Ways to solve the optimal mobility of forest complex machines in the formation of a logging enterprise

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Abstract. The paper discusses solving the problem of machine mobility using an hybrid evolutionary modeled algorithm. Until now, the problem of optimizing the mobility of machines has been considered as a private problem that does not take into account the completeness of all factors affecting the process. The goal of our research is to develop a method that allows it to be used effectively to find optimization problems. The proposed method includes three concepts: optimization of mode, structural parameters and control process. We relied on the basic provisions of mathematical statistics, methods of mathematical modeling, evolutionary modeling and parameter optimization. A system of functions has been compiled to perform the task of multi-criterion optimization of the mobility parameters of forest equipment based on four criteria: cross-country ability, speed, relative turning radius and probability of failure-free operation. A metagenetic approach has been applied, which made it possible to achieve the best combination of traditionally used optimization methods and a genetic algorithm. Tests of the received algorithm were performed on standard tasks. The test results showed that the proposed method makes it possible to obtain high-quality solutions at minimum cost. The PRADIS//FRONT information system was used in calculations and plotting.

1. Introduction

Machines of the forest complex (MFC) have a certain set of operational properties. These properties determine the quality of the machine. Mobility is the most common operational property for this type of equipment. It consists of the ability of the technician to perform the task with minimal costs and takes into account the operating conditions and condition of the machine itself.

A literary review on the modern theory of machine movement of a support-type forest complex with an autonomous course orientation system (L V Barakhtanov, V V Belyakov, V N Kravets, V Ya Anilovich, Y T Vodolazhchenko, V V Belyakov, M E Bushueva, V I Sagunov), showed that the authors mainly note that most of the operational properties of machines primarily depend on the interaction of the engine with the reference base. Article [1] states that the control index of the motion of the machine-tractor unit is highly dependent on the design parameters of the unit. Therefore, when optimizing the mobility of forest machinery, it is necessary to take into account the structural features of the units.

In their work [2], the authors considered simulation calculations of vehicle cross-country capacity. At the same time, special attention was paid to elucidating the influence of operating conditions on the
cross-country ability of the vehicle. A A Stadukhin and R D Peskov [3] examined the profile patency of the wheel machine. They proposed to determine the interaction of the support base and the wheel of the transport machine using the Gilbert-Johnson-Curty polygon crossing algorithm. The fundamental approaches to increasing the cross-country capacity of wheeled vehicles, as well as information on the designs of mechanisms that increase cross-country capacity, were carried out by Maclaurin B [4]. The author performed their classification, investigated the effect of means of increasing cross-country ability on the performance of machines. Bruce McLaurin, in his studies on the suspension characteristics of a wheeled vehicle [5], believes that the main difference between a wheeled suspension and a caterpillar vehicle suspension is a greater degree of freedom due to the presence of pneumatic tires. Of particular note is book [5], in which the authors presented the theory of electronically controlled vehicle dynamics. Therefore, when determining the mobility of a wheeled vehicle, this factor must be taken into account.

As a result of the analysis, it was found that the problem of optimizing the mobility of MFC was considered by the authors as a private problem that does not take into account the completeness of all factors affecting the process. Mathematical and imitation models of machine mobility that allow optimizing this process have not been developed. The aim of the study is to develop a method that allows it to be effectively used to search for problems of optimizing the mobility of forest machinery. The method we propose will include three concepts: optimization of mode, structural parameters and the control process.

In this work, we relied on the basic provisions of mathematical statistics, methods of mathematical modeling, evolutionary modeling and parameter optimization. In order to achieve more confidence, we compared the results by testing with the following methods: Classic Genetic Algorithm, (Heuristics Combination Method, crowd behavior, ant colony.

A simple genetic algorithm (PHA) was first described by D Goldberg on the basis of the work of D Holland. Models of genetic algorithms were created on the basis of evolution in wildlife and random search methods. At the same time, a random search is an implementation of the simplest evolution function – random mutations and subsequent selection [6].

