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ПРИМЕНЕНИЕ ТЕОРИИ МАССОВОГО ОБСЛУЖИВАНИЯ К МОДЕЛИРОВАНИЮ РЕЖИМОВ РАБОТЫ ЛЕСОЗАГОТОВИТЕЛЬНЫХ МАШИН

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В статье рассмотрены результаты выбора режимов работы лесосечных машин путем оптимизации процесса заготовки сортиментов с применением методов теории очередей

Ключевые слова: ЗАГОТОВКА ЛЕСА, МОДЕЛИРОВАНИЕ, ТЕОРИЯ МАССОВОГО ОБСЛУЖИВАНИЯ, ХАРВЕСТЕР, ФОРВАРДЕР

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APPLYING OF THE QUEUEING THEORY TO MODEL OPERATING MODES OF A LOGGING MACHINE

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The results of operating conditions of harvesting forest machines by means of optimization harvesting forest process with application of the queueing theory are considered

Keywords: LOGGING, MODELING, WAITING THEORY, HARVESTER, FORWARDER

The research of logging technology is conducted at Petrozavodsk State University, and it is reflected, for instance in works [3–5]. A goal of the research is to improve the technological processes of industrial and energy wood harvesting. This research has demonstrated a promising perspective of the queueing theory application for this purpose [1–2].

This approach has allowed studying the resulting effect caused by simultaneous utilization of a few harvesters and forwarders in the cutting area [6].

From the point of view of the queueing theory methodology [6], the technological timber harvesting process, using both harvesters and forwarders, may be considered as a $G/G/c$ queueing system with batch arrivals.

A harvester fells trees, cuts branches and bucks up on industrial and energy assortments. After that, a forwarder picks up assortments, loads them on its dray and then transports the assortments to a holding area.

A Job has N assortments.

The harvester work can be fully described by the mean arrival rate $l_i(B)$ which is the average number of the batches generating by the harvester ***i*** per unit of time. After the harvester produces N assortments, then the job arrives to a factory. In general, the number N is random and has an arbitrary distribution. If a workstation (forwarder) is busy then an arriving job goes to a waiting area. The waiting area is a collecting network. After the forwarder becomes free the job proceeds to process.

The forwarder work determines the mean processing rate (the average number of batches which any forwarder is processing per unit of time).

If there are m working harvesters then the mean arrival rate (the average number of the assortments which all harvesters are generating per unit of time) is the sum of the rates of m (independent) streams, that is

$$l(I) = \sum_{i=1}^{m} l_i(I), \qquad (1)$$

where m is the total number of the harvesters and $l_i(I)$ is the mean arrival rate of harvester ***i***. Values $l(I)$ and $l(B)$ are connected by the following expression $l(B) = l(I)/E[N]$, where $E[N]$ is the mean number of assortments in a batch.

There are two the most important performance measures of the factory. It is the mean of cycle time $E[CT_s]$ and the mean of work-in-process $E[WIP]$. The mean of cycle time is the average time that the job spends within a system, and it includes the time $T_q(B)$ which the job spends in a waiting area, and the time

$T_s(B)$ which the job is processed by the forwarder. For the queuing system the value $E[CT_s]$ is defined as follows:

$$E[CT_s] = E[D] + E[T_q(B)] + E[T_s(B)], \qquad (2)$$

where $E[D]$ is the mean time which the harvester processes an assortments batch; $E[CT_q]$ is the mean time which the job spends in a waiting area (in a queue); $E[T_s(B)]$ is the mean time which the job is processed by the forwarder.

The mean value $E[D]$ can be obtained from the Wald's identity as follows

$$E[D] = E[N] \cdot E[T_a(I)], \qquad (3)$$

where $E[T_a(I)] = 1/l(I)$ is the mean time between the moments of assortments' cut out (if all harvesters are taken into account).

