System analysis of the technological efficiency of the complex feller buncher - skidder - processor

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Abstract. In the article, based on experimental data obtained in typical natural production conditions of the Irkutsk region during logging operations by the system of machines feller buncher–skidder–processor, it is proposed to improve timber flows from felling trees to stacking assortments in a pile with this timber harvesting technology and machines used. The system analysis of the technological efficiency of the feller buncher–skidder–processor complex is based on the solution of the following problem: from the standpoint of the system-dynamic approach, the most informative criteria for the dynamic connectivity and interdependence of the complexes of machines, mechanisms and equipment, as deeply integrated spatio-temporal structures, are formulated. According to the systems approach in subsystems, there is between the operational storage of items produced by the previous operations of the machines before the start of the subsequent operations of the machines of the complex. The technological efficiency of this complex is indicated in the systemic connectivity of roundwood production cycle operations as a multistage structure. On the basis of the principles of system-dynamic optimization of the integrated logging process as a whole, a generalization of the principle of harmonization to multi-stage managed clusters has been formulated as a necessary condition for sustainable development.

1. Introduction
An increase in the productivity of complexes of machines, mechanisms and equipment for logging production is a prerequisite for the sustainable development of a timber industry enterprise and the forest cluster as a whole. This becomes possible only on the basis of logging logistics, as a scientific basis for forestry technology, capable of formulating the basic principles of interconnection for single integrated timber flows from the start of production and movement to the final point of consumption with energy-saving modes of forest machinery operation. The basic criteria of logging logistics include: time, speed, distance, the aggregate of which forms a system in relation to the specifics of timber flows in the «equipment-forest» system. According to the approach proposed by a group of scientists at SPbFTU, the systemic connectivity of flows is complemented by dynamic - effective time, which determines the effective technological speed as a whole [1, 2]. The improvement of logging technologies can be based on scientifically grounded knowledge of the basic principles of logging (forestry) logistics and its tools – the most informative criteria for assessing the efficiency of
production and movement of timber flows directly in the forest: the shortest time and paths under energy-resource-saving modes. At the moment, whiplash technology, along with the Scandinavian cut-to-length technology of timber harvesting, is widespread in Siberia. In the cycle of the complex of forest machines «feller–buncher–skidder–processor», the following technological operations are performed sequentially: felling and bundling of feller buncher trees, skidding a bundle of trees with a skidder to the processor, deliming and cut-to-length of trees into logs by the processor [3,4]. However, due to a larger number of mechanisms than with the Scandinavian cut-to-length technology of timber harvesting, there is a low coherence of technological operations, which leads to a decrease in the increase in overall productivity when organizing a technological process with such a technology and a system of machines [5,6].

2. Methods and Materials

The experimental data were obtained in typical natural production conditions of Kata CJSC: Irkutsk region, Zelindinsko-Katinsko forestry, block 229, unit 10.14, plot 1, operating area 10.3 ha, average log volume: 0.43 m³, species composition: 9P1L, average timber stock 220 m³/ha. Machine system: feller–buncher - John Deere 853J, skidder– John Deere 848H, processor – John Deere 2154D, loader–John Deere 2154D [7].

3. Results and Discussion

In the cycle «feller buncher – skidder – processor», the following technological operations are performed sequentially: felling and bundling of trees by the feller buncher, skidding a bundle of trees with a skidder to the processor, deliming and cut-to-length of trees by the processor [8].

The technological connectivity of machine cycle operations[9,10] can be represented by a simple three-step structure is shown, figure 1.

![Figure 1](image1.png)

**Figure 1.** Three-stage connectivity of the complex feller buncher – skidder – processor.

Three-step connectivity of technological operations of the complex is represented by a superposition of two step ones.

The two-stage structure of the feller buncher – skidder subsystem is shown, figure 2.

![Figure 2](image2.png)

**Figure 2.** Two-stage structure of the feller buncher – skidder subsystem.

The two-stage structure of the skidder-processor subsystem is shown, figure 3.

![Figure 3](image3.png)

**Figure 3.** Two-stage structure of the skidder-processor subsystem.

The technological diagrams of the figures reflect the integrated connectivity of the process of roundwood production by the complex under consideration and show the connectivity of the subsystemsfeller buncher – skidder and skidder – processor. According to the systems approach in
subsystems, there is between the operational storage of items produced by previous machine operations before the start of subsequent operations of the machines of the complex.

In a systematic analysis of the performance of the feller buncher – skidder – processor complex, we will take a kind of quantum approach to the production of an object of labor. The volume of a bundle of trees formed by the feller buncher, which sequentially passes through all the operations of the complex, is taken as the general quantum of production.

The formation of a pack of feller buncher trees at one site can be represented as a simple multistage structure, is shown, figure 4.

**Figure 4.** Scheme of the formation of a pack of feller buncher trees as a simple multistage process (n is the number of trees forming a pack).

