Analiza značaja konstrukcijskih i radnih parametara na produktivnost mašina za zemljane radove

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Metoda stohastičke analize razmatrana je u primeni na produktivnost buldozera i to kao nelinearna funkcija devet nezavisnih faktora koji opisuju konstrukcijske i radne karakteristike standardnih mašina različitih veličina sa neodređenim varijacijama faktora. Dobijen je matematički model funkcionalnim razlaganjem produktivnosti u višedimenzionalni Taylorov niz sa određenim koeficijentom značaja i parametrima raspoređenim prema smanjenju značaja.

Ključne reči: produktivnost, buldozer, Taylorov niz, rangiranje parametara, stohastička analiza, težinski koeficijenti

1. UVODNA RAZMATRANJA

Razmatrana je metoda stohastičke analize za varijacije u produktivnosti zemljanih mašina, tj. na primeru buldozera. Produktivnost je data kao nelinearna funkcija koja utiče na konstrukcione i radne parametre kada postoje neodređene varijacije u njima. Ponuđen je matematički model razlaganja ove funkcije na višedimenzionalni prema broju parametara, izračunati su Taylorovi nizovi sa koeficijentom značajnosti uticaja i parametrima raspoređenim prema smanjenju značaja.

2. DEFINISANJE PROBLEMA

Produktivnost zemljanih mašina je složen indeks radne efikasnosti, koji je funkcija standardnih tehničkih parametara, kao i radnih uslova i tačaka procesa sa stohastičkim varijacijama koje nisu definisane standardima.

Neodređenost takvih parametara uzrokuje problem planiranja multifaktorskih istraživanja produktivnosti, posebno kada se radi o velikim veličinama faktorskih prostora (više od 3-4).

Procena značaja uticaja koji nastaju promenom tehničkih i radnih parametara na moguće promene u produktivnosti, posebno za grupe mašina koje se razlikuju po tipu i nameni takođe postaje problematična.

3. ANALIZA ZNAČAJA UTICAJA OPERATIVNIH PARAMETARA

Analiza značaja uticaja operativnih parametara na produktivnost mašina cilj je planiranja i unapređenja tokom izgradnje matematičkih modela inženjerskih sistema [1]. Metode rešavanja takvih zadataka dobro su razvijene, posebno za regresijsku analizu u planiranju aktivnih eksperimenata [2, 3]. Međutim, ovi eksperimenti zahtevaju veliki niz uzorkovanih podataka, posebno kada faktorski prostori imaju velike veličine. Osiguravanje reprezentativnih multivarijantnih podataka za ove eksperimente nezavisan je problem koji je često nerešiv.

Cilj ovog rada je otkrivanje potencijala verovatnoće analize matematičkih modela produktivnosti zemljanih mašina kao nelinearnih funkcija konačnog skupa radnih

parametara i opisivanje metode za procenu značaja uticaja ovih parametara na varijacije u produktivnosti mašine.

4. FUNKCIONALNI MODEL PRODUKTIVNOSTI

Bez obzira na tip mašine za zemljane radove (buldozer, skreper, grejder, utovarivač), produktivnost je jednostruka funkcija najmanje četiri promenljive:

$$P = \frac{3600 \cdot F_f \cdot V}{F_{rp} \cdot T_c} \left(\frac{m^3}{h} \right), \quad (1)$$

gde su: V - geometrijska zapremina zemlje pomerena u jednom ciklusu; F_f - koeficijent punjenja kašike; F_{rp} - faktor gubitka zemlje; T_c - vreme trajanja ciklusa (sec.)

S druge strane, vreme ciklusa zavisi od veličina (dužina putovanja, brzina) koji opisuju faze proizvodnog ciklusa (odsecanje, kretanje i kretanje unazad) i opisano je, npr. za buldozere preko izraza

$$T_c = \frac{l_{ct}}{V_{ct}} + \frac{l_t}{V_t} + \frac{l_{ct} + l_t}{l_{rv}} + t_{ad}, \quad (2)$$

gde su: (l_{ct}, l_t) - dužina odsecanja i dužina transporta; (V_{ct}, V_t) - brzina rezanja i brzina kretanja; (l_{rv}) - brzina pri povratku; (t_{ad}) dodatno vreme vezano za procese tranzicije pri promene faze.

