Different Evaluations of Motor-Manual Wood Harvesting Processes on the Basis of Conjoint Analysis

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Abstract – Nacrtak

The aim of this paper was the conjoint analysis of wood harvesting processes performed using motor-manual methods. Distribution of the characteristics consisted of nine features, based on the results of multidimensional scaling, which were aggregated into two groups: ergonomic (5) and technological (4). The scope of research was limited to four wood harvesting processes. The cuts were carried out in selected 100-year old spruce stands on the steep terrain (13–30°) in the Beskid Żywiecki Mts. The value of utility function was defined on the basis of normalized eigenvectors for the comparison matrix. The weight of the features was defined on the basis of the Tytyk (2001) simplified method of rank aggregation by preserving the maximum values (for ergonomic issues), the Satty method of subjective assessment and the partially determined stochastic factors (for technological issues). The results of the calculations indicate the occurrence of dominant preferences within two groups of factors and their mutual polarization. The results of the total evaluation indicate disappearance of the strong dominance of alternatives.

Key words: Conjoint Analysis, ergonomics, forestry, wood utilization

1. Introduction – *Uvod*

The research concept and methodology of *Conjoint Analysis* (*C.A.*) method was derived from conjoint measurements executed in psychology and constitutes a mathematical model (Kuhfeld 2005), where statistic methods are used to set estimation error easily. The theoretical background for *C.A.* method was developed by R.D. Luce (psychologist and mathematician) and J.W. Tukey (statistician). In the seventies it became one of the main tools for measuring customer preferences and simulation of consumer behavior. It uses the utility theory with the functioning notion of a preference as a relation between multidimensional objects. In order to measure the structure of a preference the following formal model is constructed:

$$U_i = f(u_{1(i)},\dots, u_{m(i)}) \tag{1}$$

Where:

U_i defines total utility of i-th profile,

f preference function,

u_j location of i-th profile in regard of j-th variable.

The main area of application of *C.A.* method covers preference analysis, market segmentation and simulation analyses. Research procedure consists of a number of stages comprising:

⇒ Specification of a research problem,

⇒ Selection of a dependence model for variables and preferences,

⇒ Generating profile sets,

⇒ Defining the measurement scale for dependent variables,

⇒ Selection of a parameter estimation method,

⇒ Reliability assessment and interpretation of the results.

Basically, the process of analysis consists in searching for partial utility by decomposition of a known final utility. The main objective is a monotonic transformation of an explanatory variable to the attribute sum equation – independent explanatory variables. The effect of such action is the objectification of decisions that are made by qualitative and quantitative approach to the possessed information about variables and interdependencies (Forman and Selly 2001). The concept presented here is used both in marketing and finance as well as in natural environment management and technology analysis and optimization (Stampfer and Lexer 2001; Kangas et al. 2002; Bodelschwingh et al. 2005; Heinimann 2007).

2. Aim and scope of the paper – *Cilj i svrha rada*

The aim of this paper was the conjoint analysis of work processes based on nine selected ergonomic and technological aspects. The scope of the research concerned four wood harvesting processes performed by petrol chainsaw operators (30–40 years old) who periodically carried out the following tasks:

⇒ S1 – felling of trees,

⇒ S2 – debranching,

⇒ S3 – wood assortments cross-cutting at the temporary depot,

⇒ S4 – wood stacking and sorting.

The cuts were carried out in selected 100-year old spruce stands on the steep terrain (13–30°) in the Beskid Żywiecki Mts.

3. Materials and methods – *Materijal i metode*

For the purpose of realizing the research assumption adopted in this study, a system of two experimental factors was established, which includes work processes (S1–S4) and a group of parameters:

⇒ Ergonomic:
- ✓ noise level of daily exposure – LEX8h, dB(A);
- ✓ equivalent value of mechanical vibration – aweq, ms^{-2},
- ✓ daily concentration of carbon monoxide – Cw, mgm^{-3},
- ✓ Lundqvist burden index of musculoskeletal system – Lunq,
- ✓ energy expenditure for working shift – WE8h, kJ.

⇒ technological:
- ✓ relative part on effective time in operating time – K02,
- ✓ relative part on effective time in overall working shift time – K07,
- ✓ efficiency in operating time – W02, m^3/h,
- ✓ working time efficiency – W07, m^3/h.

