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Application of a primarily deductive framework describing time consumption for hauling of logs to road-side

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Abstract

Forest management planning decisions are often based on the forest owner's goals, which typically focus on economic criteria. Logging operation work productivity functions are used when costing forest operations. These functions affect the conclusions drawn during forest management analyses because different logging environments give rise to different harvesting costs. When evaluating new combinations of machines and environments, there is generally a shortage of field data on productivity that can be examined in advance. We applied a previously published deductive framework describing time consumption in forwarding to known environments, in which field studies on forwarding have been conducted and for which extensive data are available. We then adapted the deductive framework to better reproduce the results obtained in the time studies. The deductive framework accurately reproduced the observed forwarding productivities; on average, the adaptation process improved the accuracy of this reproduction. However, it may also have reduced the accuracy of individual predictions. We conclude that the deductive framework can be used as a basis for constructing work productivity functions for forest management analyses, and can serve as a foundation when constructing new productivity functions based on time study results to use when pricing forwarding.

Keywords: Deductive framework, forwarding, hauling, logging, productivity, time consumption

1 Introduction

Forest management planning can be seen as a large decision making problem in which the timing and type of forest management activities are chosen to fulfill the decision maker’s goals (cf. Bettinger et al. 2009). The complexity of the planning problem varies in time and extent. Forest management planning is usually divided across three levels: *strategic*, *tactical* and *operational*. Aspects of the different levels have been described by authors including Church et al. (2000), Epstein et al. (2007), and Bettinger et al. (2009). Moving from the strategic level to the tactical, or from the tactical level to the operational entails an increase in temporal resolution, ranging from 5-year periods to weeks, shorter planning horizons, ranging from 100 years to 1-6 months, increased spatial resolution, ranging from the forest estate level to the stand level, and considering increased levels of detail, ranging from growth and yield over time to number of logs of specific dimensions. At all of these levels, decision support systems (DSS) can be used to assist the decision-makers in balancing efforts towards different goals and properties, often using operations research methods to optimize complex planning problems (Anon. 2011a). Forest owners’ goals often center on economic criteria, and hence accurate cost models are crucial in forest management planning.

As an example, one of the most common economic problems in forest planning concerns the maximization of the net present value of all future forest management activities in the forest stand as represented by equation (1) (Faustmann, 1995), where B_u is net present value of rotation length u years, i.e, the length of a generation from regeneration to final felling. Furthermore, A_u is final felling net revenue, D_x is thinning net revenue of thinning in year x, c is regeneration costs and r is the discount rate.

$$\max B_u = \frac{A_u + \sum D_x \times (1+r)^{u-x_D} - c \times (1+r)^u}{(1+r)^u - 1} \qquad (1)$$

The term D_x in equation (1) can be expanded into one gross revenue part and one cost part. The cost part to a large extent consists of the cost for the work of e.g. felling, processing and hauling the trees to roadside and is a function of cost per unit time and productivity of the operation. Numerous methods and technologies to perform this work exist. In e.g. the Nordic countries, felling the trees and processing the stems into 3 – 6 m logs are usually done with a harvester, hauling of the processed logs to roadside is done carrying them with a forwarder, and further transportation of the processed logs is done with a timber truck. This is known as the cut-to-length system. Cost in this example is then a function of e.g. the hourly cost of the harvester, the forwarder, and the timber truck, and their productivities, respectively.

Consider four examples of forest management problems, all affected by forest operations costs, and all of which could be regarded as specific sub-problems of equation (1);

i) How does optimal rotation length *u* depend on the technology for hauling?;
ii) Which kind of hauling equipment should be used when harvesting a particular stand at a given time?;
iii) How much should a contractor be paid for hauling a particular load?; and
iv) What kind of new hauling machines should a forest machine manufacturer focus its development efforts on in order to achieve the greatest increases in productivity?

In all cases, variation in the cost of e.g. forest haulage will influence the outcome of the problem solving exercise, which brings us back to the general formulation of the problem in equation (1). As such, an improved understanding of the accuracy of harvesting and hauling work productivity functions should be useful in forest management planning. Forestry DSS often contain functions for forest growth, mortality and wood quality, work productivity functions for cost calculations, and price models for revenue calculations (e.g. Wikström et al. 2011). The consequences of using erroneous growth models and prices and input data of poor quality in forest management planning situations are all well-known (e.g. Kangas 1998; Lohmander 2000; Duvemo & Lämås 2006). However, the consequences of using erroneous work productivity functions in the same contexts are still unexplored.