Genetic algorithms are adaptive methods that are used to solve search and optimization problems. It is based on the genetic process of living organisms. The genetic algorithm is used to explain the adaptation mechanisms both in the natural environment and in the intellectual-study (artificial) system; modeling of evolutionary functions and its application for the effective search for solutions of various problems, mainly optimization [7].

One of the main differences between the genetic algorithm (GA) and other evolutionary algorithms (EA) is that the GA models evolution at the level of genomes, in other methods phenotypes evolve. As baseline data and results, many modifications of EA use different representations for individuals of a population of evolving individuals. In genetic programming, tree-based representations are used, evolutionary programming was originally based on graph representations, and now it uses phenotype representations adequate to the problem to be solved [8].

2. Experimental part, materials and methods
Assuming that the power expended in the movement is a function of the speed of the machine \( W = W(v, \Phi_\rho, \Phi_\gamma, \lambda) \), and the indicator of course orientation is a function of the specific turning radius \( \Phi_R = \Phi_R(\rho, \Phi_\rho, \Phi_\gamma, \lambda) \). You can create a system of target functions for the formulation of the problem of multi-criteria optimization of the mobility indicators of forestry equipment:

1) Possibility criterion:
\[
\Delta \Phi = \Phi_\phi - \Phi_\phi \rightarrow \max ,
\]
where the characteristics \( \Phi_\phi \) and \( \Phi_\phi \) are called the generalized parameters of the interaction of MFC with the canvas:
– generalized function of coupling the thruster with the track $\Phi_\phi(\lambda) \rightarrow \max_{\lambda \in \Lambda}$

$$\Phi_\phi = \Phi_\phi^{\text{max}} \left(1 - e^{k_1 \lambda_1 \lambda_1}\right), 0 \leq \Phi_\phi \leq 1,$$

there is $\Phi_\phi^{\text{max}} = \lambda_0 \left(1 + \lambda_0 \lambda_1\right)$;

– generalized function for the resistance of the coil to the movement of the machine boards $\Phi_f(\lambda) \rightarrow \min_{\lambda \in \Lambda}$

$$\Phi_f = \Phi_f^{\text{min}} e^{k_2 \lambda_1 \lambda_1}, 0 \leq \Phi_f \leq 1$$

where

$$\Phi_f^{\text{min}} = \Phi_f^{\text{max}} \left(1 + \lambda_0^2\right)^{-1}.$$ 

$\Phi_f^{\text{max}}$ – table value [3].

2) the speed of the machine $v(\lambda) \rightarrow \max_{\lambda \in \Lambda}$

$$v = k \left(e^{k_3 \lambda_1 \lambda_1} - 1\right)^{\frac{1}{2}}, k \leq v \leq 10k,$$  (2)

where $k$ is a scale parameter, is selected from physically justified assumptions about the speed of the machine;

3) relative turning radius $\rho(\lambda) \rightarrow \min_{\lambda \in \Lambda}$

$$\rho = \lambda_1 \lambda_1 \lambda_1, \approx 0 \leq \rho \leq 10;$$  (3)

4) machine uptime probability $\rho(\lambda) \rightarrow \max_{\lambda \in \Lambda}$

$$P = e^{k_4 \lambda_1 \lambda_1}, 0 \leq P \leq 1.$$  (4)

The objective functions (2)–(4) are dependent on the function (1): $v(\Delta \Phi, \lambda) \rightarrow \max_{\lambda \in \Lambda}$;

$$\rho(\Delta \Phi, \lambda) \rightarrow \min_{\lambda \in \Lambda}; P(\Delta \Phi, \lambda) \rightarrow \max_{\lambda \in \Lambda}.$$

The task of maintaining reliability (4) is of an independent nature and can be solved separately.

Based on the criteria considered, it is possible to build control algorithms for the systems for eliminating critical situations and maintaining stable MFC mobility, since indirectly it contains indicators of sustainability.