Kombinovanjem jednačina (1) i (2) dobija se matematički funkcionalni model produktivnosti buldozera, čije karakteristike su jednoznačno određene sa devet promenljivih $V, F_f, \dots, V_{rv}, t_g$:

$$P = \frac{3600 \cdot F_f \cdot V}{F_{rp} \cdot \left(\frac{l_{ct}}{V_{ct}} + \frac{l_t}{V_t} + \frac{l_{ct}}{V_{rv}} + \frac{l_t}{V_{rv}} + t_{ad} \right)}. \quad (3)$$

5. STOHAISTIČKI MODEL PRODUKTIVNOSTI

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Bilo koje promene u vrednostima promenljivih dovode do fluktuacija u funkciji P . Ukoliko se pretpostavi da su varijacije u vrednostima promenljivih fiksne kao i konstantna odstupanja od unapred postavljenih (rangiranih) vrednosti unutar jednog ciklusa buldozera.

Razmotrimo redosled ciklusa buldozera. U ovom slučaju, odstupanja parametara su slučajne vrednosti, jer se ni njihovi znakovi ni apsolutne vrednosti ne ponavljaju iz jednog u drugi ciklus. Funkcija (3) se sada može smatrati slučajnom vrednošću određenom nelinearnom transformacijom nezavisnih početnih slučajnih vrednosti $V, F_f, \dots, V_{rv}, t_{ad}$, koja imaju stalna matematička očekivanja. Odstupanja (priraštaji) originalnih slučajnih vrednosti takođe se mogu smatrati konstantnim ili unapred postavljenim jer su disperzije tih vrednosti konstantne.

Stepen uticaja nastalog povećanjima argumenata funkcije $Y = P$ na priraštaj funkcije određuje se kao

$$x_1 = V, x_2 = F_f, x_3 = F_{rp}, x_4 = l_{cb}, x_5 = l_b, x_6 = V_{cb}, x_7 = V_b, x_8 = V_{rv}, x_9 = t_{ad}.$$

U skladu sa novim simbolima, jednačina (3) poprima oblik

$$Y = \frac{3600 \cdot x_1 \cdot x_2}{x_3 \cdot \left(\frac{x_4}{x_6} + \frac{x_5}{x_7} + \frac{x_4}{x_8} + \frac{x_5}{x_8} + x_9 \right)}. \quad (4)$$

Neka su $\bar{Y}$ i $\bar{x}_i$ srednje vrijednosti funkcije Y i argumenata x_i , $i = 1, 9$. Nelinearna funkcija Y se dekomponuje u m -dimenzionalni Tailorov niz [4], $m = 9$, s povećanjem stepena argumenata $x_1, \dots, x_{ad}$ funkcije (4).

$$\Delta x_i = x_i - \bar{x}_i \quad (5)$$

Ukoliko je srednja vrednost funkcije Y

$$\bar{Y} = \bar{f}(\bar{x}_1, \dots, \bar{x}_m) \quad (6)$$

onda je dekompozicija

$$Y = \bar{f}(\bar{x}_1, \dots, \bar{x}_m) - \sum_{i=1}^m \left(\frac{d\bar{Y}}{dx_i} \cdot \Delta x_i \right) + A_T, \quad (7)$$

gde je A_T – ostatak Tejlorovog niza:

$$A_T = \frac{1}{2} \left(\sum_{i=1}^m \frac{d^2 \Delta x_i}{dx_i^2} \right) \cdot \bar{f} \cdot \left[(\bar{x}_1 + \Delta x_1), \dots, (\bar{x}_m + \Delta x_m) \right]. \quad (8)$$

Funkcionalna zavisnost jednačine (6) odgovara zavisnosti osnovnog izraza (2) sa odgovarajućim simbolima arfumenata $V = x_1, \dots, t_{ad} = x_9$.

Pretpostavljajući da je

$$Y = \bar{Y} - \Delta Y,$$

Izrazi za ΔY funkcije Y dobijaju se iz izraza (7)

$$\Delta Y = \sum_{i=1}^m \left(\frac{d\bar{Y}}{dx_i} \cdot \Delta x_i \right) - A_T \quad (9)$$

Ako ostatak A_T ispunjava zahteve [5]

$$A_T \leq 0,8 \cdot \sqrt{\sum_{i=1}^m \left(\frac{d\bar{Y}}{dx_i} \cdot \Delta x_i \right)^2} \cdot \sigma_i^2 \quad (10)$$

gde je σ_i^2 – disperzija odstupanja Δx_i . Interval pouzdanosti za odstupanje Δy se može odrediti iz izraza

$$\Delta y = \sqrt{\sum_{i=1}^m \left(\frac{d\bar{Y}}{dx_i} \cdot \Delta x_i \right)^2}, \quad (11)$$

sa konstantnom disperzijom σ_y^2 .