The experiment covered a balanced system with nine replications. The value of the daily noise exposure level, the equivalent vibration level and concentration of carbon monoxide were determined with the use of direct (dosimetric) methods. Assessment of the burden on the musculoskeletal system was carried out by using the OWAS method (Karhu et al. 1986), separately for different technological operations. A total result was obtained by calculation of Lundqvist burden index, which accounts for the percent share (pi) of distinguished categories of work processes (*i*=1–4). The first number denotes to which of the four categories of work processes it belongs (Stampfer 1996).

Work energy expenditure was generally calculated using a simplified Lehman method. However, the correctness of the adopted values for unit expenditure was tested by performing a comparative analysis of the results of pulmonary function measurement and the table values found in many studies (Lehmann 1966, Ronay Slama 1989, Löffler 1990, Lipoglavsek 1997, Sowa et al. 2006). The values of technological indicators were the final result of structural analysis of the work-day. For the purpose of enabling comparison of variables, the values were converted to a time-frame of 480 minutes.

The variables obtained underwent a similarity analysis applying *Multi Dimensional Scaling* (*MDS*). The number of dimensions constituted a basis for the identification of a group of descriptive variables.

The variables obtained are characterized by different ranges and measurement scales resulting from specific features examined, therefore the data have been subjected to standardization using quotient transformations. In this way relative values were obtained from a closed interval [0, 1], where 0 denotes the smallest and 1 the biggest preference. Final utility was calculated using additive model:

$$U_i = \sum_{j=1}^{m} w_j \times c_{ij} \qquad (2)$$

Where:

U_i is general alternative utility *i*,

c_{ij} alternative value and taking into account *j* alternative,

w_j weight of *j* criterion.

The adopted method of feature aggregation is analogous to the *Analytic Hierarchy Process* (*AHP*) method suggested by Satty (2000). Therefore, it was adopted that the weights of individual attributes constitute normalized values, right eigenvector (w) defined for the highest own value (λ_{max}) of comparison matrix (A):

$$A \times w = \lambda \times w; \sum_{j=1}^{n} w_j = 1 \qquad (3)$$

Where:

$A = (a_{ij})$

$a_{ji} = 1/a_{ij}$

The domination degree of *i* over *j* was defined according to ranks suggested by Satty, where: 1 – denotes equal significance, 3 – moderate advantage, 5 – strong domination, 7 – very strong domination, 9 – extremely strong domination.

In case of ergonomic criteria, the weights were defined according to a schema suggested by Tytyk (2001). This method imposes the need to carry out the assessment of five features of ergonomic factors taking into account features such as pathogenicity, cumulativity, inclination towards synergy, aggressiveness and destructiveness towards the environment. Each of them is given a partial rank (slight – 0.1, low – 0.3, moderate – 0.5, high – 0.7, very high – 0.9). However, the final value of the rank is obtained after the aggregation of ordered partial values $x_i > x_{i+1}$ according to the equation:

$$r_k = \sum 10^{i-1} \times x_i \tag{4}$$

Preserving extreme values is a characteristic feature of this method. This attitude is explained by Tytyk who explains this by the fact that it is difficult to expect that strong influence of one feature (e.g. pathogenicity) will weaken by weaker influence of the other feature (e.g. cumulativity).

The correctness of weight estimation was reviewed using the criterion of Satty (2000), which says that the estimation of values is considered stable when the consistency ratio (*CR*) is smaller than 0.1:

$$P_{\mathrm{e\times kor}} = \frac{\lambda_{\max} - n}{n-1} \tag{5}$$

$$CR = \frac{CI}{RI} \tag{6}$$

Where:

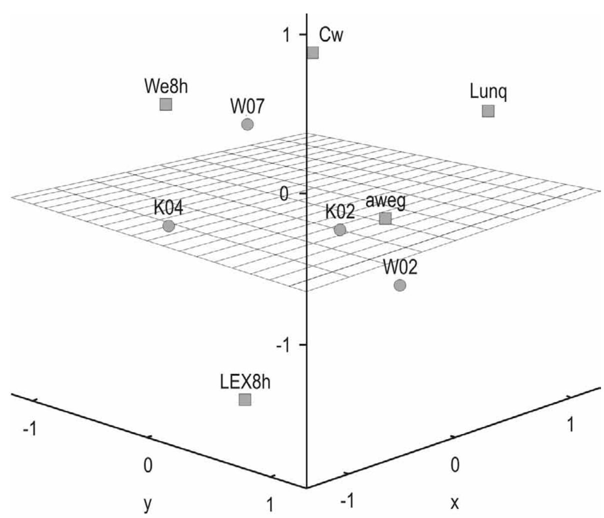
CI consistency index,

RI random index for *n*-dimensional matrix.

