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Productivity and costs of the mechanised cut-to-length wood harvesting system in clear-felling operations

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ABSTRACT: A study of labour productivity was conducted in fully mechanised harvesting technologies. The study revealed that the productivity of harvesters was particularly affected by the average tree volume of the felled trees, and the productivity of forwarders was affected mainly by two factors – haulage distance and machine payload. Dependences of other factors such as natural and site conditions, technical parameters and skills of operators could not be demonstrated. Regression equations of dependences were created for all these three significant criteria and costs per cubic meter of processed timber were calculated for them according to the cost function. A regression function was then developed for the forwarder that takes into account both significant criteria influencing the forwarder productivity.

Keywords: average tree volume; hauling distance; payload; harvester

Mechanised cut-to-length (CTL) wood harvesting methods have become widely used in many industrialised European countries such as Sweden (ca. 98%), Ireland (ca. 95%) and Finland (ca. 91%) compared to motor-manual harvesting (Karjalainen et al. 2001). During the last two decades the mechanisation of working processes in forestry has increased rapidly. Due to labour shortage and the need for economical wood production, a lot of developments were made towards rationalisation especially in harvesting (Schaeffer et al. 2001). The CTL system requires less labour, less road construction, and fewer landing areas than the other ground-based systems (Bettinger, Kellogg 1993).

Productivity of the CTL system depends on the forest stand, site and operational factors such as ground conditions, slope, operator's motivation and skill, branch size, operational layout, tree size, tree form, log assortments processed, numbers of unmerchantable and merchantable trees per unit area, hauling distance, undergrowth density and machine design (Brunberg et al. 1989; Spinelli et al. 2002; Stampfer 1999; Makkonen 1991; Richardson 1989). Harvester productivity is closely related to the tree size and stand characteristics (Bulley 1999).

The aim of this study was to generalise productivity trends of different machine classes and to show general trends of productivity in relation to the most demanding factors in clear-cutting operations and to determine the operation cost for different harvester and forwarder classes.

MATERIAL AND METHODS

Altogether 21 field studies for harvester and 8 field studies for forwarder were carried out. Both types of purpose-built and excavator-based machines were investigated. In harvesting operations 15 different machines were studied, out of which 12 were excavator-based and 3 purpose-built harvesters, and in hauling operations 7 different machines were studied, out of which 1 was excavator-based and 6 purpose-built forwarders.

The experiments were carried out in standard working conditions typical for Ireland. The average tree size varied between 0.1 m^3 and 1.0 m^3 and the hauling distance varied from 80 to 1,400 m. All the

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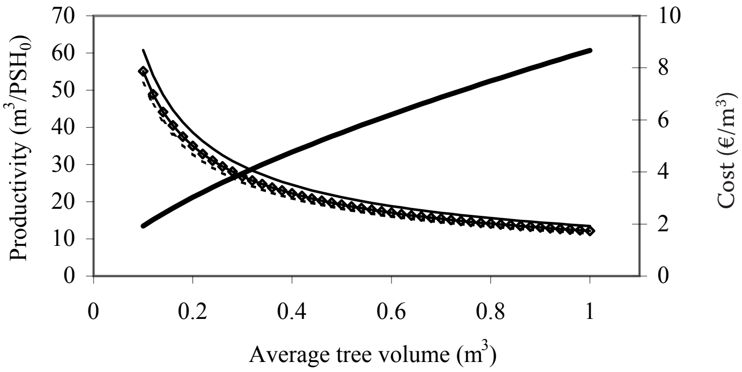

Fig. 1. Relationship between tree size and productivity (including costs) of a harvester in clear-cutting operation

other relevant factors affecting the productivity were as much as possible levelled (such as operator, ground condition, species of tree, slope and log assortment process).

