Modeling of cleaning up forest debris technology from wood natural mortality

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Abstract. The article considers the problem of cleaning up forest debris caused by fallen dead wood or wood natural mortality (WNM). Solution to the problem of cleaning and utilization of the WNM and quality control of these sanitary measures in forest was proposed. For conditions of "Medynskiy forestry" enterprise it was proposed technological process of cleaning forest from the WNM. A mathematical model and a conceptual model of the technological process were developed. The maximum values of the utilization coefficients of the winch and the feller are achieved at 30-meter length of the rope (Figure 8). With the increase in the volume of the WNM, the utilization coefficient of the winch increases, and the utilization coefficient of the feller are falls (Figure 9). However, these changes are insignificant (no more than 3.5%) and may not be taken into account in practice. Therefore, for the conditions adopted in the experiments, the length of the traction rope equal to 30 m can be considered optimal for portable hand winches.

1. Introduction

The article considers the problem of cleaning up forest debris and whole trees caused by fallen dead wood or wood natural mortality (WNM) (Figure 1).

The volume of the WNM in urban forests of Central Russia is estimated from 5 to 15% of the wood stock. According to the Committee of forestry of the Moscow region only in the forests of the Moscow region has accumulated about 20 million cubic meters of the WNM. Urban forests are used not only for logging, but, above all, they perform sanitary and health functions, are protective strips along the railways and roads. In such forests, cleaning of the WNM for aesthetic, fire protection and phytosanitation purposes, as well as for the safety of visitors should be carried out regularly. Cleaning of the forest from the WNM is regulated by sanitary rules and is appointed according to the results of forest pathology examination. One of the main objectives of these sanitary measures is to clear the forest from the WNM.

The existing technologies of cleaning of the forest from the WNM are imperfect, based on the use of manual labor. This article discusses an approach to the development of technology for harvesting and utilization of the WNM based on logging machines and their systems, which are used in low-volume logging.
Figure 1. The WNM in the forest in the form of whole fallen trees (photo by the author).

2. General approaches to cleaning forest from the WNM and recycling of the WNM

Schematically, the solution of the tasks of cleaning forest from the WNM and recycling of the WNM is presented in the form of a block diagram (Figure 2), consisting of four stages.

The first and last stages can be referred to the preparatory and final works. The purpose of the first stage is the justification and appointment of sanitary measures for cleaning of the forest from the WNM. At this stage, the scope, quality (for example, the percentage of commercial timber) and the distribution of the WNM on the forest plot. At the last stage, the quality of the forest cleaning from the WNM is monitored.

With data on the volume of the WNM, the second and third stages are formed systems of machines for cleaning forest from the WNM and recycling of the WNM. It should be noted that the volume of the WNM is usually many times less than the forest fund on the same plot. Therefore, the use of conventional logging machines for cleaning forest from the WNM is not economically feasible.
Figure 2. Block diagram of the solution of the tasks of cleaning forest from the WNM and recycling of the WNM.
In recent decades, technologies of low-volume logging operations based on specialized low-power machines and modular machines have been successfully recommended [2-13].

Specialized machines for low-volume logging are various mini-harvesters, mini-forwarders, mini-harvesters, etc. machines that perform the same technological operations as conventional logging machines, but have less power and some features depending on the purpose, for example, remote control.

In modular machines, the main process equipment is mounted or trailed, which is aggregated with the energy module. For example, a General-purpose wheeled tractor can act as an energy module. One energy module can be used for various logging and forestry operations. This significantly reduces economic risks and provides technological flexibility to a small enterprise. In the world practice, a lot of experience has been gained in the design of various trailed machines, from skidding trailers to harvester processors [12-13].

In the works of various scientists [2-13] shows the effectiveness of both small-size machines of the modular principle, and specialized machines for low-volume logging operations. All machines and equipment for cleaning forest from the WNM were divided into two groups:
1-on the basis of special forest machines and equipment;
2-on the basis of modular machines and equipment.