The mean time which the job is staying in a waiting area of some forwarders is defined as

$$E[CT_q] = \left(\frac{C_a^2(B) + C_s^2(B)}{2} \right) \cdot \left(\frac{u(B)^{\sqrt{2 \cdot c + 2} - 1}}{c \cdot (1 - u(B))} \right) \cdot E[T_s(B)], \qquad (4)$$

where $C_a^2(B)$ is the squared coefficient of variation of time which all harvesters process batch of assortments; $C_s^2(B)$ is the squared coefficient of variation for the time which forwarder processes batch of assortments; $u(B)$ is the utilization factor; c is the total number of forwarders.

The utilization factor of c forwarders is defined as $u(B) = l(I)/(m(B) \cdot E[N] \cdot c)$. The value $C_a^2(B)$ is defined by the formula

$$C_a^2(B) = \sum_{i=1}^{m} \frac{l_i(B)}{l(B)} \cdot C_{a,i}^2(B), \qquad (5)$$

where $l_i(B)$ is the average number of batches generating by harvester *i* per unit of time, and it connects with the value $l_i(I)$ by the formula

$l_i(B) = l_i(I)/E[N]$; $C^2_{a,i}(B)$ is the squared coefficient of variation of the time which harvester *i* processes a batch of assortments. The value $C^2_{a,i}(B)$ is defined as

$$C^2_{a,i}(B) = \frac{C^2[T_{a,i}(I)]}{E[N]} + C^2[N], \qquad (6)$$

where $C^2[T_{a,i}(I)]$ is the squared coefficient of variation for the time which harvester *i* processes assortment; $C^2[N]$ is the squared coefficient of variation for the total number assortments which are located on a dray of the forwarder.

The connection between the values $E[WIP]$ and $E[CT_s]$ is expressed by the Little's law $E[WIP] = l(B) \cdot E[CT_s]$.

The reduction of $E[CT_s]$ can be achieved by the decreasing of time when the assortments are located on a cutting area. This may correspond to increased productivity and / or increase of the uniformity of the system if values $E[N]$ and $C^2[N]$ do not change.

We note that the utilization factor shows how much the forwarder is loaded. If we have one forwarder and $u(B) > 1$, then the forwarder is overloaded. If $u(B) < 1$ then the (limiting) fraction of time the forwarder is free is $1 - u(B)$. When the utilization factor approaches to 1 (from below) then the queue grows up nonlinearly. It leads to an overloading of the system and finally breaks up production.

At the time when the job is in a waiting area (in a queue) tends to 0 the system works more regularly.

We note that the mean work-in-process shows how many assortments are in the cutting area. Also we note that the considered forwarder is able to take 10 m^3 of assortments on the dray. It means that one job is according to 10 m^3 of logs.

To calculate the means $E[CT_s]$ and $E[WIP]$, a few experiments have been realized in Pryazha region, the republic of Karelia. The harvester John Deere 1270D Eco III and the forwarder John Deere 1110D Eco III worked in the cutting area. As a result, the following values $E[N]=147$, $C^2[N]=0{,}059$, $E[T_a(I)]=34c$, $C^2[T_a(I)]=0{,}803$, $E[T_s(B)]=3628c$, $C_s^2(B)=0{,}059$ have been obtained.

In such a case, calculation of the means are based on the standard estimate

$$E[x]=\frac{\sum_{i=1}^{k} m_i \cdot x_i}{n}, \qquad (7)$$

where x_i is the ***i***-th observation; m_i is the absolute frequency; n is the sample size; k is the number of intervals. The empirical variance is defined as

$$V[x]=\frac{\sum_{i=1}^{k}(x_i - E[x])^2 \cdot m_i}{n-1}. \qquad (8)$$

The squared coefficient of variation is defined by the formula

$$C^2[x]=\frac{V[x]}{E[x]^2}. \qquad (9)$$

Using formulas (1) – (6) and the model from the paper [1], we have obtained the following results:

