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# Mathematical models for optimization of group work in harvesting operation

Zečić Željko, Marenče Jurij

## Summary

This paper research of productivity and work organization were investigated of a group made of five workers (two cutters, two tractor drivers and one cutter-inspector) and a team leader. The team was equipped with two tractors and three chain saws. The research was carried out in the area of management unit – Južna Krndija Kutjevačka, at an altitude ranging between 550 m and 750 m in a 55-year beech stand.

Standard time was calculated on the basis of the mathematical model of multiple linear regression of effective time. The average team standard time for two cutters is 25.92 min/m<sup>3</sup> and the average standard time for two tractors ranges between 25.06 min/m<sup>3</sup> (150 m) and 33.20 min/m<sup>3</sup> (650 m). Standard time of the cutter-inspector is 4.93 min/m<sup>3</sup> and it was used as the basic unit. If one cutter-inspector were on the roadside landing, then the group should be made of 5.25 cutters and 5.08 (150 m) to 6.73 (650 m) tractors to achieve the optimum work results. The optimum size of the team changes depending on the distance of tractor skidding and it ranges between 11.33 members (150 m) and 12.98 members (650 m). The optimally organized team can produce 97.29 m<sup>3</sup>/day of wood assortments.

Daily efficiency was calculated per member of team and it ranges between 7.68 m<sup>3</sup>/day (150 m) and 5.79 m<sup>3</sup>/day (650 m) and it is consequently by 79.3 % (150 m) to 35.2 % (650 m) higher than the realized daily efficiency of 4.28 m<sup>3</sup>/day per member.

On the basis of the modelled daily efficiency, the costs range between EUR 14.17 per m<sup>3</sup> (150 m) and EUR 18.80 per m<sup>3</sup> (650 m) and it is consequently lower by 44.2 % (150 m) to 26.0 % (650 m) compared to the realized costs of EUR 25.41 per m<sup>3</sup>.

*Key words:* mathematical model, team work, time study, productivity, costs

## 1. Introduction and objectives of the research – Uvod i ciljevi istraživanja

Forest harvesting should be based on environmentally friendly principles, humanized labour and minimum costs of a carefully selected and optimum work method. Teamwork in forest harvesting has been implemented in Slovenia since 1976. In Croatia teamwork in forest harvesting was first introduced in preparatory and finishing felling in Bjelovar Forest Administration in 1979. The main reasons were the increase of productivity achieved by processing several meter-long cordwood and the cut of production costs per 1 m<sup>3</sup>.

The objective of this research is to calculate the optimum size of a workers' group by use of mathematical models, and then, based on the obtained results, to model and calculate the maximum daily efficiency at the lowest costs per product unit. The ba-

sic assumption of the research is that the actual work organisation fails to meet the requirements, because the standard times and daily efficiencies are too low. On the basis of such research higher productivity can be achieved, planning of work activities can be improved and production costs can be met more efficiently.

## 2. Place and method of research – Mjesto i metode istraživanja

On-site investigations were carried out in the area management unit – Južna Krndija I. Its altitude ranges between 240 m and 792 m and its relief is well indented. Distric brown soil is developed there with the plant community of the Illyrian mountain beech forest with dead nettle (*Lamio orvale* – *Fagetum sylvaticae* /Ht. 1938.). Road openness of this management

unit is 17.28 m/ha. On-site investigations were carried out in the compartments 55 and 56 at an altitude ranging between 550 m and 750 m.

Air temperatures have a considerable impact on the workers activity. During the on-site research, morning and daily temperatures were recorded and an average air temperature of 16 °C was calculated. The soil was wet on average. Longitudinal slope of skid trail was 14 % on average. Relative air moisture was mainly high – 81 % on average.

There are 892 trees per hectare. The volume of an average stand tree is 0.502 m<sup>3</sup>. The growing stock is 216 m<sup>3</sup>/ha, and the annual cut is 40 m<sup>3</sup>/ha. Utilization depends on the method of felling and processing. Out of the total (gross) volume, 92.0 % of wood assortments were processed. The average distance of the marked trees is 10.1 m. Tractors move partly on strip roads and partly off-road to get to the cut trees.

On-site investigations were carried out by use of work and time studies, i.e. by use of snap-back chronometry method recommended by REFA (1976). Checklists were adapted to the work organization of cutters, tractors and cutters-inspectors.

