System analysis of technological efficiency of forestry equipment module compositions

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Abstracts. One of the perspective directions of increasing productivity in forestry production is the application of a modular approach to the formation of forestry machine systems. The modular approach makes it possible to form coherent and flexible technological processes, the technological efficiency of which depends on the extent to which the basis of system analysis is used in the formation of the forestry equipment fleet. The system analysis provides an analytical view of the effective capacity and performance at the functional time of the production process. The article explores the energy and production efficiency of several of the most typical compositions of formation of modules and submodules of timber harvesting operations: trees (feller-buncher module, energy module, skidding module), fuel wood (cutting module, energy module, chipper module, chipper-transporting module), logs with sub-sorting in the cutting areas (technological modules of cutting, delimbing and cut-to-length, energy module, skidding module), three-length (feller-buncher module, delimer module, energy module, skidding module).

1. Introduction

Progress of technical processes, technical level of development of forestry machines, as well as efficiency of their operation - the driver of technical progress in the forestry industry [1]. Many scientists of the Russian Federation have studied the means of mechanization of forestry industry processes with emphasis on the development of theory about forestry machines [2, 3].

Now, taking into account climatic, market and other factors, the reserves of increasing the efficiency of forestry machines without fundamental change of technical solutions and technology of timber harvesting operations are at the limit [4].

One promising direction is the use of integrated technologies in the forestry industry, which are the basis for improving economic, technical, technological and environmental efficiency [5]. At present, the world’s leading producers of technical solutions for forestry industry (PONSE Oyj, KOMATSU Forest AB) have begun to develop and actively introduce machine systems for flexible timber harvesting technology, some results are being actively introduced among forestry workers of the North-Western Federal District of the Russian Federation.

The trend of development of this direction is the creation of a serial series of forestry machines for flexible logging technology based on the modular principle of layout [6]. Scientists of SPbPTU [7] developed its basic concept.

Task of the industry - effective development of forest exploitation (timber harvesting and wood processing) in the Russian Federation, long-term planning, deep processing of wood, updating of
information on a condition of the woods, improvement of technical armament, steady practice of management of the woods, use, protection, protection and reproduction of the woods on the forest land. This imposes the following requirements on the equipment and technology of timber harvesting production: satisfaction of the economic interests of forestry workers and early, qualitative reforestation.

Implementation of requirements is:
- development of timber harvesting technologies appropriate to available forestry machines (taking into account minimization of forest damage);
- development of new efficient forestry machines (in terms of improving logging production and reforestation).

2. Methods and Materials
Flexible technological processes with integrated coherence of production operations are the basis of variability in development of wood harvesting technologies taking into account improvement of flexible system of machines, which provides increase of efficiency of wood products production.

In order to implement flexible technological processes, new technical solutions are constantly being found. One of the ways to implement the concept is the modular principle of building a system of forestry machines [8].

The capabilities of modular systems are currently actively used in the automotive industry, forestry, road construction industry, etc. Successful experience can be broadcast for forestry engineering needs.

Power modules should have multiple power levels to meet the needs of the model series.

Proposed module consists of running gear with propulsion and process equipment. These modules can carry out different technological operations in the cutting area (depending on the natural production conditions of the rental base).

Forestry skidding modules solve the problems of skidding.

In general, the transport module is a rear semi-frame of a wheel tractor equipped with a wheel propulsor and a variable-design connecting unit. The role of the power module (PM) connected to the transport module can be played by the front half-frame of wheel skidding tractors, figure 1.

![Figure 1. Schematic diagrams of forestry transport modules.](image)

The modular system of machines is formed of the following modules:
- power (E);
- technological (T);
- transport or skidding (L);

Sometimes loading and unloading modules are also isolated.

Module classification is shown, figure 2.
where,
E1 – High-power module (EMB) or \( N_1 \).
E2 – Medium-power module (EMC) or \( N_2 \).
E3 – Low-power module (EMM) or \( N_3 \).
E4 – Power module of particularly low-power (EMO) or \( N_4 \).

Generalization of power of modules is presented as \( N_i, i = 1, 2, 3, 4 \).

T1 – Feller-buncher module (MBP) or \( P_1 \).
T2 – Delimber module (MO) or \( P_2 \).
T3 – Cut-to-length module (MR) or \( P_3 \).
T4 – Cut-to-length-sorting module (MPC) or \( P_4 \).
T5 – Wood chipping module (MFA) or \( P_5 \).
T6 – Cutting module (MV) or \( P_6 \).

Generalization of modules performance is presented as \( P_j, j = 1, 2, 3, 4 \).