4. Results and Discussion – *Rezultati s raspravom*

In order to define the variable structure, a similarity analysis was carried out using Multi Dimensional Scaling (*MDS*). In the course of the analysis a significantly smaller number of dimensions were identified in comparison to a number of descriptive variables and the results obtained enabled the picture of similarity (Fig. 1).

The map of variable similarities obtained indicates central location of technological indicators surrounded by dispersed ergonomic elements. The emergence of two dimensions that can be used to describe the analyzed work processes proves the correctness of the adopted variable groups (Leszczyñski and



Workplaces *Radna mjesta*	Dimension 1 *Veličina 1*	Dimension 2 *Veličina 2*
S1	-0.0311	-0.6389
S2	-0.4731	0.9385
S3	1.3011	0.0883
S4	-0.7969	-0.3880

Fig. 1 Map of variable similarity as the result of Multi Dimensional Scaling
Slika 1. *Prikaz sličnosti varijabli na osnovi multidimenzionalnoga skaliranja*

Jałowska 2009). Similar values of coordinates of work processes S1 and S4 prove their similarity.

The descriptive statistics analysis (Fig. 2) of ergonomic aspects suggests that the largest burden on

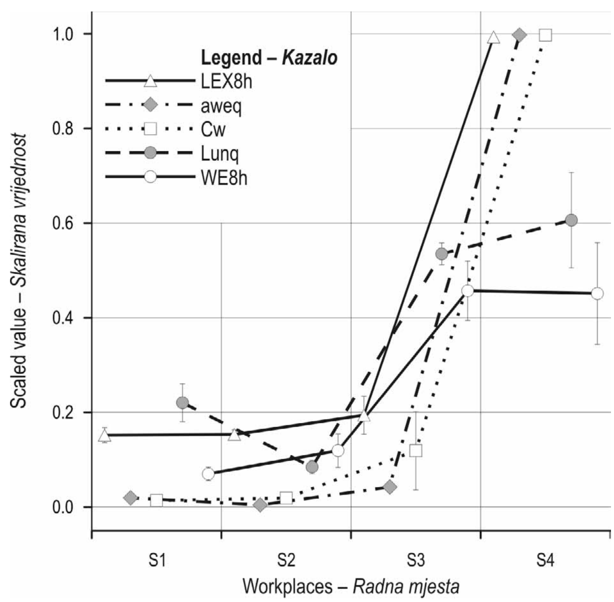


Fig. 2 Mean and standard error of scaled value of ergonomics attributes
Slika 2. *Srednja vrijednost i standardna pogreška skaliranih vrijednosti ergonomskih pokazatelja*

Table 1 Normalized eigenvector for paired comparison

Tablica 1. *Normalizirani svojstveni vektori za usporedbu u parovima*

Factor – *Čimbenik*	Attribute *Pokazatelj*	Workplace – *Radno mjesto*				*CR* *Konzistentnost*
		S1	S2	S3	S4	
Ergonomics – *Ergonomski*	LEX8h, dB(A)	0.2333	0.2340	0.2363	0.2964	0.000
	Aweq, ms^{-2}	0.0217	0.0160	0.0258	0.9365	0.000
	Cw, mgm^{-3}	0.0386	0.0519	0.0512	0.8584	0.000
	Lunq	0.2254	0.2069	0.2846	0.2831	0.000
	WE8h, kJ	0.1964	0.2101	0.3035	0.2900	0.000
Technological – *Tehnološki*	K02	0.1571	0.2821	0.2884	0.2725	0.000
	K07	0.2084	0.3629	0.2383	0.1905	0.000
	W02, m^3/h	0.3915	0.2233	0.1805	0.2047	0.000
	W07, m^3/h	0.4595	0.2757	0.1278	0.1370	0.000

musculoskeletal system of the worker occurs in the work process S2.

