Annals of Warsaw University of Life Sciences – SGGW
Agriculture No 62 (Agricultural and Forest Engineering) 2013: 37–45
(Ann. Warsaw Univ. Life Sci. – SGGW, Agricult. 62, 2013)

Analysis of harvester's operation time utilization – mathematical model

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Abstract: *Analysis of harvester's operation time utilization – mathematical model.* Economic effects of application of large-productivity machines is closely related to organization of the harvesting process. The time losses on additional, unconnected with production phases of that process are especially important. Under Polish conditions, such phase includes e.g. machine passages to a night parking place, as well as passages between particular tasks resulted from splitting of these tasks. The undertaken investigations aim at explaining of the effect of selected organization factors on operating productivity of multifunctional machines. The dependences that determine duration of particular phases have been formulated together with the balance indices of working shift time. The presented model enables to learn the working day structure and can be useful in the process of undertaking decisions to improve organization of large-productivity machines' operation in Polish forests.

Key words: timber harvesting, harvester's productivity, organization of timber harvesting process, working shift structure

INTRODUCTION

Application of specialized forest machines of very large productivity has become a real fact in Poland [Więsik and Nurek 2002]. More and more forest inspectorates perform timber harvesting with the use of harvesters, logging with the use of forwarders or general purpose agricultural tractors coupled to the self-loading trailers. These technologies combine many advantages. Undoubtedly, the most important are: improvement of produced raw material quality, improvement of work safety, reduction of realization time in particular tasks. However, a basic condition for application of mechanized timber harvesting is achievement of lower specific costs, when compared to traditional technologies. Under conditions of Polish forestry, obtaining of satisfactory specific costs of timber harvesting with multi-functional machines (resulted directly from their productivity) meets the objective difficulties [Moskalik 2000]. Most important of them result from: structure of forest complex area, used methods of silviculture, methods of final cuttings and culture conditions. The following facts (unfavourable from economic point of view) are especially important: small area and scattering of forest complexes, small area of cuttings resulted from the methods used in silviculture (growing importance of the group cutting), traditional one-shift working day, leaving machines on the working site not possible (on the forest site) [Giefing 1999]. As a most favourable situation one can assume the machine operation on very large area (final cutting) that provides the scope of work for many days in the two- or three-day shift system. The machine would be left on forest site, while the operators and exploitation material would be delivered to the working site [Nurek 2005]. Such organization of machine timber harvesting can be found in Scandinavia. It can be regarded as optimal solution that enable to obtain the highest operating productivity (executed during a single working day). Unfortunately, due to above circumstances, a certain part of working day is taken by the operations unconnected with production; it results in a decrease in operating productivity and a increase in specific costs of timber harvesting [Więsik and Nurek 2005].

MATERIAL AND METHODS

The undertaken investigations aim at determination of the effect of selected factors on the structure of working day utilization. The carried out analyses concern realization of forest operations on a large area (forest inspectorate, regional management of the state forests), since some of considered events cannot be taken into account in the case of single task only. The preliminary analyses [Botwin 1993, Jabłoński 1998] enabled to distinguish and define the following phases of working day and to assign them the appropriate times:

– execution of technological operations, T^c_{02},
– passages between tasks, T^c_{61},
– passages between tasks and bases, T^c_{62} ,
– identification of tasks, T^c_{71},
– identification and taking of bases, T^c_{72},
– breaks, T^c_{3-5} ,
– down-times, T^c_{73}.

Among these phases only execution of technological operations is directly connected to production (T^c_{02}). It includes the times of tree processing (felling, debranching, cross cutting) and the times of necessary passages between subsequent trees. Duration of this phase is most often independent of organization factors. It results from the stand properties and nature of the executed task (number of cut assortments, type of cutting). The remaining distinguished phases include auxiliary operations that occur always and are independent of taken up organization variant and the current natural-forest conditions. For example, it is necessary to provide the regenerative breaks for staff and the down-times for machine servicing (T^c_{3-5}, and T^c_{73}.). Duration of the remaining mentioned phases depends on taken up technological solutions and conditions of operations. The other organization factors (that are rarely discussed in available references) are also very important: scope of tasks, their concentration on a relatively small area, distance of machine passages.

RESULTS AND DISCUSSION

Passages between tasks (T^c_{61}) and between tasks and bases (T^c_{62})

The initial observations showed that under Polish forest conditions the large part of working day is taken by machine passages. Two kinds of passages can be distinguished: between parking place and the task, and between the tasks. During a single working day (assuming occurrence of many tasks and necessity of machine parking in bases) one can distinguish the following situations (Fig. 1).

