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Optimization of a forest harvesting set based on the Queueing Theory: Case study from Karelia

Optimalizácia zostavy ťažbových zariadení na báze teórie hromadnej obsluhy: Prípadová štúdia z Karélie

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Abstract
The modern technological process of timber harvesting is a complex system both technically and organizationally. Nowadays, the study of such systems and improvement of their efficiency is impossible without the use of mathematical modeling methods. The paper presents the methodology for the optimization of logging operations based on the queueing theory. We show the adapted queueing model, which characterizes the process of logging with the use of a harvesting set consisting of harvesters and forwarders. We also present the experimental verification of the designated model that confirmed mode`s adequacy. The analysis of the effectiveness of the investigated harvesting set was conducted and the recommendations for its optimization were drawn. The research was conducted in the Pryazhinsky District in the Republic of Karelia. We showed that significant improvement of operational efficiency of the investigated harvesting set in the study area cannot be done by adjusting separate machine operations (i.e. by reducing the time of operations execution and their steadiness). However, a change in the number of machines allowed significant improvement in the operational efficiency. The most optimal harvesting set design for the experimental area consisted of two harvesters and two forwarders.

Key words: queueing theory; harvester; forwarder; harvesting set; moddeling

Abstrakt
Moderný ťažbový proces predstavuje technicky aj organizačne komplexný systém. Štúdium takýchto systémov a zvyšovanie ich efektívnosti v súčasnosti nie je možné bez využitia metód matematického modelovania. V článku prezentujeme metódu na optimalizáciu ťažbového procesu založenú na báze teórie hromadnej obsluhy. Prezentujeme model hromadnej obsluhy pre zostavu ťažobných strojov pozostávajúcu z harvestorov a vývozných súprav. Okrem toho prezentujeme výsledky experimentálnej validácie navrhnutého modelu, ktoré potvrdili jeho funkčnosť. Výskum bol realizovaný v Prijažinskom regióne v Karélii. Z výsledkov vyplynulo, že významnejšie zlepšenie výkonnosti zostavy ťažbových zariadení v modelovom území nemôže byť dosiahnuté úpravou jednotlivých operácií (napr. skrátením času výkonu operácie). Naopak, zmeny počtu zariadení majú na výkonnosť ťažbovej zostavy zásadný vplyv. Optimálna ťažbová zostava pre podmienky modelového územia pozostáva z dvoch harvestorov a dvoch vývozných súprav.

Kľúčové slová: teória hromadnej obsluhy; harvestor; vývozná súprava; zostava ťažobných strojov; modelovanie

1. Introduction

The modern technological process of timber harvesting is a complex system both technically and organizationally. For example, in the European part of Russia and, in particular, in the Republic of Karelia, the Scandinavian mechanical harvesting method with the application of multi-operational machines, such as harvesters and forwarders, is widely used. Nowadays, the study of such systems and the improvement of their efficiency are impossible without the use of mathematical modeling methods. Recently, forest management optimization has received much attention. The mathematical models are, for example, widely used in harvest planning (Goycoolea et al. 2005; Constantino et al. 2008; Palma & Nelson 2009; Bohle et al. 2010; Wei & Murray 2012). An important area of the application of the methods of mathematical modeling is the selection of the optimal number, size and location of the logging camps (Shulman 1991; Peeters & Antunes 2001; Melo et al. 2005; Troncoso & Garrido 2005; Jena et al. 2012).

Mathematical modeling methods are actively used to optimize the processes of logging in steep terrain using air vehicles and cable haulage (Heinimann 1998; Epstein et al. 2006; Chung et al. 2008; Bont et al. 2012) or to optimize tree stem cutting (Sessions et al. 2005; Carlsson & Rönnqvist 2005; Flisberg et al. 2007; Chauhan et al. 2009; Dems et al. 2012).

The application of the mathematical modeling methods for the analysis and improvement of the logging operations has become a frequent practice. In Karelia, these methods have been developed by Voronin and Kuznetsov (2000), Shegelman (2003), Gerasimov (2011).

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One of the approaches widely applied in timber industry for the analysis and identification of options to improve technological processes is simulation using the queueing theory (QT). The QT is the branch of the theory of probability, which has recently gained considerable attention (Vinck & Bruneel 2006; Morozov et al. 2011; Atencia & Pechinkin 2013; Atencia et al. 2013; Atencia 2014). The QT has gained currency in transport, machine building, light industry, agriculture and other sectors (Buzacott & Shanthikumar 1993; Shanthikumar et al. 2003; Song 2013).

The methods of QT are used to determine the optimum supply of spare parts and units, as well as for the research and optimization of operations (Spanjers et al. 2006; Houtum & Kranenburg 2015; Moharana & Sarmah 2015). One of the important problems addressed by the QT and the probability theory is the analysis of processes performed on the assembly line or in flow-line production. In this case, the problem usually resides in the choice of a rational number of service channels.

The QT can be used to solve the problem of justification of the amount of raw materials or products, as well as managing these stocks (Ahiska & Kurtul 2014; Seyedhoseini et al. 2015). Another promising area is production scheduling, where in addition to optimization methods models and methods of the QT are used. The QT has been successfully used for the simulation of woodworking processes at lower landing (Rönnqvist 2003). The upcoming trend of the application of the QT methods is using them for the analysis and optimization of harvesting technological processes (Jakimovich & Teterin 2007).

Discontinuity is common for the operations performed by harvesting equipment. The question is whether this discontinuity is temporary or persisting. If the reasons of discontinuity cannot be removed, how can the discontinuity in raw material processing and forest product release be reduced? The importance and the need to settle these issues lie in the fact that this discontinuity is one of the main reasons which lead to a significant increase in freight operations during handling and transport operations, reduce machine utilization, result in the need for buffer and reserve stocks of raw materials and products, and lead to losses in productive efficiency. Undoubtedly, these questions can be answered with the help of the QT.