3. Description of the technological scheme of cleaning forest from the WNM and recycling of the WNM

General approaches were applied in the development of technology for cleaning forest from the WNM and recycling of the WNM for the conditions of the "Medyn forestry" enterprise.

Field surveys were established the WNM volume sand their quality. The volume of the WNM was determined by the line intersect method [1]. The main part of the WNM proved to be of poor quality and was classified as illiquid wood. It was decided to leave illiquid wood in the woodpile for further rotting in the forest. Part of the WNM of satisfactory quality was supposed to be sold to the population for firewood.

In the technological chain, the following types of the WNM were sequentially the subject of labor:
- unprocessed trees - processed trees (trunks) - skidding groups of trunks - stockpiles of trunks - crosscutted trunks (short logs) - stockpiles of short logs.

To perform most of the technological operations it was decided to use the existing forestry machines and equipment:
- processing the trees on the trunks for skidding - chain saws;
- skidding the groups of trunks to stockpiles - portable hand winch;
- crosscutting the trunks on the short logs and laying them in stockpiles - chain saws.

The process of cleaning up forest from the WNM is shown in Figure 3. The woodcutter with the chainsaw moves along the technological line and releases dangerous trees (dead, hanging, fallen trees, etc.). Woodcutter cuts the branches, getting the trunks. In addition, the woodcutter marks the trunks. Commercial and illiquid timber is marked with different colors.
The main objective of these activities is to prepare trees of the WNM for safe skidding in stockpiles of trunks. In the proposed technology, the trunks are crosscutted on the short logs and laid them in stockpiles of short logs. The skidding operation of the trunks is carried out as groups of several trunks. Equipment for trunks skidding includes:
- portable winch,
- plastic cones,
- durable polyester tapes and synthetic rope.

A portable winch is fixed using polyester straps to the tree. Trunks are choked through the cones in groups and skidded in stockpiles of trunks. The efficiency of the described technology was decided to be investigated on mathematical models.

Technological chains of forest cleaning from the WNM, according to the scheme in Figure 2, were divided into the steps of:
Phase 2. Woodcutter with the chainsaw + operator of portable winch.
Phase 3. Woodcutter with the chainsaw + stacker of shot logs into stockpiles.

This separation is due, in particular, to the fact that the two operations are performed separately. For example, the stockpiles of trunks formed by the winch can be in line and wait for processing them into shot logs for a long time without stopping the winch work. This article considers only the second stage of work (Figure 2), including the production chain: Woodcutter with the chainsaw + operator of portable winch.

4. Mathematical model of technological process
Productivity per shift of several chainsaws can be represented as the sum of the volumes prepared trunks for skidding per shift.

The time of the cycles and the productivity of the chainsaws per shift during the processing of the trees in the model are defined as the sum of all cycles and the volume of all processed trees:
\[
\sum_{i=1}^{n} \sum_{j=1}^{N} t_{ji} = T \cdot \eta \quad \Rightarrow \quad \text{Productivity per shift} = \sum_{i=1}^{n} \sum_{j=1}^{N} q_{ji},
\]

where:
- \( t_{ji} \) – time of the \( i \)-th cycle of the \( j \)-th chainsaw, sec;
- \( q_{ji} \) – volume of the \( j \)-th tree during the \( i \)-th work cycle, m\(^3\);
- \( N \) – number of complete cycles of one roller per shift;
- \( T \) – duration of the shift, sec;
- \( \eta \) – chainsaw utilization factor;
- \( n \) – number of chainsaws.

The period of the cycle for tree processing is determined by the formula:
\[
t = t_1 + t_2 + t_3 + t_4,
\]

where:
- \( t_1 \) – time for sawing twigs and the movement of the woodcutter from the butt to the top, sec;
- \( t_2 \) – time to turn the trunk, sec;
- \( t_3 \) – time for sawing supporting branches, sec;
- \( t_4 \) – time for the transition of the woodcutter between the trees, sec.

