# A Deductive Time Consumption Model for Loading Shortwood

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## ABSTRACT

A partly deductive time consumption model was constructed by using earlier knowledge about the importance of grapple size and pile size on the time consumption for loading shortwood. In order to estimate a complete model, only the function for the loading cycle time needs to be known.

The potential advantages of this model are an improved understanding of causal relations and the increased efficiency in producing time consumption models.

Comparison with conventionally estimated models based on large empirical studies indicated relatively good agreement, concerning both time consumption level and the influence of various loading conditions.

**Keywords:** *forwarding, grapple loader, logging, time study method, productivity study, modeling productivity.*

## INTRODUCTION

Off-road transport of shortwood with forwarders or with farm tractors pulling grapple-loading trailers is the dominating hauling method in the Nordic countries [4, 7]. The shortwood method also seems to be increasing in importance in other parts of the world, e.g. in Central Europe, North America, and Australia [3, 13, 14].

A great deal of effort has been put into productivity studies of loading shortwood in the Nordic countries during a period of more than 30 years.

Time-studies have mainly been used to estimate time consumption models used for payment and planning. Most models are mainly descriptive statistics for one machine size. The models have, without a doubt, been useful tools in operational forestry.

The dominating method for modeling the productivity of forest machines is based mainly on operational field studies, i.e. under non-experimental conditions. Because of the complexity of the working method and the large variation in working conditions, huge field studies are necessary in order to estimate a general model. Time studies, therefore, need to encompass many thousands of cubic metres of transported logs. As an example, one source made time studies of 19,400 $m^3$, using only one forwarder size [9].

Normally time consumption is recorded for different work elements, each one affected by a smaller number of factors than that of the total working cycle [1, 15]. The working cycle is often divided into the sub-operations loading, moving during loading, driving with load, unloading, and driving empty. The analysis is made of the sub-operation or work element level using regression analysis.

However, the results often indicate a large unexplained variation and few significant variables. The regression functions, or models, obtained are often difficult to understand and seldom include any variables for basic machine characteristics except the load size.

If work methods are changed or the machines are further developed, the whole model then needs to be replaced. The theoretical value of the regression functions is often quite limited because the basic or fundamental mechanism is only indirectly described.

A more deductive approach could give a logical model structure and facilitate updating the model as methods and machines change.

Although a pure deductive model is difficult to build, there may be some major structures or relations that are easier to formulate. One simple example of a partly deductive model is for the sub-operation *driving with load*. The time consumption model is usually built up by transport distance, load size, and mean driving speed. The load size is mainly dependent on the load area, log length, and the proportion of solid volume. The driving speed is more difficult to calculate theoretically and is there-

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fore estimated through analysis of field studies. This is one simple example of where some basic theoretical principles are built into the model, thereby considerably reducing the need for field studies.

The purpose of this paper is to formulate some theoretical basic structures for a time consumption model for loading shortwood with a grapple loader.

In principle the work can be described as a trial to formalize old knowledge and build it into an explicit model structure. The reason for making this model structure is to have the possibility to:

- increase understanding of causal relationships between time consumption, machine characteristics and working conditions.
- increase efficiency in producing time consumption models.

## MODEL

Loading, as well as unloading, can be considered as a flow of timber. The maximum productivity for a specific machine is obtained when the grapple is full and loading conditions are easy. Loading well-arranged piles of optimal size (n ¥ maximum grapple volume) gives the highest productivity. The importance of the grapple volume is well known [2, 6, 11, 12].

The maximum grapple volume may be estimated from grapple area, log length, and proportion of solid wood. There seem to be good reasons for using the grapple area as a key variable in a theoretically constructed time consumption model.

In operational loading, productivity is reduced by an inoptimal pile size that only fills the grapple partially, and by difficult loading conditions that increase the loading cycle time. In some cases it is possible to take additional logs from other piles, thereby increasing the volume in the grapple. This type of loading will be referred to as *multiple pile loading*.

The time consumption per loading cycle is dependent on a lot of different conditions. Some of those factors which are difficult to define and measure are:

- pile characteristics (volume, distance from strip road, shape, etc.),
- loading method (multiple pile loading, etc.),
- loading conditions (remaining trees etc.),
- operator-machine system characteristics.