The traditional method of the simulation with the use of the QT is to describe harvesting processes with Markov processes and corresponding detailed equations for stationary probabilities of these processes. Such an approach, if it does not contain the final formulae with a small number of basic parameters, actually stultifies the models for at least two fundamental reasons. First, any similar model requires huge amounts of the initial data that is quite problematic to obtain. For example, correct determination of a possible state space of Markov process, or estimation of intensities of the process transitions between the states are separate complex problems. Second, even if such an array of the initial data can be obtained, the study of the developed complex model is extremely time-consuming without significant simplification of the final solution. Such a simplification stultifies the efforts spent on the development and the analysis of the detailed mathematical models. Moreover, even if recommendations can be obtained on the basis of this analysis, they turn out to be hardly applicable in the improvement of the harvesting processes structure. This implies that for the description of such processes only such models can be used, which can be parameterized using accessible data that can be collected in the field (average duration of an operation, its dispersion, etc.).

Developed models must adequately describe the real manufacturing systems and at the same time require only those initial data that is available for the researchers and correspond to the level of specification accepted in the mathematical model. Moreover, it is necessary to adapt the already well-developed probability models to the description of these processes to the maximum extent. The operating formulae in such models are, on the one hand, obtained on the basis of a detailed analysis reflecting the probabilistic nature and specificity of the process, and, on the other, they usually include only those parameters for which sample estimates can be relatively easily obtained as a result of the basic operations timing.

The main objective of this study is to optimize the logging operations equipment set by reducing the discontinuity of raw material processing and production on the basis of a probability model developed in this study. We propose the principles of rational choice of the structure of service system and service process by examining the flow of requests (demands) coming in and out of the system, service waiting time and the queue length. The research was conducted using the example of the Scandinavian mechanical logging method.

2. Materials and methods

2.1. Process of timber harvesting according to the Queueing Theory

The Scandinavian mechanical method of wood harvesting is based on the work of a machines complex consisting of a harvester and a forwarder. When developing harvesting areas, a harvester fells trees, abnodates and cross-cuts trunks into assortments, putting them lengthwise the skidding track. A forwarder collects assortments and trucks them on its platform, and then transports them to the place of stacking.

According to the queueing theory, the Scandinavian mechanical logging method can be regarded as a single-phase queueing system (QS). The QS consists of one or more machines that are generating requests and one or more machines that service these incoming requests. The request is a service demand. The service machine is called a service channel. Each channel is characterized by the service time. The service time is the period of time during which the request is served. Requests enter the system at random forming a random request flow.

The QS performs certain operations at requests. Timber assortments, separate trees or tree trunks, bundles of trees, etc., are considered as requests. Requests can enter the system individually or in groups. If requests exceed system`s capacity, they have to wait for service and queue occurs. In the opposite case, a harvesting machine stands idle.

Important characteristics of the QS are the average request service cycle time ($E[CT_s]$) and the quantity of requests in the system ($E[WIP]$). The cycle time of the QS (the workstation) is the period during which the request is in the QS. The quantity of the requests in the system is the average number or the service time expectation of the requests within the QS that are in service or waiting in the queue. The average service cycle time is generally defined as the sum of two components: the service time expectation ($E[T_s]$) and the average waiting time of the request waiting in the queue ($E[CT_q]$). The reciprocal of the service time expectation is the service flow rate (μ):

$$\mu = 1 / E[T_s] \qquad [1]$$

The relationship between the quantity of the requests in the system and the average cycle time is expressed by Little`s Law:

$$E[WIP] = \lambda \cdot E[CT_s] \qquad [2]$$

where λ is the requests arrival rate.

The requests arrival rate (λ) refers to the average number of requests per time unit or, in other words, the reciprocal of the time between the requests arrivals to the system ($E[T_a]$):

$$\lambda = 1 / E[T_a] \qquad [3]$$

The requests arrival rate is given by the machine that performs the set of preceding technological operations, and the requests service flow rate depends on the machine that performs the following operations.

In the QS simulation, it is primarily necessary to adopt several assumptions of the characterization of the input (λ) and service (μ) requests flows. Firstly, the statistical law of the requests arrival is the same at any time period, i.e. the flow is stationary. Secondly, the requests or the groups of requests enter the system independently. If $\lambda < \mu$ the system has a stationary mode describing the constancy of the statistical characteristics of the system performance.

2.2. Model Specification

A special notation, called Kendall`s notation, is used to describe a queueing system. The notation has the form *A / B / c / K,* where *A* describes the inter-arrival time distribution, *B* the service time distribution, *c* the number of servers, and *K* the size of the system capacity (Glover & Luguna 1997). The symbols traditionally used for *A* and *B* are *M* for exponential distribution, *D* for deterministic distribution, *G* for general distribution. When the system capacity is infinite ($K = \infty$) one simply uses the symbols *A / B / c*.

The approach proposed by Curry and Feldman (2009) was used in the analysis of wood harvesting. The method is based on the strict probabilistic analysis of the service processes for a wide range of industrial and technological systems.

Based on the work of the above authors, the Scandinavian mechanical method of wood harvesting can be considered as a queueing system with batch arrivals, where a tree load consisting of number of assortments serves as a request. G stands for a general distribution with known mean and variance.

A model diagram of the Scandinavian mechanical method of wood harvesting is shown in Figure 1.

The harvester`s work determines the intensity of the input flow ($\lambda_i(B)$). The variable $\lambda_i(B)$ describes the average number of tree loads produced by the *i–m* harvester per time unit. When producing *N* number of assortments, the request is considered to enter the system. The variable *N* is assumed random (integer-valued) with a general distribution (i.e., arbitrary distribution with known mean and variance). If a request (a group of *N* assortments) finds a servicer (forwarder) busy, it goes to the collector (skidding track). If the forwarder is free it starts servicing the request.