The recorded times were analysed according to teamwork time distribution used by the Forest Harvesting Institute of the Faculty of Forestry Zagreb. Individual analysis was conducted of recorded times for each member of the team, i.e. for the means of work. Fix and variable times were analysed separately. Effective time in tree felling and processing was analysed by multiple regression analysis, taking into consideration the dependence of effective time consumption in relation to the breast-height diameter and the height.

In timber skidding, part of effective time is analysed as fix time, and part of it as variable time. Fix times do not depend on skidding distance or distance of pulling the chocker or winching, and in this event they refer to the effective time of the felling site work (loading) and roadside landing work (unloading). Arithmetic mean, dispersion rate, percentage error of the arithmetic mean and number of required records were calculated for fix times. Variable times were processed by multiple regression analyses using the software package – *Statistica 6*. Four variables were taken into consideration for the calculation of the loaded tractor travel: skidding distance, load volume, number of load pieces and road slope. The travel distance and road slope were taken into account for calculating the time of unloaded tractor travel.

Multiple regression analysis was also used for determining the time consumed by the cutter-in-

spector in final processing, measuring and inspecting at the roadside landing. Attention was focused on the dependence of effective time consumption on the processed volume and number of pieces.

In the process of wood felling, processing and skidding performed by teamwork, time distribution differs from the standard ones because the cutter is also present in specific operations and at specific places (felling site, skidding trail and roadside landing).

Effective time of felling and processing is divided into tree time and assortment time. The time consumed by the cutter for load hooking, is analysed as part of the tractor's effective time consumed working at the felling site. The effective time of the tractor cycle is divided into fix and variable times. Delay times involve the times of all breaks, production delays and preparation time.

After filling in the data of all team members into the PC (database), statistical analysis of data was carried out by use of software packages *Microsoft Excel* and *Statistica 6*. The required statistical values were calculated for each operation, depending on the type of time. Variable times were processed by the software package *Statistika 6*.

The so-called descriptive statistics was used for the description of the basic characteristics of the researched group of data (survey of data regarding the structure at a specific workplace, and work times of machines and men); mean values of variables were expressed by arithmetic means, and their variability by range, variance and standard error.

On the basis of the measured data ( $d$  – breast-height diameter,  $h$  – tree height), the total volume of felled trees was calculated, Shummacher – Hall – by use of this equation:

$$V = b^0 \cdot d^{b_1} \cdot h^{b_2} \cdot f \dots \text{ (m}^3\text{)},$$

where:  $V$  – is the tree volume (m<sup>3</sup>),  $b_0$ ,  $b_1$ ,  $b_2$  – are the parameters of the equation,  $f$  – is Mayer's correction factor.

The processed volume of each tree, i.e. of wood assortments, was calculated by use of Huber's formula:  $V = \left[ \frac{d^2 \cdot \pi}{4000} \right] \cdot l$ , (m<sup>3</sup>), where:  $V$  – is the volume of wood assortment (m<sup>3</sup>),  $d$  – is the mean diameter (cm),  $l$  – is the length of assortment (m).

### 3. Teamwork characteristics – *Značajke skupnoga rada*

A work team is a synchronized group of workers formed so as to carry out a work order as an independent unit with the necessary means of work. The

task of the work team is to achieve better connection and performance of all operations, starting with the preparation work and ending with the delivery of the forest assortments to the buyer. The basic characteristics of teamwork is a single work order determined on the basis of individual daily standard efficiencies of each member of the team. The daily standard efficiency is calculated and showed averagely per member of the team. The workers carry out the work at the same workplace with the same means and object of work (Fig. 1).



**Figure 1** Cutter and tractor driver's work related to load hooking

**Slika 1.** Sjekač i traktorista pri vezanju tovara

In teamwork, more than a few workers take part in carrying out the work order. Work technology is adapted to the factors of the workplace. The workers distribute evenly their efficiency and their income subject to days spent at work in the accounting period. Joint responsibility is established in the team for meeting the requirements specified in the work order. All members of the team go to work together and they also go back to their place of residence together. In the team with two cutters, costs for fuels and lubricants are evenly distributed in accordance with the achieved efficiency. Tractor fuel and lubricants are distributed in the same way. Each team has a leader whose presence is required at the workplace every day. The team efficiency is measured by the volume of daily efficiency of two tractors.

#### 4. Teamwork factors – Čimbenici skupnoga rada

##### 4.1 Time analysis – Analiza vremena

Records were being made of the cutter S1 for 5,324.70 minutes, and of the cutter S2 for 5,309.67 minutes. The effective time of the cutter S1 accounts

for 42.93 % of total time consumption, and delay times for 57.07 %. The effective time of the cutter S2 is 35.95 %, and delay time 64.05 %. The cutter S1 requires 986.71 minutes or 1.59 minute per tree, i.e. 43.17 % of effective time for preparing the load, and the cutter S2 681.89 minutes or 1.35 minute per tree, i.e. 35.72 % of effective time.