The physical factors (mechanical vibration and noise) in the work processes S1, S2 and S3 stay at a similar unfavorable level. Technological factor values (Fig. 3) are characterized by larger degree of diversity.

The highest level of efficiency during the working time (W07) was reported on the work process S1 together with the lowest indicator of operating time-use (K02).

In order to set the preference values for individual factors, mutual comparison matrix *A* was developed, characterized by paired consistency $a_{ij} = a_{ji}^{-1}$ and global consistency $a_{ik} \times a_{kj} = a_{ij}$, for $i,j,k \in \{1\dots n\}$. Using the Schur's theorem, which says that the sum of module squares of eigenvalues is limited from the top by the Euclidean norm square, a matrix spectrum was set $Sp(A) = \{\lambda_1, \lambda_2, \lambda_3, \dots\}$. Solving the matrix eigenequation, a normalized eigenvector was set for the highest eigenvalues of j-th priority (aspect), which as suggested by Satty (2000) defines the value of preference.

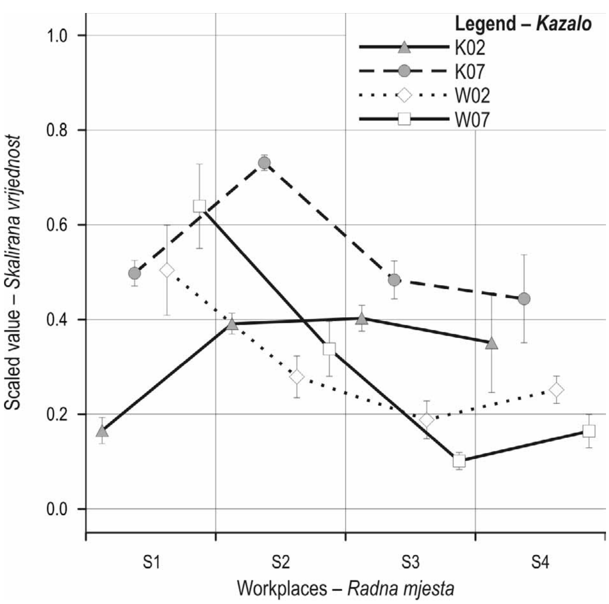


Fig. 3 Mean and standard error of scaled value of technological attributes

Slika 3. *Srednja vrijednost i standardna pogreška skaliranih vrijednosti tehnoloških pokazatelja*

The results obtained (Table 1) suggest similar preference values for LEX8h (0.23–0.29) factor and the domination of the work process S4 because of high value of aweq factor.

The analysis of technological aspects, however, indicates preference for the work process S1 (W07=0.46). The calculated value of *CR* (*Consistency Ratio*) confirms the stability of estimated parameters.

The next step of the analysis was to define weights for individual ergonomic and technological aspects. Partial ranks for ergonomic criteria were calculated using the described Tytyk's method (2001), and individual stages were presented in Table 2.

Satty's method of ranks was used (2000) for the assessment of technological aspects. The value of dominance of individual features was established in a group of five experts. The assessment values obtained enabled the definition of values of partial weights: K02=0.1250, K07=0.2083, W02=0.2917, W07=0.3750. Taking into consideration the results obtained, the value of partial utilities was calculated (Table 3).

The analysis of Table 3 shows strong polarity of partial utility for the distinguished ergonomic and technological aspects. The highest value due to ergonomic factors can be found in the work process S4

Table 2 Calculation of partial range for ergonomic issues

Tablica 2. *Izračun djelomičnoga raspona ergonomskih pokazatelja*

	LEX8h, dB(A)	aweq, ms^{-2}	Cw, mgm^{-3}	Lunq	WE8h, kJ
Pathogenity – *Patogenost*	0.9	0.9	0.9	0.7	0.7
Cumulativity – *Kumulativnost*	0.7	0.9	0.9	0.5	0.5
Tendency to synergy – *Težnja sinergiji*	0.7	0.7	0.9	0.3	0.3
Aggressiveness to Environment – *Agresivnost prema okolišu*	0.3	0.5	0.7	0.1	0.1
Destructiveness to man – *Destruktivnost za čovjeka*	0.3	0.3	0.7	0.1	0.1
Rang – *Rang*	0.97733	0.99753	0.99977	0.75311	0.75310
Normalized rang – *Normalizirani rang*	0.21811	0.22262	0.22312	0.16807	0.16807

Table 3 Partial utility

Tablica 3. *Djelomična korisnost*

Workplace *Radno mjesto*	Ergonomics *Ergonomska*	Technological *Tehnološka*
S1	0.1352	0.3495
S2	0.1362	0.2794
S3	0.1676	0.1862
S4	0.5610	0.1849

(0.561) with the lowest value of technological indicators (0.184). For the work process S1 the highest utilities were determined due to technological aspects (0.349) with the lowest value of ergonomic indicators (0.135).