The forwarder work is characterized by the service rate ($\mu_i(B)$). The variable $\mu_i(B)$ is the average number of the requests served by the *j–m* forwarder per time unit.

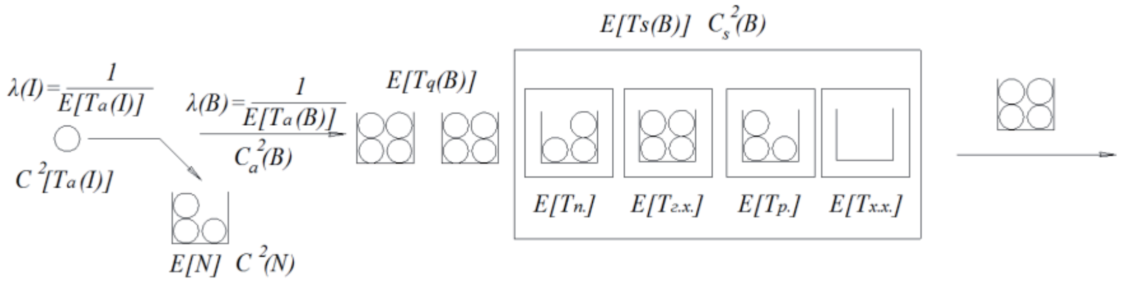

Fig. 1. Model diagram of the Scandinavian mechanical method of wood harvesting.

$\lambda(I)$ is the average number of assortments produced by all harvesters per time unit, $E[T_a(I)]$ is the mathematical expectation of the time between the periods of cutting the tree logs taking into account the work of all harvesters, $C^2[T_a(I)]$ is the square of the coefficient of variation of time of producing one assortment by the harvester, $E[N]$ is the mathematical expectation of the number of assortments in the tree load, $C^2[N]$ is the square of the coefficient of variation of the assortments number placed on the platform of the forwarder, $\lambda(B)$ is the average number of tree loads that are produced by all harvesters per time unit, $E[T_a(B)]$ is the mathematical expectation of the time between the periods of cutting the tree logs taking into account the work of all harvesters, $C_a^2(B)$ is the square of the coefficient of variation of the time of cutting the tree logs by all harvesters, $E[T_q(B)]$ is the average time of the request in the queue, $E[T_s(B)]$ is the average service time of the request, $C_s^2(B)$ is the square of the coefficient of variation of the service time of a tree load by a forwarder, $E[T_n]$ is the average loading time of the assortments by the forwarder, $E[T_{s.x.}]$ is the average transportation time, $E[T_p]$ is the average offload time of assortments at the loading site, $E[T_{x.x.}]$ is the average empty forwarder traveling time.

If m number of harvesters are at work, the arrival rate (the average number of assortments produced by all harvesters per time unit) can be considered as a sum of m independent flows with the total intensity of the input flow (the average number of assortments produced by all harvesters per time unit):

$$\lambda(I) = \sum_{i=1}^{m} \lambda_i(I) \qquad [4]$$

where m is the total number of the harvesters, $\lambda_t(I)$ is the average number of assortments produced by the $i–m$ harvester per time unit.

Note that the variable $\lambda(I)$ is linked up with $\lambda(B)$ (the average number of tree loads that are produced by all harvesters per time unit) by the formula $\lambda(B) = \lambda(I) / E[N]$, where $E[N]$ is the mathematical expectation of the number of assortments in the tree load.

Modeling is aimed at identifying two most important steady-state characteristics: the average length of the request service cycle ($E[CT_s]$) and the average number of the requests in the system ($E[WIP]$).

For the queueing system with batch arrivals the variable $E[CT_s]$ is defined as:

$$E[CT_s] = E[D] + E[T_q(B)] + E[T_s(B)] \qquad [5]$$

where $E[D]$ is the mathematical expectation of the time for cutting the tree loads by all harvesters (request forming time), $E[T_q(B)]$ is the average time the request spends in the queue, $E[T_s(B)]$ is the average service time of the request.

The variable $E[D]$ is determined on the basis of Wald's identity:

$$E[D] = E[N] \cdot E[T_s(I)] \qquad [6]$$

where $E[T_s(I)] = 1/\lambda(I)$ is the mathematical expectation of the time between the periods of cutting the tree loads taking into account the work of all harvesters.

The average time spent by a pack of assortments in the queue during the work of several forwarders is given by the following formula:

$$E[CT_q] = \left(\frac{C_a^2(B) + C_s^2(B)}{2}\right) \cdot \left(\frac{u(B)^{\sqrt{2 \cdot c + 2} - 1}}{c \cdot (1 - u(B))}\right) \cdot E\left[T_s(B)\right] \qquad [7]$$

where $C^2_a(B)$ is the square of the coefficient of variation of the time of cutting the tree loads by all harvesters, $C^2_s(B)$ is the square of the coefficient of variation of the service time of a pack by a forwarder, is the coefficient of loading, $u(B)$ is the number of the servicers (the number of the forwarders).

The coefficient of loading for several servicers is determined by the relation:

$$u(B) = \lambda(I) / (u(B) \cdot E[N] \cdot c) \qquad [8]$$

where c number of forwarders work the service total intensity is determined by:

$$\mu(B) = \sum_{j=1}^{c} \mu_j(B) \qquad [9]$$

The variable $C^2_a(B)$ is given by the formula:

$$C_a^2(B) = \sum_{i=1}^{m} \frac{\lambda_i(B)}{\lambda(B)} \cdot C_{a,i}^2(B) \qquad [10]$$

where the variable $\lambda_t(B)$ is the average number of tree loads produced by the $i–m$ harvester per time unit which is linked up with the variable $\lambda_t(I)$ following the expression $\lambda_t(B) = \lambda_t(I) / E[N]$, $C^2_{a,i}(B)$ is the square of the coefficient of variation of the time of cutting the tree loads by the $i–m$ harvester.