Three different classes of machines were used:

– Class I (small): harvester engine output power up to 80 kW, forwarder payload up to 10 tonnes,
– Class II (medium): harvester engine output power from 80 to 120 kW, forwarder payload from 10 to 12 tonnes,
– Class III (large): harvester engine output power higher than 120 kW, forwarder payload higher than 12 tonnes.

The class deviation was adopted from Athanassiadis et al. (1999) and Klvac et al. (2003).

The data collection procedure consisted of preliminary information (i.e. terrain classification, timber quality, sub-compartment details and additional information) and of the time study. The information on the terrain classification provided a description of ground conditions, roughness and slope, the information on timber quality provided a description of stand straightness, taper and branchiness, the sub-compartment details included a species breakdown, mean diameter at breast height (dbh), mean heights, tariff number, average tree volume (m^3), stocking (stems/ha) and growing stock (m^3/ha). The additional information included contractor, machine type, harvester head type, location, soil type, soil shearing capacity, soil moisture content, description of the ground cultivation method and working direction (i.e. uphill or downhill).

Cycle times for each machine were split into the time elements (i.e. for a forwarder: unloading, driving into the stand, loading, driving to the roadside and idle time, respectively; for a harvester: cutting, processing, movement and idle time, respectively) considered to be typical of the functional process analysed and all time elements and related time-motion data were recorded. Machine productivity was measured in cubic meters per productive hour (m^3/PMH_0) without any delays.

All the records were filtered using an Excel program into different categories and the productivity trend curve was analysed by CurveExpert 1.3. The basis of machine cost equation was adopted from Spinelli et al. (2002) and the costs per m^3 produced for different classes were calculated.

RESULTS

Harvester productivity and cost

Harvester productivity varies from 13.5 to 60.5 m^3 per PMH_0 in Irish conditions according to the average tree size. Average tree size was found to be a factor affecting productivity in the most significant way. A trend curve based on the data of all harvesters investigated in the study was constructed:

$$Y = 60.711x^{0.6545} \quad (1)$$

where: Y – productivity (m^3/PMH_0),
x – average tree size (m^3) with the correlation coefficient $R^2 = 0.9219$.

Fig. 1 shows the relationship between average tree size and productivity (on y-axis), and costs per cubic metre (set on secondary y-axis).

Machine costs per hour are reported (see Table 1) as both Productive Machine Hours excluding delays (PMH_0) and Scheduled Machine Hours (SMH). The latter was obtained by dividing PMH_0 by 0.75 for each class of harvester. The coefficient 0.75 is realistic compared to other analyses of forestry machine operations (Brinker et al. 1989) and was adopted to reflect the better working conditions offered. Better working conditions are expected to result in higher machine utilisation rates. Different values for repair and maintenance were set according to Athanassiadis et al. (2000). They found the harvester and forwarder replaced mass during the life cycle in percentage as 56% and 52%, respectively, therefore the repair costs during the life cycle were set as 56% of the purchase price. The fuel consumption rate varies according to the engine output power

