A New Approach To Derive A Productivity Model for the Harvester "Valmet 911 Snake"

Karl Stampfer and Thomas Steinmüller
Institute of Forest and Mountain Risk Engineering, University of Agricultural Science Vienna, Austria. E-Mail: stampfer@mail.boku.ac.at

ABSTRACT - Productivity models are important decision support tools for harvesting operations. They should be derived with the least possible effort but with the highest possible precision. Models based on production monitoring or time studies are time consuming in their derivation. No models are available for new machine developments although it is particularly important to estimate productivity under given conditions and make statements about parameters such as climbing limits on steep terrain.

The Valmet 911 Snake is a tracked harvester that has been specially developed for harvesting operations on steep terrain. A standard four-wheeled Valmet harvester serves as a carrier platform whereby the four wheel sets are replaced with trapezoidal tracked undercarriages. This construction results in better traction, reduced impact to the ground and greater climbing possibilities on slopes.

For the productivity model derivation a combined approach has been used. The model consists of three parts: tree processing model, locomotion model and delay model. The delay model has been chosen from literature, the tree processing and locomotion model have been derived from empirical studies. The productivity potential and climbing capabilities of the Valmet 911 Snake steep terrain harvester up to an inclination of 70% could be verified.

Keywords: Steep terrain harvesting, tracked-based harvester, Valmet Snake, productivity study.

INTRODUCTION

Efforts to design more efficient timber harvesting systems on steep terrain have led to mechanization of working systems. Technology improvements were driving forces for economic improvements and therefore provide a significant contribution to sustaining the competitiveness of forest enterprises. Adaptations of different carrier platforms enabled harvester applications on steep terrain. On good soil conditions tracked-based harvester can operate up to a slope gradient of 60%. However, stands with obstacles and/or rough terrain are not passable for tracked harvesters. Hybrid harvesters have advantages on rough terrain, however they are limited to a maximum slope gradient of approximately 50%. The use of walking harvesters in its current prototype configuration is not emphasized on steep terrain at the time.

The Valmet 911 Snake is a tracked harvester that has been specially designed for steep terrain. The standard four-wheeled Valmet harvester serves as a carrier platform. The four single wheels are replaced with trapezoidal tracked undercarriages. This construction results in better ground traction, reduced impact to the ground and greater climbing possibilities. In comparison to conventional tracked harvesters, the four independent trapezoidal tracks makes the application on rough terrain feasible.

Prior to the implementation of this machine prototype, the objective is to find an approach to determine efficiency limits and application possibilities. The derivation of productivity models provides a possibility to analyze new machinery concepts. Models based on empirical studies as well as production monitoring are relatively time consuming in their derivation.

The goal of the paper is to generate a productivity model for the tracked-based harvester Snake by using a combined derivation approach. The model intends to allow a productivity estimation depending on stand and terrain parameters and to derive statements about limits of mobility. The basic concept contains tree processing, locomotion and delay models.

METHODOLOGY

Valmet 911 Snake

The tracked based harvester Valmet 911 Snake was developed in Austria. Based on new knowledge on how the power of the harvester is transfered to the ground on steep terrain in addition to the disadvantages of two full-length tracks, the standard wheeled harvester has been equipped with four independent trapezoidal tracks (Figure 1). This construction improves traction and makes the travel across rough ground a lot smoother. This also reduces ground impact. Altogether, climbing capabilities and machine stability has been substantially increased without making changes on the basic machine. The result is the possibility to operate uphill as well as downhill and improve the feasibility of operations on rough terrain.

Figure 1. Valmet 911 Snake operating on steep terrain

The carrier base is a four-wheel harvester Valmet 911 (Table 1) that is fitted with a turbo diesel-engine (130 kW). The tracked-based harvester has a total weight of 20,000 kg, whereas each trapezoidal track weighs 2,000 kg. The machines width is 2.9 m. The boom range of 9.5 m leads to a maximum corridor spacing of 19 m. The cab can be leveled in all directions.