The variable $\lambda_t(I)$ is given by the following formula:

$$\lambda_t(I) = 1/E[T_{a,i}(I)] \qquad [11]$$

where $E[T_{a,i}(I)]$ is the mathematical expectation of the time of cutting the tree loads by the $i–m$ harvester.

The variable $C^2_{a,i}(B)$ is determined by the formula:

$$C_{a,i}^2(B) = \frac{C^2\left[T_{a,i}(I)\right]}{E\left[N\right]} + C^2[N] \qquad [12]$$

where $C^2[T_{a,i}(I)]$ is the square of the coefficient of variation of time of cutting one assortment by the $i–m$ harvester, $C^2[N]$ is the square of the coefficient of variation of the assortments number placed on the platform of the forwarder.

The variable $C^2[T_{a,i}(I)]$ is given by the formula:

$$C^2[T_{a,i}(I)] = V[T_{a,i}(I)] / E[T_{a,i}(I)]^2 \qquad [13]$$

where $V[T_{a,i}(I)]$ is the dispersion of assortment sawing time by the $i–m$ harvester.

The value of the variable $C_s^2(B)$ is defined as the weighted average:

$$C_s^2(B) = \sum_{j=1}^{c} \frac{\mu_j(B)}{\mu(B)} \cdot C_{s,j}^2(B) \qquad [14]$$

where $\mu_i(B)$ is the average number of the tree loads serviced by the $j–m$ forwarder per time unit, $\mu(B)$ is the total intensity of the service flow, $C^2_{s,j}(B)$ is the square of the coefficient of variation of the service time of the tree load by the $j–m$ forwarder.

The value of $C^2_{s,j}(B)$ is determined by the following expression:

$$C^2_{s,j}(B) = V[T_{s,j}(B)] / E[T_{s,j}(B)]^2 \qquad [15]$$

where $V[T_{s,j}(B)]$ is the dispersion of the service time of the tree load by the $j–m$ forwarder, $E[T_{s,j}(B)]$ is the service time expectation of the tree load by the $j–m$ forwarder.

During the operation of c forwarders, the variable $E[T_s(B)]$ is defined as the arithmetic average:

$$E\left[T_s(B)\right] = \sum_{i=j}^{c} E\left[T_{s,j}(B)\right] \Big/ c \qquad [16]$$

The service time of the pack of assortments by the $j–m$ forwarder consists of four components:

$$T_{s,j}(B) = T_n + T_{s.x.} + T_p + T_{x.x.} \qquad [17]$$

where T_n is the loading time of the assortments by the forwarder, $T_{s.x.}$ is the tree load transportation time, T_p is the assortments off-load time at the loading site, $T_{x.x.}$ is the empty forwarder traveling time.

The general expression for the calculation of the average requests service cycle length for the harvesting set consisting of one harvester and one forwarder is:

$$E[CT_s] = E[N] \cdot E[T_a(I)] + \left(\frac{C^2\left[T_a(I)\right] \big/ E[N] + C^2[N] + C_s^2(B)}{2}\right) \cdot \rightarrow$$
$$\rightarrow \cdot \left(u(B)/1 - u(B)\right) \cdot E\left[T_s(B)\right] + E\left[T_s(B)\right] \qquad [18]$$

We emphasize that in practice all mentioned variables that characterize the properties of the service of the tree load by the forwarder and the assortments sawing time of the harvester are defined as the sample estimates derived from the field measurements.

2.3. Experimental Test Procedure

To test the above described model, the experimental studies aimed at collecting statistical data to determine the variables: $E[T_a(I)]$, $C^2[T_a(I)]$, $E[T_s(B)]$, $C_s^2(B)$, $E[N]$, $C^2[N]$ as well as to obtain the empirical value of $E[CT_s]$, were carried out.

The experiments were performed in a harvesting area in the Pryazhinsky District of the Republic of Karelia. The harvesting area was reclaimed by the harvesting set owned by the closed joint stock company (CJSC) "Shuyales". The harvesting set included John Deere 1270D Eco III harvester and John Deere 1110D Eco III forwarder. The harvesting area can be thought of as typical of the southern region of the Republic of Karelia.

The statistical data were obtained from the measurements of the forwarder work and the harvester microtime work.

The microtime work measurements were carried out continuously using a video camera. The observations were made twice per shift, the first time an hour after the start of the shift and the second time 2 hours before the end of the shift. The time between assortments arrivals was found on the ground of footage.

The beginning and the end of the operations performed by the forwarder were registered with the use of the stopwatch and the prearranged observation checklists. The time-study was conducted twice per shift, first 30 minutes after the start, and the second time 4 hours prior to the end of the shift.

During the work measurements, shooting of the rear part of the forwarder platform packed with the assortments was made to determine the number of the loaded assortments.

2.4. Estimated Characteristics of the Model

The important estimated characteristics of the model are the average cycle length ($E[CT_s]$), the load factor ($u(B)$), the average dwelling time of the request (the pack of the assortments) in the queue ($E[T_q(B)]$), the average number of the requests in the system ($E[WIP]$) and the average number of the requests in the queue ($E[WIP_q]$).

The average time spent by a request (a pack of assortments) in the queue ($E[T_q(B)]$) shows how lon the request that arrived to the system (the pack of the assortments produced by the harvester) waited for the service. The smaller this variable is, the more regularly the system works and, in general, the more efficient it is.

The average cycle length ($E[CT_s]$) includes the time of the request formation, the time spent by the request in the queue, and the time of its service. The decrease of this variable means the reduction of the average time spent by the assortments in the harvesting are, that eventually leads to more productive work of the harvesting machines providing that the average characteristics of the tree load stay unchanged ($E[N]$ and $C^2[N]$).