The volume per loading cycle is, on the other hand, dependent on a limited number of variables. Most of these, which are well-defined and measurable, are:

- pile characteristics (volume, log length, proportion of solid wood),
- loading method (possible multiple pile loading),
- grapple area,
- machine characteristics (net lifting force, stability).

The model can only describe the relations between pile characteristics, grapple size, and the number and conditions of loading cycles, while the time consumption per loading cycle is assumed to be known or estimated in another way.

The time consumption per loading cycle may be described either by empirical time studies or by theoretical models that include machine characteristics such as oil flow, hydraulic cylinder size, human reaction times, etc.

The model presented here is based on the following assumptions and conditions:

- logs are arranged in piles,
- it is possible to estimate maximum grapple volume by using the grapple area, log length and proportion of solid wood,
- loading cycle time is independent of the order logs are taken from a pile,
- loading is done with full grapples when possible,
- lifting force is sufficient.

If the grapple area is over-dimensioned it is necessary to use an *effective* useful grapple area in the model instead of the real grapple area.

One simple example of time per loading cycle will be used to demonstrate the principles of the model:

*(Model 1)* $LCT = A + B \times V + C \times N$

where

$LCT$ = loading cycle time,
$A,B,C$ = coefficients,
$V$ = volume per loading cycle,
$N$ = number of additional piles in the loading cycle.

In figures 1 to 4 the time consumption per loading cycle is assumed to increase 50% between empty and full grapple.

The additional time to collect one more pile in the same loading cycle (coefficient C) is assumed to be 50% of A.

**Time Consumption for Individual Piles**

Two principally different situations can be separated:

1. Single pile loading. This most simple alternative, and also probably the most frequent, is defined as a pile where loading is started with an empty grapple (base pile). The time consumption can be formulated by the following model:

*(Model 2)* $T = n_s \times A + B \times PV$

where

$T$ = time consumption per pile,
$A, B$ = figures from the loading cycle in model 1,
$n_s$ = number of loading cycles per pile in

$$\text{single pile loading} = Int\left(\frac{PV}{GV}\right) + 1,$$

$PV$ = pile volume,
$GV$ = maximum grapple volume = grapple area $\times$ log length $\times$ proportion of solid wood.

2. Multiple pile loading. This type of pile is defined as a pile where loading is started with a partially filled grapple (additional pile).

*(Model 3)* $T = C + n_m \times A + B \times PV$

where

$A, B, C$ = figures from loading cycle in model 1,
$n_m$ = number of extra loading cycles for the pile in multiple pile loading:
$AV = PV$ *if then* $n_m = 0$

$$\text{else } n_m = Int\left(\frac{PV - AV}{GV}\right) + 1,$$

$AV$ = additional volume taken in the same loading cycle as a previous pile.

Time consumption versus pile size gets a staircase-looking shape (Fig. 1). The width of the "steps" depends on the maximum grapple volume or the remaining empty grapple volume in the case of multiple pile loading.

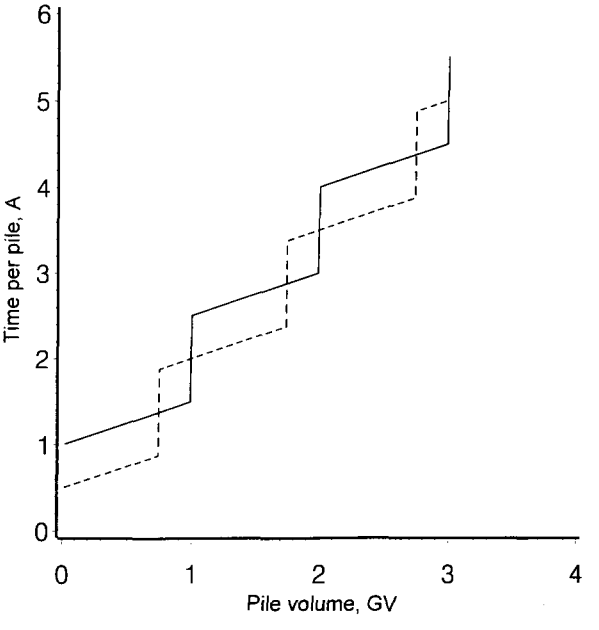


**Figure 1.** The principal shape of the time consumption curve per pile loaded, single pile (____) or multiple piles (---). In the example of multiple pile loading, the maximum additional volume was 75% of grapple volume.