The next step of the analysis was to define weights for the group of ergonomic and technological criteria. The process of their determination consisted in defining the value of dominance by a group of experts. It was made of five people with higher education diploma who were professionally connected with designing and analysis of wood harvesting technology. The values of assessments were obtained by providing independent answers, i.e. excluding the knowledge of the opinion of the others. The values obtained are characterized by divergence of work process.

In order to handle an unknown random error, the weight estimator of the ergonomic criteria was determined by means of simulation tests that were carried out. The experiment covered 15 tests which covered the process of drawing 1000 elements. The values obtained in this way enabled setting of the target estimators: *Mean* = 0.2495, *Standard Deviation* = 0.1135.

Since the density function of ergonomic factor weights was unknown, there was an attempt to determine it using non-parametric methods. The aim of such action was to extend the values of the obtained discrete variables to the whole area of variable arguments and to smooth the histogram facilitating the interpretation of the results. Therefore, at this analysis stage, estimation of the probability density was carried out setting the kernel estimator Parzen (1961):

$$f_{\mathrm{n}}(x) = \frac{1}{n \times h_n} \sum_{i=1}^{n} K\left(\frac{x - Xi}{h_n}\right) \qquad (7)$$

Where:

K estimation kernel,

h_{n} smoothing coefficient,

x grid points,

X_{i} value of variable realization.

Probability distribution was established using Gauss's kernel for the range width adopted according to *Silverman's* criterion. The scope of estimation was limited to the interval [0,1]. In order to verify the correctness of calculations, a relative Mean Squared Error of function estimator was developed (relative Mean Squared Error, $MSE_{\%}$) from the equation:

$$MSE_{\%} = \frac{E\int (f_n(x) - (x))^2\, dx}{\int f^2(x) dx} \times 100\ \% \qquad (8)$$

The value of $MSE_{\%}$ amounted to 13.6%, which indicates the permissible estimation error, and hence the correctness of the achieved density. On the basis of the calculations, the estimated density was drawn as well (Fig. 4).

The density function presented in Fig. 4 implies the occurrence of double modal distribution and at the same time the isolation of two groups of experts who represent different work processes. Cutting the density function at local minimum x=0.4, the following distribution was obtained with the following parameters:

$$Mean_1 = 0.1929,\ StandardDeviation_1 = 0.0945,$$

$$Mean_2 = 0.5839,\ StandardDeviation_2 = 0.1650.$$

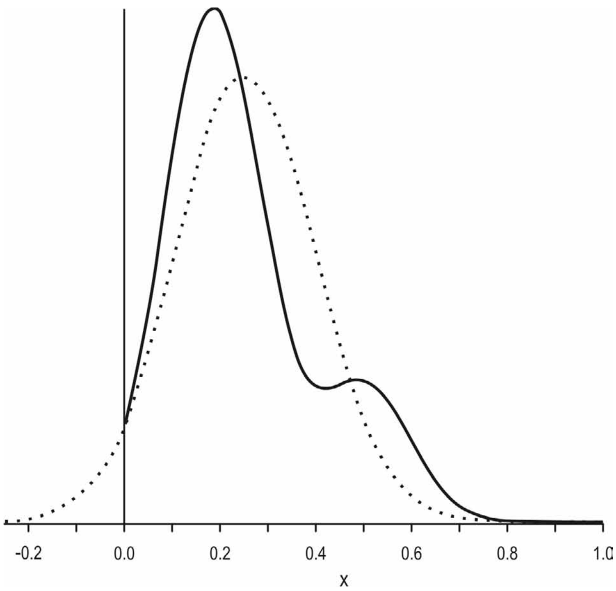


Fig. 4 Results of kernel smoothing estimations of density function
Slika 4. *Rezultati izjednačivanja procjena funkcije gustoće vjerojatnosti*