The load factor ($u(B)$) shows how much the servicers (the forwarders) are loaded. In the case of a single device, if $u(B) > 1$, the servicer overloaded. If $u(B) < 1$, the servicer is underloaded and will stand idle during the time period that equals $1–u(B)$. It is important to note that when the load factor is approaching one, the variable of the queue (and the work in progress) increases nonlinearly, which is one of the main reasons that lead to overloading of the production system and, as a result, the breakdown of the production schedule.

The average number of the requests in the system ($E[WIP]$) show, how many finished assortments are in the cutting area on average. The forwarder platform John Deere 1110D Eco III has a room for about 10 m^3 of assortments. Thus, one request has an average volume of 10 m^3.

3. Results

3.1. Practical Implementation of the Model

The spread (dispersion) of the assortments arrival time and the pack of the assortments service time are defined in the model by the variables $C^2[T_a(I)]$, $C^2_s(B)$. Their reduction indicates the increase in work steadiness of the machine. The relationship between the variables $C^2[T_a(I)]$, $C^2_s(B)$ and the calculated variables ($E[CT_s]$, $E[T_q(B)]$, $E[WIP]$) is positive linear. For example, if $C^2_s(B)$ is reduced by 10% compared with the initial value, the average time spent by the request in the system ($E[CT_a]$) and the average number of the requests in the system ($E[WIP]$) is reduced by only 0.31%. The load factor ($u(B)$) does not change. The average request residence time in the queue will decrease by 4.78%. This implies that the change in the steadiness of the machine work over a fairly wide interval (the changes of the variables $C^2[T_a(I)]$ and $C^2_s(B)$ up to 100% at the constant variable $E[T_a(I)]$) has no significant effect on the harvesting set performance.

The change in the average time between assortment sawing periods ($E[T_a(I)]$) influences the calculated variables more significantly (Fig. 2).

The analysis showed that the decrease in the average time between assortment sawing periods ($E[T_a(I)]$) up to 20% allows to slightly shorten the average cycle length ($E[CT_s]$) and the average request (tree load) residence time in the queue ($E[T_q(B)]$) with a slight decrease of the load factor ($u(B)$). The decrease of the variable ($E[T_a(I)]$) by more than 20% leads to the forwarder overloading as $u(B) > 1$. At the same time, the increase in the average time between assortment sawing periods leads to the increase in the average cycle length and the decrease of the load factor.

The change of the variable ($E[T_a(I)]$) can lead to significant changes of the calculated variables. In practice, this variable depends on harvester construction, operator`s experience and running performance, taxational indicators of the harvesting area and other characteristics.

To a large extent, the calculated variables are influenced by the mathematical expectation (average sampling) of the tree load service time ($E[T_s(B)]$) (Fig. 3).

The reduction of the variable $E[T_s(B)]$ leads to the reduction of the variable $E[T_s(B)]$ by 10%, reduction of $E[CT_s]$

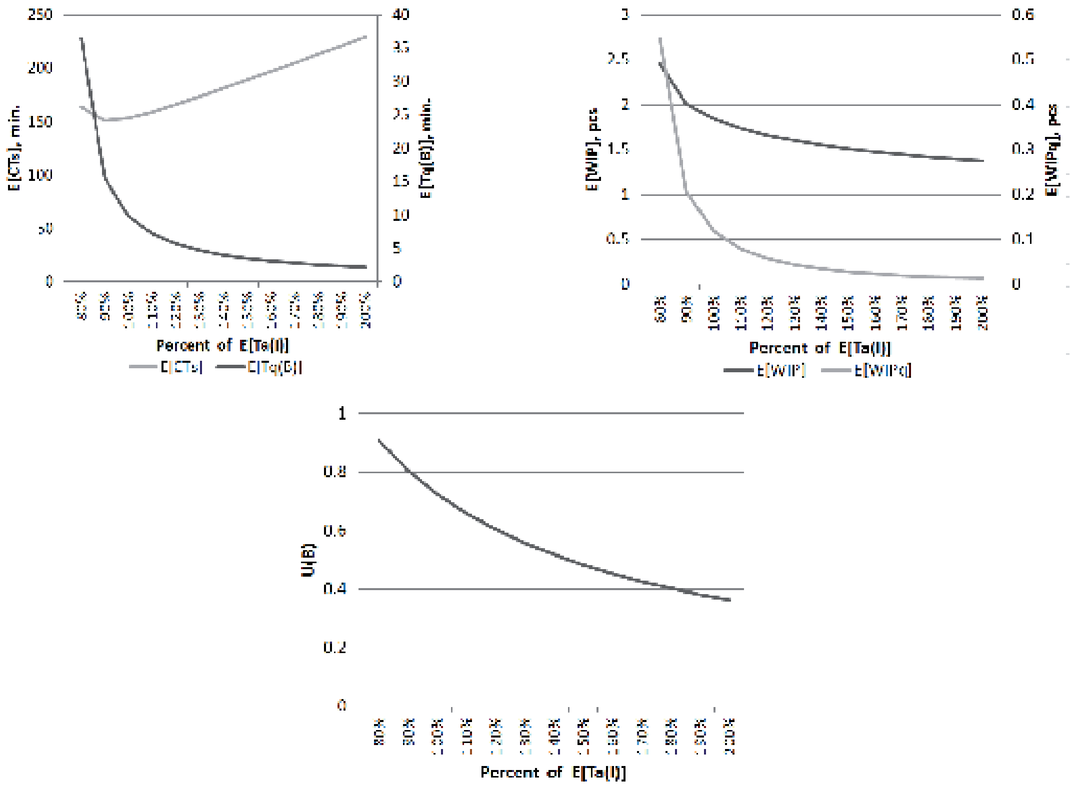

Fig. 2. Plots of the calculated variables against the mathematical expectation of the time between the periods of cutting out the tree where $E[T_a(I)]$ is the average time between assortments sawing periods, $E[CT_s]$ is the average cycle length, $E[WIP]$ is the average number of the requests in the system, $E[WIP_q]$ is the average number of the requests in the queue, $u(B)$ is the load factor.