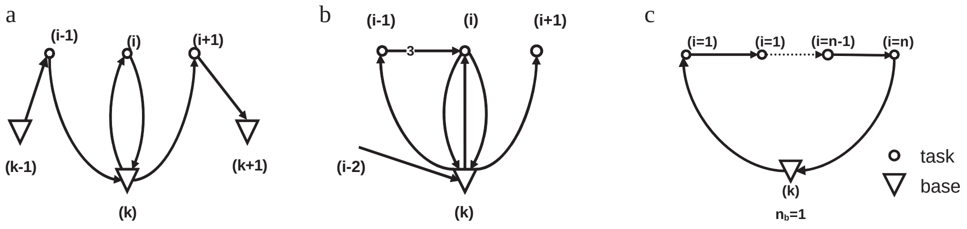

FIGURE 1. Routes of harvester passages during working day

Direct passages between tasks (*i*) during the working day do not occur, if upon completion of every task (with limited time of working day) the operator has the time left only for the passage to base (Fig. 1a). It is a special case, when the task volume equals with the harvester's daily productivity or its multiplicity.

Another special case is situation when the harvester after every working day stays on the site and does not return to overnight base (*k*) (e.g. when operator is transported to machine parking place). Therefore, during the realization period of all tasks only two harvester's passages occur: between the base (central) and the tasks – passage to the first task and passage to base upon completion of the last one (Fig. 1c).

Under Polish conditions one cannot leave the machine on the felling site upon completion of working day; therefore, in some cases the harvester's passages both between tasks and between the task and base occur (Fig. 1b). Please note, that after execution of task (*i* – 1) the realization of 3-day task (*i*) starts the same day, an then (*i* + 1).

Considering these cases, duration of all the passages between tasks on a given site can be described with equation:

$$T_{61}^{c} = \frac{(n_z - 1) \cdot l_{zz} \cdot \eta_{61}}{v_1} \quad [\mathrm{h}]$$

where:
n_z – number of tasks;
l_{zz} – distance between tasks in km;
v_1 – speed of machine travel between tasks in km/h.

If number of tasks is big, one can roughly assume that:

$$T_{61}^{c} = \frac{n_z \cdot l_{zz} \cdot \eta_{61}}{v_1} \quad [\mathrm{h}]$$

Coefficient η_{61} determines the real number of passages between tasks in relation to number of tasks realized on the site. Its value, as it is evident from previous considerations, can be contained in the interval $0 \leq \eta_{61} \leq 1$ ($\eta_{61} = 0$ – Fig. 1a, $\eta_{61} = 1$ – Fig. 1c, neglecting two passages to the central base).

It is evident from the above equations that duration of passages between tasks increases along with an increase in number of tasks (n_z), distance (l_{zz}) and value of coefficient (η_{61}), while it decreases with an increase in ground speed (v_1).

There is exact connection between n_z and l_{zz}, since both magnitudes are considered for the same area. An increase in number of tasks causes a decrease in distance between them l_{zz}. However, one should bear in mind that along with an increase in number of tasks, the value of coefficient η_{61} increases also.

Assuming the regular distribution of tasks on area s_o (e.g. on the area of forest inspectorate) and introducing coefficient that determines timber quantity harvested from area unit, one can obtain the equation to determine time of passages of the following form:

$$T_{61}^{c} = \frac{\eta_{61}}{10 \cdot v_1} \cdot \sqrt{\frac{Q_c \cdot n_z}{\gamma}} \quad [\mathrm{h}]$$

where:
Q_c – timber quantity harvested from administrative area unit in m^3;
$\gamma = \frac{Q_c}{S_o}$ – coefficient that determines quantity of timber harvested from administrative area unit in m^3/ha.

The above dependence enables to investigate relations between the basic quantities that characterize tasks planned for realization on the large area (forest inspectorate) and the time for passages between them. A significant parameter resulting from abundance of Polish tree stands and the taken up principles of forest utilization is the coefficient that determines the timber quantity harvested from administrative area unit of forest inspectorate.

In order to determine the sum of harvester's passage time between tasks one can assume that at the end of every working day the machine returns to the base closest to the next task. As it is evident from Figure 1, it can be return to the same base or passage to the next one. Similarly to distribution of tasks, the regular distribution of bases was assumed. Therefore, the distance between them can be determined with equation:

$$l_{bb} = \frac{1}{10} \cdot \sqrt{\frac{S_o}{n_b}} \quad [\mathrm{km}]$$

where:
n_b – number of bases;
S_o – considered area in ha.