The problem of maintaining MFC mobility includes three tasks (concepts):

1) motion control concept ($\lambda_1 = \text{var}, \lambda_2 = \text{const}, \lambda_3 = \text{const}$) for the given operating conditions and the given machine configuration, the optimal modes of motion control are determined;

2) machine design concept ($\lambda_1 = \text{var}, \lambda_2 = \text{const}, \lambda_3 = \text{const}$) for the given operating conditions and the selected motion control modes, the rational constructional configuration of the machine is determined;

3) concept of operating conditions ($\lambda_1 = \text{var}, \lambda_2 = \text{const}, \lambda_3 = \text{const}$) for this structural configuration of the machine and the selected motion control modes, the critical characteristics of the operating conditions are determined.

The solution of these problems is necessary for the implementation of the algorithm for calculating the dynamics of the machine [3]. To solve the problem of mobility of MFC units, it is proposed to use the developed modified evolutionary algorithm.

The essence of the proposed method is to use the metagenetic approach – a combination of the classical optimization method and the genetic algorithm (GA). In the developed algorithm, the authors propose to form the initial population not randomly, but using the generation of LP-sequence. Such an approach will allow selecting individuals satisfying the imposed functional and parametric constraints already at the initial stage, which will make it possible in the future not to check individuals for compliance with the constraints. LP $\tau$-search also allows generating individuals with the most diverse properties.
At the separation stage, the following parameters are calculated: the number $m_i$ that characterizes how many individuals in the population are in the niche of individual $i$ and the separation parameter $\sigma$, the quality criterion $F_s$. Selection of individuals is performed based on the results of the quality function. This method provides confidence, since it makes it possible to avoid premature convergence of the algorithm.

At the crossover stage, it is proposed to use a crossing-over operator based on prime numbers. With this approach, the number of break points is determined by a prime number within the chromosome length. Repetitive genes of the descendant are replaced by missing ones from the parent set. If the resulting solution is unsatisfactory, then the next prime number is selected, within the length of the chromosome, which determines the number of break points. Such an approach allows to significantly diversify the population and allows you to adjust the number of break points, according to the result obtained.

The results of testing the developed algorithm on standard problems showed that this approach allows us to obtain high-quality solutions in a reasonable time.

We use the developed algorithm to find the optimal operating parameters of the TDT-55 skidder. For calculations and graphing, we will use the PRADIS // FRONT software system [9], but instead of the GPGA (Global Parallel Genetic Algorithm) implemented in the GA system, we propose to implement the developed evolutionary algorithm.

The construction of the Pareto set in the problem of multicriteria optimization of dynamic systems requires multiple modeling of the dynamic system under study with different values of the variable parameters. Modeling of dynamic systems is an independent problem, for the solution of which a significant number of software systems have been developed [10, 11]. In the software system PRADIS // FRONT, modeling is performed using the software package PRADIS [11].

The software package PRADIS operates under the control of the Windows operating system and is intended for the analysis of dynamic processes in objects described by systems of ordinary differential equations. In this work, the software system PRADIS // FRONT is used to build the Pareto front in the problem of multi-criteria optimization of the parameters for controlling the movement of the TDT-55 skidder tractor. The generalized structure of the tractor model is shown in figure 1.

**Figure 1.** Generalized block diagram model.

The model of the TDT-55 tractor in the form of the Qucs editor of the PRADIS system is shown in figure 2.
The main elements of the model are: DVTBL1 engine; MUFTA1 coupling; Gearbox MGEAR1; traffic management system SX1; differential DIFMC1; MUNL1, MUNL2 wheels. The characteristic of the engine (the dependence of the torque on the shaft rotational speed) is given in tabular form using a piecewise linear function.

The variable parameters of the model are the following 10 parameters (10):

- $N_1, N_2, N_3, N_4, N_5$ – gear ratios for all 5 gears (five-speed gearbox is used);
- $T_1$ is the clutch release time;
- $T_2, T_3, T_4, T_5$ are the start times of the 2nd, 3rd, etc. gears.