New silvicultural treatments and new harvesting equipment are sometimes appended to or employed in ordinary forest management without altering the timing, e.g. time points for thinning operations, or management type. This presents a risk of achieving a sub-optimal total net present value (cf. equation (1)), or of falling short on some measure of goal achievement. That is to say, it is generally likely that better results would be obtained if the timing and type of forest management activities were different. In order to obtain reliable estimates of the harvestable volume using economic, ecological and technical criteria, it is necessary to understand their properties and influence. Moreover, the increasing complexity of modern forestry operations requires more detailed pricing models.

In this paper, we apply one approach to modeling productivity in forest operations under both previously known and novel conditions, aiming to evaluate the usefulness of such an approach when trying to address the example problems i) – iv) above. The evaluation is done using and comparing our approach with published time study results.

2 Background

The methodology and application of work studies in forestry is well described by Sundberg & Silversides (1988) and Samset (1990). Work studies in forestry often focus on productivity, defined as the ratio of the input and the output of a system. The input is typically calculated in terms of the working time for employees or machines, so time studies are widely used in this context. There are two different kinds of time studies: comparative and correlation (Eliasson 1998; Lindroos 2010; Samset, 1990). In comparative studies, environmental factors are kept constant to facilitate comparisons between different working techniques, systems and methods. This type of time study is usually performed quite early in the life-cycle of a technique, system or method (e.g. Bergström 2009). In correlation studies, the effects of different influencing factors are examined using the same methods, systems or techniques (e.g. Laitila et al. 2007; Nurminen et al. 2006). This type of time study is often performed during the later stages of the life-cycle, e.g. to provide a basis for a fair and general piece-rate-based salary system.

Work studies are inductive, meaning that their results and the conclusions drawn about the behavior of a system are based on empirical observations. Alternatively, one could adopt a deductive approach, in which predictions regarding the behavior of a system are made on the basis of theories, laws and models (Ford 2000). To illustrate the difference between inductive and deductive reasoning in forest engineering, an inductive approach might entail measuring the time consumed by different work elements, e.g. the time it takes to cut and process a tree, and afterwards trying to correlate differences in time consumption with independent variables relating to the forest and machine environment. Conversely, in a deductive approach, one would use theoretical methods to analyze the work elements and identify the independent variables that affect the time required for specific work elements; with these data in hand, one would estimate the productivity of the system. For example, with estimates of the cutting and processing speed of the machine in hand, one could compute the expected time required for cutting and processing a given size of tree. Productivity, and its inverse time consumption, is typically described using the following function (2):

$$\hat{o} = f\left(A, X\right) \quad (2)$$

where $\hat{o}$ is a vector containing the estimated productivities per work element. X is the vector of the independent variables that affect productivity, such as stand characteristics, and belong to the set of environments X in which the studied operation would typically be performed. A is a vector of the same length as X whose coefficients determine the impact of different independent variables on time consumption. In time studies, conclusions are drawn on the basis of observed data and, at best, some perception of the models, theories and laws underpinning those observations. The true productivity values, o_i are observed and correlated with appropriate independent variables X_i. A is then estimated using tools such as regression analysis to yield $\hat{A}$. For reasonable independent variables $X_i \in \mathrm{X}$, one can then obtain a productivity estimate (3):

$$\hat{o}_i = f\left(A, X_i\right) \quad (3)$$

When a machine is transferred to a new environment $X_i \in \mathrm{X}_k, X_i \notin \mathrm{X}$, the validity of $\hat{A}$ is no longer known, and hence the validity of $\hat{o}_k$ is also questionable. This can be handled by expanding X to include all new environments in which the operation can be performed, $\mathrm{X}' = \mathrm{X} \cup \mathrm{X}_\mathrm{k}$. In practice, this means that additional time studies or simulations must be performed. Consequently, the coefficients must then be updated through e.g. new regression analyses, yielding $\hat{A}'$. Every time the composition of X' changes, a new $\hat{A}'$ has to be created to obtain a valid productivity estimate $\hat{o}'$.