$$u(B)=\frac{3628}{147\cdot 34}=0{,}726$$

$$E[T_q(B)]=\left(\frac{\frac{0{,}803}{147}+0{,}059+0{,}059}{2}\right)\cdot\left(\frac{\frac{3628}{147\cdot 34}}{1-\frac{3628}{147\cdot 34}}\right)\cdot 3628=593c$$

$$E[CT_s]=147\cdot 34+593+3628=9219c=2{,}56ч$$

$$E[WIP]=\frac{9219}{147\cdot 34}=1{,}84$$

Now we show how the system performance is changed depending on the changes of given parameters. We assume that the variances of the assortments' arriving time and the assortments' processing time decrease. It means that the machines are working more evenly. To realize it in the model, we must reduce values $C^2[T_a(I)]$ and $C_s^2(B)$. For example, if $C_s^2(B)$ is reduced on 10 % then $E[CT_s]$ and $E[WIP]$ are reduced on 0,31 %. In that case the utilization factor remains the same. The mean time the job is in a waiting area $E[T_q(B)]$ is reduced on 4,78 %.

If $C^2[T_a(I)]$ is reduced on 10 % then $E[CT_s]$ и $E[WIP]$ are reduced on 0.03 %. (At that again the utilization factor $u(B)$ is not changed.) The mean time the job is in a waiting area $E[T_q(B)]$ is reduced on 0.44 %.

If we increase $C_s^2(B)$ on 10 % then the values $E[CT_s]$ and $E[WIP]$ also increase on 0,31 %, while the value $E[T_q(B)]$ increases on 4,78 %.

If $C^2[T_a(I)]$ increases on 10 % then, as we can see, $E[CT_s]$ and $E[WIP]$ increase as well. Moreover, the value $E[T_q(B)]$ increases on 0.44 %.

If $C^2[T_a(I)]$ increases on 10 % and $C_s^2(B)$ is reduced at one time. Then the values $E[CT_s]$ and $E[WIP]$ decrease on 0,28 %, and $E[T_q(B)]$ also decreases on 4,34 %. The utilization factor hasn't changed again.

If $C^2[T_a(I)]$ reduces on 10 % and $C_s^2(B)$ increases at one time. Then the values $E[CT_s]$ and $E[WIP]$ increase on 0,28 %, and the value $E[T_q(B)]$ also decreases on 4,34 %.

The small change of values $C^2[T_a(I)]$ and $C_s^2(B)$ doesn't influence on the system.

If $E[T_a(I)]$ is increased on 10 % then $E[CT_s]$ increases on 3,7 % and $E[WIP]$ reduces on 5,72 %. The value $E[T_q(B)]$ reduces on 26,73 %. The utilization factor is 0,66. It reduces on 9,09 %.

If $E[T_a(I)]$ is reduced on 10 % then $E[CT_s]$ is reduced on 1,73 % and $E[WIP]$ is increased on 9,19 %, and the value $E[T_q(B)]$ is increased on 57,44 %. In that case the utilization factor increases on 11,11 % and becomes 0,81.

A change of $E[T_a(I)]$ may lead to a considerable change of $E[CT_s]$ and other parameters. In practice, the value $E[T_a(I)]$ depends on the construction of the harvester, skill of the driver, type of the cutting area, and other factors.

The value $E[T_s(B)]$ influences strongly on the mean cycle time $E[CT_s]$ and the mean of work-in-process $E[WIP]$. For example, if the value $E[T_s(B)]$ is reduced on 10 % then $E[CT_s]$ and $E[WIP]$ are reduced on 6,25 %, $E[T_q(B)]$ is reduced on 35,96 % and $u(B)$ is reduced on 10%.

If we increase $E[T_s(B)]$ on 10%, then $E[CT_s]$ and $E[WIP]$ increase on 8,09 %, and $E[T_q(B)]$, $u(B)$ increases on 64,59 % and 10 %, respectively.