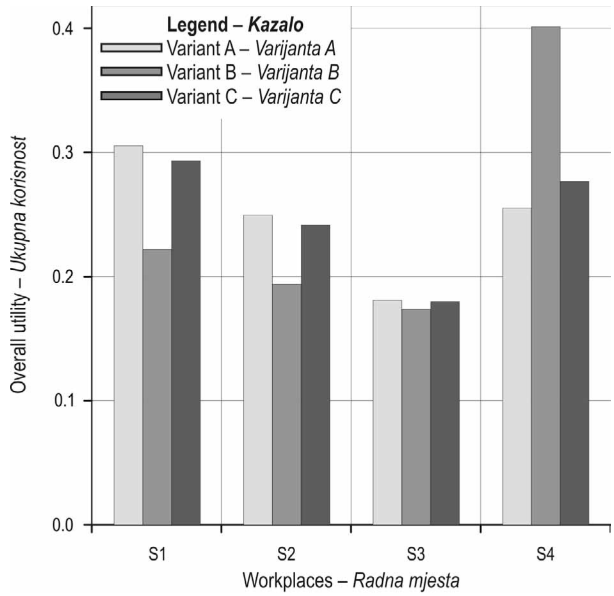


Fig. 5 Overall utility of workspaces
Slika 5. *Ukupna korisnost radnih mjesta*

Table 4 Relative weight for groups of attributes
Tablica 4. *Relativne težine za grupe pokazatelja*

Variant *Inačica*	Ergonomic, w_1 *Ergonomski,* w_1	Technological, w_2 *Tehnološki,* w_2
A	0.1929	0.8071
B	0.5839	0.4161
C	0.2495	0.7505

The calculations of ergonomic factor weights imply the occurrence of several correct values which are difficult to get rid of in this stage of work. Therefore, the overall utility value of the analyzed work process was calculated for three variants, concurrently ordering the obtained weight values in Table 4.

The calculated values of final utility were presented in Fig. 5.

The data analysis shows that in the variant A – characterized by over four times higher value of technological criterion over the ergonomic one, the highest value was stated for the work process S1 – felling of trees. In variant B – with a slight domination of ergonomic criterion, the highest value was defined for the work process S4 (wood stacking and sorting), for which the calculated value was 2.3 times higher than for S3 (wood assortments cross-cutting at the temporary depot). The variant C, whose indicators were defined based on stochastic sample realization, is characterized by the smallest gap of utility values with the highest value for S1 and the lowest value for S3.

The results of the calculations presented in Fig. 5 show that in each variant the lowest values were established for the work process S3. However, the isolation of the work process S1 – felling of trees (variant A and C), which took place twice, enables its description as dominant with the highest final utility.

It has been observed that the dual problem of defining the weight factors is specific. It results from the occurrence of two independent elements of opposed character of the analyzed object such as human being – machine. The subsystem such as human being is characterized by invariability of nature and the subsystem – a technical object – by many possibilities of adaptation (Tytyk 2001). Therefore, for many years different aspects of work systems have been considered looping for such criteria that would enable the definition of optimal solutions. (Luczak 1993, Sowa 1995, Stampfer 2001).

5. Conclusions –*Zaključci*

⇒ The results of multidimensional scaling indicate the classification correctness of indicator groups and work process similarity S1 – felling of trees and S4 – wood stacking and sorting with the estimated final utility of 0.29 and 0.28, respectively, in the general variant (C).

⇒ The analysis of ergonomic aspects indicated that in the work process S2 – debranching, the worker musculoskeletal system was exposed to the highest load.

⇒ The greatest efficiency in working time was observed in the work process S1 – felling of trees, with the lowest operating time-use indicator.

⇒ The kernel estimation results (Parzen) of ergonomic aspect weight density indicate the mixture of two distributions, the first of which describes strong advantage of technological aspects and the second – weak advantage of ergonomic criteria.

⇒ The analysis of three variants of final utility (A, B, C) enables the classification of the work process S3 – wood assortments cross-cutting at the temporary depot as the least preferable, and the work process S1 – feeling of trees as the most useful.