If the distribution of various pile sizes is known, it is then possible to calculate the total time consumption by summarizing the time consumption for all piles according to models 2 and 3.

However, in operational forestry this detailed information is seldom available for practical and economical reasons. The average pile size is, on the other hand, rather easy to estimate where, for

example, cut volume removal per hectare and number of piles are known.

### Time Consumption Based on Mean Pile Characteristics

In operational work there is always variation in the pile sizes. Some piles have a "good" size, i.e. yield a fixed number of one or several full grapples. Other piles give a small volume in the grapple in the last loading cycle.

A simulation of single pile loading was made in order to evaluate the importance of the distribution on various pile sizes. The distribution was a truncated normal distribution (no piles smaller than 0.02 $m^3$ solid wood). Four levels of variation were used with a relative standard deviation of 10, 25, 50, and 100% of the average pile size.

The results of the simulation are shown in Figure 2.

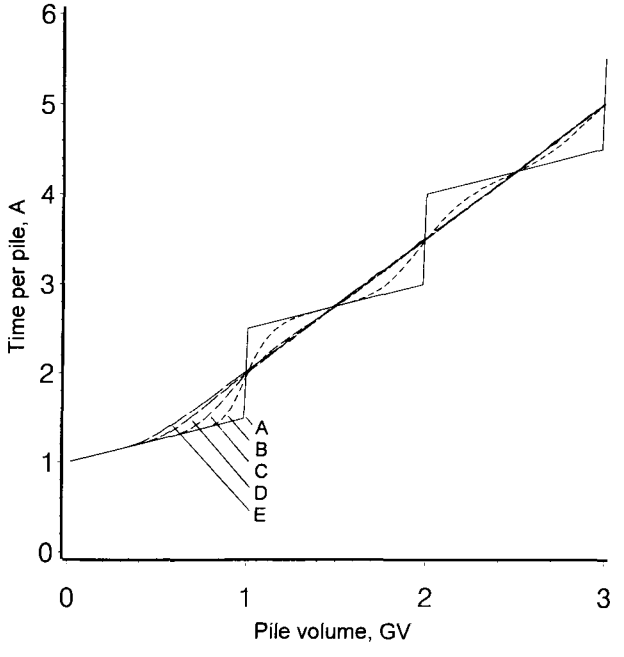


**Figure 2.** Average time consumption per pile with a normal distribution of various pile sizes. Standard deviation in percent of mean pile volume: A = 0, B = 10, C = 25, D = 50, E = 100.

As can be seen, the curves are close to a straight line if pile sizes exceed the grapple volume and the standard deviation is at least 25% of the mean pile volume. The equation for this straight line can be formulated as:

$$(Model\ 4)\quad T = \frac{A}{2} + \frac{A + B\,x\,GV}{GV}\,x\,PV$$

This straight line equation seems to work rather well for large, but not for small piles, since the *straight line* equation gives a significantly lower time consumption for small piles. If no piles exceed the grapple volume, then models 1 or 2 can be used. Model 1 is equal to the *staircase* Model 2 where there is only one loading cycle per pile.

A general model for single pile loading should include a successive change from the Model 1 to the *straight line* Model 4.

The following gives a reasonable shape to the curve for piles with a standard deviation of about 50% of mean pile volume:

*(Model 5)*

$$T = \frac{1}{e^x}x(A + BxPV) + \frac{e^x - 1}{e^x}\,x\left(\frac{A}{2} + \frac{A + B\,x\,GV}{GV}\,xPV\right)$$

where

$$x = 5x\left(\frac{PV}{GV}\right)^3$$

An alternative model that is simpler but more approximate can be formulated as follows. This model is mainly based on Model 4, but forces the curve through the same point as Model 2 when the pile volume = 0.

$$(Model\ 6)\quad T = \frac{A}{2-y} + \frac{A + BxGV}{GV}\,xPV$$

where

$$y = e^{-2\frac{PV}{GV}}$$

### Time Consumption Per Cubic Metre

Figure 3 shows the time consumption in single pile loading based on models 2, 4, and 6.