If $E[T_s(B)]$ is increased on 10 % and $E[T_a(I)]$ is reduced at one time then $E[CT_s]$ increases on 13,10 %, the value $E[WIP]$ increases on 25,67 %, $E[T_q(B)]$ increases on 26,71 %, and utilization $u(B)$ increases on 22,22 %. If $E[T_s(B)]$ is reduced on 10 % and $E[T_a(I)]$ is increased on 10 % at one time, then the reduction of the corresponding values are 1,75 %, 10,68 %, 50,29 %, 18,18 %, respectively.

We also can reduce $E[CT_s]$ and $E[WIP]$ by changing the number of forwarders c (and keeping rest of parameters, with exception of utilization factor, fixed). For instance, for $c = 2$, then the reduction of the values $E[CT_s]$, $E[WIP]$, $E[T_q(B)]$ are respectively 5,99 %, 93,18 %, 50 % (with factor $u(B)$

equals 0,36). For $c = 3$, values $E[CT_s]$ and $E[WIP]$ reduce on 6,35 %, $E[T_q(B)]$ reduces on 98,76 %, and $u(B)$ becomes 0,24 that is reduced on 66,67 %.

If we want to model the work of m harvesters on the cutting area, we need to reduce the value $E[T_a(I)]$ twice.

Then, for instance, for $c = 2$, the value $E[CT_s]$ reduces on 30,75 % and $E[T_q(B)]$ reduces on 56,71 %, but the value $E[WIP]$ increases on 38,49 %. At the same time, the utilization factor does not change. For $c = 3$, $E[CT_s]$ reduces on 33,12 % and $E[T_q(B)]$ reduces on 93,53 % but $E[WIP]$ increases on 33,75 %. The utilization factor reduces on 33,33 % to be 0,48.

A complex of forest machines which has two harvesters and one forwarder is not used because the utilization factor is more than 1. It means that the mean time when the job is in a waiting area would increase with no limit.

Now we illustrate situation for $m = 3$ harvesters on the cutting area. First, the value $E[T_a(I)]$ is reduced in 3 times. For this case and for $c = 3$ the value $E[CT_s]$ reduces on 40,93 %, the value $E[T_q(B)]$ reduces on 74,44 %, while the value $E[WIP]$ increases on 77,21 %. The utilization factor does not change.

If we continue to increase the number of machines, then we obtain the following. For 3 harvesters and 4 forwarders, the value $E[CT_s]$ decreases on 42,21 %, the value $E[T_q(B)]$ decreases on 94,44 % , but $E[WIP]$ increases on 73,35 %. The utilization factor $u(B)$ is reduced on 25 % and becomes equals 0,54. For 4 harvesters and 4 forwarders, we obtain reduction of $E[CT_s]$ and $E[T_q(B)]$ on 45,99 % and 82,77 %, respectively, while the quantity $E[WIP]$ increases on 116,06 %. The utilization factor does not change.

The mean of cycle time, the mean time which the job is staying in a waiting area, the mean of work-in-process and the utilization factor for different complexes of forest machines are displayed in Fig. 1 – 4.