We define the volume of a pack of trees formed by the feller buncher, $V_w$, as the sum of the volumes of trees and can be estimated by formula:

$$V_w = \sum V_i, i = 1, 2, 3, \ldots, n.$$  

(1)

Each tree in the bundle being formed has its own productivity, determined by the volume of wood of the tree $V_i$ and the total time of its formation into a bundle $t_i$ and the time $t_{pi}$ of its stay in the bundle until the end of its formation. The last term of time is a consequence of a systematic approach to the technological process of forming the feller buncher of a pack of trees.

The technological process of forming a pack of trees takes place in a connected functional production time of 1 m$^3$ of wood for each tree, therefore, it is possible to write down a chain of formulas for the productivity $P_n$ and the corresponding functional time $T_n$ for each tree and can be estimated by the formulas:

$$P_1 = \frac{V_1}{t_1 + t_{p1}},$$

$$T_1 = \frac{t_1 + t_{p1}}{V_1},$$

(2)

Here is the residence time of the tree in the formed burst $t_{p1}$ can be estimated by formula:

$$t_{p1} = \sum t_{pi}, i = 2, 3, \ldots, n.$$  

(3)

Here the time $t_2$ can be estimated by formula:

$$t_2 = \sum t_{pi}, i = 3, 4, \ldots, n.$$  

(4)
Thus, the total functional production time \( n \) m\(^3\) of tree wood during the formation of a pack of feller buncher \( T_m \) can be estimated by formula:

\[
T_m = \sum T_i, i = 1, 2, \ldots, n. \tag{5}
\]

Then the productivity of the formation of a pack of trees feller buncher \( P \) can be estimated by formula:

\[
P = \frac{1}{T_m}. \tag{6}
\]

Formula (6) describes the productivity of the formation of a pack of feller buncher trees with a systematic approach to the technological process in the total functional time of its coherent course.

In the cutting area, the work of the feller buncher and the skidder is separated from each other by a safety distance (50-100 m and more). At this distance, the stacks of trees formed by the feller buncher are stored. From the standpoint of a systematic approach, the waiting time for a pack of trees to pick it up by a skidder becomes a time term in determining its performance of the feller buncher.

Therefore, the performance of the feller buncher should be determined in the subsystem of operations: formation of a pack – waiting for skidding is shown, figure 5.

![Figure 5. Scheme of the subsystem of operations – formation of a pack – waiting for skidder skidding.](image)

Therefore, in the subsystem feller buncher– skidder, the productivity of forming a pack of trees feller buncher \( P_n \) and the functional time \( T_m \), respectively, can be estimated by the formulas:

\[
P_{*1} = \frac{V_1}{t_1 + t_{p1} + t_0}, \quad T_{*1} = \frac{V_1}{t_1 + t_{p1} + t_0} \tag{7}
\]

Here the time \( t_{p1} \) can be estimated by formula:

\[
t_{p1} = \sum t_{pi}, i = 2, 3, \ldots, n.
\]

\[
P_{*2} = \frac{V_2}{t_2 + t_{p2} + t_0}, \quad T_{*2} = \frac{V_2}{t_2 + t_{p2} + t_0} \tag{8}
\]

Here the time \( t_{p2} \) can be estimated by formula:

\[
t_{p2} = \sum t_{pi}, i = 3, 4, \ldots, n.
\]

\[
P_{*n} = \frac{V_n}{t_n + t_0}, \quad T_{*n} = \frac{V_n}{t_n + t_0} \tag{9}
\]
The total functional production time \( n \) m\(^3\) of wood of the bundle trees in a single subsystem of the feller buncher – skidder \( T_{sm} \) can be estimated by formula:

\[
T_{sm} = \sum T_{si}, \quad i = 1,2, \ldots, n. \tag{10}
\]

Then, in the considered system views, the productivity of the formation of a pack of feller buncher trees \( P_{sm} \) can be estimated by formula:

\[
P_{sm} = \frac{1}{T_{sm}}. \tag{11}
\]

Thus, with a systematic approach, the productivity of the technological process of forming a pack of feller buncher trees depends on the superposition of times: felling and packing a tree, waiting for the pack to form and waiting for the pack to be picked up by a skidder.

The skidder skids the stacks of trees formed by the feller buncher in a semi-submerged state. Skidder performance \( P_c \) can be estimated by formula:

\[
P_c = V_n T_c, \tag{12}
\]

where, \( V_n \) – the volume of the pack formed by the feller buncher, \( T_c \) – skid cycle time: \( T_c = t_1 + t_2 + t_3 + t_4 + t_5 + t_6 + t_7 \) – time of freight traffic, \( t_2 \) – idle time, \( t_3 \) – time of formation of a pack and its capture, \( t_4 \) – unloading time, \( t_5 \) – stacking time, \( t_6 \) – maneuvering time.