When using a deductive approach, A is not determined as a function of o and $X \in \mathrm{X}$; instead, it is computed on the basis of premises such as the characteristics of the machine or reasoning based on empirical data in a broader sense. Hence, when X changes to X', $A = A'$ may remain the same, and the productivity estimates $\hat{o}$ remain valid for all $X \in \mathrm{X}'$. A simulation approach is somewhat more deductive than time studies, since simulation model algorithms and parameter values may be based on deductive reasoning. It may however still be necessary to simplify the acquired data, e.g. by means of regression analysis.

Simulation models of forest machines represent an intermediate between the inductive and deductive approaches. Their structures and inputs are designed using a combination of deductive and inductive reasoning, and their outputs are often interpreted as empirical observations and used as an alternative to time study results.

3 Literature review

The forwarder is by far the most common machine used in off-road forest haulage in the mechanized cut-to-length system commonly applied in the Nordic countries, and so most of the time studies conducted in recent years have been correlation studies. Even productivity models based on relatively small data sets may include several independent variables (e.g. Nurminen et al. 2006). However, forwarders are constantly being used with new assortments and in new working environments, so it can be challenging to accurately predict forwarder productivity in advance (cf. Nurmi 2007). When extending the applications of forest technology in this way, theoretical assessments can be useful in determining which machine concepts are worth developing and converting into prototypes for further field studies (Lindroos (in press); Ringdahl et al. 2012; Sängstuvall et al. 2012). For example, the price of and demand for biofuels have both increased in recent years. Consequently, there has been an increase in the amount of research and development aimed at identifying more efficient and cost-effective techniques and systems for energy wood extraction, involving new and improved approaches to extracting logging residues, stumps and whole trees from young stands (e.g. Bergström et al. 2007). In other parts of the world forest haulage is most often done as skidding; partly carrying and partly dragging the logs, stems or trees. Similarly, skidding is also well described in the literature (e.g. Clark et al. 2000, Pan et al. 2008).

Simulation models are widely used as an alternative to time studies in forest engineering (e.g. AedoOrtiz et al. 1997; Eliasson 1999; Newnham 1966; Ringdahl et al. 2012; Sängstuvall et al. 2012; Talbot et al. 2003; Wang et al. 2005). Simulation is a flexible tool for evaluating or comparing forest machines that are not presently available for practical testing. A simulation approach also ensures that uncontrollable factors such as operator effects (Lindroos 2010) or weather conditions cannot affect the results of the work study. Simulation models of machines such as single-grip harvesters have estimated their productivity with good accuracy (Eliasson 1999; Eliasson and Lageson 1999; Wang et al. 2005). However, each simulation run is merely an observation of productivity under the specific conditions for that particular scenario, and is essentially dependent on the design of the simulation model. In order to quantify the effects of variation in the environment, multiple simulation runs must be performed, and the results are often simplified using tools such as regression analyses, with the characteristics of the simulated stand and machine being treated as independent variables. Thus, while simulation models make it possible to analyze hypothetical machines, they produce individual rather than general productivity estimates.

Gullberg (1997a, 1997b) attempted to provide a complete description of forwarder time consumption using independent variables and deductive parameters. The model was derived by thoroughly reviewing previous studies in the area; this led to the identification of four main work elements, which together comprise the entire work of a forwarder. These four work elements were then described in terms of independent variables and coefficients. He emphasized that rather than being a perfect representation of reality, his model was intended to act as a deductive framework (DF) or a starting point for further research, both deductive and inductive. A comparison of the inductive and deductive approaches is shown in Fig. 1, in which two time consumption functions are plotted. Within the range of environments examined in the time study, roughly $0.1 \leq X \leq 0.3$, the time study curve is probably most reliable. However, outside this region, the deductive approach may be more reliable. That is especially so for the extreme environments of X, represented by high values on the x-axis, where the inductive function yields negative estimates.

The simplified time consumption functions for the four work elements that comprise the entire DF (Gullberg 1997b) are shown in equations (4) – (7) below:

$$\hat{o}_{Load} = \left(\left(\frac{A}{2 - e^{\left(-2 \times \frac{GV}{HV}\right)}} + \frac{A + B \times GV}{GV} \times HV \right) \times \left(1 + K \times \left(L - 3\right)\right) \right) \times HV^{-1} \quad (4)$$

$$\hat{o}_{DWL} = \frac{ST}{VU} + \frac{KS}{HL} \quad (5)$$

$$\hat{o}_{Driving} = \left(\frac{2A_{st}}{H_{st}\left(H, I\right)} + J \right) \times \left(LS\right)^{-1} \quad (6)$$

$$\hat{o}_{Unload} = \frac{KC}{GV} \times \left(1 + K \times \left(L - 3\right)\right) \quad (7)$$