At regular distribution of tasks and bases, the distance of passage between the base and task (l_{zb}) is smaller than the distance between bases (l_{bb}). If the base is situated in the center of square area of side l_{bb}, the closest task can be situated at distance ranged from $l_{zb} = 0$ to $l_{zb} = l_{bb} \cdot \sqrt{\frac{1}{2}} \approx 0.71 \cdot l_{bb}$. Generally, the average distance between base and tasks can be determined with expression:

$$l_{zb} = \eta_{62} \cdot l_{bb} \quad [\mathrm{km}]$$

Value of coefficient η_{62} is a characteristic quantity for the real forest areas; its value is contained in interval $0 \leq \eta_{62} \leq$ ≤ 0.71.

The time of all passages between bases and tasks on the analyzed area can be calculated with equation:

$$T_{62}^{c} = \frac{2 \cdot n_d \cdot \eta_{62}}{10 \cdot v_2} \sqrt{\frac{S_o}{n_b}} = \frac{2 \cdot n_d \cdot \eta_{62}}{10 \cdot v_2} \sqrt{\frac{Q_c}{\gamma \cdot n_b}} \quad [\mathrm{h}]$$

where:
v_z – speed of machine travel between base and task in km/h;
n_d – number of task realization days.

Identification of tasks (T_{71}) and identification and taking of bases (T_{72})

The safe and most effective execution of every task calls for operator's knowledge of working conditions. Especially important are information that concern:

- direction of machine movement during felling and cutting assortments,
- type of cut assortments,
- method for arranging assortments on the site.

In every started task the operator has to devote time for:

- programming of board computer,
- checking accuracy of measurements executed by the harvester's head.

The hitherto observations and information of machine users point out that it needs always from 0.5 h – on open fellings and at cutting of two assortments of different length to 1 h – in thinning or harvesting of bigger number of more diversified assortments.

Assuming average value of the task identification time (t_{71}) one can calculate the total time for these operations:

$$T^{c}_{71} = t_{71} \cdot n_z \quad [\mathrm{h}]$$

Necessity of proper machine protection during night parking and during free days calls also for appropriate preparation of the equipment parking base. Usually, these are not constant bases, therefore, the passage to them calls for proper organization and functional adaptation, namely:

- preventing access of outsiders,
- enabling execution of daily maintenance of machines,
- securing of materials needed for daily operation of machines (fuel, lubricants, chain saws).

The users' information point out that the time needed for base preparation ranges from 2 to even 4 h, depending on state of base and the assumed requirements.

Taking into consideration that it is substantial time, the organizers of harvester's work should plan the machine parking places so, that every base can service the bigger number of tasks realized longer than one day. However, a decrease in number of bases results in an increase in the distance of machine travel to them.

Considering the method for utilization of bases one can distinguish the two extreme cases:

- machine will stay in every base only once (many subsequent days),
- execution of every task calls for preparation of a "new base".

The total time for base preparation on considered area will be included in the following interval:

$$t_{72} \cdot n_b \le T^{c}_{72(\max)} \le t_{72} \cdot n_z \quad [\mathrm{h}]$$

where t_{72} is preparation time for one base in h.

General equation that corresponds with various conditions of harvesting can be written as follows:

$$T^{c}_{72} = t_{72} \cdot n_z \cdot \eta_{72} \quad [\mathrm{h}]$$

where: η_{72} is coefficient included in the range:

$$\frac{n_b}{n_z} \le \eta_{72} \le 1$$

Phase of breaks (T^c_{3-5})

Two groups of breaks in operation were taken into consideration. The breaks essential for operator and caused by his evacuation and also the technical and technological breaks. These breaks will be considered together, with their assumed share in the working day. These times during a single working day can be described by dependence:

$$T_{3-5} = \alpha \cdot T_{07}$$

Time of breaks related to realization of all tasks on the investigated area will be determined by equation:

$$T^c_{3-5} = \alpha \cdot T^c_{07}$$

where:

T^c_{3-5} – total time of breaks;
α – coefficient of break time.

The carried out initial investigations point out that during one working shift (480 minutes) the sum of break times ranges from 30 to 90 minutes. Therefore, one can assume that average value of break time coefficient equals to $\alpha = 0.15$.

