesting intensity. In the second case the quantification can only be addressed categorially on an ordinal scale.[7] This can of course produce valuable input information for an experiment but cannot be translated into a meta-context since most other studies do not provide this information. Those providing it were probably conducted by a different author team with another subjective evaluation and categorization of the terrain ruggedness caused by rocks.

Another factor that cannot be compared between studies is human labor. There are studies that investigate the training effect (Ottaviani Aalmo and Talbot 2014) or crew effect (Hoffmann et al. 2016a), which provide data on these factors' influence on performance, but the comparability to results from other studies is not given, since experience of employed workers as well as their motivation are hard – or even impossible to quantify.

The weather probably has a significant effect on performance in cable yarding operations, which is not displayed in the frame of the present work. It is very likely that heavy rain and wet conditions in the stand will decrease performance, since the choker setter's movement will be more cautious and consequently slower. Furthermore, the workers' motivation may be lower under rainy work conditions. Applicable data was not found in an extent that allows further analysis. Most of the sources reviewed do not provide detailed information on weather conditions. A possible explanation could be that work measurement is mostly conducted under good weather conditions, which seems to be conclusive since safety could decrease under bad weather conditions for research personnel.

Discussion of the results from the meta-analysis

The quantitative analysis of the gathered data may provide meaningful information for many other researchers, especially for modeling studies or other kind of simulation and prediction modeling purposes. Main principles found in individual studies regarding the impact of different influencing factors, can be proven even in a highly aggregated manner like the underlying meta-dataset. To our knowledge this is one of the rare attempts to do a meta-data analysis extracted from published research studies in the field of cable yarding operations. Surprinsigly a relative high correlation between productivity, cycle volume, and yarding distance were observed with the heterogenety of the dataset in mind.

However, due to the small sample size within the meta-dataset this result must be considered as a trend. Although, additional variables could be extracted from many sources used. By far not all data has been explored in depth. Judging from the existing information, further investigation may deliver valuable deeper insights, but was out of the scope of this article.

Conclusions

A collection of cable yarding specific performance studies is presented that gives an insight on the scientific appraisal of this topic. The review of a selection of statistical models presented allows for insights on the influencing factors. The comparative view on cable yarding productivity is underlying many limitations with respect to the reasons presented. The diversity in problem formulation and the corresponding diversity in methodical approaches account for these limitations. With great care and attention to details of the single work studies, a quantitative meta-analysis was performed and yields at least a few results that were expected to be displayed. It would be beneficial for comparability of yarding operations to consider the principles that are already presented in the guiding literature. A bigger collection of complete datasets would result in more coherence that could be displayed from a statistical meta-analysis. Advances in sensor, data logger, and data-processing technologies allow us to automate productivity studies to some extent as recent publications demonstrate, but at the time of writing this article these technologies cannot replace field work for researchers. We hope that this review may support researchers in their individual preparation of cable yarding performance studies and provide insights into research activities done in the field of forest engineering to researchers from other forest science disciplines.

Notes

1. Direct evaluation means that the performance is evaluated by one statistical model for the whole yarding cycle. Models that are an aggregation of sub models, e.g. Huber and Stampfer (2015) are not considered in this list.
2. PMH (productive machine hour) is provided in most of the literature reviewed. However, there are differences regarding the inclusion of short delays. PMH_{15} indicates that delays shorter than 15 min were not recorded as delay and therefore count as productive work time. PMH_0 indicates that every delay, noticed by the researcher was timed as delay.
3. PSH (productive system hour) expresses that the output is related to the productive time of the whole yarding system instead of the machine only.
4. This does not include significance levels for specific predictors as presented in several models e.g. Erber et al. (2017).
5. Since the performance is not directly influenced by qualitative criteria of expanded energy and produced emissions and their quantity is not a limiting factor in the yarding cycle, they are not considered in the present work.
6. ub: under bark; bark volume is not considered. ob: over bark; bark volume is considered.
7. Without exceeding effort
8. Probably means continuous timing
9. Data from Limbeck-Lilienau (2002) and Stampfer et al. (2003).
10. Probably means n.cycle.
11. Delay free cycle time was measured and an overall delay factor according to Spinelli and Visser (2008) was applied.

Disclosure statement

No potential conflict of interest was reported by the authors.

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