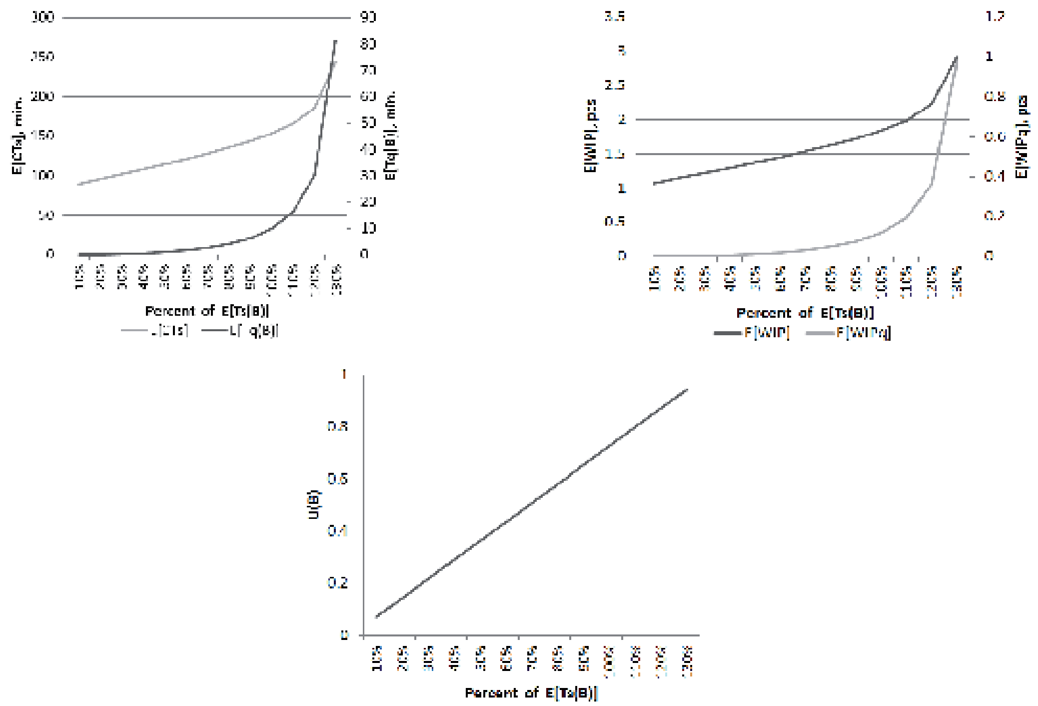

Fig. 3. Plots of the calculated variables against the average service time of the request where $E[T_s(B)]$ is the mathematical expectation (average sampling) of the tree load service time, $E[CT_s]$ is the average cycle length, $E[WIP]$ is the average number of the requests in the system, $E[WIP_q]$ is the average number of the requests in the queue, $u(B)$ is the load factor.

and $E[WIP]$ by 6%, $E[T_q(B)]$ by 36%, and $u(B)$ by 10%. The increase of the mathematical expectation of the tree load service time by more than by 30% leads to forwarder`s overloading ($u(B) > 1$).

A simultaneous increase of $E[T_s(B)]$ by 10% and a reduction of $E[T_a(B)]$ by 10% results in the increase of $E[CT_s]$ by 13.10%, $E[WIP]$ by 25.67%, $E[T_q(B)]$ by 226. 71%, and $u(B)$ by 22.22%.

Reducing $E[T_s(B)]$ by 10% and increasing $E[T_a(I)]$ by 10% at the same time causes reduction of $E[CT_s]$ by 1.75%, $E[WIP]$ by 10.68%, $E[T_q(B)]$ by 50.29%, and $u(B)$ by 18.18%.

The above observations imply that the operational efficiency of the investigated harvesting sets cannot be improved considerably by controlling their operations (i.e., by changing the variables $E[T_a(I)]$, $E[T_s(B)]$, $C^2[T_a(I)]$, $C^2_s(B)$.

The pattern of the calculated values changes depending on the changes in the number of operating harvesting machines (Fig. 4). In the figure, 1–1 is a harvesting set consisting of one harvester and one forwarder, 2–2 is a harvesting set consisting of two harvesters and two forwarders, etc.

The increase of the number of the forwarders operating in conjunction with one harvester reduces the average cycle length ($E[CT_s]$), and the average request (tree load) residence time in the queue ($E[T_q(B)]$). However, in this case, the load factor ($u(B)$) is significantly reduced. In practical terms, this will lead to the forwarders idle time. To make a decision in such a case it is necessary to carry out additional cost estimates.

The multiple increase of the arrival rate, which corresponds to the parallel operation of several harvesters, also leads to a decrease of the calculated variables ($E[CT_s]$, $u(B)$, $E[T_q(B)]$, $E[WIP]$, $E[WIP_q]$). However, in this case, we obtain higher values of the load factor. The graphs in figure 4 show that the use of 2–2 sets (i.e. two harvesters and two forwarders work in the same complex) and 3–3 leads to the reduction of the calculated variables ($E[CT_s]$, $E[T_q(B)]$ as compared to the set of 1–1, while the load factor remains unchanged. Such an increase of efficiency is due to the fact that while working in the same complex they compensate the irregularity in operation of separate harvesting machines.

Besides note that the sets of 2–1, 3–2 and 3–3 are not recommended to use since in these cases the load factor exceeds one.

3.2. Model Validation

To determine the variables $E[T_a(I)]$, $C^2[T_a(I)]$, the sampling from 685 field measurements was performed. Then, 100 measurements were taken to calculate the variables $E[T_s(B)]$, $C^2_s(B)$, $E[N]$ and $C^2[N]$. The results of the statistical analyses of field measurements are shown in distribution histograms (Fig. 5).