For felling and processing 165.39 m<sup>3</sup> of wood, the cutter S1 consumed 13.82 min/m<sup>3</sup> of effective time, 18.38 min/m<sup>3</sup> of delay times or in total 32.21 min/m<sup>3</sup>. For felling and processing 140.76 m<sup>3</sup> of wood, the cutter S2 consumed 13.56 min/m<sup>3</sup> of effective time, 24.16 min/m<sup>3</sup> of delay times or in total 37.72 min/m<sup>3</sup>.

Records of the tractor E were being taken for 6,295.08 minutes, and of the tractor T for 6,008.75 minutes. The effective time of the tractor E is 51.46 %, and of the tractor T 59.00 %, being therefore higher by 7.54 %. Delay times are 48.54 % and 41.00%, respectively.

The effective time of the tractor E per unit is 21.64 min/m<sup>3</sup>, and of the tractor T 20.67 min/m<sup>3</sup>, which is by 4.5 % lower than the tractor E. Total time consumption per unit of the tractor E is 42.05 min/m<sup>3</sup>, and of the tractor T 35.04 minutes and hence by 7.01 min/m<sup>3</sup> lower. The average daily efficiency of the tractor E is 9.98 m<sup>3</sup>/day, and of the tractor T it is 11.43 m<sup>3</sup>/day. The tractor T skidded on average 1.45 m<sup>3</sup>/day more than the tractor E, which is by 12.7 % more.



**Figure 2** Cutter engaged in felling and processing

**Slika 2.** Sjekač pri sječi i izradbi stabla

During 13 days, the cutter-inspector consumed a total of 4,521.55 minutes, i.e. 347.81 min/day on average for final processing and inspecting. The effective time accounts for 20.69 % and delay times for 79.31 % of total time. The effective time for 2,012 pieces, i.e. 273.19 m<sup>3</sup> of inspected wood assortments, is 3.43 min/m<sup>3</sup>, delay times 13.13 min/m<sup>3</sup> and the total time 16.55 min/m<sup>3</sup> on average.

4.1.1 Allowance time – *Dodatno vrijeme*

Allowance time is made of parts of delay times necessary for executing the work order. Allowance time is determined in order to establish standard times and standard efficiencies, and it is added to the effective time in the form of the allowance time coefficient or in the form of an absolute value. Allowance time is modelled by the analysis of work delays. Allowance time factor of the cutter S1 is 1.55, of the cutter S2 it is 1.70, of the tractor E it is 1.29, of the tractor T 1.24, and of the cutter-inspector (CI), engaged in inspecting wood assortments at the landing, it is 1.67. High percentage of allowance time is the effect of low consumption of effective time, i.e. insufficient utilization of prescribed work time of 480 minutes. The team worked at the workplace 78.37 % of the prescribed work time.

4.2 Effective time of cutters engaged in felling and processing of wood – *Efektivno vrijeme sjekača pri sječi i izradbi stabala*

Statistical analysis was carried out on the basis of total time records related to the cutter S1. The effective

time of felling and processing was sorted out and its variability was investigated.

Multiple linear regression was applied, and the values of breast-height diameter, tree height and the pertaining effective time were taken as independent variables for each tree.

Based on distribution of the number of trees and value of the descriptive statistics, the software package selected the most favourable form for calculating mathematically the effective time of felling and processing performed by the cutter S1. Table 2 shows the indicators of regression and the parameters of the regression equation of effective time of the cutter S1.

The calculated effective time of the cutters S1 and S2; The equation:

$$Y_{S1} = -1.47393 + 0.13933 \cdot 20.5 + 0.04648 \cdot 15.0 = 2.08 \text{ (min)}, R = 0.74581563 \quad (1)$$

$$Y_{S2} = -0.603243 + 0.132254 \cdot 20.2 + 0.004016 \cdot 15.2 = 2.13 \text{ (min)}, R = 0.73573390 \quad (2),$$

of effective time per tree.