Productivity per shift of the winch can be represented as skidded sum of the volumes of groups of trunks. The volume of the group of trunks is determined by the limit skidding volume of trunks. In the limiting case, the group may consist of a single trunk. The volume of the stockpiles of trunks is defined as the skidding sum of groups of trunks from one working station of the winch. This volume is determined by the covered winch area, which depends on the length of the traction rope:
\[
Q_{\text{group}} = q \cdot \frac{\pi \cdot l_{\text{rope}}^2}{20000},
\]

where:
- \( l_{\text{rope}} \) – length of the traction rope winch, m;
- \( q \) – volume of the WNM per 1 ha, m\(^3\)/ha.

The time of the cycles and the productivity per shift of the winch in the model is defined as the sum of all cycles and the volume of all skidded groups of trunks by the winch:
\[
\sum_{i=1}^{N} t_i = T \cdot \eta \quad \Rightarrow \quad \text{Productivity per shift} = \sum_{i=1}^{N} Q_{i - \text{group}},
\]

where:
- \( t_i \) – time of the \( i \)-th cycle of the winch, sec;
- \( Q_{i - \text{group}} \) – volume of the group of trunks during the \( i \)-th winch operation cycle, m\(^3\);
- \( N \) – number of complete cycles of operation per shift;
- \( \eta \) – winch utilization factor.

The time duration of the \( i \)-th skidding cycle of one group of trunks:
\[
T_{i - \text{group}} = (t_1 + t_2 + t_3 + t_4)_i,
\]

where:
- \( t_1, t_2 \) – time of movement of the winch traction rope, respectively, without and with the load, c.

\[
t_1 + t_2 = \frac{l}{V_1} + \frac{l}{V_2},
\]

where:
- \( V_1, V_2 \) – speed of movement of the winch traction rope, respectively, without and with the
load, m/sec.
l – average skidding distance, m;
\( t_3 \) – time for formation of the group of trunks for skidding, sec;
\( t_4 \) – time to unload the group of trunks after skidding, sec.

With one working station, the winch is skidding \( M_{\text{group}} \) groups of trunks with the volume \( Q_{\text{group}} \) each. These groups form the skidding sum of groups of trunks with the volume of \( Q_{\text{pile}} \):

\[
M_{\text{group}} = \frac{Q_{\text{pile}}}{Q_{\text{group}}},
\]

The time duration of the \( j \)-th cycle of the winch on the formation of the \( j \)-th group of trunks:

\[
T_{j_{\text{group}}} = \left( \sum_{i=1}^{M_{\text{group}}} T_{i_{\text{group}}} \right) + t_{j_{\text{winch}}},
\]

where:

\( t_{j_{\text{group}}} \) – time to relocate the winch after the formation of the \( j \)-th group of trunks, sec.

5. A conceptual model of the technological process

We will present the process as a Queuing system (QS).

Technology process can be presented in the form of a diagram in Figure 4. In terms of QS the service requests are trees – processed trees (trunks) group of trunks – stockpiles of trunks. Service devices are chainsaws on processing of the trees for skidding \( (K_1) \) and a portable winch on skidding of groups of trunks to the stockpiles of trunks \( (K_2) \). With the beginning of the work, the system receives one demand, which generates \( n \) service requests, equal to the number of unprocessed trees in the working area of the winch. These are the service requests of the first level.

The service requests of the first level are served through channels \( K_{1n} \). This is multi-channel service unit. It simulates the time of trees processing for skidding. The service time in the \( i \)-th channel \( K_i \) is determined by the work of the chainsaw.

The accumulated service requests of the first level form the service request of the second level – groups of trunks. The second level service request are queued to the \( Q_{\text{group}} \) and served through the channel \( K_2 \). After the channel \( K_2 \), the demand of the second level are accumulated and form the service requests of the third level \( Q_{\text{pile}} \), which simulate the stockpiles of trunks. Channel \( K_3 \) simulates the relocation of the winch to the new work station. After going through the service channel \( K_3 \), the service requests of the first level are placed in the queue and form the service requests of the second level \( Q_{\text{group}} \).
Thus, in the model adopted by us, service requests are divided into three levels:
- service requests of the first level – unprocessed trees of the WNM and processed trees;
- service requests of the second level – skidding groups of trunks;
- service requests of the third level – stockpiles of trunks.