L1 – Skidding module (TM) or \( PT_1 \).
L2 – Chipping module (SCM) or \( PT_2 \).
L3 – Forwarding module (SM) or \( PT_3 \).
L4 – Bunching module (PM) or \( PT_4 \).

Generalization of performance of transport modules is presented as \( PT_k, k = 1, 2, 3, 4 \).

3. Results and Discussion

Based on the formulated classification of the modules, it becomes possible to form a plurality of their compositions.

The energy and production efficiency of the selected module is carried out from the position of systems theory in the functional time of the production process [9].

Depending on the natural and production conditions of the rental base, economic strategy and other factors, a specific modular system of machines for flexible logging production is formed. From the perspective of the system approach, we will present a study of the technological efficiency of several module compositions.

The tree-harvesting process. Feller-buncher module (MBP), receiving energy from a higher-power module (EMB), cut a pack of trees, and a second medium-power module (EMC) coupled to a skidding module (TM) skidding the pack of trees to a loading station. The tree-harvesting process is shown, figure 3.
The effective power of the tree-harvesting module in energy functional time \( N_{m1} \) is described by the expression:

\[
N_{m1} = \frac{9}{\frac{1}{N_1} + \frac{1}{N_2} + \frac{1}{N_2}}. \tag{1}
\]

Moreover, the energy efficiency factor of the tree-harvesting module \( K_{n1} \) can be estimated by the formula:

\[
K_{n1} = \frac{N_{m1}}{N_1 + 2N_2}. \tag{2}
\]

Efficient productivity of the tree-harvesting module in energy functional time \( P_{m1} \) is described by the expression:

\[
P_{m1} = \frac{9}{\frac{1}{P_1} + \frac{1}{PT_1} + \frac{1}{PT_1}}. \tag{3}
\]

In addition, the effectiveness ratio of capacity of the module of the tree-harvesting module \( K_{p1} \) can be estimated a formula:

\[
K_{p1} = \frac{P_{m1}}{P_1 + 2PT_1}. \tag{4}
\]

Harvesting of fuel wood on the cutting area is expedient under conditions of low tree volume (up to 0.10 m\(^3\)). Under these conditions, in order to provide energy to the cutting module (MV), it is sufficient in the system to have an average power module, which, when the capacity is matched, can provide energy and chipping module (SCM). The wood chipping module (MFA) will require a high-power module (EMB) to operate. The fuel wood process is shown, figure 4.
Figure 4. Diagram of the modular system of machines for the fuel timber harvesting process in cutting area.

The effective power of the fuel wood module in energy functional time \( (N_{m2}) \) is described by the expression:

\[
N_{m2} = \frac{9}{N_2 + \frac{1}{N_1} + \frac{1}{N_2}}, \tag{5}
\]

Moreover, the energy efficiency factor of the fuel wood module \( (K_{m2}) \) can be estimated by the formula:

\[
K_{m2} = \frac{N_{m2}}{N_1 + 2N_2}. \tag{6}
\]

Efficient productivity of the fuel wood module in energy functional time \( (P_{m2}) \) is described by the expression:

\[
P_{m2} = \frac{3}{P_6 + \frac{1}{P_5} + \frac{1}{PT_2}}, \tag{7}
\]

In addition, the effectiveness ratio of capacity of the module of the fuel wood module \( (K_{p2}) \) can be estimated a formula:

\[
K_{p2} = \frac{P_{m2}}{P_6 + P_5 + PT_2}. \tag{8}
\]

Cut-to-length timber harvesting with sub-sorting on the cutting area, it is advisable to perform in conditions of average the tree volume \((0.10 – 0.30 \text{ m}^3\)). The medium-power module (EMC) supplies power simultaneously to two technological modules: the delimming module (MO) and the cut-to-length-subsorting module (MPC). The power module provides loading of the cut-to-length logs on the s forwarder and in connection with the forwarding and bunching modules (SM and PM) skidding the cut-to-length logs and branches. The cut-to-length timber harvesting with sub-sorting on the cutting area is shown, figure 5.

When forming production processes of timber cutting operations, modules are formed from super positions of submodules.
Figure 5. Diagram of the modular system of machines for the cut-to-length timber harvesting process with sub-sorting on the cutting area.

Further assessment for option of configuration of a submodule “$P_1 (N_1) – P_2 (N_1) – P_4 (N_1) – PT_3 (N_2) – PT_3 (N_2)$” is presented.