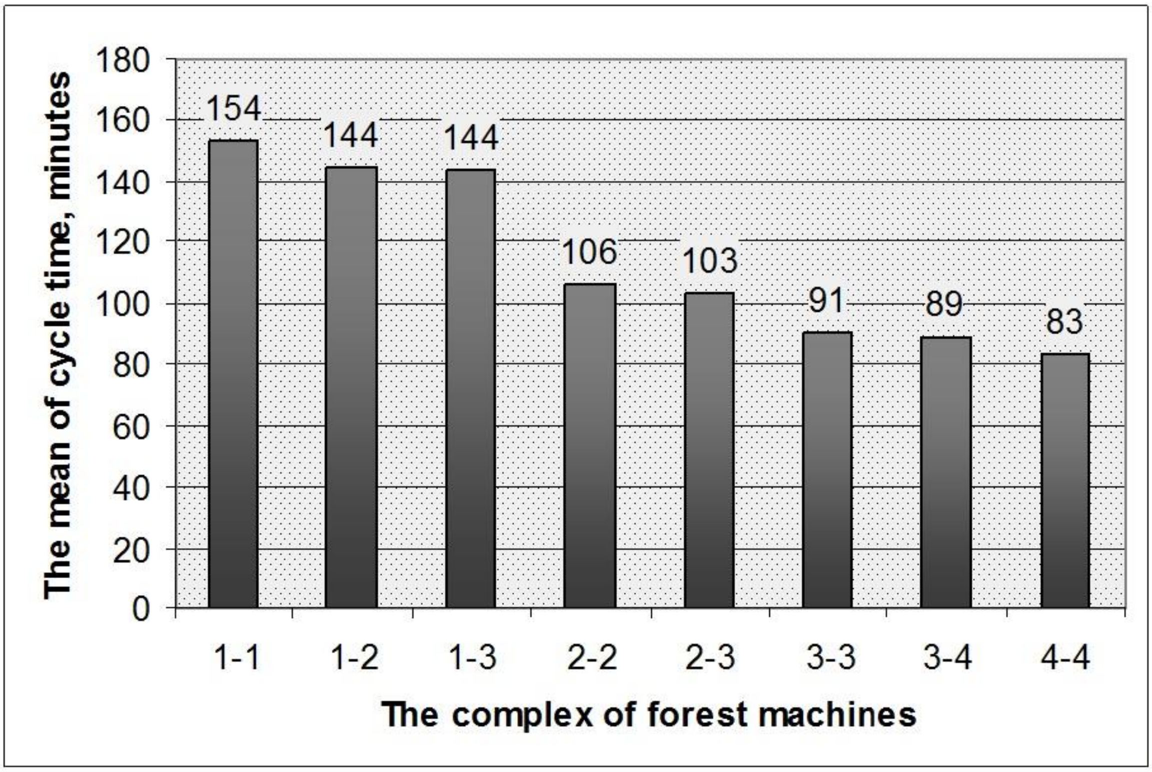

Fig 1. The mean of cycle time for different complexes of forest machines

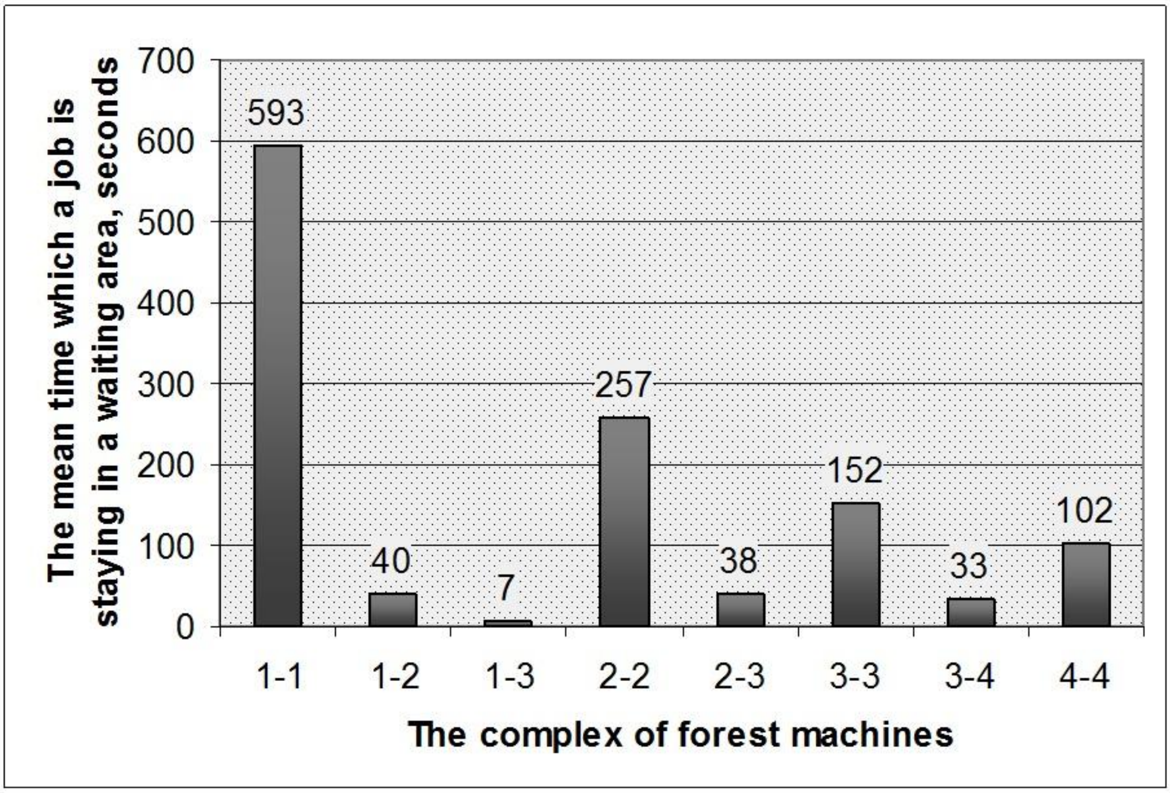

Fig 2. The mean time which the job is staying in a waiting area for different complexes of forest machines