Here, the terms *GV* (grapple volume in m^3), *HV* (pile volume in m^3), *L* (log length in m), *VU* (volume per loading stop in m^3), *KS* (driving distance per loaded m^3), A_{st} (forwarding distance on strip roads in m), H_{st} (driving speed on strip roads in m/min), and *LS* (load size in m^3) are components of X and the other terms are components of *A*; see Table 2. To explain one of the equations in the DF in words, what Gullberg did in equation (7) was to decide, for different machine sizes, how long it takes to perform a boom work cycle in the unloading work element (which is represented by the *KC* term). This time per boom work cycle was then converted to time per m^3 by simply dividing *KC* by the average grapple volume *GV* handled in one boom work cycle.

Gullberg (1997a) validated his model for the “loading” work element against an inductive model and presented the results graphically, showing that the two were in good agreement. The model’s work elements can be exchanged, in whole or in part, for newer ones as new findings are reported. Gullberg’s (1997a, 1997b) approach is the most deductive model of the time consumed by logging operations that has yet been presented in the literature; other models are more empirical and inductive. However, many hybrid approaches are conceivable and have been investigated. An alternative, relatively deductive harvesting model was presented by Clark et al. (2000).

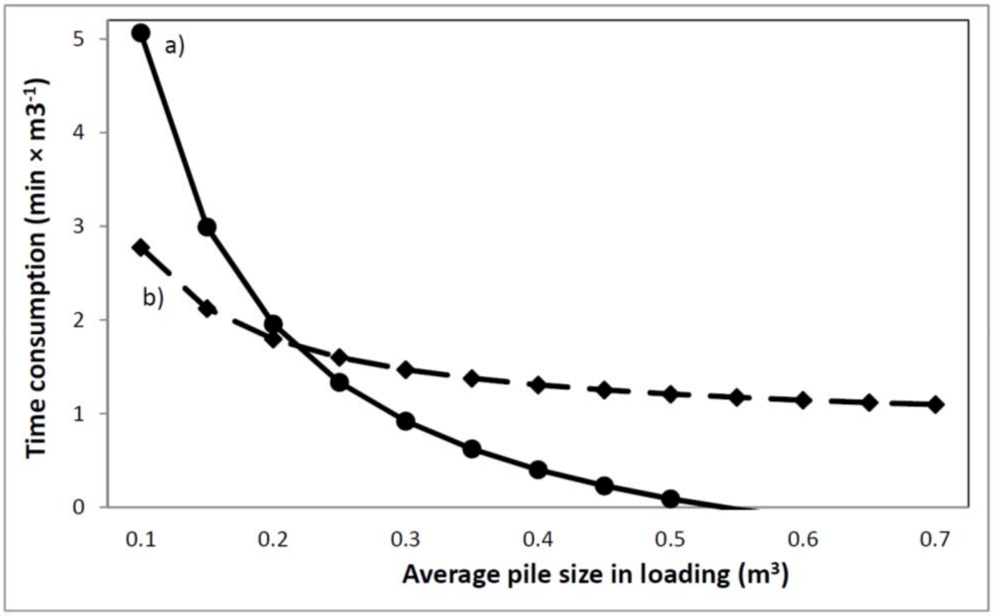

Fig. 1 Predictions of the time consumption for a forwarder when loading whole trees using a) the time consumption function of Laitila et al. (2007), and predictions obtained using b) Gullberg's (1997a) deductive framework.

4 Objectives

Increased complexity in forest operations leads to, and requires, more detailed work productivity functions. While more or less deductive approaches to modeling forest haulage operations have been discussed in previous literature (e.g. Gullberg, 1997a; Samset, 1990), no adaptations, further validations or applications of such frameworks have since been published to the best of our knowledge.

In this paper we aim to assess the usefulness of the entire deductive framework (Gullberg 1997b), comprising all work elements, and adaptations thereof for estimating time consumption in forwarding. The framework's usefulness in forest management analysis applications, especially those that examine new combinations of machines and environments, and in costing forest operations is considered.