U ovom slučaju, verovatnoća poverenja P je ista za interval Δy i intervale Δx_i $i = 1, m$, u okviru koga je ispunjen uslov (10).

6. OCENA ZNAČAJA UTICAJA

Koristimo izraz (11) za procenu značaja uticaja devijacija Δx_i argumenata $x_1, \dots, x_m$ na odstupanje funkcije Y (produktivnost buldozera).

Uvedimo koeficijent pojma uticaja i označimo ga kao

$$F_i = \frac{\partial \bar{Y}}{\partial \bar{x}_i} \quad (12)$$

Tada jednačina (11) dobija oblik

$$\Delta y = \sqrt{\sum_{i=1}^m (F_i \cdot \Delta x_i)^2} \quad (13)$$

Tabela 1 daje početne podatke, funkcionalne transformacije i izračunate rezultate komponenti funkcije Y (u apsolutnim vrednostima i procentima u odnosu na odstupanje $(\Delta y)^2$).

Tabela 1. Početni podaci i izračunati rezultati za komponente funkcionalnog uticaja

Argument x_i	Granica odstupanja $X_{iH} - X_{iB}$	Srednja vrednost $\bar{x}_i$	Koeficijent uticaja na Y F_i	Funkcionalni uticaj na produktivnost	
				apsolutni	relativni (%)
$X_1 = V$ (cu m)	(0.9V – 1.1V) cu m	određen	$F_1 = \bar{Y} \cdot V^{-1}$	$1 \cdot 10^{-2}$	20. 205
$X_2 = F_f$	0.9 Kf – 1.1 Kf	određen	$F_2 = \bar{Y} \cdot F_f^{-1}$	$1 \cdot 10^{-2}$	20. 205

$X_3=F_{rp}$	$0.9 K_{rp}-1.1 K_{rp}$	određen	$F_3 = \bar{Y} \cdot F_{rp}^{-1}$	$1 \cdot 10^{-2}$	20.205
$X_4=l_{ct}$ (m)	(6–10) m	8 (m)	$F_4 = -\bar{Y} \cdot \left(\frac{1}{V_{ct}} + \frac{1}{V_{rv}}\right) \cdot S^{-1}$	$2.142 \cdot 10^{-4}$	0.433
$X_5=l_t$ (m)	(50–100) m	75 (m)	$F_5 = -\bar{Y} \cdot \left(\frac{1}{V_t} + \frac{1}{V_{rv}}\right) \cdot S^{-1}$	$72.69 \cdot 10^{-4}$	14.687
$X_6=V_{ct}$ (m/sec)	(0.4–0.5) m/sec	0.45 (m/sec)	$F_6 = \bar{Y} \cdot \frac{l_{ct}}{V_{ct}^2} \cdot S^{-1}$	$1.107 \cdot 10^{-4}$	0.224
$X_7=V_t$ (m/sec)	(0.9–1.0) m/sec	0.95 (m/sec)	$F_7 = \bar{Y} \cdot \frac{l_t}{V_t^2} \cdot S^{-1}$	$21.848 \cdot 10^{-4}$	4.414
$X_8=V_{rv}$ (m/sec)	(1.1–1.2) m/sec	1.15 (m/sec)	$F_8 = \bar{Y} \cdot \left(\frac{l_{ct}}{V_{rv}^2} + \frac{l_t}{V_{rv}^2}\right) \cdot S^{-1}$	$18.259 \cdot 10^{-4}$	3.689
$X_9=t_{ad}$ (sec)	(10–20) sec	15 (sec)	$F_9 = -\bar{Y} \cdot S^{-1}$	$78.87 \cdot 10^{-4}$	15.936