The parallelepiped $P$ the permissible values of the vector of variable parameters is determined by the inequalities:

$$1 \leq N_i \leq 10, \quad N_i \in \mathbb{Z}, \quad i = 1, \ldots, 5,$$

$$0 \leq T_i \leq 1, \quad T_i \in \mathbb{R},$$

$$1 \leq T_j \leq 10, \quad T_j \in \mathbb{R}, \quad j = 2, \ldots, 5$$

where $\mathbb{Z}$ is the set of natural numbers, $\mathbb{R}$ is the space of real numbers.

The set of permissible values of $D$ is formed by the inequalities:

$$T_2 < T_3 < T_4 < T_5.$$

3. Results and discussion

Output variables of the model:
- TimeWork – acceleration time to working speed;
- MaxTorque – the maximum moment in the transmission;
- Torque – the moment in the transmission;
- Torque_Engine – the moment on the motor shaft;
- V_Engine – engine shaft speed;
- Out_Gear is the rotational speed of the gearbox output shaft;
- Efficiency – efficiency transmissions.

Based on the specified output parameters of the model, as well as according to the task of optimizing the mobility of the MFC, the following optimality criteria are formed:
- MFC criterion – KritProh (to be maximized);
- MFC Velocity speed (to be maximized);
- The radius of rotation MFC (Rad (to be minimized).
Taking into account that the functions Velocity and Rad are derived from the functions of KritProh, using the software system PRADIS // FRONT, we obtain approximations of the Pareto set for the following tasks of multi-criteria optimization:

1) two-criterion task ($\phi_1 = \text{KritProh}$, $\phi_2 = \text{Rad}$);
2) the three-criterion task ($\phi_1 = \text{KritProh}$, $\phi_2 = \text{Velocity}$, $\phi_3 = \text{Rad}$);

The results of calculations for problems 1 and 2 are shown in figures 3-4, respectively.

**Figure 3.** Pareto front approximation for a two-criterion problem.

**Figure 4.** Approximation of the Pareto front for the three-criterion problem.
The solution of the problem of maintaining mobility in the other two concepts is carried out similarly.

One of the main test tasks reflecting the features of space-time synthesis tasks is the task of synthesizing schedules – JSSP (Job Shop Scheduling Problem). The performed study of the recombination potential allows us to conclude that there are optimal values of the lengths of the $L$ fragments into which chromosomes are separated during the crossover. To confirm this conclusion, an experimental study of the dependence of utility functions on $L$ was conducted using the example of the JSSP task.

It was previously noted that the decrease in the effectiveness of genetic search occurs due to the phenomenon of premature stagnation. This phenomenon was investigated on the application of HCM methods and the proposed hybrid algorithm to the task of synthesizing schedules with the following initial data: the number of stages for servicing work $q = 4$ stages, the number of works $n = 105$, the number of machines $m = 15$. The results of two options for solving the problem when applying each of the compared methods are given in Table 1, where $N$ is the number of chromosome breaks during the crossover (note that the length of the chromosome in this problem is $q \cdot n = 420$), Evals is the number of estimates of the objective function.

| Evals | 270 | 20 | 30 | 40 | 50 | 75 | 100 | 125 |
|-------|-----|----|----|----|----|----|-----|-----|
| $N=20$ | 22570 | 22293 | 22121 | 21963 | 21901 | 21834 | 21821 | 21811 |
| $N=20$ | 23498 | 22147 | 22073 | 21970 | 21850 | 21798 | 21789 | 21781 |
| $N=1$  | 22570 | 22145 | 22126 | 22118 | 22118 | 22118 | 22118 | 22118 |
| $N=1$  | 23498 | 22134 | 22119 | 22100 | 22099 | 22083 | 22072 | 22072 |

The results show that with a multipoint crossover, the probability of premature stagnation decreases, accordingly, it is possible to get noticeably closer to the extreme point.

Figure 5 shows the dependence of the coefficient of gene diversity $r$ (the proportion of genes that have different values in parents' chromosomes in the next crossover act) on the generation number.