The effective power of the cut-to-length timber harvesting with sub-sorting on the cutting area submodule in energy functional time ($N_{m3}$) is described by the expression:

$$N_{m3} = \frac{9}{N_1 + \frac{1}{N_2} + \frac{1}{N_2}}. \quad (9)$$

Moreover, the energy efficiency factor of the cut-to-length timber harvesting with sub-sorting on the cutting area submodule ($K_{n3}$) can be estimated by the formula:

$$K_{n3} = \frac{N_{m3}}{N_1 + 2N_2}. \quad (10)$$

Efficient productivity of the cut-to-length timber harvesting with sub-sorting on the cutting area submodule in energy functional time ($P_{m3}$) is described by the expression:

$$P_{m3} = \frac{5}{\frac{1}{P_1} + \frac{1}{P_2} + \frac{1}{P_4} + \frac{1}{PT_2} + \frac{1}{PT_2}}. \quad (11)$$

In addition, the effectiveness ratio of capacity of the submodule of the cut-to-length timber harvesting with sub-sorting on the cutting area submodule ($K_{p3}$) can be estimated a formula:

$$K_{p3} = \frac{P_{m3}}{P_1 + P_2 + P_4 + 2PT_2}. \quad (12)$$

Three power modules may be required for log process. The first (EMB) supplies energy to the feller-bunching module (MBP), the second (EMC) gives energy to the delimbing module (MO) and in coordination with the bunching module (PM) takes out branches, the third (EMC) provides energy to the forwarding module (SM). All modules shall have quick connections. The log process is shown, figure 6.
Further assessment for option of configuration of a submodule “\(P_1 (N_1) - P_2 (N_1) - PT_3 (N_2) - PT_3 (N_3)\)” is presented.

The effective power of the log-harvesting submodule in energy functional time \((N_{m4})\) is described by the expression:

\[
N_{m4} = \frac{16}{\frac{1}{N_1} + \frac{1}{N_2} + \frac{1}{N_3} + \frac{1}{N_4}},
\]

(13)

Moreover, the energy efficiency factor of the log-harvesting submodule \((K_{n4})\) can be estimated by the formula:

\[
K_{n4} = \frac{N_{m4}}{2N_1 + 2N_2}.
\]

(14)

Efficient productivity of the log-harvesting submodule in energy functional time \((P_{m4})\) is described by the expression:

\[
P_{m4} = \frac{4}{\frac{1}{P_1} + \frac{1}{P_2} + \frac{1}{PT_3} + \frac{1}{PT_4}},
\]

(15)

and the effectiveness ratio of capacity of the submodule of the log harvesting submodule \((K_{p4})\) can be estimated a formula:

\[
K_{p4} = \frac{P_{m4}}{P_1 + P_2 + 2PT_2}.
\]

(16)

An example of implementation of the concept of modular systems of forestry machines for the process of harvesting trees and fuel wood is small class harwarder PONSSE WisentDual [10] equipped with a grapple for harvesting PONSSE EH25.

An example of the implementation of the concept of modular systems of machines for the process of harvesting logs and cut-to-length logs in the cutting area is the medium class harwarder PONSSE BuffaloDual [11] with the PONSSE H53 harvester head.
Differentiation of energy, technological and transport functions will allow controlling modules at the level of the decision maker (DM), the utilization factor of forestry machines and working time will increase, the task of process synchronization will be simplified.

Depending on the variability of natural production conditions, the modular system for flexible logging production has a differentiated hierarchy, which places high requirements of modules to the level of unification in horizontal and vertical directions.

An example in the North-Western Federal District of the Russian Federation is an experiment to implement a horizontal scheme of a modular system of forestry machines for skidding in the leased forests of Ustyan area by LLC "GC" ULK" company (implemented since January 2020). Heavy-class PONSSE forwarder ElephantKing 8W [12] with load capacity up to 30 m³, having an elongated loading area compartment compared to the basic model, allowing to transport two joints of four-meter logs and more load capacity.

The modular principle of construction of the system of forestry machines will provide less pressure on the soils of the forests than the aggregate equipment, will allow harvesting timber in hard to reach cutting areas (wetlands, hills).

Studies carried out in Scandinavian countries [13] claim that harwarders are mainly used in areas with low timber reserve and small average volume of the tree, and where long-range movements of the forestry machine. They are frequent, typically have eight wheels and loading area 4.5 m², the diameter of the tree to be harvested in the first cut is on average 0.098 m. The productivity of the harwarder varies from 4.1 to 5.0 m³ in the effective hour of operation of the forestry machine. The harwarders show similar productivity to specialized harvesters and forwarders when thinning. The cost of one machine hour is 14% higher on average compare to medium class harvester and 34% higher compare to the medium class forwarder. The researchers found that in order for the harwarder to be competitive in value with set of machines (harvester and forwarder), it should have operating costs lower by 20-30% per hour.