U Tabeli 1 množitelji $\bar{Y}$ i S definisani jednačinama

$$\bar{Y} = \frac{3600 \cdot \bar{X}_1 \cdot \bar{X}_2}{\bar{X}_3 \cdot \left(\frac{\bar{X}_4}{\bar{X}_6} + \frac{\bar{X}_5}{\bar{X}_7} + \frac{\bar{X}_4}{\bar{X}_8} + \frac{\bar{X}_5}{\bar{X}_8} + \bar{X}_9\right)},$$

$$S = \frac{\bar{X}_4}{\bar{X}_6} + \frac{\bar{X}_5}{\bar{X}_7} + \frac{\bar{X}_4}{\bar{X}_8} + \frac{\bar{X}_5}{\bar{X}_8} + \bar{X}_9.$$

Svi rezultati dobijeni su za 10% variranje u početnim argumentima $X_1, \dots, X_9$ funkcije Y , što osigurava ispunjavanje uslova (10).

Kao što sledi iz Tabele 1, argumenti se mogu rasporediti u skladu sa smanjenjem značajnog uticaja na produktivnost buldozera (Tabela 2).

Tabela 2. Niz argumenata (operativnih parametara) raspoređenih u skladu sa smanjenjem značajnog uticaja na produktivnost buldozera

Rang prema značaju uticaja na produktivnost	1. 2. 3	4	5	6	7	8	9
Težina (%)	20.205	15.936	14.687	4.414	3.689	0.433	0.224
Operacioni parametar	V, F_f, F_{rp}	t_{ad}	l_t	V_t	V_{rv}	l_{ct}	V_{ct}

7. PRAKTIČNI ZNAČAJ

Predloženi metod transformisanja nelinearnih funkcija više varijabli sa naknadnom stohastičkom analizom odstupanja od tih funkcija omogućava procenu komponentenata ovih odstupanja prema tipovima koji utiču na početne parametre. Metoda se može koristiti za preliminarno minimiziranje niza takvih parametara prilikom planiranja daljih eksperimentalnih faktora kako bi se identifikovali modeli produktivnosti za mašine za zemljane radove.

8. ZAKLJUČCI

1. Razvijena metoda stohastičke analize nelinearnih multiparametarskih zavisnosti omogućava kvantitativne procene bilo kojih operativnih parametara u skladu sa njihovim značajnim uticajem na produktivnost zemljanih mašina.

2. Rangiranje parametara prema njihovom značajnom uticaju na produktivnost omogućava formiranje bezbroj parametara koji osiguravaju maksimalan uticaj, planirajući tako multifaktorske mašinske testove pri minimalnim obimima ispitivanja.

LITERATURA

- [1] Барабашук В.И. и др. Планирование эксперимента в технике / В.И. Барабашук, Б.П. Креденцер, В.И. Мирошниченко; под ред. Б.П. Креденцера. – К.: Техника. 1984. – 200с.
- [2] Джонсон Н., Лион Ф. Статистика и планирование эксперимента в технике и науке: Методы планирования эксперимента / Н. Джонсон, Ф. Лион; пер. с англ. под ред. Э.К. Лецкого. – М.: Мир, 1981. – 520 с.
- [3] И.Г. Кириченко. Модульная концепция проектирования ... Х. ХНАДУ, 2002. – 119с.
- [4] Корн Г., Корн Т. Справочник по математике для научных работников и инженеров. – М.: Наука, 1978. – 832с.
- [5] Вентцель Е.С., Овчаров Л.А. Теория вероятностей и ее инженерные приложения: Учеб. пособие для вузов. – М.: Высш. шк., 2000. – 480 с.:ил.

The Analysis of Significance of Design and Operational Parameters that Affect the Productivity of Earthmoving Machines

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The method of stochastic analysis has been considered in application to bulldozer productivity as a non-linear function of nine independent factors that describe design and operational features of machines of various standard sizes with present indeterminate variations in the factors. A mathematic model of productivity functional decomposition into multidimensional Taylor's series with a subsequent significance coefficient determined and parameters arranged according to reduction in significance has been obtained.

Keywords: productivity, bulldozer, Taylor's series, parameter ranking, stochastic analysis, weight coefficients.

1. INTRODUCTION

A method of stochastic analysis has been considered for variations in productivity of earthmoving machines, with bulldozers as an example. The productivity is given as a non-linear function of affecting design and operational parameters when indeterminate variations in the latter are present.

A mathematic model of this function decomposition into multidimensional, by number of parameters, Taylor's series with a subsequent impact significance coefficient calculated and parameters arranged according to reduction in significance has been offered.