**Table 1** Descriptive statistics of basic distributions: breast-height diameter, tree height and effective time of felling and processing, cutter S1

**Tablica 1.** Opisna statistika temeljnih raspodjela: prsnog promjera, visine stabla te efektivnog vremena sječe i izradbe, sjekač S1

Variables Varijable	Descriptive Statistics (Spreadsheet2 in Workbook1.stw) - Opisna statistika				
	N. of trees, N Broj stabala,	Mean value Srednja vrijednost	Minimum Minimum	Maximum Maksimum	Std. dev. Standardna devijacija
Breast-height diameter, $d_{1.30}$ (cm) Prsni promjer, $d_{1.30}$ (cm)	375	20.533	9.000	42.000	6.549
Tree height, h (m) Visina stabla, h (m)	375	14.978	9.000	20.000	2.204
Effective time, (min) Efektivno vrijeme, (min)	375	2.083	0.240	7.900	1.325

**Table 2** Indicators of regression and parameters of regression equation of effective time of the cutter S1

**Tablica 2.** Pokazatelji regresije i parametri regresijske jednadžbe efektivnog vremena sjekača S1

N=375	Regression Summary for Dependent Var.:(Workbook1.stw) R=,74581563 R2=,55624095 Adjusted R2=,55385515 F(2,372)=233,15 p<0,0000 Std.Error of estimate:,88545					
	Beta	Std.Err. of Beta	B	Std.Err. of B	T (372)	p-level
Independent member Nezavisni član			-1.47393	0.334622	-4.40475	0.000014
Breast-height diameter, $d_{1.30}$ (cm) Prsni promjer, $d_{1.30}$ (cm)	0.688388	0.049605	0.13933	0.010040	13.87747	0.000000
Tree height, h (m) Visina stabla, h (m)	0.077299	0.049605	0.04648	0.029827	1.55830	0.120012

**4.3 Effective time of tractor cycle – Efektivno vrijeme turnusa traktora**

Tractor cycle is made of four cyclic operations. Two of these working operations are considered as variable time and two as fix time. The times of loaded and unloaded tractor travel belong to variable times, while the felling site tractor work and the roadside landing tractor work belong to the second group.

Fix time accounts for 19.11 min/cycle (E) and 19.65 min/cycle (T), respectively.

Due to a large number of data and results, this paper will only show as an example the method of calculating the time of loaded Ecotrac (E) tractor travel and for all other variable times only the calculation equation will be showed.

**Travel time of loaded tractors on skid trail and felling site**

Based on distribution of the load volume, skidding distance, road slope and number of load pieces as well as on the values of the descriptive statistics, the software package selected the most favourable form for the mathematical calculation of travel time of the loaded Ecotrac tractor (E) on skid trail and felling site.

Table 3 shows the values of multiple regression used for obtaining the equation for calculating time consumption ( $y_{O-E}$ ) of the loaded tractor E on skid trail and felling site, which is as follows:

$$Y_{O-E} = 1.932822 - 0.413439 \cdot q + 0.006290 \cdot l - 0.043047 \cdot p + 0.014397 \cdot n \quad (3)$$

For the researched sample of records, where the average load volume  $q = 1.124 \text{ m}^3$ , the average skidding distance  $l = 212.3 \text{ m}$ , the average terrain slope  $p = 14.4 \%$  and the average number of load pieces  $n = 7.6$ , the time of the loaded tractor E is 2.291 minutes.

Mathematical form for calculating time consumption ( $y_{O-T}$ ) of the loaded Torpedo tractor (T) on skid trail and felling site is as follows:

$$Y_{O-T} = 0.0874076 - 0.174104 \cdot q + 0.007700 \cdot l - 0.021937 \cdot p + 0.101793 \cdot n \quad (4)$$

where the average load volume  $q = 1.211 \text{ m}^3$ , the mean skidding distance  $l = 215.3 \text{ m}$ , the average terrain slope  $p = 15.9 \%$  and the average number of load pieces  $n = 8.2$ , and the time of the loaded tractor T is 2.81 minutes. The coefficient of the multiple correlation is  $R = 0.80131674$ .

**Travel time of unloaded tractors on skid trail and felling site**

The equation for the calculation of travel time of unloaded Ecotrac tractor (E) on skid trail and felling site is as follows:

$$Y_{N-E} = 1.001102 + 0.07935 \cdot l - 0.037377 \cdot p \quad (5)$$

In the researched sample of records, the mean skidding  $l = 213.7 \text{ m}$  and the average road slope  $p = 14.5 \%$ . Travel time of unloaded tractor E was calculated by use of the above equation No. 5 and it is namely 2.156 minutes. The coefficient of the multiple correlation  $R = 0.91443280$  shows complete correlation.