The functional production time of 1 m\(^3\) of timber \( T_c \) can be estimated by formula:

\[
T_c = \frac{T_c}{P_c} = \frac{t_1 + t_2 + t_3 + t_4 + t_5 + t_6}{P_c}. \tag{13}
\]

In the two-stage skidder-processor subsystem the skidder stores a bundle of wood in a stack and stays in the stack before processing by the processor is shown, figure 6.

\[\text{Figure 6. Scheme of a two-stage subsystem: skidding a bundle of trees by a skidder – waiting for a bundle of trees to be bucked by a processor.}\]

Therefore, from the standpoint of the systems approach, the performance of the skidder \( P_c \) should be evaluated taking into account the time spent by a pack of trees in a stack before the processor starts working with it and can be estimated by formula:

\[
P_c = \frac{V_n}{T_c}. \tag{14}
\]

Here the time \( T_c \) can be estimated by formula:

\[
T_c = t_1 + t_2 + t_3 + t_4 + t_5 + t_6 + t_7, \tag{15}
\]

where, \( t_7 \) – time spent in a stack of trees.

Then the functional production time of 1 m\(^3\) skidder \( T_{ck} \) in a single skidder – processor subsystem can be estimated by formula:

\[
T_{ck} = \frac{T_c}{P_c} = \frac{T_c}{V_n}. \tag{16}
\]

Thus, in a generalized view, the uniform functional cycle time of the skidder operation is determined based on the time interval from the beginning of the formation of the bundle for skidding and until the beginning of crosscutting by the processor.

The process of bucking a pack of trees can be viewed from the perspective of a simple multi-step process is shown, figure 7.
Each tree in a bundle has its own productivity determined by the volume of wood of the tree $V_i$, the total time of its bucking $t_i$ and the time $t_{pi}$ of its stay in the bundle until the end of its bucking. The last term of time is a consequence of a systematic approach to the technological process of bucking a pack of trees by a processor.

The technological process of bucking a pack of trees by a processor takes place in a coherent functional production time of 1 m$^3$ of wood for each tree, therefore, it is possible to write a chain of formulas for productivity $P$ and the corresponding functional time $T$ for each bucking tree and can be estimated by the formulas:

$$P_{*1} = \frac{V_1}{t_1},$$
$$T_{*1} = \frac{t_1}{V_1},$$

(17)

$$P_{*2} = \frac{V_2}{t_1 + t_2},$$
$$T_{*2} = \frac{t_1 + t_2}{V_2},$$

(18)

$$P_{*n} = \frac{V_n}{t_n + \sum t_{pi}}, i = 1, 2, 3, \ldots, (n - 1),$$
$$T_{*n} = \frac{t_n + \sum t_{pi}}{V_n}.$$  

(19)

Thus, the total functional production time $n$ m$^3$ of tree wood when bucking a bundle by the processor $T_n$ can be estimated by formula:

$$T_m = \sum T_{*i}, i = 1, 2, \ldots, n.$$  

(20)

Then the productivity of bucking a pack of trees by the processor $P_n$ can be estimated by formula:

$$P_n = \frac{1}{T_{*n}}.$$  

(21)

Formula (21) describes the productivity of bucking a pack of trees by a processor with a systematic approach to the technological process in the total functional time of its connected course.

We define the technological efficiency of this complex in the systemic connectivity of the operations of the round timber production cycle, as a multi-stage structure is shown, figure 8.

The total functional time of production of a unit of an object of labor in multistage systemically connected operations $T_{mps}$ of the complex feller buncher – skidder – processor according to formulas (10), (15) and (20) can be estimated by formula:

$$T_{mps} = T_m + T_{*c} + T_{*n}.$$  

(22)
Figure 8. Scheme of multistage system connectivity of the operations of the feller buncher – skidder – processor complex.

Formula 22 corresponds to the productivity of $P_{mps}$ assortments, as a result of the entire cycle of production of assortments by systemically connected technological operations and can be estimated by formula:

$$P_{mps} = \frac{1}{T_{mps}}$$

Thus, the average value of the functional time $T_{mps}$ per one machine operation of the cycle feller buncher– skidder – delimbing and bucking machine can be estimated by formula:

$$T_{*mps} = \frac{T_{mps}}{3}$$

Formula 24 corresponds to the average productivity of a cycle machine operation and can be estimated by formula:

$$\Pi_{*mps} = \frac{3}{T_{*mps}}$$

Formula 25 serves as a benchmark for the synchronized operation of machines in a complex. From the obtained formulas (22) – (25) it can be seen that the shorter the functional cycle time, the higher the productivity.

During the research, the following main results were obtained:

1. The spatio-temporal base is formulated – the basis of mechanical and moving operations at the stage «felling–bundling–skidding–pruning from delimbing–bucking–stacking» with the technology using «feller buncher–skidder–processor», as a theoretical basis for improving timber flows from felling trees before stacking logs.

2. Improvement of timber flows from felling trees to stacking logs in a pile with this timber harvesting technology and the mechanisms used is carried out on the basis of solving the following problem: from the standpoint of the system-dynamic approach, the most informative criteria of dynamic connectivity and interdependence of complexes of machines, mechanisms and equipment are formulated as deeply integrated space-time structures.

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