6. Planning of experiments and analysis of research results
The main objective of the experiments with the simulation model of the first technological stage was to determine the effect of the WNM volume on the forest plot on the process performance.

In the first series of experiments, the task was to establish the effect of the characteristics of the winch (the length of the winch traction rope, and hence the covered area, and the speed of the traction rope) on the performance of the technology.

The generalized results are given in Table 1-2, the experimental results were systematized and presented in the form of graphs in Figure 5-8.
Table 1. Results of experiments with simulation model 1 (1 chainsaw, 1 winch, volume of the WNM = 20 m$^3$/ha).

| Winch rope length, m | Winch rope speed, m/sec | The utilization of a winch | The utilization of a chainsaw |
|----------------------|-------------------------|---------------------------|-------------------------------|
| 10                   | 0.2                     | 0.618                     | 0.647                         |
| 30                   | 0.2                     | 0.947                     | 0.684                         |
| 50                   | 0.2                     | 0.983                     | 0.542                         |
| 70                   | 0.2                     | 0.992                     | 0.444                         |
| 90                   | 0.2                     | 0.995                     | 0.375                         |
| 10                   | 0.4                     | 0.585                     | 0.666                         |
| 30                   | 0.4                     | 0.938                     | 0.813                         |
| 50                   | 0.4                     | 0.979                     | 0.684                         |
| 70                   | 0.4                     | 0.989                     | 0.581                         |
| 90                   | 0.4                     | 0.994                     | 0.500                         |

Table 2. Results of experiments with simulation model 1 (continuation) (1 chainsaw, 1 winch, volume of the WNM = 20 m$^3$/ha).

| Winch rope length, m | Winch rope speed, m/sec | The volume formed by the group of trunks, m$^3$ | Number of trees of the WNM on the forest plot | The volume of trunksskidded per shift, m$^3$/shift | The total numbers of groups of trunks skidded per shift, m$^3$/shift |
|----------------------|-------------------------|-----------------------------------------------|-----------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| 10                   | 0.2                     | 0.300                                         | 2                                            | 17,220                                          | 54.40                                           |
| 30                   | 0.2                     | 2,702                                         | 18                                           | 18,206                                          | 6.73                                            |
| 50                   | 0.2                     | 7,837                                         | 52                                           | 14,400                                          | 1.84                                            |
| 70                   | 0.2                     | 15,396                                        | 102                                          | 11,739                                          | 0.76                                            |
| 90                   | 0.2                     | 25,500                                        | 169                                          | 9,881                                           | 0.39                                            |
| 10                   | 0.4                     | 0.300                                         | 2                                            | 17,738                                          | 59.13                                           |
| 30                   | 0.4                     | 2,703                                         | 18                                           | 21,626                                          | 8.00                                            |
| 50                   | 0.4                     | 7,824                                         | 52                                           | 18,191                                          | 2.33                                            |
| 70                   | 0.4                     | 15,403                                        | 102                                          | 15,403                                          | 1.00                                            |
| 90                   | 0.4                     | 25,350                                        | 169                                          | 13,309                                          | 0.33                                            |
Figure 5. Dependence of the volume of the stockpile of groups of trunks formed on one working station of the winch, from the length of the traction rope winch (1 chainsaw, 1 winch, volume of the WNM = 20 m³/ha).

Figure 6. Dependence of the total numbers of groups of the trunks formed on one working station of the winch per shift, from the length of the traction rope winch (1 chainsaw, 1 winch, volume of the WNM = 20 m³/ha).
Note that the speed of the winch rope does not affect the volume of the formed groups of trunks on one working station of the winch, which is understandable. From the chart in Figure 5 it can be seen that the volume of the formed stockpile of the trunks from one working station of the winch depends on the length of the winch traction rope. Note that with the increase of the length of the rope, the number of trunks in the working zone of the winch increases according to the power law. And the degree is close to 2. This was to be expected, since the area of the operation is proportional to the square of the length of the traction rope of the winch.