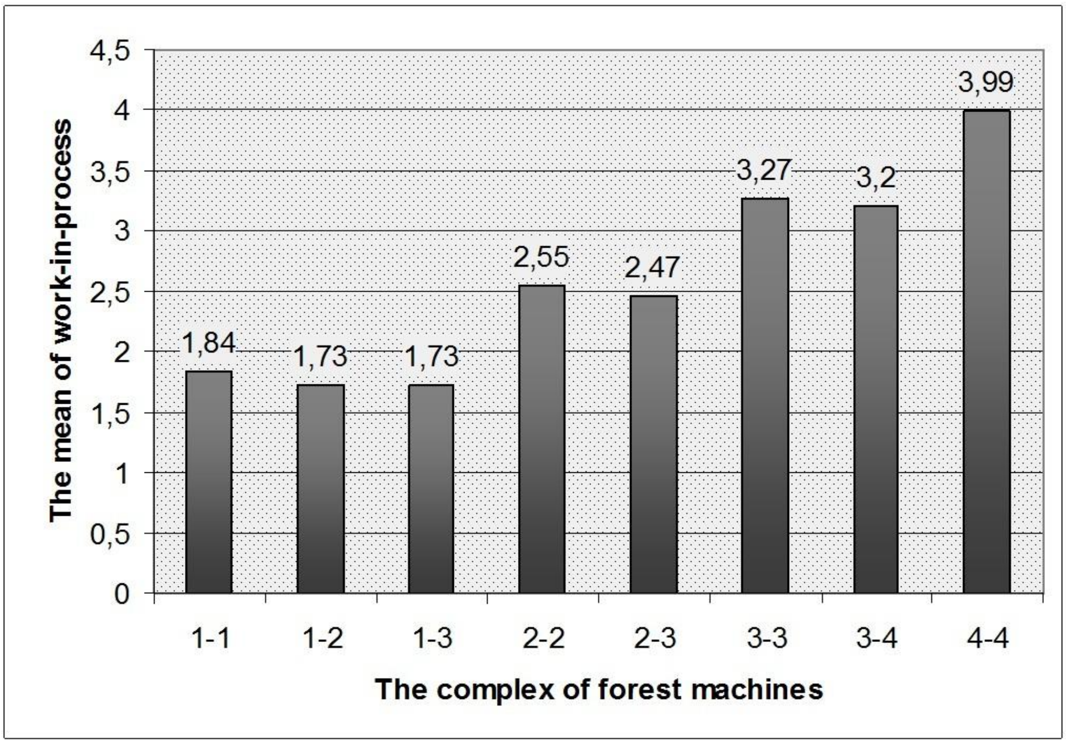

Fig 3. The mean of work-in-process for different complexes of forest machines

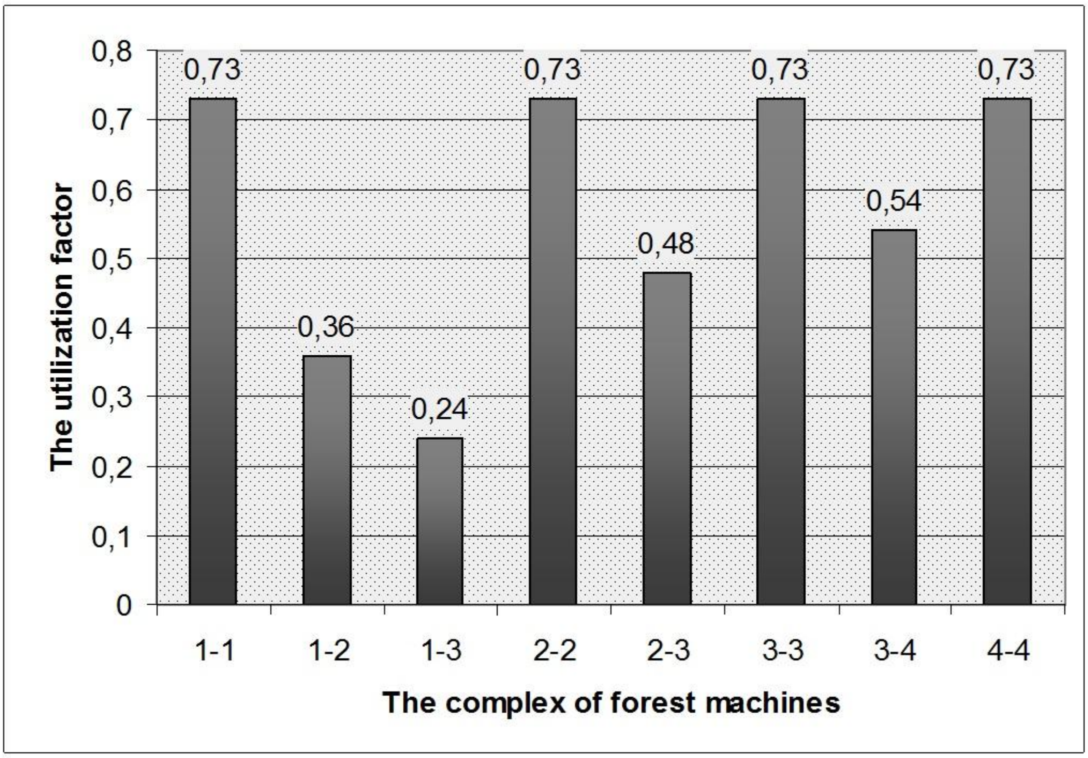

Fig 4. The utilization factor for different complexes of forest machines

Now we summarize our observations. If we use 1 harvester and 2 forwarders, then we obtain a considerable decrease of the mean time which the job is in the waiting area (93,18 %). However, the mean cycle time is reduced only on 5,99 % and the utilization factor is 0,36 so the forwarders will have too much free time. The increase of the number of forest machines increases the mean work-in-process. For example, assume that initial value $E[WIP]=$ 1,84. It means that the cutting area has 18,4 m^3 of the assortments. For 4 harvesters and 4 forwarders, $E[WIP]$=3,99. Assume, the cutting area has 39,9 m^3 of assortments. The use of a large number of forest machines is difficult because in the case there appear problems with organization of working of several machines on the cutting area. In addition, the negative impact of machines on the forest increases.

On the basis of analysis of the model we can summarize that 2 harvesters and 2 forwarders is an optimal combination in conditions of the cutting area because in the situation we obtain considerable decrease of the mean cycle time $E[CT_s]$ and the mean job waiting time, while the utilization factor remains unchanged.

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