Table 1. Machine cost calculations

Costing factor	Harvester			Forwarder		
	Class I	Class II	Class III	Class I	Class II	Class III
Machine cost data						
Purchase price (P), EUR	300,000	320,000	360,000	190,000	220,000	260,000
Engine output power, kW	80	120	150	90	110	140
Machine life (*n*), years	5	5	5	6	6	6
Salvage value (sv), % purchase price	10	10	10	10	10	10
Machine utilisation rate (u), % SMH	75	75	75	75	75	75
Repair and maintenance cost (rm), % capital over life	56	56	56	52	52	52
Interest rate (in), % of average yearly investment (Y)	8	8	8	8	8	8
Insurance and tax rate (it), % of average yearly investment (Y)	7	7	7	7	7	7
Fuel consumption rate (fcr), l/h	10.93	12.8	14.18	11.4	12.33	13.72
Fuel cost (fc), EUR/l	0.5	0.5	0.5	0.5	0.5	0.5
Oil and lubrication consumption rate (ocr), l/h	0.62	0.62	0.62	0.27	0.27	0.27
Oil and lubrication cost (lo), EUR/l	1	1	1	1	1	1
Operator's wage (w), EUR/SMH	12	12	12	12	12	12
Scheduled machine hours (SMH), h/year	2,000	2,000	2,000	2,000	2,000	2,000
Salvage value (S), EUR	30,000	32,000	36,000	19,000	22,000	26,000
Annual depreciation (D) in EUR/year, D = [(P – S)/n]	54,000	57,600	64,800	28,500	33,000	39,000
Average yearly investment (Y) in EUR/year, Y = [((P – S) × (n + 1))/2n) + S]	192,000	204,800	230,400	118,750	137,500	162,500
Productive machine hours (PMH) in h/year, PMH = (SMH × u)	1,500	1,500	1,500	1,500	1,500	1,500
Ownership costs						
Interest on capital (I) in EUR/year, I = (in × Y)	15,360	16,384	18,432	9,500	11,000	13,000
Insurance and tax cost (IT) in EUR/year, IT = (it × Y)	13,440	14,336	16,128	8,312.5	9,625	11,375
Annual ownership cost (F) in EUR/year), F = (D + I + IT)	82,800	88,320	99,360	46,312.5	53,625	63,375
Ownership cost per SMH (Os) in EUR, Os = (F/SMH)	41.4	44.16	49.68	23.16	26.81	31.69
Ownership cost per PMH (Op) in EUR, Op = (F/PMH)	55.20	58.88	66.24	30.88	35.75	42.25
Operating costs						
Fuel cost (Fu) in EUR/PMH, Fu = (fcr × fc)	5.47	6.40	7.09	5.70	6.17	6.86
Lube cost (L) in EUR/PMH, L = (ocr × lo)	0.62	0.62	0.62	0.27	0.27	0.27

Table 1 to be continued

Costing factor	Harvester			Forwarder		
	Class I	Class II	Class III	Class I	Class II	Class III
Repair and maintenance cost (RM) in EUR/PMH, RM = [rm × P/(PMH × n)]	22.40	23.89	26.88	10.98	12.71	15.02
Operator cost (Opc) in EUR/PMH, Opc = (W/u)	16.00	16.00	16.00	16.00	16.00	16.00
Machine operating cost per PMH (Vp) in EUR/PMH, V = (Fu + L + RM + Opc)	44.49	46.91	50.59	32.95	35.15	38.15
Machine operating cost per SMH (Vs) in EUR/SMH, Vs = (Vp × ut)	33.36	35.19	37.94	24.71	26.36	28.61
Total costs						
Total machine cost per SMH in EUR/SMH, TCS = (Os + Vs)	74.76	79.35	87.62	47.87	53.17	60.30
Total machine cost per PMH in EUR/PMH, TCP= (Op + Vp)	99.69	105.79	116.83	63.82	70.90	80.40

(Lyons 2002 personal communication). For the oil consumption rate the best estimate according to Klvac et al. (2003) was set. The cost equation was adopted from Miyata (1980). The characteristic variation of machine productivity and operation costs with tree size (harvester) and hauling distance (forwarders) were evaluated to compare the cost of different machinery classes.

Forwarder productivity and cost

Forwarder productivity was studied globally according to hauling distance and according to load size for all forwarders, and particularly according to hauling distance for specified classes of forwarders. The curve trends are as follows:

$$Y = 8.1466e^{0.0943x} \quad (2)$$

where: Y – productivity (m^3/PMH_0),
x – average load size (m^3) with the correlation coefficient $R^2 = 0.5534$.

$$Y = -7.6881\text{Ln}(x) + 64.351 \quad (3)$$

where: Y – productivity (m^3/PMH_0),
x – average hauling distance (m) with the correlation coefficient $R^2 = 0.3549$.