**Table 3** Indicators of regression and parameters of the regression equation of time of loaded Ecotrac tractor (E) on skid trail and felling site

**Tablica 3.** Pokazatelji regresije i parametri regresijske jednadžbe vremena vožnje opterećenog traktora Ecotrac (E) po vlaci i sječini

N=127	Regression Summary for Dependent Variable: Var3 R=,78362356 R2=,61406589 Adjusted R2=,60141231 F(4,122)=48,529 p<0,0000 Std.Error of estimate:,71905					
	Beta	Std.Err.	B	Std.Err.	t(122)	p-level
Independent member, $b_0$ Nezavisni član, $b_0$			1.932822	0.466254	4.14543	0.000063
Load volume, $q \text{ (m}^3\text{)}$ Obujam tovara, $q \text{ (m}^3\text{)}$	-0.092057	0.057938	-0.413439	0.260206	-1.58889	0.114673
Distance, $l \text{ (m)}$ Udaljenost privlačenja, $l \text{ (m)}$	0.795491	0.062225	0.006290	0.000492	12.78414	0.000000
Road slope, $p \text{ (%)}$ Nagib puta, $p \text{ (%)}$	-0.139574	0.060734	-0.043047	0.018731	-2.29812	0.023258
Number of pieces, $n \text{ (pcs)}$ Broj komada, $n \text{ (kom)}$	0.020859	0.056672	0.014397	0.039117	0.36806	0.713467

The equation for calculating time consumption of the unloaded Torpedo tractor (T) on skid trail and felling site is as follows:

$$Y_{N-T} = 0.726786 + 0.008099 \cdot l - 0.010348 \cdot p \quad (6)$$

For the researched sample of records, the mean skidding distance  $l = 216.8$  m and the average terrain slope  $p = 15.9$  %. Travel time of the unloaded tractor T was calculated by inserting the mean skidding distance and the average terrain slope in the equation No. 6 and it is 2.32 minutes. The coefficient of the multiple correlation is  $R = 0.89206835$  and it shows very strong correlation.

#### Times of loaded tractors at roadside landing

Travel time of loaded tractor on the roadside landing was observed in dependence on the load volume, skidding distance and number of load pieces. Skidding was carried out on macadam road. The mathematical form for calculating time consumption of the loaded tractor  $E_o$  at roadside landing is as follows:

$$Y_{E_o} = 1.145363 - 0.014330 \cdot q + 0.009319 \cdot l - 0.003870 \cdot n \quad (7)$$

With the average load volume  $q = 1.117$  m<sup>3</sup>, the mean skidding distance and the average number of load pieces  $n = 7.6$  in accordance with the equation 7, the time of the loaded tractor  $E_o$  is 0.417 minutes.

The equation for calculating time consumption of the loaded Torpedo tractor ( $T_o$ ) on the roadside landing is as follows:

$$Y_{T_o} = 0.253301 + 0.054996 \cdot q + 0.008769 \cdot l - 0.004396 \cdot n \quad (8)$$

With the average load volume  $q = 1.195$  m<sup>3</sup>, the mean skidding distance  $l = 44.4$  m and the average number of pieces in the tractor load,  $n = 8.0$ , the travel time of the loaded tractor  $T_o$  on the roadside landing is 0.673 minutes.

#### Times of unloaded tractors at roadside landing

Travel times of unloaded tractors were only investigated with a single independent variable and namely with the travel distance. The general form of the equation is as follows:

$$Y_{E_n} = 0.06336 + 0.006298 \cdot l \quad (9)$$

Travel time of the unloaded tractor  $E_n$  at roadside landing was calculated for the average travel distance  $l = 25.3$  m, by use of the equation 9 and it is 0.265 minutes.

The mathematical form for the calculation of time consumption of the unloaded tractor  $T_n$  at roadside landing is as follows:

$$Y_{T_n} = 0.198731 + 0.005417 \cdot l \quad (10).$$

Travel time of unloaded tractor  $T_n$  of 0.440 minutes was calculated by inserting the mean travel distance,  $l = 44.5$  m in the equation 10.

#### 4.4 Standard time of the group

##### – Norma vremena skupine

Standard time of the group is calculated as the sum of individual standard times of each member of the group, i.e. cutter and tractor working together as well cutter-inspector engaged in inspecting wood assortments. Standard time of a group of workers per product unit is expressed by the mathematical pattern:

$$NV_{SK} = NV_S + NV_t + NVp_S \dots \text{ (min/m}^3\text{)} \quad (11),$$

where  $NV_{SK}$  – is the standard time of the team,  $NV_S$  – is the standard time of the cutter,  $NV_t$  – is the standard time of the tractor,  $NVp_S$  – is the standard time of the cutter-inspector.