Model Deriving Process

Productivity models for harvesters contain three basic components: a model for (1) tree processing, (2) locomotion and (3) delays. To construct such a model the following hypothesis is assumed (Stampfer, 1999; Stampfer, 2001):

- Time of tree processing = f(tree volume, harvesting intensity, stand density and silvicultural treatment strategy)
- Time of locomotion = f(slope gradient, stand density and soil bearing capacity)

Table 1. Technical parameters of the tracked harvester Valmet 911 Snake

		value	**unit**
Machine description	Weight (including harvesting head Valmet 960 S-2)	20,000	kg
	Width	2.9	m
	Height	4.4	m
	Boom reach	9.5	m
	Engine/Power	Valmet/130	KW
Undercarriage	Operating-speed	0 – 3,3	km/h
	Speed	0 – 9,8	km/h
	Width of the tracks	500	mm
	Ground clearance	700	mm
Self-leveling cab and boom	On both sides	+/- 17	°
	To the front	+ 22	°
	To the rear	+ 20	°
Harvesting head (standard) Valmet 960 S-2	Approx. weight	1,155	kg
	Max. cutting capacity	Approx. 65	cm

Figure 2 shows the planned procedure for model derivation. Existing models from the literature should be used for tree processing. The productivity model should contain the variables from the model hypothesis. The tree processing capacity of the harvesting head and the boom reach are machine determined selection criteria. The comparability of the time measuring concept is an important auxiliary condition. The locomotion model is derived from empirical studies. To quantify the impact of slope on locomotion, a study layout of corridors with moderate to extreme slopes have been selected. Delays are included in the total model through a conversion factor from PSH_0 (productive system hours) to PSH_{15} (productive system hour including delays shorter than 15 min).

Study Sites

The stands to be harvested as part of this study are located in the semi-mountainous and mountainous areas of Austria and are characterized in Table 2. The length of the individual harvester corridors is between 84 and 167 meters, with slopes ranging from 22 to 56%. They are mixed stands with an age of either 55 or 100 years. The younger stand had 1,200 stems per hectare whereby the other two stands had stem densities from 609 to 925 per hectare. In the stands approximately 31 - 43% of the standing tree volume was removed.

Data Collection

An established data collection protocol developed by Stampfer (1999) was chosen. The work study procedure, the collection of the physical variables and the time measurement system is described by Stampfer (1999).