5 Method

We considered two machine configurations, representing small and medium-sized forwarders with load carrying capacities of maximum 8.5 and 10-12 tons respectively, from here on denoted A_G referring to their terms in Gullberg's (1997b) DF (see further Table 2). These machines were applied to a set of environments $\{X_m\} = \{X_1, X_2, ..., X_n\} \subset \mathrm{X}$ (see Table 1). The simpler version of Gullberg's time consumption model for loading was used, only single-assortment loads were considered, and it was assumed that all driving was to be done on strip roads. The time consumption estimates obtained using the DF were converted to productivity expressed as solid cubic meters per productive machine hour (m^3 /

PMH) according to Björheden (1991). In the case of the small forwarder, the operation examined involved hauling whole trees for energy purpose in the aftermath of mechanized felling for thinning (Laitila et al. 2007). Conversely, in the case of the medium sized forwarder, the operation of interest was the hauling of pulpwood during thinning (Nurminen et al. 2006). These two publications were analyzed carefully to obtain accurate descriptions of parameters relating to the machine and the environment, such as the grapple area or the mean pile size in the loading phase. In some cases however, not all environmental factors of interest were mentioned. Values for these parameters were selected on the basis of qualified estimates made by analyzing similar studies. For instance, the proportion of solid volume was altered to fit average load sizes reported in field studies, and the terrain roughness was assumed to be modest. Parts of the DF were also adjusted in advance to match the conditions in the field studies. Estimated productivities $\{\hat{o}_{G_1}, \hat{o}_{G_2}, \ldots, \hat{o}_{G_n}\}$ for each machine were calculated using the DF; the corresponding productivities $\{\hat{o}_1, \hat{o}_2, \ldots, \hat{o}_n\}$ were calculated using the work productivity functions by Nurminen et al. (2006) and Laitila et al. (2007).

We then sought to alter the coefficients of the DF in order to improve the accuracy of the DF, as follows: The squared sums of the differences between the productivity estimates (8) were minimized for each machine separately by adjusting the default values in A_G, resulting in a new set of coefficients A_G' and corresponding productivity estimates $\{\hat{o}_{G_1}', \hat{o}_{G_2}', \ldots, \hat{o}_{G_n}'\}$. To ensure that the values in A_G' did not deviate excessively from the original values in A_G, conditions (9) and (10) were applied. Thus, no single coefficient in the adapted DF was allowed to deviate from its original value by more than 50%.

$$\min \sum_{m=1}^{n} \left(\hat{o}_{G_m} - \hat{o}_m\right)^2 \quad (8)$$

subject to

$$\left(\frac{A_{G'm} - A_{Gm}}{A_{Gm}}\right) \leq 1.5 \qquad \forall \; m \quad (9)$$

$$\left(\frac{A_{G'm} - A_{Gm}}{A_{Gm}}\right) \geq 0.5 \qquad \forall \; m \quad (10)$$

All data management and calculations were performed with Microsoft Excel 2007 using the Solver add-in.

Table 1 Combinations $\{X_1, X_2, \ldots, X_n\} \subset X$ used in the analyses of productivity estimates for small and medium-sized forwarders (average load sizes of 6.2 and 11.0 solid cubic meters, respectively). It should be noted that the values reported in m^3 in this table do not all refer to the same quantities; Laitila et al. (2007) reported their results in terms of solid cubic meters of biomass, while Nurminen et al. (2006) used solid cubic meters of stemwood on bark.

Combination	Forwarding distance	Mean loading pile size	Volume density along strip road	Unloading grapple volume
No.	m	m^3	m^3/100m	m^3
1	100	0,15	5	0,4
2	100	0,15	5	0,7
3	100	0,15	15	0,4
4	100	0,15	15	0,7
5	100	0,25	5	0,4
6	100	0,25	5	0,7
7	100	0,25	15	0,4
8	100	0,25	15	0,7
9	400	0,15	5	0,4
10	400	0,15	5	0,7
11	400	0,15	15	0,4
12	400	0,15	15	0,7
13	400	0,25	5	0,4
14	400	0,25	5	0,7
15	400	0,25	15	0,4
16	400	0,25	15	0,7

The accuracy of the adapted versus the unadapted DF were quantified using equation (8) as the difference in predictions of total time consumption per m^3 between the DF predictions and the time study function predictions ($\hat{A}$) for the environments listed in Table 1. Relative RMSE of the differences, in relation to the time consumption estimate was used as statistical measure.

For illustrational purposes, we also applied the DF using both (A_G) and (A_G') to a set of environments more similar to the original time study conditions reported by Laitila et al. (2007). Mean pile sizes of 0.234 and 0.15 m^3, volumes along the strip road of 9.9 and 8 m^3/100 m and unloading grapple volumes of 0.59 and 0.7 m^3, constitute two scenarios for which productivities were estimated and illustrated in Fig. 2 a) and b), respectively.