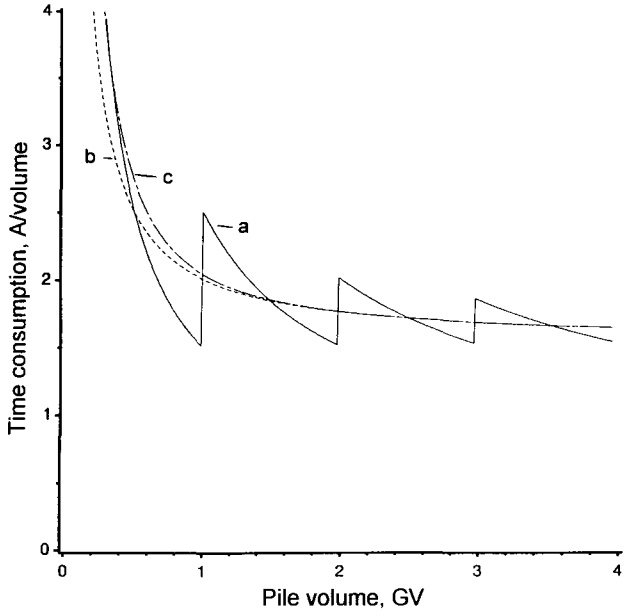


**Figure 3.** Time consumption per volume according to a) *staircase* Model 2, b) *straight line* Model 4, and c) *simple general leveling-out* Model 6.

Figure 4 shows the principal importance of the grapple volume when using Model 6.

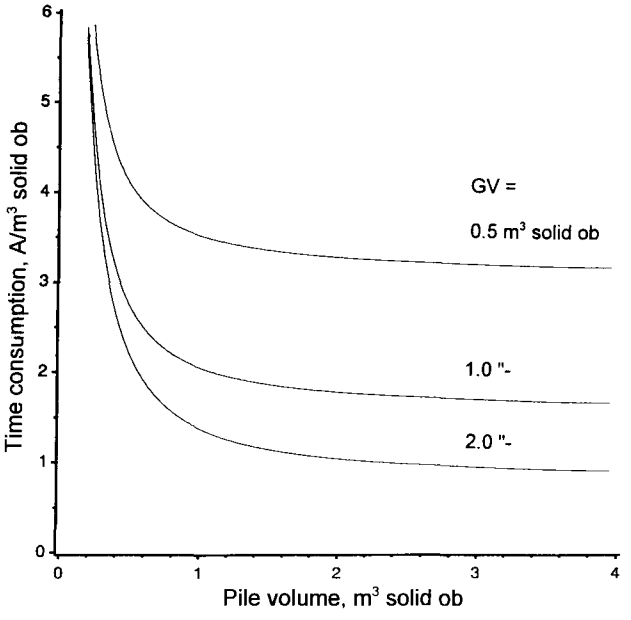


**Figure 4.** Principal differences in time consumption when loading with different grapple sizes.

A general model including possibilities for multiple pile loading is quite complicated to construct. One problem is to estimate the extent and time consumption of multiple pile loading beforehand. This is not handled automatically by the present model. In fact, multiple pile loading is a complex optimization problem. The operator has to choose between using multiple pile loading only in clearly favourable cases or, more often, in some less favorable situations, where he also takes the risk of reducing productivity.

Other necessary information includes how much volume can be added in the grapple and the sizes of base piles and additional piles, if these are different.

The suggested model is based upon the following assumptions:

- the average additional volume in one grapple lift:

$$if\ PV \leq \frac{GV}{2}\ then\ the\ volume = PV$$

$$else\ the\ volume = \frac{GV}{2}$$

- the same average size of additional piles as base piles.

The model is constructed with the goal of describing the average time consumption and the volume loaded together with the base pile. This means that the calculation unit includes more than one pile if multiple pile loading is used.

The model, including possibilities for multiple pile loading, can be formulated as:

*(Model 7)*

$$T = \left(\frac{A}{2 - e^{-2(PV/GV)}} + MPxAT + \frac{A + BxGV}{GV} x(PV + MPxAV)\right) 1$$

$$1(PV + MPxAV)$$

where

$T$ = time consumption per cubic metre,

$MP$ = average multiple pile loading, defined as:

$$\frac{\text{no. piles or part of pile loaded in addition to } \textit{base}\text{ pile}}{\text{no. } \textit{base piles}}$$

where *base pile* is all piles which are started with an empty grapple,

*AV* = average additional volume,
*AT* = additional time for collecting, when additional filling of the grapple is from another pile.