The evaluation of the mathematical expectations was carried out by determining the sample means:

$$E[x] = \sum_{i=1}^{k} m_i \cdot x_i \Big/ n \qquad [19]$$

where x_i is the class mark, m_i is the absolute frequency, n is the amount of sampling, k is the number of the intervals.

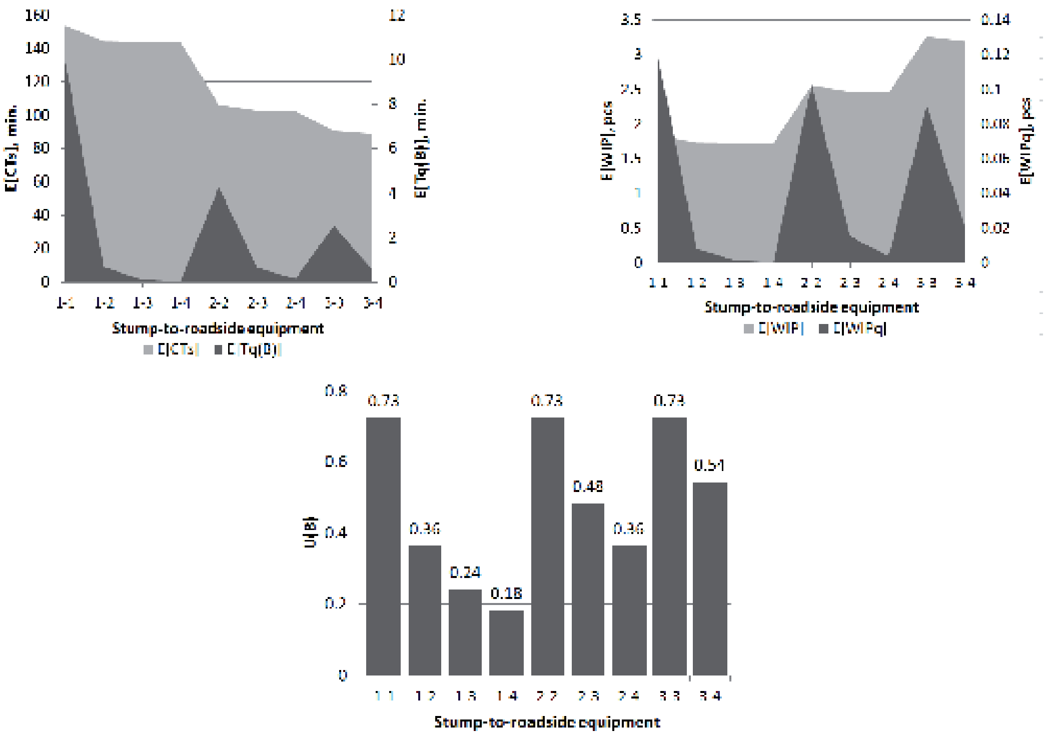

Fig. 4. Plots of the calculated variables for various harvesting sets. $E[CT_s]$ is the average cycle length, $E[WIP]$ is the average number of the requests in the system, $E[T_Q(B)]$ is the average dwelling time of the request (the pack of the assortments) in the queue, $E[WIP_Q]$ the average number of the requests in the queue, $u(B)$ is the load factor, 1–1 is a harvesting set, which consists of one harvester and one forwarder, and 2–2 is a harvesting set, which consists of two harvesters and two forwarders, etc.

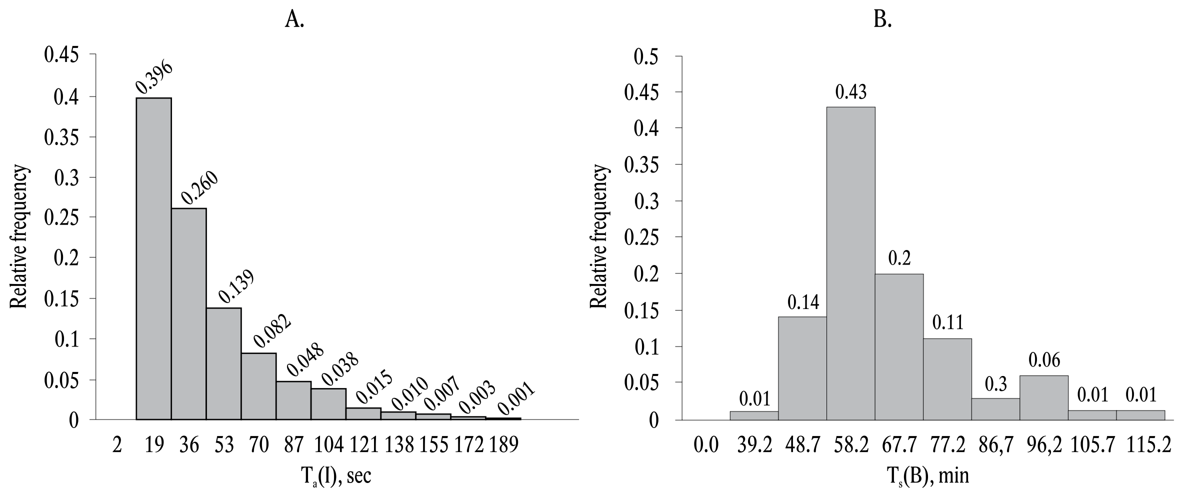

Fig. 5. The results of statistical analyses of field measurements. A is the distribution of the time between the periods of cutting the tree by a harvester ($T_a(I)$) and B is the distribution of service time of the request by a forwarder ($T_s(B)$).