6 Results

Both the original and the adapted DF yielded results that agreed well with the time study functions. The difference between predictions of total time consumption per m^3 between the unadapted DF functions (A_G) and the time study functions ($\hat{A}$) for the environments listed in Table 1 were 6.1% and 6.9% relative RMSE for the small and medium-sized forwarders, respectively (data not shown). The adapted DF (A_G') yielded somewhat lower difference towards the time study functions ($\hat{A}$); relative RMSE amounted to 4.1% and 5.5% for the small and medium-sized forwarders, respectively (data not shown). The parts of the framework that were altered in the adaptation process are shown in Table 2.

Another example of the estimated productivities obtained using the three sets of coefficients is given in Fig. 2. An illustrative set of detailed results, for the time taken unloading using medium-sized forwarder, is presented in Table 3.

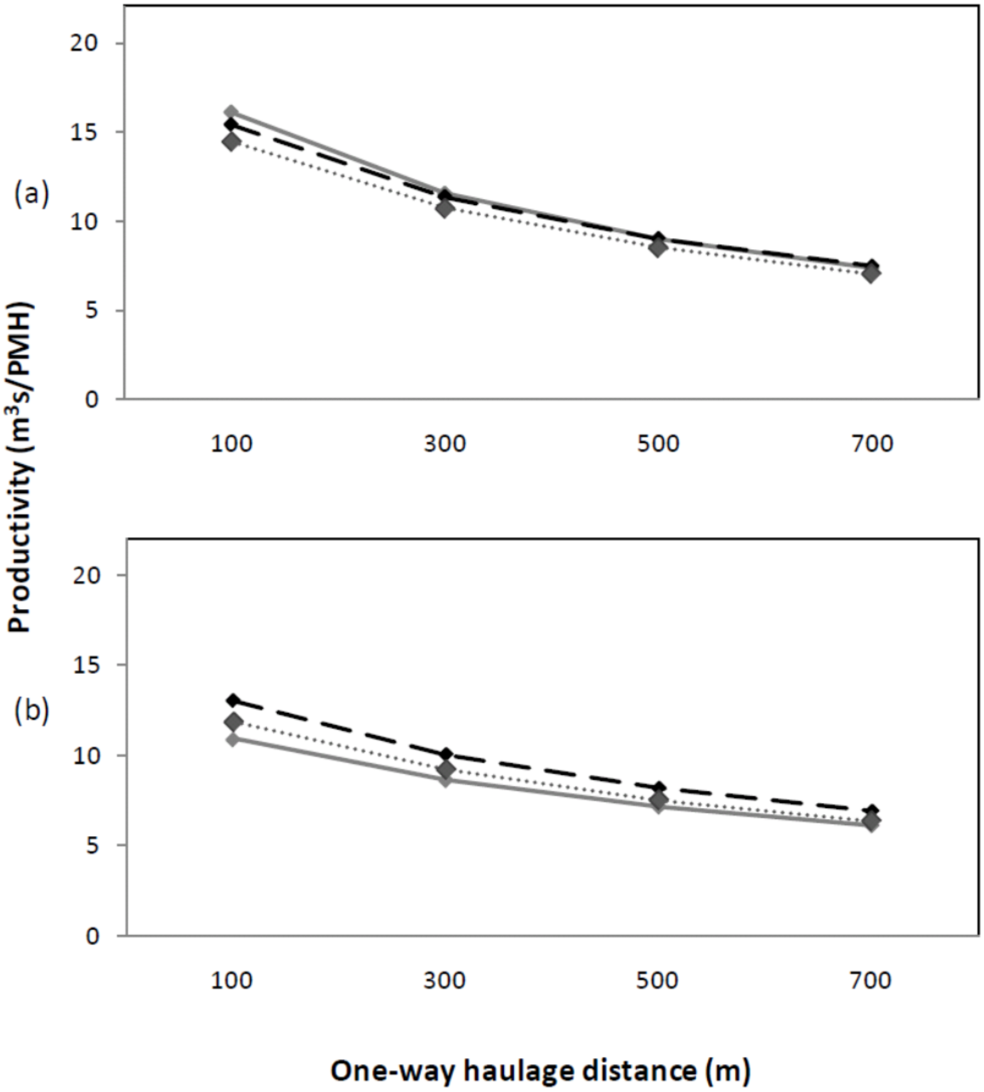

Fig. 2 Productivity of a small forwarder transporting whole trees. Productivities based on the work productivity functions ($\hat{A}$) are shown with solid lines (Laitila et al. 2007); productivities based on A_G are indicated by dashed lines (Gullberg 1997b), while those obtained using an adapted version of the DF (A_G') are indicated by dotted lines (Table 2).