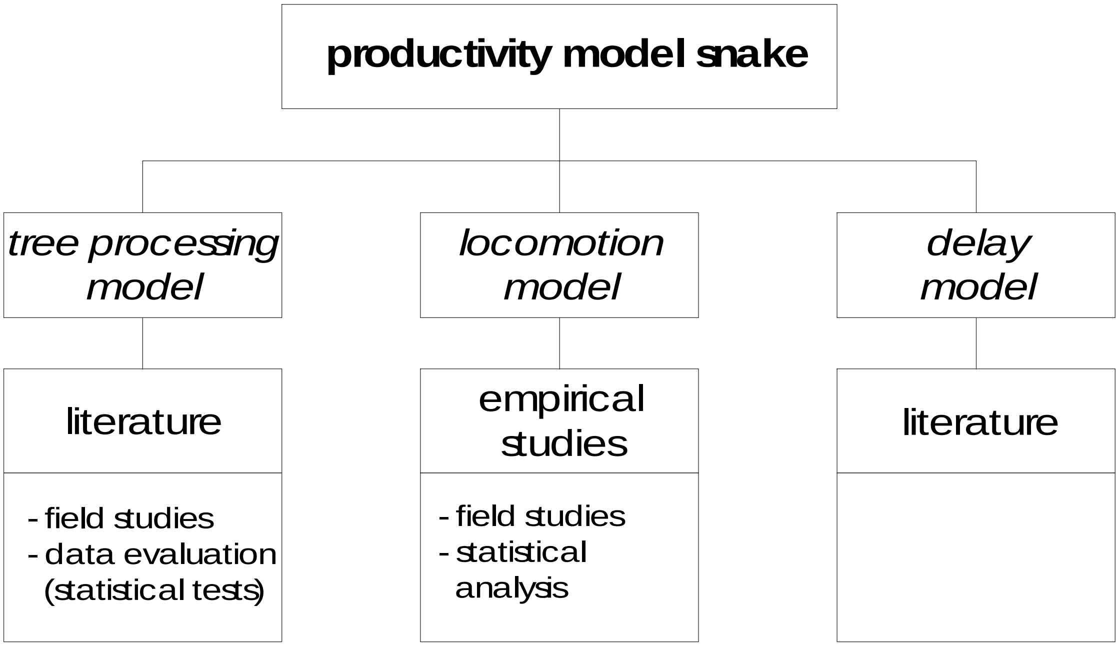

Figure 2: Model deriving process

Table 2. Stand descriptions

	Stand 1	Stand 2	Stand 3
Corridors (n)	2	5	3
Mid-Corridor length (m)	130	84	167
Mid-Corridor slope (%)	56	22	38
Working progress	Uphill	downhill/uphill	downhill
Mid-tree height (m)	19.0	18.8	20.6
Mid-tree diameter (cm)	25.2	21.8	30.4
Mid-tree volume (m^3)	0.46	0.35	0.60
Stand density (n/ha)	1,200	925	609
Harvesting intensity (%)	43	31	40
Age (n)	100	55	55
Tree species	spruce/larch/beech	spruce/pine/larch/birch	spruce/larch
Location	Mautern	Feistritz	Kraubath

Statistical Analyses

Variance analysis attempts to quantify the influence of nominal or ordinal-scaled variables. The following analyses were carried out with S-Plus, whereby the statistical fundamentals are described in Venables and Ripley (1997). For each part of the model the following analysis strategy was chosen (Heinimann et al., 1998):

- development of a linear model with all the co-variables and factors (Table 3);

- evaluating on the non-linearity of the co-variables;
- choosing a number of sub-models through the removal of non-significant variable;
- choose two-way interactions of the sub-models.

Tree volume is a major part of all production functions but the relationship between productivity and tree volume is not linear (Häberle 1984). Therefore a power factor is used on the co-variable *treevol*. Häberle (1984) recommends the estimation of this power value with an iterative procedure. Box and Cox (1964) describe a method whereby the optimal transformation is carried out using a maximum likelihood function. Venables and Ripley (1997) show how such a Box-Cox transformation procedure can be carried out in S-Plus. Similarly, this principle of the maximum likelihood function can also be used on the independent co-variables (Heinimann, 1998). Subsequently, using multiple linear regressions the parameters of the model are estimated, with which the productivity of the steep terrain harvester Valmet 911 Snake under given conditions can best be quantified.

Table 3. Conditions of the investigated harvesting units

Variable	Mean	0.05 Quantile	0.95 Quantile	Unit
$cycle_{manip}$	0.92	0.35	1.86	min
DBH	31	19	42	cm
stand density	609	407	872	n/ha
tree height	21	15	26	m
tree volume	0.61	0.18	1.16	m^3 without bark
$cycle_{locom}$	0.29	0.1	0.66	min
soil bearing capacity	2.47	1.42	4	%CBR
trees processed per stop	2.84	1.00	6.00	n
terrain slope	36	19	68	%

RESULTS AND DISCUSSION

The approach of selecting an appropriate tree-processing model from literature failed with independent Snake data sets after evaluation. There are hardly any models in the literature that fulfill the requirements. No goal oriented model could be found that suited the harvester head and boom reach as well as the demand for stand and terrain depending parameters, An evaluation of the Koenigstiger tree-processing model of Stampfer (2001) resulted in a significantly higher productivity level for the Valmet Snake. This can be explained by the different boom reaches (10 meters for Snake against 15 meters for Koenigstiger), although the tree processing head has roughly the same capabilities.