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Sažetak

Ocjena ručno-strojnih postupaka pridobivanja drva na osnovi objedinjene analize

Koncept i metodologija objedinjene (conjoint) analize razvijeni su na osnovi mjerenja i istraživanja provedenih u psihologiji i predstavljaju matematički model u kojem se statističke metode primjenjuju za neizravno otkrivanje preferencija. Metoda je našla široku primjenu, ponajprije u marketinškim istraživanjima potrošačkih sklonosti, a *danas nalazi svoje mjesto i u drugim područjima. Postupak se objedinjene analize oslanja na teoriju korisnosti i u osnovi se sastoji u traženju djelomične korisnosti na temelju rastavljanja poznate konačne funkcije korisnosti.*

Svrha je ovoga rada bila da se primijeni objedinjena analiza u ocjeni ručno-strojnih postupaka pridobivanja drva s obzirom na devet odabranih ergonomskih i tehnoloških čimbenika. Predmet su istraživanja četiri različita procesa koja su na izvršavanje radnih zadataka u pridobivanju drva povremeno obavljali rukovatelji motornom pilom u dobi 30 – 40 godina. To su:

- ⇒ *S1 – sječa, obaranje stabala*
- ⇒ *S2 – čišćenje, kresanje grana*
- ⇒ *S3 – izrada sortimenata, prepiljivanje na stovarištu*
- ⇒ *S4 – slaganje i sortiranje drva.*

Sječa je obavljena u odabranim 100-godišnjim smrekovim sastojinama na strmom terenu (13–30°) u predjelu Beskid Żywiecki (gorske, srednje visoke šume).

S namjerom ostvarivanja pretpostavki i ciljeva istraživanja u radu je postavljen sustav s dva eksperimentalna čimbenika koje sačinjavaju radna mjesta (S1 – S4) i grupa pokazatelja:

- ⇒ *ergonomski pokazatelji:*
  - ✓ *dnevna razina buke (LEX8h, dB(A))*
  - ✓ *ekvivalentna vrijednost mehaničkih vibracija (aweq, ms^{-2})*
  - ✓ *dnevna koncentracija ugljikova monoksida (Cw, mgm^{-3})*
  - ✓ *Lundqvistov indeks opterećenja mišićno-koštanoga sustava (Lunq)*
  - ✓ *energetska potrošnja u radnoj smjeni (WE8h, kJ)*
- ⇒ *tehnološki pokazatelji:*
  - ✓ *relativni udio efektivnoga vremena u vremenu rada (KO2)*
  - ✓ *relativni udio efektivnoga vremena u trajanju radne smjene (KO7)*
  - ✓ *učinkovitost pri radu (W02, m^3/h)*
  - ✓ *učinkovitost u radnom vremenu (W07, m^3/h).*

Rezultati izjednačivanja Parzenove funkcije gustoće vjerojatnosti upućuju na pomiješanost dviju distribucija. Prva od njih opisuje snažnu prednost tehnoloških aspekata (inačice A – više od četiri puta veća vrijednost tehnoloških kriterija u odnosu na ergonomske i C – dva puta veća vrijednost tehnoloških kriterija) i slabu prednost ergonomskih kriterija (u varijanti B). Analiza ukupne korisnosti u trima inačicama (A, B, C) omogućuje klasifikaciju radnoga procesa S3 kao najmanje poželjnoga i radnoga procesa S1 kao najkorisnijega. Rezultati višedimenzionalnoga skaliranja upućuju na ispravnost klasifikacije grupa pokazatelja i sličnost između radnih procesa S1 i S4, s procijenjenim iznosom konačne korisnosti od 0,29, odnosno 0,28 za opću varijantu (C). Analiza ergonomskih kriterija pokazuje da je u radnom procesu S2 prisutno najveće opterećenje mišićno-koštanoga sustava radnika.

Problem određivanja težina uspoređivanih pokazatelja koji se obrađuje u radu je vrlo specifičan. On proizlazi iz pojave dvaju neovisnih elemenata koji su suprotnoga karaktera s obzirom na analizirane objekte, kao što su ljudsko biće – stroj. Podsustav koji se može promatrati u ljudskom biću obilježava nepromjenjivost prirode, a podsustav tehnički objekt opisuje mnoge mogućnosti prilagodbe. Zbog toga se različiti aspekti radnih sustava razmatraju već godinama u potrazi za takvim kriterijima koji bi omogućili definiranje optimalnih rješenja.

Ključne riječi: objedinjena (conjoint) analiza, šumarstvo, ergonomija, pridobivanje drva, učinkovitost

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