The graph in Figure 6 is very indicative. The number of groups of the trunks skidded per shift decreases sharply (according to the power law) with the increase of the length of the traction rope of the winch. This was to be expected, since the volume of the stockpile of the trunks and hence the time to form it, increases with the length of the winch rope (Figure 6).

The graph in Figure 7 is very interesting. (The dependence of the skidded volume of groups of the trunks from the length of the traction winch rope).

The curves in the graph Figure 7 have maximums that is, at some length of the winch traction rope, the system achieves maximum performance. In the case of the WNM volume of 20 m³/ha, the maximum capacity of the system will be achieved at 30-meter rope length.

On Figure 8 the graph of the dependence of coefficient of utilization of the winch and the chainsaw from the length of the traction rope of the winch is given. Analysis of curves of the chart Figure 8 shows that the maximum values of the coefficients of utilization of the winch and the chainsaw are reached at 30-meter length of the traction rope. And this occurs both at the speed of the winch traction rope equal to 0,2 m/sec, and at 0,4 m /sec.

Note that the coefficient of utilization of the winch (Figure 8) from the length of the traction rope winch grows rapidly with increasing traction rope length and at 40 m becomes close to 1.

In order to establish the effect on the coefficients of utilization of the winch and the chainsaw from the volume of the WNM, an additional series of experiments was carried out.
The planning matrix of the experiments is given in Table 3. The results of the experiments were systematized and presented in the form of a graph in Figure 9.

From the chart in Figure 9 follows that with the increase of the volume of the WNM, the coefficient of utilization of the winch increases, and the coefficient of utilization of the chainsaw decreases. However, these changes are insignificant (no more than 3.5%) and may not be taken into account in practice. Therefore, for the conditions adopted in the experiments, the length of the traction rope equal to 30 m can be considered optimal for portable hand winches.

**Table 3.** Planning matrix of experiments with simulation model 1 (1 chainsaw, 1 winch, traction rope length = 30 m, rope speed = 0.2 m/sec).

| Winch rope length, m | Winch rope speed, m/sec | Volume of the WNM, m³/ha |
|----------------------|-------------------------|--------------------------|
| 30                   | 0.2                     | 20                       |
| 30                   | 0.2                     | 40                       |
| 30                   | 0.2                     | 60                       |

**Figure 8.** Dependence of the coefficients of utilization of the winch and the chainsaw from the length of the traction rope of the winch (1 chainsaw, 1 winch, the volume of the WNM = 20 m³/ha).
7. Conclusion and practical recommendations

The simulation experiments that were carried out with the dead wood or wood natural mortality (WNM) made it possible to draw the following conclusions:

1. The technology cleaning and utilization of the DEO is proposed, which consists of four stages, including quality control of sanitary measures (Figure 2).

2. In the framework of the proposed multi-stage technology, the article considers the second stage of the DEO cleaning (Figure 2), including the process chain: chainsaw + portable winch (Figure 2).

3. A mathematical and conceptual model of cleaning the DEO was developed. The model considers a winch with a rope length from 10 to 90 m and DEO volume on a site from 20 to 60 m$^3$/ha.

4. It is established that the volume of the DEO from one winch parking depends on the length of the winch traction rope. As the length of the rope increases, the number of the DEO that contains inside the winch's operating zone increases by a power law.

For practice, we can conclude that the length of the winch rope should be chosen taking into account the volume of DEO on the site (Figure 5).

5. Maximum performance is achieved with a certain length of the winch traction rope. For example, in the case of the DEO volume of 20 m$^3$/ha, the maximum productivity of the system will be achieved with a 30-meter rope length (Figure 7).

In practice, this means that the length of the winch rope should be chosen based on the volume of the DEO on the site and the winch power.

6. With the increase of the DEO volume on the site, the winch utilization rate increases, and the chainsaw utilization rate of the chainsaw falls. However, these changes are insignificant (no more than 3.5%) and may not be taken into account in practice (Figure 9).

In practice, for the conditions adopted in the experiments, the length of the traction rope equal to 30 m can be considered optimal for portable hand winches.

8. References

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