## AN EXAMPLE OF AN ESTIMATED MODEL

The basic structure of the model presented above is possible for use in combination with any time function that works with the loading cycle as a base. The spread in the use of the application ranges from an average time per loading cycle up to detailed functions where many variables are used to describe the pile and loading conditions.

In this section which follows here, a time function for a small forwarder (Bruunett Mini 678F) is used to demonstrate a complete time consumption model for loading. The time study [6] was made in a thinning with 3 m log lengths, and the total volume cut was 54 m³s. The time per loading cycle was described as:

$$LCT = 31 + 31xVOL + 4xD + 19xNO$$

where

*LCT* = loading cycle time, cmin,
*VOL* = volume in the grapple, m³ solid ob,
*D* = dummy for difficult pile, defined according to Bergstrand [1],
*NO* = number of additional piles or parts of piles in the grapple.

This model is only valid for thinning conditions and 3 m log lengths. By assuming a multiplicative impact of log length and cutting type on the loading cycle time, it was possible to get a more general model.

The correction for log length was estimated by my own analysis of another study [9]. The correction for logging type (thinning/clearcutting) was based upon two studies [2, 9].

The complete general model for time consumption per m³ solid could be formulated as follows:

where

*T* = time consumption for loading, cmin/m³ solid ob,
*PD* = proportion of difficult piles,
*PV* = average pile volume, m³ solid ob,
*GV* = maximum grapple volume, m³ solid ob = grapple area (0.26 m²) x log length, m x proportion of solid wood (0.65 for softwood pulpwood, 0.67 for softwood sawlogs [6],
*AV* = additional volume when taking another pile or part of a pile in the same loading cycle.

$$PV \; if \; PV \le \frac{GV}{2}$$

$$\frac{GV}{2} \; if \; PV > \frac{GV}{2}$$

*MP* = average multiple pile loading,
*C* = coefficient, in thinning 0.10, in clearcutting 0.05,
*LL* = log length, m,
*CT* = dummy for clearcutting.

The model requires the following information for estimating time consumption:

- pile size, average,
- proportion of difficult piles,
- grapple area,
- log length,
- proportion of solid wood in the grapple area,
- extent of multiple-pile loading,
- cutting type (thinning/clearcutting).

### Results and Discussion

Some characteristics of the model are illustrated in figures 5 and 6. Figure 5 indicates that short log lengths are preferable if the piles are small, while long log lengths are preferable for large piles (where the grapple area limits the loaded volume per grapple lift and loading cycle).

This result is in good agreement with the other study [9], however they used loaded volume per 100 m of strip road, instead of pile size, as the explanatory variable.

The break-even point between 3 and 5 m log lengths appears in smaller clear-cut pile sizes rather than in thinnings. This is due to less sensitivity to log length when there are no residual trees to consider when loading.

$$T = \left[\left(\frac{31 + 4xPD}{2 - e^{-2(PV1GV)}} + MPx19 + \frac{31 + 31xGV + 4xPD}{GV}\right)x(PV + MPxAV)\right]x(1 + Cx(LL - 3) - 0.15xCT)\Big]1(PV + MPxAV)$$