2. PROBLEM - SETTING

Productivity of earthmoving machines is a complex index of operational efficiency, which is a function of standard technical parameters as well as of operational conditions and process flowsheets with stochastic variations not determined by standards.

Indeterminacy of such parameters causes a problem of planning multi-factor research into productivity, especially when dealing with large (more than 3-4) sizes of factor spaces.

Evaluation of significance of impact made by varying technical and operational parameters on probable variations in productivity, especially for groups of machines that differ in type and purpose becomes problematic as well.

3. ANALYSIS OF WRITINGS

To analyse the significance of impact made by operational parameters on machine productivity is a goal for planning and improving while building mathematic models of engineering systems [1].

Methods of solving such tasks are well-developed, especially for regression analysis in planning active experiments [2, 3].

However, these experiments require large arrays of sampled data, in particular when factor spaces feature

large sizes. To ensure representative multivariate data for these experiments is an independent problem, which is quite often unsolvable.

The aim of this article is to reveal the potential of probabilistic analysis of mathematic models for productivity of earthmoving machines as non-linear functions of finite aggregate of operational parameters and to describe a method to evaluate the significance of impact made by these parameters on variations in machine productivity.

4. FUNCTIONAL MODEL OF PRODUCTIVITY

Irrespective of the earthmoving machine type (bulldozer, scraper, motor grader, loader), the productivity is a one-valued function of at least four variables

$$P = \frac{3600 \cdot F_f \cdot V}{F_{rp} \cdot T_c} \left(\frac{m^3}{h} \right), \quad (1)$$

where are: V - geometric volume of earth moved within one cycle; F_f - bucket fill factor; F_{rp} - soil loosening factor; T_c - cycle time (sec.)

In its turn, cycle time depends on arguments (travel length, velocity) describing stages of the production cycle (cutting, travel, and reverse motion) and is described, e.g. for bulldozers:

$$T_c = \frac{l_{ct}}{V_{ct}} + \frac{l_t}{V_t} + \frac{l_{ct} + l_t}{l_{rv}} + t_{ad}, \quad (2)$$

where are: (l_{ct}, l_t) - cutting length and travel length; (V_{ct}, V_t) - cutting velocity and travel velocity; (l_{rv}) - reverse speed; (t_{ad}) additional time related to transition processes when stages change.

Combining equations (1) and (2) we obtain a mathematic functional model of bulldozer productivity, which properties are singly valued with nine variables: $V, F_f, \dots, V_{rv}, t_g$:

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$$P = \frac{3600 \cdot F_f \cdot V}{F_{rp} \cdot \left(\frac{l_{ct}}{V_{ct}} + \frac{l_t}{V_t} + \frac{l_{rv}}{V_{rv}} + \frac{l_{ad}}{V_{ad}} + t_{ad} \right)}. \quad (3)$$

5. STOCHASTIC MODEL OF PRODUCTION

Any variations in values of the variables lead to fluctuations in function P. We shall assume variations in values of the variables to be fixed and constant deviations from preset (rated) values within one bulldozer cycle.

Let us consider the sequence of bulldozer cycles. In this case, parameter deviations are random values as neither their signs nor absolute values recur from one cycle to another. Function (3) can now be considered a random value determined by non-linear transformation of independent initial random values $V, F_f, \dots, V_{rv}, t_{ad}$, that have constant mathematic expectations. Deviations (increments) of original random values can also be considered constant or preset as dispersions of these values are constant.

The degree of impact made by argument increments on increment of function $Y = P$ is found

$$x_1 = V, x_2 = F_f, x_3 = F_{rp}, x_4 = l_{ct}, x_5 = l_t, x_6 = V_{ct}, x_7 = V_t, x_8 = V_{rv}, x_9 = t_{ad}.$$

In accordance to new symbols, the equation (3) takes the form

$$Y = \frac{3600 \cdot x_1 \cdot x_2}{x_3 \cdot \left(\frac{x_4}{x_6} + \frac{x_5}{x_7} + \frac{x_4}{x_8} + \frac{x_5}{x_8} + x_9 \right)}. \quad (4)$$

Let $\bar{Y}$ и $\bar{x}_i$ be mean values of function Y and arguments $x_i, i = 1.9$. Non-linear function Y is decomposed into m-dimensional Taylor's series [4], $m = 9$, by increment degrees of arguments $x_1, \dots, x_{ad}$ of the function (4).