Productivity Model

The statistical analysis resulted in the time models shown in Equation (2) and (3). The time for tree felling and processing is a function of the tree volume and the silvicultural treatment strategy. 39% of the time variability (R^2=0.387) can be explained through these parameters. The standard error of the estimated value is 0.72. The locomotion of the harvester is influenced by the terrain slope, the number of trees felled and processed per harvester stop and the soil bearing capacity. 27% of the variation of the locomotion time (R^2=0.274) can be explained through these variables. The standard error of the estimated time is 0.89. All model parameters are significant at $\alpha = 0.01$.

Through the summation of the system efficiency for the locomotion and the tree manipulation it is possible to determine the productivity of the system (Equation 1). Models 2 and 3 are based on productive system time without delays (PSH_0). For practical reasons it is usual to include delays less than 15 min (PSH_{15}), whereby the time required per cycle is increased. The chosen conversion factor is 1.35 (Stampfer, 2001).

$$prod_{snake} = \frac{60}{k * (effic_{locom} + effic_{manip})} \tag{1}$$

$prod_{snake}$ ....System productivity tracked harvester (m^3/PSH_{15})
$effic_{locom}$ ....System efficiency locomotion (min/m^3)
$effic_{manip}$ ....System efficiency tree manipulation (min/m^3)
k.............................Conversion factor from PSH_0 to PSH_{15}

$$effic_{locom} = e^{0.1480-0.3894*stop+0.0002*slope^2-0.2674*soilb} \tag{2}$$

$effic_{locom}$ ....System efficiency locomotion (min/m^3)
$slope$.......................Terrain slope (%)
$stop$ ....Number of trees felled per stop (n)
$soilb$ ....Soil bearing capacity (% CBR)

$$effic_{manip} = 1.0667 + 0.3094 * treevol^{-1} - 0.1846 * TREAT \tag{3}$$

$effic_{locom}$ ....System efficiency tree manipulation (min/m^3)
$treevol$ ....Tree volume (m^3 without bark)
$TREAT$....................Silvicultural system: (0) single tree extraction and (1) clear-cut

Statistical models only represent the range of the existing database; extrapolation can result in prediction errors. Therefore it is necessary to recognize that statements related to the database are only valid for the range limited by the 5% and 95% quartile. That means that 90% of the data is within this range.

A summary of the results is presented in Table 3. The average cycle time for felling and processing a 0.6 m3 tree is approximately one minute, which is typical for harvester operations (Stampfer, 2001). Noticeable is the relatively high tree volume (between 0.16 and 1.16), while normally harvesters are used in small sized timber (Heinimann, 1998). Johansson (1995) gives an upper limit for tree volume of 0.5 m3.

The average locomotion time is 0.3 minutes, whereby approximately three trees per harvester stop are felled and processed. The soil bearing capacity with an average value of 2.5 %CBR is unfavorable due to the higher probability of developing ruts on the ground. The slope gradient ranges between 19 and 68%, average terrain slope that was operated on was 36%. In comparison to conventional tracked harvesters, which are able to pass slopes with good soil conditions to a maximum of 60%, the Valmet Snake is able to operate on slopes with a maximum gradient of 70%. Steeper slopes or insufficient soil bearing capacities require cable yarding systems for extraction.

Figure 3 shows the productivity for thinning operations with the tracked harvester Valmet Snake in relation to tree volume and terrain slope. A slope gradient of 25% is typical for moderate terrain while 65% is very steep terrain. For the key effects, soil bearing capacity and number of trees processed per harvester stop, the values of 2.5 and 2.8 where used respectively. Under similar conditions with an average tree volume of 0.6 m³, a 2.88 m³/PSH$_{15}$ productivity decrease was established between the moderate and steep terrain (a 12% decrease).