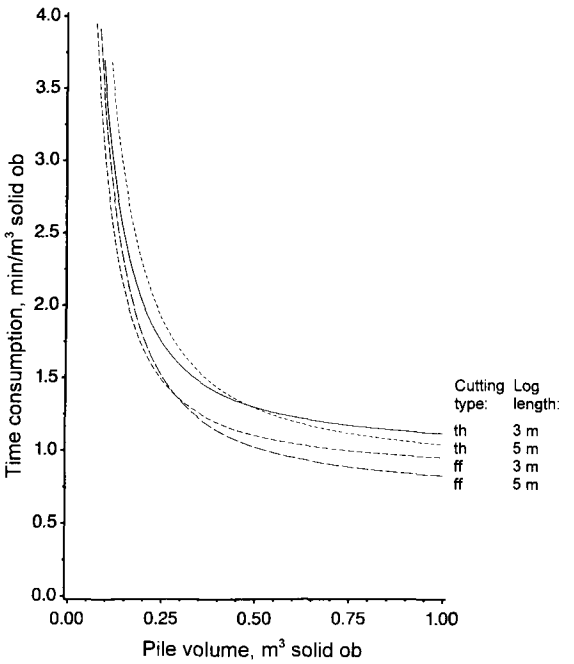


**Figure 5.** Time consumption for loading by varying cutting type (thinning (th) or final felling (ff)) and log length.

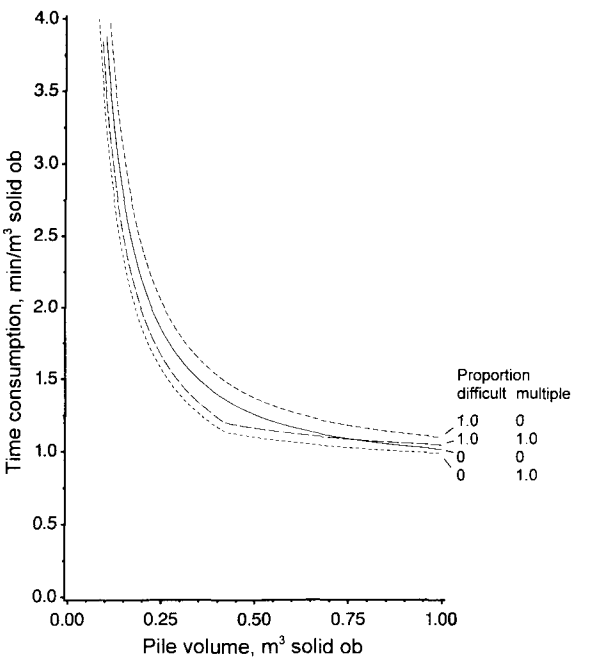


**Figure 6.** Time consumption for loading by varying the proportion of difficult piles and multiple pile loading.

Figure 6 shows the possibility for reducing time consumption by doing multiple pile loading. The sharp bends on the curves are caused by the rough estimation of average additional volume. The conditions shown in the figure are chosen in order to demonstrate the principles involved. In operational harvesting it is not likely that there will be proportions of either difficult piles or multiple pile loading which are as high as 1.0. Especially for the multiple pile loading, this is nearly impossible when the pile size exceeds half of the maximum grapple volume. The importance and potential of multiple pile loading has not been demonstrated earlier, but has been discussed elsewhere [2]. The influence of difficult piles was relatively small in that study, as compared to [1], which stresses the problem of separating the influence of difficulties from that of volume when using regression analysis, because the variables are correlated in non-experimental operational studies.

## Comparison with Other Models

Validation of a time consumption model for loading is important, but difficult to obtain [8, 16]. If empirical models of loading could *tell the truth* the problem should already have been solved. The lack of a key or *true* factor for validation makes it necessary to talk instead about the level of reliability or usefulness.

Many large empirical studies such as [5, 9] are, in this case, difficult to use for validation because the pile volume is not described and included in the models.

In this case the choice has been to make comparisons with a well established productivity norm based mainly upon empirical studies by a forest company (STORA) [17].

The comparison is illustrated in Figure 7. The immediate impression is that the level and shape of the curves are similar. However, a more detailed analysis indicates some significant differences:

(1) STORA's model is based on a linear model over time per pile and pile size, which makes the time consumption higher for small piles and lower for big piles. However, the agreement is good for *very small* piles and *medium size* piles.

(2) STORA's model indicates a large difference between sawlogs and pulpwood when log lengths and pile sizes are similar. One possible explanation for these results is that sawlog piles are often large, making it difficult to see a possible principal bias in the model structure.

In STORA's model, differences between log length and assortments are estimated in the

shape of a relative correction figure for specified assortments, which makes it impossible to get crossing lines.

Our model presented here uses the log length as a variable within the model structure. The only difference between sawlogs and pulpwood is a slightly higher proportion of solid wood for sawlogs for a given grapple area. Early studies by [10, 12] indicate limited or no differences caused by the assortment or average log volume within a pile. Studies of unloading [9, 17] also indicate small differences between sawlogs and pulpwood of the same length. Thus, log diameter has little influence on loading time consumption.

(3) STORA's model indicates a greater time variation influence by difficult piles. The correction in STORA's model is based on one fixed time per pile and one relative correction figure for the whole loading time. This structure looks more logical, but it is more difficult to evaluate from empirical studies where the loading cycle is the observed work element.