If all parameters from the mathematical patterns for each member of the group are inserted in the mathematical pattern 11, then the following pattern is obtained:

$$NV_{SK} = \left[ \frac{1 \left( (b_0 + b_1 \cdot d_{1,30} + b_2 \cdot h) + I_f \right) \cdot k_{ds}}{q_n} \right] + \left[ \frac{2 \left( (t_{nv} + t_{ov} + t_{nps} + t_{ops}) + (t_u + t_i) \right) \cdot k_{dt}}{q_n} \right] + \left( (b_0 + b_1 \cdot n_1 + b_2 \cdot q_1) \cdot k_{dps} \right) \dots \text{ (min/m}^3\text{)} \quad (11a)$$

where:  $b_0, b_1, b_2$  – are the parameters of the linear mathematical regression model (<sup>1 and 2</sup> the pertaining parameter of the mathematical model is used for each member of the team),  $d_{1,30}$  – is the breast-height diameter of the tree (cm),  $h$  – is the tree height (m),  $I_f$  – is the time consumed by cutter for load hooking (min),  $k_{ds}$  – is the cutter's allowance time factor,  $q_n$  – is the net tree volume (m<sup>3</sup>),  $t_{nv}$  – is the travel time of the unloaded tractor on skid trail and felling site (min),  $t_{ov}$  – is the travel time of the loaded tractor on skid trail and felling site (min),  $t_{nps}$  – is the travel time of unloaded tractor at roadside landing (min),  $t_{ops}$  – is the travel time of loaded tractor at roadside landing (min),  $t_u$  – is the tractor work time at felling site (min),  $t_i$  – is the tractor work time at roadside landing (min),  $k_{dt}$  – is the allowance time factor of the

**Table 4** Optimum team size in view of minimum standard time

**Tablica 4.** Optimalna veličina skupine s obzirom na najmanju normu vremena

Skidding distance, m <i>Udaljenost privlačenja, m</i>	Cutter <i>Sjekač</i>	Tractor <i>Traktor</i>	Cutter-inspector <i>Sjekač-pruzimač</i>	Cutter <i>Sjekač</i>	Tractor <i>Traktor</i>	Cutter-inspector <i>Sjekač-pruzimač</i>	Optimum team size <i>Optimalna veličina skupine</i>
	Standard time, min/m <sup>3</sup> <i>Norma vremena, min/m<sup>3</sup></i>			Number of team members <i>Broj članova skupine</i>			Number of workers <i>Broj radnika</i>
150	25.92	25.06	4.93	5.25	5.08	1.00	11.33
250	25.92	26.69	4.93	5.25	5.41	1.00	11.66
350	25.92	28.32	4.93	5.25	5.74	1.00	11.99
450	25.92	29.95	4.93	5.25	6.07	1.00	12.32
550	25.92	31.58	4.93	5.25	6.40	1.00	12.65
650	25.92	33.20	4.93	5.25	6.73	1.00	12.98

tractor,  $q_t$  – is the average load volume of the tractor (m<sup>3</sup>),  $n_1$  – is the average number of pieces in a working operation of the cutter-inspector engaged in inspecting wood assortments (pcs),  $q_1$  – is the average wood volume in a working operation of the cutter-inspector engaged in inspecting wood assortments (m<sup>3</sup>),  $k_{dps}$  – is the allowance time factor of the cutter-inspector engaged in inspecting wood assortments.

Optimum size of the work team is calculated based on the minimum standard time of an individual member and it is taken as the basic unit. The average standard time of the cutter, tractor and cutter-inspector is calculated in the team. The average standard time for two cutters is 25.92 min/m<sup>3</sup>, and the average standard time for two tractors ranges between 25.06 min/m<sup>3</sup> (150 m) and 33.20 min/m<sup>3</sup> (650 m).

Standard time of the cutter-inspector is 4.93 min/m<sup>3</sup> and it is taken as the basic unit. If there is a cutter-inspector at the roadside landing, then 5.25 cut-

ters and 5.08 (150 m) to 6.73 (650 m) tractors are required for achieving optimum work effects of the team. The optimum team size changes depending on the tractor skidding distance and it ranges between 11.33 members (150 m) and 12.98 members (Table 4). The team organized in this way can produce 97.29 m<sup>3</sup>/day of wood assortments.