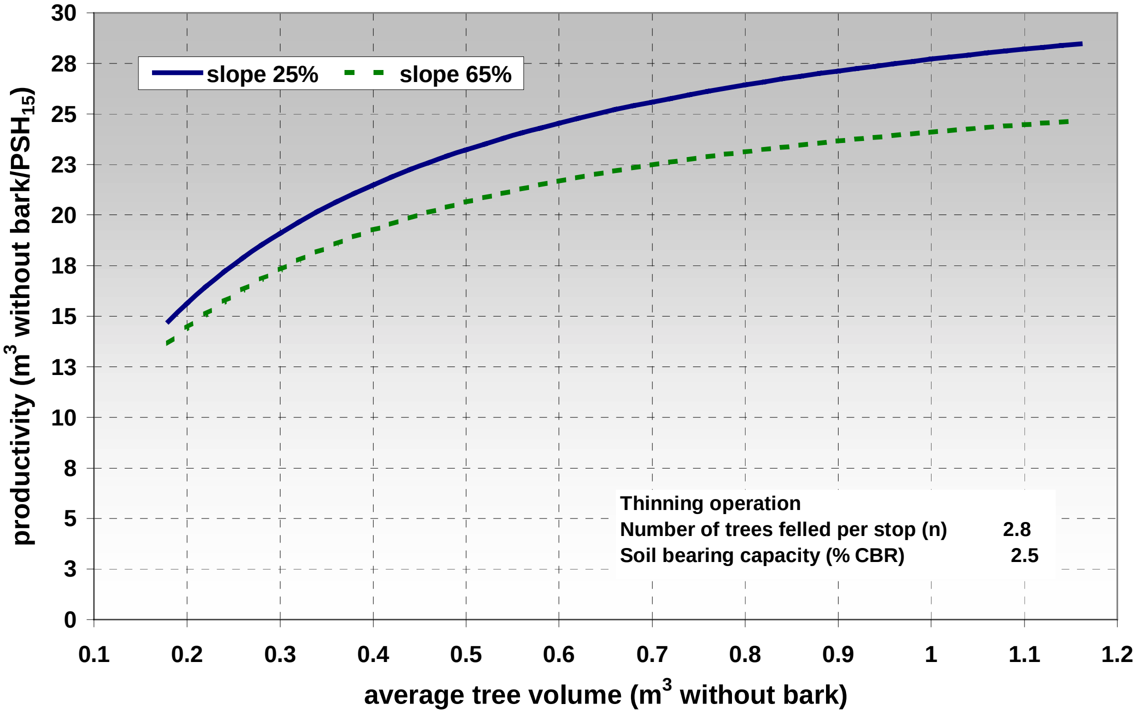

Figure 3. System productivity (m^3/PSH$_{15}$) for the harvester Snake in relation to average tree volume and terrain slope

The impact of terrain on the Snake harvester productivity could be clearly quantified. Locomotion time within the productive system time amounts to only 10% (Stampfer, 1999; Dale und Nitteberg, 1999), which made the verification of influence of terrain to system productivity by using conventional time studies difficult. Only a change in the productivity study concept was successful (Stampfer, 1999). Harvesting operations on steep terrain result in a productivity decrease with increasing terrain slope (Stampfer, 1999; Stampfer, 2001). In general the achieved productivity with Valmet Snake is very high and can be compared to Scandinavian harvester studies (Asikainen, 1995).

Figure 4 shows a productivity comparison for the harvester Snake depending on average tree volume and silvicultural system. The productivity of the clear-cut is 2.68 m^3/PSH_{15} greater than that of the single-tree operation. Considering an average tree volume of 0.6 m^3 this means a productivity increase of 11%.