The individual trend lines for each class of forwarders according to hauling distance were as follows:

$$\text{Class I} - Y = 10.5193x^{(24.9181/x)} \quad (4)$$

where: Y – productivity (m^3/PMH_0),
x – average hauling distance (m) with the correlation coefficient $R^2 = 0.5221$.

$$\text{Class II} - Y = 17.0068x^{(13.2533/x)} \quad (5)$$

where: Y – productivity (m^3/PMH_0),
x – average hauling distance (m) with the correlation coefficient $R^2 = 0.6263$.

$$\text{Class III} - Y = 10.5193x^{(24.9181/x)} + 10 \quad (6)$$

where: Y – productivity (m^3/PMH_0),
x – average hauling distance (m).

Equation (6) could be only predicted due to the insufficient amount of relevant data. Therefore the correlation coefficient is not given.

General trends of forwarder productivity in clear-cutting operations affected by hauling distance and load size are shown in Figs. 2 and 3, respectively. The costs are included. The forwarder productivity varies according to hauling distance and according to load size, respectively. Obviously, the higher the hauling distance, the lower the productivity; and the higher the load size, the higher the productivity.

Bigger and more expensive machines are more cost demanding per working hour. However, higher productivity is expected of a bigger machine, which is contradictory affecting costs per m^3 (the higher

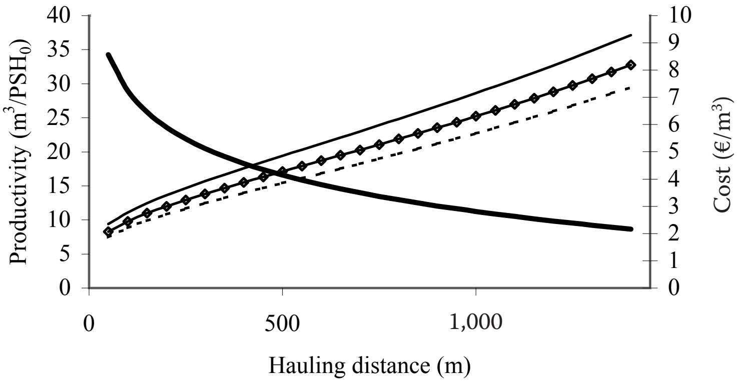

Fig. 2. Relationship between hauling distance and productivity (including costs) of a forwarder in clear-cutting operation

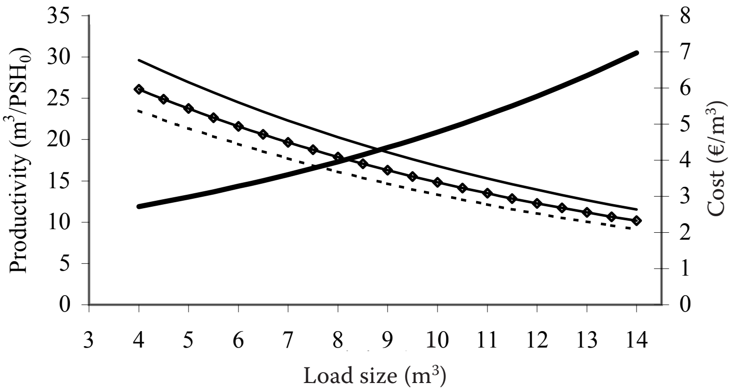

Fig. 3. Relationship between load size and productivity (including costs) of a forwarder in clear-cutting operation