Table 2 Results of the adaptation process for different forwarder sizes and work elements. The table shows the coefficients and original values (*A_G*) reported by Gullberg (1997), the maximum (equation (9)) and minimum (equation (10)) values allowed during the adaptation process, final adapted values (*A_G'*) and the sum-of-squares values calculated during the adaptation process using equation (8) for the error per work element.

Work element	Coeff-icient	Forwarder size									
		Medium					Small				
		Original value	Min	Max	Adapted value	Sum of squares	Original value	Min	Max	Adapted value	Sum of squares
Loading (Equation (4))	A	0.340	0.170	0.510	0.342	10736	0.320	0.160	0.480	0.447	12813
	B	0.230	0.115	0.345	0.345		0.32	0.16	0.48	0.16	
	E	0.030	0.015	0.045	0.045		0.050	0.025	0.075	0.025	
Driving while loading (Equation (5))	ST	0.06	0.03	0.09	0.03	5.3	0.06	0.03	0.09	0.09	13.4
	HL	25.0	12.5	37.5	29.5		25.0	12.5	37.5	33.1	
Driving (Equation (6))	J	0.700	0.350	1.05	1.05	44.9	0.70	0.35	1.05	0.35	4.1
	H	60.0	30.0	90.0	61.6		56.0	28.0	84.0	55.6	
	I	-4.70	-7.05	-2.35	-2.37		-4.70	-7.05	-2.35	-5.56	
Unloading (Equation (7))	KC	0.400	0.200	0.600	0.253	1268.5	0.400	0.200	0.600	0.373	254.4
	K	0.030	0.015	0.045	0.045		0.050	0.025	0.075	0.046	

Table 3 Time taken associated with unloading (equation (7)) for the DFs applied on a medium-sized forwarded, expressed as minutes per m^3. Corresponding time taken in the time study is 0.564 minutes per m^3 (Nurminen et al. 2006).

Framework	Unloading grapple volume (m^3)	
	0.4	0.7
Original	1.04	0.59
Adapted	0.75	0.43

7 Interpretation of the results

The results obtained in this work indicate that the DF successfully reproduced the productivity achieved in the forwarding of whole trees and pulpwood using small and medium-sized forwarders in thinning operations. Adaptation of the framework over a wide set of environments (Table 1) by altering its coefficients within certain intervals (Table 2) yielded a higher accuracy, but the improvement was not spectacular. For a specific dimension of the environment set, A_G may in fact appear to be in better agreement with $\hat{A}$ than is A_G' (e.g. Fig. 2 (a)). The DF thus appears to be useful without modification. One could argue that the adaptation process employed in this work made the DF more inductive since we fitted the framework to existing data (or more correctly, to estimates thereof). The adapted values often took the maximum or minimum value allowed during the adaptation process (Table 2), which may indicate that better accuracy would have been obtained had the restrictions been removed or relaxed. However, doing this could have unexpected consequences, such as changing the signs of specific coefficients and thus making the framework even more inductive. The differences between work productivity functions based on time studies and the DFs were most pronounced for the “loading” work element (Table 2). This is the most complex work element in the overall process and is modeled by the most elaborate and deductive term of the DF (Gullberg 1997a).

It is possible that the adaptation process may in fact decrease the accuracy of the framework, if it is adapted to data or inductive functions that do not fully reflect the effects of extreme environments corresponding to outlying environments of X. In the case of the medium-sized forwarder, the unloading time was assumed to be a constant with a value of 0.564 minutes per m^3, regardless of the unloading grapple volume (Nurminen et al. 2006). However, the DF (equation (7)) was applied to two different grapple volumes (Tables 1 and 3). As such, the adaptation process improved the accuracy of the estimated unloading time but also de-emphasized the influence of the grapple volume on the unloading time. In reality, one would like the framework to reflect this effect as accurately as possible, rather than in accordance with a work productivity function that evens out this effect. Since time studies and derived work productivity functions are based on limited (though sometimes vast) datasets, not every relationship with independent variables can be clarified. In addition, significant relationships may be excluded when constructing work productivity functions to simplify future usage. The high RMSE for the DF in loading (Table 2) may thus be somewhat more attributable to simplifications made when drawing up the work productivity functions based on the time studies than to deficiencies of the DF.