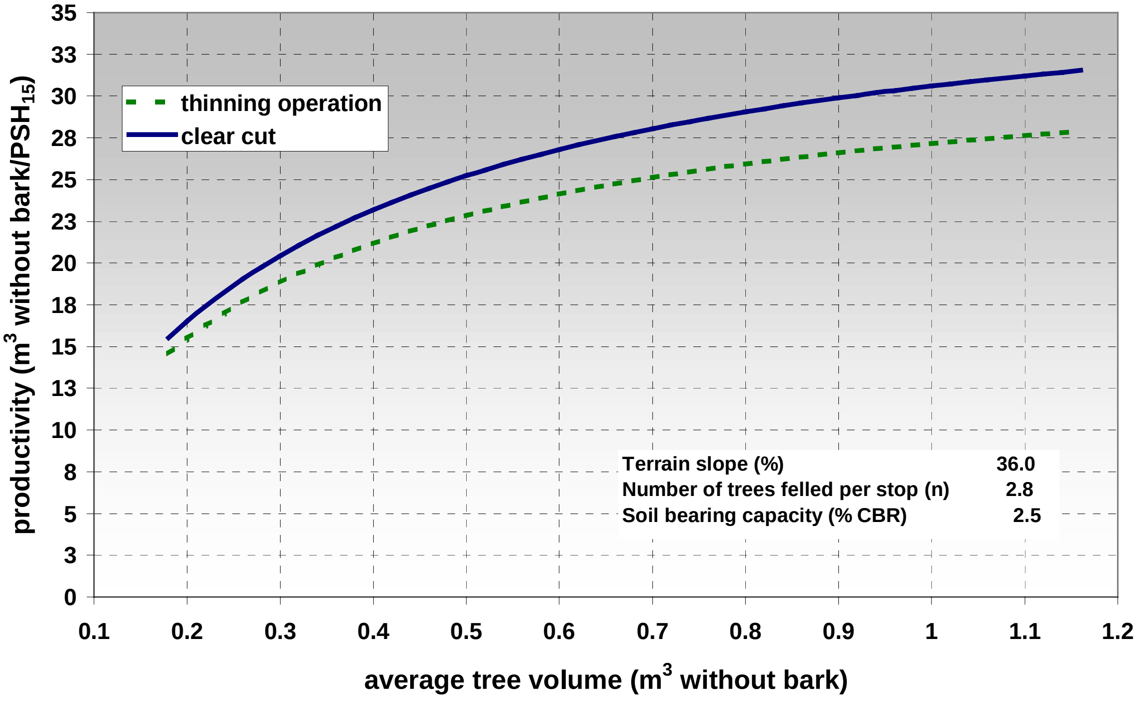

Figure 4. System productivity (m^3/PSH_{15}) for the harvester Snake with regard to average tree volume and silvicultural system

SUMMARY

The goal of this paper was to develop a productivity model for the steep terrain harvester Valmet 911 Snake. The influence of different terrain and stand parameters needed to be quantified within the model. For productivity model derivation a combined approach of empirical studies and results from the literature was selected. The model consists of tree processing, locomotion and delay components. The applicability of the proposed approach failed in part because no tree-processing model fulfilled the requirements for this specific harvesting head and boom reach. The evaluation of Koenigstiger model resulted in significant higher productivity of Valmet Snake harvester. For these reasons, tree processing and locomotion model components were derived from conventional approaches.

The time consumption for felling and processing with Valmet Snake is a function of tree volume and silvicultural treatment strategy. The locomotion time depends on number of trees felled per harvester stop, soil bearing capacity and terrain slope. The relation between productive system time (PSH_0) and productive system time including delays up to 15 minutes (PSH_{15}) was included with the conversion factor of 1.35.

The tracked harvester Valmet Snake operates on slopes up to 70%. The productivity for an average tree volume of 0.6 m^3 is 22 m^3/PSH_{15}, which is very high for steep terrain. In comparison productivity on moderate terrain is 2.9 m^3/PSH_{15} higher, which is an increase of 12%. The influence of the silvicultural treatment strategy is significant. At an average tree volume of 0.6 m^3 the productivity on clear-cuts is 2.7 m^3/PSH_{15} higher than on single-tree operations. This corresponds to an increase of 11%. In general the estimated productivity level is very high and comparable to Scandinavian harvester studies (Asikainen, 1995). While many harvesters in middle Europe have their operation emphasis in thinnings, the Snake harvester is very flexible in accomplishing different silvicultural treatment strategies. Operations on slopes with marginal soil bearable capacity and steep terrain are possible.

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