**4.5 Team daily efficiency – Dnevni učinak skupine**

The team daily efficiency is calculated as the sum of daily efficiency of two tractors in accordance with the skidding distance.

The daily efficiency of each tractor is calculated as the ratio between the prescribed work time of 480 minutes and standard time of the tractor.

The work team achieves the daily efficiency proportionally to the volume of wood skidded to the roadside landing. The efficiency ranging between 38.39 m<sup>3</sup>/day (150 m) and 28.95 m<sup>3</sup>/day (650 m) (Table 5) can be achieved by a team where skidding is performed by two tractors.

**Table 5** Daily efficiency (m<sup>3</sup>/day) of the team and by member

**Tablica 5.** Dnevni učinak (m<sup>3</sup>/dan) skupine radnika i prosječno po članu

Team tractors <i>Traktori skupine</i>	Tractor skidding distance. m <i>Udaljenost privlačenja traktorom, m</i>					
	150	250	350	450	550	650
	Team daily efficiency. m <sup>3</sup> /day <i>Dnevni učinak skupine, m<sup>3</sup>/dan</i>					
E + T	38.39	36.04	33.96	32.10	30.44	28.95
Number of team members <i>Broj članova skupine</i>	Daily efficiency per team member. m <sup>3</sup> /day <i>Dnevni učinak po članu skupine, m<sup>3</sup>/dan</i>					
5	7.68	7.21	6.79	6.42	6.09	5.79

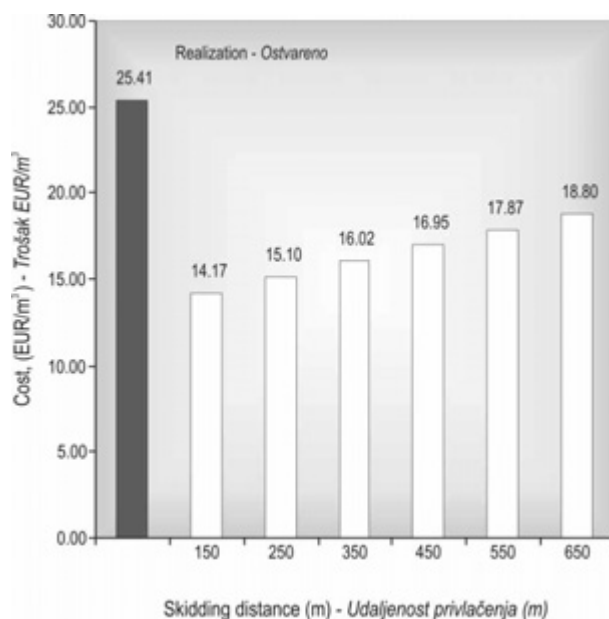


**4.6 Calculations and costs of teamwork – Kalkulacije i troškovi rada skupina**

The calculation for a cutter engaged in felling, processing and inspecting wood assortments was made based on 180 working hours per year. Total costs of the cutter with chain saw are EUR 73.35 per day.

For an adapted farming tractor – Torpedo TD 75 A, total costs of the machine, driver and hooker are EUR 154.16 per day. Total costs of the Ecotrac V 1033 skidder are EUR 169.89 per day. Daily costs of the team are EUR 544.10 per day or an average of EUR 108.82 a day per member. The average achieved daily efficiency per team member is 4.28 m<sup>3</sup>/day.

Figure 3 shows the ratio between the realized and modelled costs per product unit. The costs of wood production get higher with the increase of skidding distance. The costs range between EUR 14.17 per m<sup>3</sup> (150 m) and EUR 18.80 per m<sup>3</sup> (650 m), and in relation to the realized costs of EUR 25.41 per m<sup>3</sup> it is lower by 44.2 % (150 m) to 26.0 % (650 m).



**Figure 3** Calculated costs per product unit (EUR/m<sup>3</sup>) in accordance with the achieved and modelled daily efficiency of the team

**Slika 3.** Prikaz izračunanog troška po jedinici proizvoda (EUR/m<sup>3</sup>) prema ostvarenom i oblikovanom dnevnom učinku skupine radnika

**5. Conclusions – Zaključci**

This paper shows the characteristics and factors as well as the efficiency of a work team. On the basis of the standard time, dynamic models have been established of group. In this case, the minimum stan-

dard time (of the cutter-inspector) has been taken as the basic unit and the number of other members of the team has been determined on its basis.