8 Implications and conclusions

The DF analyzed in this work could be useful for improving predictions of hauling time consumption with a forwarder in several contexts. This in turn will lead to more accurate estimates of work amount and costs in the forestry. Consider the Swedish average annual felling of about 72,8 Mm^3sob × yr^{-1} (Anon. 2011b) and a true average forwarder productivity of 20 m^3sob × PMH^{-1}. A systematic error in the productivity estimate of 1% is then equivalent to 36,400 PMH × yr^{-1}. At an average forwarder cost of \$100 × PMH^{-1}, this 1% systematic error in productivity estimate corresponds to an error of \$3,640,000 × yr^{-1} in total estimated cost.

Returning to the four example problems presented in the introduction, we feel that the adaptations and comparisons made in this paper have demonstrated that the deductive framework methodology could be useful in all four situations as a tool for estimating forwarder productivity.

When using a DF that has not been adapted to reproduce the results of time studies, there is a risk that one may obtain systematically erroneous predictions. These errors should however be consistent across different machines and environments and so should not affect the relative performance of different machines in a specific environment. Hence it may be useful, or even preferable, to use an unadapted DF when tackling problems such as optimal rotation length (example problem i) as listed in the introduction of the paper), choice of hauling equipment (ii)) and priority of forest machine development efforts (iv)). In that problem iv), for example, the DF could be used to predict forwarding productivity for these new combinations of machines and environments, and to assess the performance of the different combinations. Moreover, this work would be inexpensive as it would not be necessary to conduct a time study.

In the example problem of a fair pricing towards a contractor (iii)), systematic errors in the estimated productivities would be counterproductive and could potentially put the forwarder contractor out of business in the long run. In such cases, the DF could instead serve as a foundation on which to construct new work productivity functions, providing both ideas as to which independent variables should be included in the new functions and reasonable indications of the impact of those variables. However, when constructing a new work productivity function for use in pricing, inductive elements should always be included because the pricing must be set at a level that will yield a fair total income for the contractor. In light of the increasing importance of accurate pricing and productivity estimates, we conclude that the DF presented by Gullberg (1997b) could be of use in developing these processes. Arguably, one could combine the advantages of the inductive and deductive approaches by using deductive reasoning to identify suitable independent variables for incorporation into work productivity functions based on time study results (cf. Laitila et al. 2007; Samset, 1990).

Aside from the example in Fig. 1, $X \in \mathrm{X}$ in all comparisons and results considered in this study. This means that the DF has only been applied to forwarding under conditions that have also been investigated in the time studies used when adapting the framework. As such, we were unable to adequately assess the validity of A_G' when $X \notin \mathrm{X}$. However, since the unadapted framework yielded results that were in good agreement with those obtained in time studies, and since it by definition is applicable to the entire $\mathrm{X}' = \mathrm{X} \cup \mathrm{X}_k$, we conclude that the DF presented by Gullberg (1997a, 1997b) is flexible and appropriate for modeling forwarder productivity under new conditions.

The reasoning employed in this paper is based on the existence of a one true productivity under each set of environments. This in turn relies on the assumption that correlations among variations in environments are consistent. In the case of operator effects that is not necessarily so, as shown by Lindroos (2010), where different operators handled different conditions with varying relative performance. However, such variations will always occur, and in order to analyze problems like examples i) – iv) in this paper, the mean performance of many operators must be utilized.

In summary, the deductive framework methodology represents an accurate, low-cost means of predicting forwarding productivity for a diverse set of environments and machines, which need not be immediately available for practical testing. The method carries a risk of systematic errors, which could be detrimental in some cases, but even in these cases the incorporation of deductive reasoning could be useful in constructing better empirical models.

Having concluded that a DF is beneficial when analyzing forwarder productivity, it is worth pointing out the lack of DFs describing the time consumed by processes such as harvester work, and more general DFs applicable to totally new forest machines. Since e.g. harvester work is more complex than that of forwarding (cf. Eliasson 1999), such frameworks would be harder to construct, but of even greater importance once obtained.

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