It should be noted that the leased forests in the North-Western Federal District of the Russian Federation have similar conditions, and taking into account the shortage of personnel, as well as climatic factors (downtime of equipment due to unfavorable weather and soil-relief conditions for timber harvesting operations and skidding). The application of solutions based on the modular system of machines will allow increasing total timber production, reducing the costs for the purchase and maintenance of the forestry equipment fleet, as well as the salary for operators.

For thinning, it is advisable to use the harwarder PONSSE WisentDual designed on a modular platform of the small-class forwarder PONSSE Wisent. For selective cuttings and cuttings in productive plantations, it is advisable to use the harwarder PONSSE BuffaloDual designed on a modular platform of the middle-class forwarder PONSSE Buffalo. A perspective direction of development of the modular system of forestry machines in the Russian Federation is the design of the heavy class harwarder based on the forwarder PONSSE ElephantKing 8W for timber harvesting operations in highly productive leased forests.

The formation of modules and submodules based on system analysis in the functional time of the production process makes it possible to represent flexible technologies as a single structure integrated into functional time. Development of a modular system of machines and active introductions among forest industry will allow cutting down costs on acquisition and the maintenance of the park of the logging equipment. Also, wage the plan of operators that will be raised by profitability of a phase of logging and realization of model of intensive forestry management in the North-Western Federal District of the Russian Federation. Many modern forest machines according to the available solutions in the logging equipment park should present a common conceptual approach to the classification of modules. Their analysis will make it possible to formulate the design of perspective logging equipment.

References
[1] Prokhorov L and Shatalov V 1996 Main directions of forestry energy base development [in
Russian – Osnovny’e napravleniya razvitiya e’nergeticheskoy bazy’ lesnogo xozyajstva]
Forest Industry 1 (Moscow: Forestry) pp 44-47
[2] Semenov M 1996 Justification of parameters and technical solutions of modular track systems
in order to increase efficiency and reduce energy intensity of the process [in Russian –
Obosnovanie parametrov i texnicheskix reshenij modul’ny’x trelevochny’x sistem s cel’yu
povy’sheniya proizvoditel’nosti i snizheniya e’nergoemkosti processa] Doctor of Technical
Sciences Thesis (Saint-Petersburg: LTA) p 36
[3] Zhukov A, Turlai I and Kirilchuk A 1989 Logging wheel machines based on serial module [in Russian –
Lesozagotovitel’n’y’e kolesny’e mashiny’ na baze serijnogo modulya] Forestry
industry 11 (Moscow: Forestry) pp 28-30
[4] Grigoriev I 2008 Modular system of machines [in Russian – Modul’naya sistema machin]
Derevo.ru 5 (Moscow: Derevo) pp 54-57
[5] Xenevich I and Yatskiewicz V 1997 On perspectives for development of unification
and creation of modular energy facilities [in Russian – O perspektivax razvitiya unifikacii I
sozdaniya modul’ny’x e’nergeticheskix sredstv] Tractors and Agricultural Machines 12
(Moscow: Nauka) pp 15-21
[6] Anisimov G 1993 New concept of forming a system of machines on a modular principle for
flexible logging production [in Russian – Novaya koncepciya formirovaniya sistemy’
machin na modul’nom principe dlya gibkogo lesozagotovitel’nogo proizvodstva] News of
SPb Forestry Academy (Saint-Petersburg: LTA) pp 183-193
[7] Anisimov G and Bolshakov B 1998 New concepts of the theory of forest machines [in Russian –
Nov’y’e koncepcii teorii lesosechny’x mashin] (Saint-Petersburg: LTA) p 114
[8] Grigoriev I and Svoykin F 2010 Modular systems of wood harvesting and processing machines
[in Russian – Modul’ny’e sistemy’ mashin dlya zagotovki i pererabotki drevesiny’]
Technology and equipment of the timber industry complex 5 (Saint-Petersburg: SPbGLTA)
pp 87-91
[9] Bazarov S, Belenkij Yu, Soloviov A 2018 Fundamentals of system analysis of production
processes (Saint-Petersburg: SPbFTU) p 60
[10] User Manual. Manual for the operator. Ponsse WisentDual 2002 (Finland: Vierema. Ponsse
Oyj) p 142
[11] User Manual. Manual for the operator. Ponsse BuffaloDual 2012 (Finland: Vierema. Ponsse
Oyj) p 181
[12] User Manual. Manual for the operator. Ponsse ElephantKing 8W 2014 (Finland: Vierema. Ponsse
Oyj) p 724
[13] Fulvio Di Fulvio and Dan Bergstrom 2013 Analyses of a single machine system for harvesting
pulwood and/or energy-wood in early (International Journal of Forest Engineering Volume
24 Issue 1) p 2-15 doi.org/10.1080/14942119.2013.798935