The dispersion was estimated according to the average sample variance:

$$V[x] = \sum_{i=1}^{k} (x_i - E[x])^2 \cdot m_i \Big/ (n-1) \qquad [20]$$

The square of the coefficient of variation was determined with the use of the formula:

$$C^2[x] = V[x] / E[x]^2 \qquad [21]$$

According to the results of the statistical processing of the experimental data, the following values of the unknown variables were obtained: $E[T_a(I)]) = 34$ sec., $C^2[T_a(I)] = 0.803$, $E[T_s(B)] = 3628$ sec., $C^2_s(B) = 0.059$, $E[N] = 147$ pcs., $C^2[N] = 0.059$.

The analysis of the experimental data showed that the empirical value of the variable $E[CT_s]$ is 8549 seconds or 2.37 hours.

The calculation of the variable $E[CT_s]$ according to the described model [Eq. 20] is provided below.

$$u(B) = 3628/(147 \cdot 34) = 0.726$$

$$E[T_q(B)] = \left(\frac{0.803/147 + 0.059 + 0.059}{2} \right) \cdot$$

$$\cdot \left(\frac{3628/(147\ .\ 34)}{1 - 3628/(147\ .\ 34)} \right) .\ 3628 = 593 \text{ sec.}$$

$$E[CT_s] = 147 \cdot 34 + 593 + 3628 = 9219 \text{ sec.} = 2.56 \text{ hrs.}$$

$$E[WIP] = 9219 / 147 \cdot 34 = 1.84 \text{ pcs.}$$

Thus, the average cycle length ($E[CT_s]$) calculated by the model is 2.56 hours, and 2.37 hours if obtained directly from the experimental data. This implies 93% match of the measured and modelled values.

4. Discussion

The efficacy of the proposed model was confirmed by the experimental data. We assume that the discrepancy between the calculated and the empirical values of the variable $E[CT_s]$ is primarily due to the method used in the experimental studies and to the method of calculation of the empirical value of the unknown variable. Specifically, there was no option to determine accurately the terminal time of the pack formation by the harvester, as it was necessary to know in advance how many assortments would fit in on the forwarder platform. To simplify the experiments, the moment when the harvester worked out the regular 10 m^3 of the assortments (the amount that fits in on the forwarder platform) was taken as the terminal time of the pack formation. We assume that this imprecision made the largest contribution to the discrepancy between the simulated and measured average cycle lengths. In addition, the influence of the simplifications made in the model should be taken into account.

To determine the optimal set of the harvesting machines using the proposed model, it is necessary to choose the smallest value of the variable $E[CT_s]$ when the value of $u(B)$ is as close as possible to 1, and the values of $E[T_q(B)]$ and $E[WIP_q]$ are close to 0. It is also necessary to consider the value of the variable $E[WIP]$. The increase in the number of machines in one harvesting set leads to the increase in the average number of packs in the system. For example, in the initial version the average number of packs is 1.84 units. That means that there are about 18.4 m^3 of assortments in the harvesting area. When 3 harvesters and 4 forwarders are at work, $E[WIP] = 3.19$, which is an equivalent of 31.9 m^3 of assortments along the skidding tracks, on average.

If we take into account the small size of the cutting area where the experiments were conducted, the most optimal harvesting set could consist of two harvesters and two forwarders. This is due to the fact that the use of a large number of harvesting machines in the investigated cutting area is difficult because of to the complexity of organization of their simultaneous work. Besides, negative impact of the machines on the environment should be considered.

The proposed model has some disadvantages. Firstly, it is necessary to understand that the model provides an approximate description of the Scandinavian mechanical method of wood harvesting, since a number of simplifications and assumptions had to be adopted during the model development. Hence, model`s capacity to adequately characterize the probabilistic processes that occur during the harvesting machines operation is limited. Therefore, when using the model one should not focus on minor changes in the estimated characteristics.

To guide the design of harvesting sets for a new cutting area, it is necessary to carry out new measurements and calculations to customize the model to fit the new conditions adequately.

It is noteworthy that the model does not allow taking into account some peculiarities of the QS, for example, limits to the queue length, differences in technical features, machine breakdown frequency and their repair time, shifts of the operators and changes in their performance during the work at the cutting area, as well as identifying some important parameters, such as downtime of separate machines.

The frequent equipment failure can adversely affect the operating conditions of the machines that will limit the applicability of the proposed model. For example, the model needs to be calibrated for different levels of operators` skills, because the adequacy of the model might decrease without calibration. Reduced adequacy can also be expected when working with a set of forwarders with different load capacities, since the model does not account for that. Different costs per operator`s working hours belong to other factors that might cause that the model does not obtain an adequate solution. For example, this situation may occur while operating the machines of different age.

Despite the mentioned drawbacks, the model allows to promptly analyze how the technological process will respond to changes in some system parameters.

The method of improvement of the efficiency of the Scandinavian mechanical method of wood harvesting based on the probabilistic mathematical models was used in the works by Jakimovich and Teterin (2007). The method was based on an attempt to describe the process of timber harvesting with the use of Markov processes. For this purpose, the differential equation systems of the subsystem state probabilities were formed and, on their basis, the linear algebraic equations were derived. To solve these equations, the specialized mathematical packages such as Maple and MatLab were used. In practice, however, such an approach can cause difficulties. Firstly, the problems may occur due to the need for a large amount of statistical data. Secondly, the specific results cannot be obtained by simple calculations, since they require the use of the specialized mathematical packages. The average worker of the forestry sector does not possess skills to use these mathematical packages.

We argue that the method based on the adaptation of the well-developed mathematical models is more practical, though rougher. One of the examples of such an approach is the proposed mathematical model, the adequacy of which was confirmed by the experimental observations.

5. Conclusion

The presented research showed the possibility to use the customized queueing models for the analysis and optimization of the logging processes. We found that the productivity of the Scandinavian mechanical harvesting method can be increased by changing the number of machines in the harvesting set. The proposed approach can be used directly by forest enterprises in harvest planning, because the characteristics of the described model are obtained fairly straightforward by observing the operations of harvesting machines. Moreover, the calculation of the indicators using the model does not require high proficiency of an operator nor specialized mathematical software.

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