$$\Delta x_i = x_i - \bar{x}_i \quad (5)$$

If the mean value of function Y is

$$\bar{Y} = \bar{f}(\bar{x}_1, \dots, \bar{x}_m) \quad (6)$$

then this decomposition

$$Y = \bar{f}(\bar{x}_1, \dots, \bar{x}_m) - \sum_{i=1}^m \left(\frac{d\bar{Y}}{dx_i} \cdot \Delta x_i \right) + A_r, \quad (7)$$

where A_r – remainder of Taylor series:

$$A_r = \frac{1}{2} \left(\sum_{i=1}^m \frac{d^2 \bar{Y}}{dx_i^2} \right) \cdot \bar{f} \cdot \left[(\bar{x}_1 + \Delta x_1), \dots, (\bar{x}_m + \Delta x_m) \right]. \quad (8)$$

Functional dependence $\bar{f}(\cdot)$ expression (6) corresponds to the dependence of general expression (2) with corresponding argument symbols $V = x_1, \dots, t_{ad} = x_9$.

Assuming that

$$Y = \bar{Y} - \Delta Y,$$

expressions for ΔY of Y function are obtained from (7)

$$\Delta Y = \sum_{i=1}^m \left(\frac{d\bar{Y}}{dx_i} \cdot \Delta x_i \right) - A_r \quad (9)$$

If the remainder A_r meets the requirement [5]

$$A_r \leq 0,8 \cdot \sqrt{\sum_{i=1}^m \left(\frac{d\bar{Y}}{dx_i} \cdot \Delta x_i \right)^2 \cdot \sigma_i^2} \quad (10)$$

where σ_i^2 - dispersion of deviations Δx_i .

The confidence interval for deviation ΔY can be calculated as

$$\Delta y = \sqrt{\sum_{i=1}^m \left(\frac{d\bar{Y}}{dx_i} \cdot \Delta x_i \right)^2}, \quad (11)$$

with dispersion σ_y^2 being constant.

In this case, confidence probability P is the same both for Δy interval and for confidence intervals $\Delta x_i, i = 1, m$, within which the requirement is met (10).

6. EVALUATION OF IMPACT SIGNIFICANCE

Let us use expression (11) for evaluating the significance of impact made by deviations Δx_i of arguments $x_1, \dots, x_m$ on deviation of function Y (bulldozer productivity).

Let us introduce the notion *coefficient of impact* and designate it as

$$F_i = \frac{\partial \bar{Y}}{\partial x_i} \quad (12)$$

Then expression (11) is

$$\Delta y = \sqrt{\sum_{i=1}^m (F_i \cdot \Delta x_i)^2} \quad (13)$$

Table 1 gives initial data, functional transformations and calculated results of function Y components (in absolute values and percentage in relation to deviation $(\Delta y)^2$).

Table 1. Initial data and calculated results for components of functional impact

Argument X_i	Variation boundary $X_{iH} - X_{iB}$	Mean value $\bar{X}_i$	Coefficient of impact on Y F_i	Functional impact made on productivity	
				absolute	relative (%)
$X_1=V$ (cu m)	(0.9V–1.1V) cu m	rated	$F_1 = \bar{Y} \cdot V^{-1}$	$1 \cdot 10^{-2}$	20.205
$X_2=F_f$	0.9 K _f –1.1 K _f	rated	$F_2 = \bar{Y} \cdot F_f^{-1}$	$1 \cdot 10^{-2}$	20.205
$X_3=F_{rp}$	0.9 K _{rp} –1.1 K _{rp}	rated	$F_3 = \bar{Y} \cdot F_{rp}^{-1}$	$1 \cdot 10^{-2}$	20.205
$X_4=l_{ct}$ (m)	(6–10) m	8 (m)	$F_4 = -\bar{Y} \cdot \left(\frac{1}{V_{ct}} + \frac{1}{V_{rv}}\right) \cdot S^{-1}$	$2.142 \cdot 10^{-4}$	0.433
$X_5=l_t$ (m)	(50–100) m	75 (m)	$F_5 = -\bar{Y} \cdot \left(\frac{1}{V_t} + \frac{1}{V_{rv}}\right) \cdot S^{-1}$	$72.69 \cdot 10^{-4}$	14.687
$X_6=V_{ct}$ (m/sec)	(0.4–0.5) m/sec	0.45 (m/sec)	$F_6 = \bar{Y} \cdot \frac{l_{ct}}{V_{ct}^2} \cdot S^{-1}$	$1.107 \cdot 10^{-4}$	0.224
$X_7=V_t$ (m/sec)	(0.9–1.0) m/sec	0.95 (m/sec)	$F_7 = \bar{Y} \cdot \frac{l_t}{V_t^2} \cdot S^{-1}$	$21.848 \cdot 10^{-4}$	4.414
$X_8=V_{rv}$ (m/sec)	(1.1–1.2) m/sec	1.15 (m/sec)	$F_8 = \bar{Y} \cdot \left(\frac{l_{ct}}{V_{rv}^2} + \frac{l_t}{V_{rv}^2}\right) \cdot S^{-1}$	$18.259 \cdot 10^{-4}$	3.689
$X_9=t_{ad}$ (sec)	(10–20) sec	15 (sec)	$F_9 = -\bar{Y} \cdot S^{-1}$	$78.87 \cdot 10^{-4}$	15.936