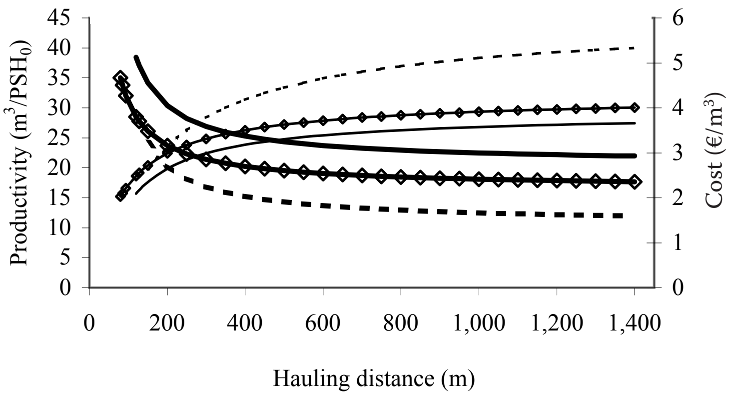

Fig. 4. Relationship between hauling distance and productivity (including costs) of each class of forwarders in clear-cutting operation

productivity of a bigger machine decreases the cost per m^3). More precise deviation of forwarders (such as class I, class II and class III) in clear-cutting operations and the relationship between hauling distance and productivity (including cost) are shown in Fig. 4. Machines cost per hour are reported in Table 1.

DISCUSSION

Average tree volume is a crucial factor in clear-cutting operations associated with harvesting. The use of different classes of harvesters depends on the potential tree size cut given by technical parameters and design of the machine. Machine costs varied between two and nine Euros per m^3. The cost difference between the classes is very small in the tree volume area larger than 0.5 m^3. However, the tree volume smaller 0.5 m^3 causes higher differentiation of costs. From the economic point of view if there exist all classes of harvesters (i.e. small, medium and large), it is better to use the small one. Only if any of the factors limits the use, the relevant (even better) machine should be used.

The productivity of harvesting in clear-cutting operations was studied by Andersson (1994). He studied a Rottne EGS Rapid (class III) harvester in Alberta and found 7.8 m^3/PMH for tree volume 0.12 m^3 per stem, 12.9 m^3/PMH for 0.19 m^3 per stem and 22.2 m^3/PMH for 0.34 m^3 per stem, which is less compared to Irish conditions. The productivity in this study was probably higher because other crucial factors affecting the productivity were minimised and the terrain conditions were very good (i.e. even terrain, slope max 17°).

The hauling distance is a key factor affecting the forwarding in clear-cutting operations. The productivity increases with higher payload of the machine and with shorter distance. From the general scenario the difference in the productivity of different classes is not so visible, therefore it is necessary to divide the forwarder to classes according to payload or to evaluate individual machines. Makkonen (1989) studied the productivity of a Timberjack 230A (class I) forwarder and found 24 m^3/PMH for 360 m hauling distance and 31.6 m^3/PMH for 170 m hauling distance, which are significantly higher values. These productivities are reached by forwarder class II in this study.

Due to the fact that bigger machines have higher productivity, the costs are decreasing with larger machines. However, the costs of different forwarder classes are not so variable between forwarder class II and III, only forwarders of class I have significantly higher costing. From the economic point of view the larger forwarders could be recommended for clear-cutting operations.

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Produktivita a náklady plně mechanizované těžební technologie v mýtních těžbách

ABSTRAKT: Byla provedena studie produktivity práce plně mechanizovaných těžebních technologií. V rámci studie bylo zjištěno, že produktivita harvesterů je ovlivněna především průměrnou hmotnatostí kácených stromů a produktivita forwarderů je ovlivněna zejména dvěma faktory, a to přibližovací vzdáleností a velikostí nákladu prostředku. Pro ostatní faktory jako přírodní a stanovištní podmínky, technické parametry a zručnost operátorů nelze stanovit prokazatelné závislosti. Pro všechna tato významná tři kritéria byly vytvořeny regresní rovnice závislostí a k nim podle nákladové funkce dopočteny náklady na kubický metr vyrobeného dříví. U forwarderu byla poté vytvořena regresní rovnice beroucí v potaz obě významná kritéria ovlivňující produktivitu forwarderů.

Klíčová slova: průměrná hmotnatost; přibližovací vzdálenost; velikost nákladu; harvester

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