The average standard time for two cutters is 25.92 min/m<sup>3</sup>, and the average standard time for two tractors ranges between 25.06 min/m<sup>3</sup> (150 m) and 33.20 min/m<sup>3</sup> (650 m). Standard time of the cutter-inspector is 4.93 min/m<sup>3</sup> and it has been taken as the basic unit. If there is a cutter-inspector at the roadside landing, then 5.25 cutters and 5.08 (150 m) to 6.73 (650 m) tractors are required for achieving optimum work effects of the team. The optimum team size changes in accordance with the tractor skidding distance and it ranges between 11.33 members (150 m) and 12.98 members. The team organized in this way can produce 97.29 m<sup>3</sup>/day of wood assortments.

Daily efficiency per team member decreases with the increase of the skidding distance and it ranges between 7.68 m<sup>3</sup>/day (150 m) and 5.79 m<sup>3</sup>/day (650 m) and consequently it is by 79.3 % (150 m) to 35.2 % (650 m) higher than the achieved daily efficiency of 4.28 m<sup>3</sup>/day.

On the basis of the modelled team daily efficiency, the costs range between EUR 14.17 per m<sup>3</sup> (150 m) and EUR 18.80 per m<sup>3</sup> (650 m), and hence they are by 44.2 % (150 m) to 26.0 % (650 m) lower than the realized costs of EUR 25.41 per m<sup>3</sup>.

Teamwork is a higher form of work organization. It has been accepted by the Croatian forestry and it brought encouraging progress compared to individual work. The researched factors are a good ground for developing dynamic optimisation of the workers team and based on them better utilization of work time, machines and human resources can be achieved as well as higher productivity at lower production costs.

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### Sažetak

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## Matematički modeli optimizacije skupine radnika pri pridobivanju drva

U radu je proučavana proizvodnost jedne skupine koju čini pet radnika (dva sjekača, dva traktorista i jedan sjekač-preuzimač) te poslovođa. Skupina je opremljena s dva traktora i tri motorne pile. Istraživanje je provedeno na području GJ Južna Krndija Kutjevačka, na nadmorskoj visini od 550 m do 750 m u bukovoj sastojini u dobi od 55 godina. Na temelju norme vremena pojedinih članova postavljen je dinamički model skupine. U ovom je slučaju uzeta najmanja norma vremena (sjekača-preuzimača) te je prema njoj određen broj ostalih članova skupine.

Norma je vremena izračunana na temelju matematičkoga modela multiple linearne regresije efektivnoga vremena svakoga člana u skupini. Prosječna norma vremena u skupini za dva sjekača iznosi 25,92 min/m<sup>3</sup>, a prosječna norma vremena za dva traktora kreće se od 25,06 min/m<sup>3</sup> (150 m) do 33,20 min/m<sup>3</sup> (650 m). Norma vremena sjekača-preuzimača iznosi 4,93 min/m<sup>3</sup> i uzeta je kao osnovna jedinica. Ako se jedan sjekač-preuzimač nalazi na pomoćnom stovarištu, tada je za optimalan rad skupine potrebno 5,25 sjekača i 5,08 (150 m) do 6,73 (650 m) traktora. Optimalna se veličina skupine mijenja u odnosu na udaljenost privlačenja traktorom, a kreće se od 11,33 člana (150 m) do 12,98 članova (650 m). Optimalno organizirana skupina može proizvesti 97,29 m<sup>3</sup>/dan drvnih sortimenata.

Dnevni je učinak izračunan po članu skupine, a kreće se od 7,68 m<sup>3</sup>/dan (150 m) do 5,79 m<sup>3</sup>/dan (650 m) te je za 79,3 % (150 m) do 35,2 % (650 m) veći u odnosu na ostvareni dnevni učinak od 4,28 m<sup>3</sup>/dan po članu.

Na temelju oblikovanoga dnevnoga učinaka trošak se kreće od 14,17 EUR/m<sup>3</sup> (150 m) do 18,80 EUR/m<sup>3</sup> (650 m) te je u odnosu na ostvareni trošak od 25,41 EUR/m<sup>3</sup> manji za 44,2 % (150 m) do 26,0 % (650 m).

Skupni je rad viši oblik organizacije rada. U hrvatskom je šumarstvu prihvaćen i donio je napredak u odnosu na pojedinačni rad. Proučavani su čimbenici osnova dinamičke optimizacije skupine radnika na temelju kojih bi se bolje koristilo radno vrijeme, strojevi i ljudski resursi te ostvarila veća proizvodnja uz niže troškove proizvodnje.

Ključne riječi: skupni rad, prorede, studij vremena, čimbenici, proizvodnost, troškovi

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