A simulated comparison of a medium with a large forwarder indicated a good agreement with STORA's model regarding the influence of machine size. The model for a medium and a large forwarder was based on the loading cycle function for a small forwarder [6]. However, the influence of grapple load volume was adjusted to give the same relative difference between an empty and a full grapple.

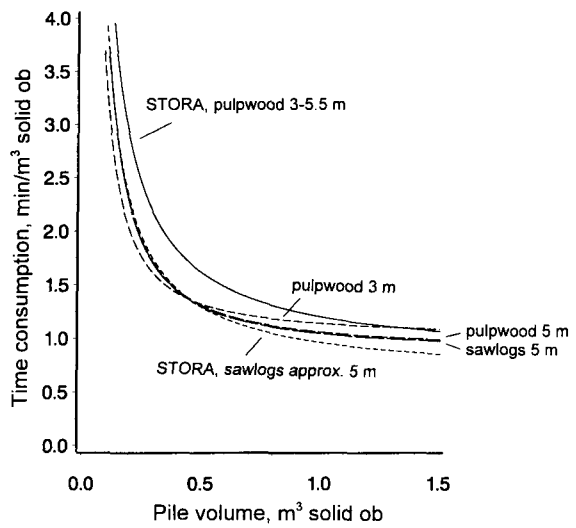


**Figure 7.** Comparison with STORA's [17] productivity norm.

## DISCUSSION

The model structure presented in this article should offer possibilities for making generalizations based on rather small empirical studies. Both levels and interactions are roughly the same as empirical models based upon larger studies. It is not possible with today's knowledge to give an absolute answer to the question of which type of model is the best.

Experimentally designed studies are probably necessary to explain the principal differences.

There is a need for field studies that differentiate between the conventional method and the theoretically built model. The conventional, highly inductive method works well with many non-experimental (i.e. operational) time studies where the aim is to cover all possible combinations of conditions. However, the method described in this article focuses more on limited, experimentally designed time studies.

The relationship between loading cycle time and field conditions is only a small part of the complete relationship affecting time consumption. However, an experimental design is needed where some variables are controlled in order to reduce interaction between variables and to get reliable results regarding the impact of single variables on loading cycle time. One suggestion is to develop standardized time study conditions where the most important variables are included. Comparisons between machines and countries could then be greatly facilitated.

The most reliable results, when using the described model, are obtained if all piles are described in detail in connection with the *Staircase model* (Fig. 1). This level is very costly and probably only a research alternative. The next level is to estimate average pile conditions by empirical studies. The third level includes estimation by a model of pile size, share of difficult piles, etc., for a given volume removal and harvesting system.

The need for personnel resources and the cost of updating a model is probably significantly lower in the suggested method described here, since most of the structure and perhaps even some basic relationships may also be useful in the new model.

A model including basic machine characteris-

tics almost automatically gives answers about differences between various machine types. Another important difference is that the method presented here more easily allows a utilization of results from earlier studies. This is very difficult to do in the pure inductive method.

What type of method is most objective and reliable regarding productivity level? The conventional method with randomized time studies of the total population may seem to give a guarantee for objectivity and reliability. However, the objectivity of the inductive method may be in question, since the researcher's choice of variables and model structure is very important for the results. The time study situation may also be a bias factor.

A more theoretically developed model is undoubtedly highly dependent on the knowledge and analytical capabilities of the researcher. However, the model will also has some objective qualities if it is based on general theories and laws.

If the purpose of the model is mainly to show the relative impact of various factors, then the reliability regarding the level of time study production is not an important question. The absolute productivity level may instead be decided on the basis of follow-up studies or negotiation. However, the conventional method has the advantage of giving a descriptive picture of the conditions, which in some cases is of great value.

The described model is a hybrid of theoretical and empirical submodels. In the future there may be possibilities for increasing the theoretical part of the model. Automation or robotization of forest machines will most likely create new possibilities for building theoretical models.

The basic principles behind the described model may seem rather simple. Some early studies in Sweden [2, 10, 12] discussed the importance and relations between grapple size and pile size. No explicit model was, however, developed. Since then the discussion about the basic physical principles seems to have lapsed.

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