In Table 1 multiplicands $\bar{Y}$ and S are determined by expressions

$$\bar{Y} = \frac{3600 \cdot \bar{X}_1 \cdot \bar{X}_2}{\bar{X}_3 \cdot \left(\frac{\bar{X}_4}{\bar{X}_6} + \frac{\bar{X}_5}{\bar{X}_7} + \frac{\bar{X}_4}{\bar{X}_8} + \frac{\bar{X}_5}{\bar{X}_8} + \bar{X}_9\right)},$$

$$S = \frac{\bar{X}_4}{\bar{X}_6} + \frac{\bar{X}_5}{\bar{X}_7} + \frac{\bar{X}_4}{\bar{X}_8} + \frac{\bar{X}_5}{\bar{X}_8} + \bar{X}_9.$$

All results have been obtained for 10%-variations in initial arguments $X_1, \dots, X_9$ of function Y, which ensures meeting the condition (10).

As follows from Table 1, arguments can be arranged according to reduction in significant impact on bulldozer productivity (Table 2).

Table 2. A series of arguments (operational parameters) arranged according to reduction in significant impact on bulldozer productivity

Rank according to significant impact on productivity	1. 2. 3	4	5	6	7	8	9
Weight (%)	20.205	15.936	14.687	4.414	3.689	0.433	0.224
Operational parameter	V, F_f, F_{rp}	t_{ad}	l_t	V_t	V_{rv}	l_{ct}	V_{ct}

7. PRACTICAL IMPORTANCE

The proposed method of transforming non-linear functions of multiple variables with subsequent stochastic analysis of deviations from these functions allows evaluating components of these deviations according to types of affecting initial parameters. The method could be used for preliminary minimization of a number of such parameters when planning further factor experiments in order to identify productivity models for earthmoving machines.

8. CONCLUSIONS

1. The developed method of stochastic analysis of non-linear multi-parametric dependencies allows quantitative evaluations of any operational parameters according to their significant impact on productivity of earthmoving machines.
2. Ranking the parameters according to their significant impact on productivity allows forming sub-multitudes of parameters that ensure maximum impact thus planning multi-factor machine tests at minimum test volumes.

REFERENCES

- [1] Барабашук В.И. и др. Планирование эксперимента в технике / В.И. Барабашук, Б.П. Креденцер, В.И. Мирошниченко; под ред. Б.П. Креденцера. – К.: Техніка. 1984. – 200с.
- [2] Джонсон Н., Лион Ф. Статистика и планирование эксперимента в технике и науке: Методы планирования эксперимента / Н. Джонсон, Ф. Лион; пер. с англ. под ред. Э.К. Лецкого.– М.: Мир, 1981. – 520 с.
- [3] И.Г. Кириченко. Модульная концепция проектирования ... Х. ХНАДУ, 2002. –119с.
- [4] Корн Г., Корн Т. Справочник по математике для научных работников и инженеров. – М.: Наука, 1978. – 832с.
- [5] Вентцель Е.С., Овчаров Л.А. Теория вероятностей и ее инженерные приложения: Учеб. пособие для вузов. – М.: Высш. шк., 2000.–480 с.:ил.