Not utilized time of working day (T_{73})

The next distinguished phase of working day is its not utilized part. In known references this part of working day was not hitherto considered, although – as it is evident from observations – it can significantly affect the effectiveness of multifunctional machine utilization. In the case of harvester operation in small felling sites and with limited time of working day, the operator has to decide where to go: to the next task or to the base. If time of working day is limited, the cases of earlier passage to base can occur. In such situation the not utilized time should be regarded as the lost time.

As it is evident from the method of harvester operation, none of the phases started on a given day cannot be interrupted. If it is assumed that the working day time cannot exceed a given value (e.g. 8 hours), the start of next task execution can occur only, if machine passage to base and its organization will be terminated within the assumed time limit. Therefore, the not utilized time depends on the next phase duration.

Apart from special case, when the task execution is completed with the harvester passage to base, one can consider the two following cases:

- task is not completed and calls for repeated machine arrival on the next day,
- completion of task occurs within the assumed limit and possibility of passage to the next task is considered.

These two cases are presented in Figure 2.

In the first case the maximal value of free time can be at most slightly lower

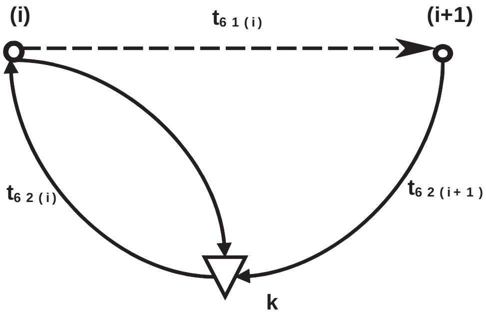

FIGURE 2. Diagram of machine passages in the final part of working day: when *i*-task is not completed (full line) and when *i*-task is completed and new task is started *i* + 1 (broken line), *k* – base

than the cycle time (t_c). In the second case, when machine is moved to the place of task $i + 1$ (travelled distance – l_{zz}) the operator has to identify the working conditions (t_{71}) and manage to execute at least one operation cycle (t_c), to complete the working day prior to passage to the *k*-base or the next one. Since the time of cycle is very short when compared to other phases, the minimal operation time anticipated for a given day for task realization should be greater than time of one cycle, so the operator could justify the change in harvesting site. Practical experiences showed that it should not be lower than 0.5 h. In this case the maximal free time will be slightly lower than the following sum of: passage time (l_{zz}/v_1), task identification (t_{71}) and minimal operation time of 0.5 h. If it is assumed that the cycle time is small (close to zero), the range of changes in not utilized time will be equal to:

$$T_{73}^{c} = n_d \cdot \eta_{73} \cdot \left(t_{71} + \frac{l_{zz}}{v_1} + 0.5 \right) =$$

$$= n_d \cdot \eta_{73} \cdot \left(t_{71} + \frac{1}{v_1} \cdot \sqrt{\frac{S_o}{100 \cdot n_z}} + 0.5 \right) \ \text{[h]}$$

Coefficient η_{73} is a characteristic parameter for real conditions of harvester's operation and its value can range to: $\eta_{73} = \{0; 1\}$

The presented mathematical description of harvester's operation enable to consider its possible effects under extreme working conditions: most favourable – that assure the highest productivity (upper boundary) and unfavourable (lower boundary) – that cause the least productivity.

To execute all the tasks by harvester in possibly shortest time (upper boundary) and achieve the highest operating productivity, the harvester's time balance (apart from operation time – T_{02} and time of breaks – $T_{3–5}$ will contain also the time of passages between tasks – T_{61} nd time of task identification – T_{71}. It was assumed that under these conditions the machine parking bases do not occur; it eliminates not only the time of passages between tasks and bases, but also the times of organization and taking bases and not utilized time of working day. The operator has no alternative – upon completion of task he proceeds to the next one. Under such conditions, the determined coefficient values amount to: $\eta_{61} = 1$, $\eta_{62} = 0$, $\eta_{72} = 0$, $\eta_{73} = 0$. Considering them, one can obtain the equation for total time of task realization on the selected area (forest inspectorate area) in the form:

$$T_{07}^{c} = \frac{\sum_{j=1}^{n_g} n_j \cdot t_{cj} + \frac{1}{10 \cdot v_1} \cdot \sqrt{S_o \cdot n_z} + t_{71} \cdot n_z}{1 - \alpha} \ \text{[h]}$$