Diversity coefficient

![Figure 5](image-url)

- single-point crossover
- HEMA

**Figure 5.** Illustration of the degeneration of the population with an increase in the number of generations.
In figure 5, light dots indicate the $r$ values obtained in some randomly selected crossover acts using the developed method, and dark dots indicate similar values obtained using a single-point crossover (CGA). The figure illustrates a markedly smaller predisposition of the developed algorithm to early stagnation.

Authors [9] gives a theoretical justification for the presence of optimal values of the lengths of $L$ fragments in the mixed evolutionary method. To confirm the theoretical results, experiments were carried out to determine the optimal values of $L$. Figure 6 shows the results of solving the problem of synthesizing multi-stage schedules with 4 stages, 200 works and 15 machines using the developed method. The points correspond to individual solutions, the curve displays the average dependence of the objective function on the size of the $L$ fragment.

![Figure 6](image)

**Figure 6.** The dependence of the results of solving the problem of synthesis of schedules on the length of fragments $L$.

The results allow us to conclude: the length of fragments $L$ affects the effectiveness of the search. For the developed algorithm in the JSSP problem, the optimal values of $L$ are in the range {5, 40} with a total chromosome length of 800. Therefore, uniform and single-point crossovers do not belong to the best versions of HA.

Similar results were obtained in solving other test problems. Figure 7 illustrates the results of solving the problem of routing vehicles with time windows (VRPTW), in which chromosomes contain 40 genes each, and figure 8 - the results of solving the problem of synthesis of topology and traffic distribution (STRT) in a computing network with chromosomes 276 genes long. In both cases, the hybrid evolutionary modeled algorithm (HEMA) method was used.

![Figure 7](image)

**Figure 7.** VRPTW problem results dependent on $L$ fragment Length.
Figure 8. Dependence of results of STPT problem solution on length of $L$ fragments.

Of interest is the comparison of the HEMA developed with particles swarm optimization (PSO) and ant colony optimization (ACO) methods. The results of this comparison are shown in figure 9, where Delta is the difference between the obtained and the best known result of solving the test problem of synthesizing multi-stage schedules with 105 works. These results demonstrate the advantage of the developed method over other compared methods.

Figure 9. Comparison of the results of solving the task of synthesizing schedules by various genetic methods.

In experiments, it is accepted: the number of works 94, the number of cars 15, the size of the population 200.
The multi-calculation averaged dependencies of the objective function $F(X)$ on the number of evals of accesses to its calculation procedure are shown in figure 10.

![Figure 10. Comparative search results by different methods.](image_url)

From the results of the calculations and the graphs given, it is possible to draw conclusions about the effectiveness of the application of the proposed methods for solving the problems of optimizing MFC mobility. This method can also be applied to solving problems of reliability optimization and other problems of multi-purpose optimization at all stages of the life cycle of MFC.

Experiments have shown that the developed hybrid modified evolutionary algorithm provides a more accurate result in comparison with the results of the use of non-adaptive genetic algorithms by an average of 7-10%.

Thus, the conducted studies have shown a significant advantage of the developed algorithm over existing methods, as well as the promising application of a metagenetic approach combining GA and classical optimization methods.

The effectiveness of evolutionary modeling depends on many factors. Their optimal choice leads to increased search speed and stability. Among evolutionary algorithms, genetic algorithms are most often used for solving optimization problems, since in constructing a specific genetic algorithm, it is often possible to effectively use various putative properties of the structure of the search space, depending on the problem being solved.

4. Conclusion
The study results make it possible to better understand the essence of the processes occurring during the interaction of MFC with a deformable support base, as well as to identify ways to improve the efficiency of the machines.

A genetic algorithm has been built to solve the problems of MFC interaction with a deformable support base within the framework of spatial-temporal representations, which makes it possible to identify effective study directions and consider various tasks from a unified methodological point of view in practice.

The considered adaptive multi-optimization optimization method is integrated into the software system for analyzing the dynamics of systems of different physical nature - PRADIS.
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