Under conditions of lower boundary it was assumed (apart from T_{02} i $T_{3–5}$) occurrence of the following times of: passages between all tasks, tasks and bases, identification and taking bases and not utilized times (to maximal degree). Under such conditions, the coefficient values amount to: $\eta_{61} = 1$, $\eta_{62} = 0.71$, $\eta_{72} = 1$, $\eta_{61} = 1$, Upon their substitution into equation, the following form was obtained:

$$T_{07}^{c} = \frac{\sum_{j=1}^{n_g} n_j \cdot t_j + \frac{1}{10 \cdot v_1} \cdot \sqrt{S_o \cdot n_z} + t_{71} \cdot n_z + n_z \cdot t_{72}}{1 - \alpha - \frac{1}{T_{07}} \cdot \left[\frac{\sqrt{S_o}}{10 \cdot v_2} \cdot \left(\frac{1.42}{\sqrt{n_b}} + \frac{1}{\sqrt{n_z}} \right) + t_{71} + 0.5 \right]} \ \text{[h]}$$

The knowledge of times of isolated working day phases does not provide a full picture of working day. Therefore, using the working phases described above and their duration, values of the following balance indices of working shift time were defined and determined:

- operation time

$$\lambda_{02} = \frac{T_{02}^{c}}{T_{07}^{c}} = \frac{Q_j \cdot t_{cj}}{T_{07}{}^{c}}$$

- time of breaks

$$\lambda_{3-5} = \alpha = \frac{T_{3-5}^{c}}{T_{07}^{c}}$$

- time of passages between tasks

$$\lambda_{61} = \frac{T_{61}^{c}}{T_{07}^{c}} = \frac{\eta_{61}}{10 \cdot v_1 \cdot T_{07}^{c}}\sqrt{S_o \cdot n_z}$$

- time of passages to bases

$$\lambda_{62} = \frac{T_{62}^{c}}{T_{07}^{c}} = \frac{2 \cdot \eta_{62}}{10 \cdot v_2 \cdot T_{07}}\sqrt{\frac{S_o}{n_b}}$$

- time of task identification

$$\lambda_{71} = \frac{T_{71}^{c}}{T_{07}^{c}} = \frac{t_{71} \cdot n_z}{T_{07}^{c}}$$

- time of organization and taking bases

$$\lambda_{72} = \frac{T_{72}^{c}}{T_{07}^{c}} = \frac{\eta_{72} \cdot t_{72} \cdot n_z}{T_{07}^{c}}$$

- not utilized time

$$\lambda_{73} = \frac{T_{73}^{c}}{T_{07}^{c}} =$$

$$= \frac{\eta_{73}}{T_{07}} \cdot \left(t_{71} + \frac{1}{10 \cdot v_1} \cdot \sqrt{\frac{S_o}{n_z}} + 0.5 \right)$$

In every case the time of subsequent phases' duration was related to the total time of working day. Such approach enables to learn the structure of working time utilization and to point out direction of actions that can improve operational effectiveness of multifunctional machines in Polish forests.

CONCLUSIONS

Application of large-productivity machines has become a real fact in Polish forestry. Besides advantages connected with shorter time of realization, the most important advantages of this technology include improvement of work safety and quality of produced cut wood assortments. However, obtaining expected productivity, thus, the reduced specific costs of harvesting is strongly determined by organization factors. It is evident from dependences presented in the paper, that some parameters as the area where tasks are realized and number of tasks determine duration of majority of distinguished phases of working day. The developed mathematical model for working day of the multifunctional machine enables to point out at factors that determine most the working day structure of the machine and its operational economic effects.

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Streszczenie: *Analiza wykorzystania czasu pracy harwestera – model matematyczny.* Warunkiem stosowania maszyn o dużej wydajności do pozyskiwania drewna jest uzyskanie kosztów jednostkowych porównywalnych, a najlepiej niższych w porównaniu do kosztów tradycyjnych technologii. Wysokość tych kosztów jest ściśle uzależniona od wydajności eksploatacyjnej maszyny – wydajności odniesionej do całkowitego dziennego czasu pracy. Podjęte rozważania mają na celu określenie struktury dnia roboczego oraz stworzenie modelu matematycznego, który umożliwi określenie znaczenia i wpływu czynników przyrodniczo-leśnych i organizacyjnych na wykorzystanie czasu roboczego. W badaniach uwzględniono wiele nieprodukcyjnych faz, takich jak na przykład: czas przygotowania i zajmowania baz postoju maszyny, czasy przejazdów do baz, czas niewykorzystany. Sformułowano także zależności określające czas trwania poszczególnych faz oraz wskaźniki bilansowe czasu zmiany roboczej.

MS. received August 2013

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