Decision support system for energy wood production

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Abstract. An approach to the application of modern information technologies and mathematical methods to solve the problem of energy wood production and logistics technologies selection is described in the article. The general statement of the problem, the methodology, methods and models used are given. A decision support system for energy wood production can evaluate and compare various technological schemes for the harvesting and processing of woody biomass to energy wood and identify the most effective choice. At the operational level, the approach allows to optimize the current plans for the harvesting, initial processing and transportation of the energy wood for available production capacities, taking into account the commercial roundwood production providing at the same time. Proposed approach is a practical tool for ensuring profitability and sustainable growth of the energy wood production, which will stimulate the development of bioenergy in Russia.

1. Introduction

There are a number of technologies for harvesting and processing of woody biomass (WB) to energy wood (EW) suitable for use in local energy production today [1]. However, there is no significant practical application experience of these technologies in Russia, which has a colossal WB resource [2]. This situation slows down the development of bioenergy production in Russia, reduces the investment attractiveness of this business. In this regard, it seems important to develop a decision support system for energy wood production that can evaluate and compare various technological schemes for the harvesting and processing of WB to EW to identify the most effective choice.

Analysis of similar problems shows that it requires the use of modern methods of mathematical modeling, including simulation and GIS technologies, due to the spatial core of the problem.

This problem has a number of significant features. First of all, it should be noted that there is a close relationship between the processes of harvesting, transportation and processing of WB to EW with the commercial roundwood (RW) production – the production of WB most often appears in a dependent, subordinate position [3]. Secondly, this is a variety of both WB sources (for example, firewood, logging residues, stumps and root wood, small-diameter trees (SDT) from thinning), and harvesting technologies (cut-to-length (CTL) [4], tree-length (TL), full trees (FT)) [5]. Thirdly, it is a permanent change in the spatial distribution of production, resulting in frequent changes of the working places, such as warehouses or harvesting sites [5]. Other significant features that are common for the production of RW and EW are the dependence on the season, road infrastructure and environmental conditions [6].

More than 40 alternative schemes of the EW production were identified in [4-6]. 12 most common schemes are considered in this study (table 1).
Table 1. Most common schemes of EW production.

| EW source          | Harvesting site | Roadside                  | Terminal                          | Consumer                          |
|--------------------|-----------------|---------------------------|-----------------------------------|-----------------------------------|
| 1 Firewood processing |                 |                           |                                   |                                   |
| 1.1 Roadside       | Harvester + forwarder | Chipper + Chip truck | –                                 | Burning                           |
| 1.2 Terminal       | Harvester + forwarder | Firewood transportation | Chipper + Chip truck              | Burning                           |
| 1.3 Consumer       | Harvester + forwarder | Firewood transportation | –                                 | Chips production and burning      |
| 2 Processing of firewood and logging residues |                 |                           |                                   |                                   |
| 2.1 Roadside       | Harvester + forwarder | Chipper + Chip truck Transportation of firewood and logging residues | –                                 | Burning                           |
| 2.2 Terminal       | Harvester + forwarder | Firewood transportation | Chipper + Chip truck              | Burning                           |
| 3 Logging residues processing |                 |                           |                                   |                                   |
| 3.1 Consumer       | Harvester + bundler + forwarder | Transportation of WB logs | –                                 | Chips production and burning Chips production and burning |
| 3.2 Consumer       | Harvester + forwarder | Transportation of logging residues | –                                 | Chips production and burning Chips production and burning |
| 4 Firewood processing |                 |                           |                                   |                                   |
| 4.1 Roadside       | Feller buncher + skidder | Processor + Chipper + Chip truck | –                                 | Burning                           |
| 5 Logging residues processing |                 |                           |                                   |                                   |
| 5.1 Roadside       | Feller buncher + skidder | Processor + Chipper + Chip truck | –                                 | Burning                           |
| 6 Processing of firewood and logging residues |                 |                           |                                   |                                   |
| 6.1 Roadside       | Feller buncher + skidder | Processor + Chipper + Chip truck | –                                 | Burning                           |
| 7 Processing of small-diameter trees after thinning |                 |                           |                                   |                                   |
| 7.1 Roadside       | Harvester + forwarder | Chipper + Chip truck | –                                 | Burning                           |
| 8 Stumps processing |                 |                           |                                   |                                   |
| 8.1 Consumer       | Stump remover + forwarder | Stump transportation | –                                 | Chips production and burning Chips production and burning |
2. Methods and Materials

The scheme of the proposed methodology (figure 1) includes two main blocks: “Roundwood production” and “Energy wood production”. The structure of the blocks is formed by separating the wood harvesting and wood transportation. This separating was done not from the standpoint of technology as such, but from the point of view of the simulation modeling subsystems structure.

![Diagram of methodology](image)

**Figure 1. Scheme of the methodology.**

The block structure consists of three sequentially executed procedures. The first of these is optimization (scheduling), the second is simulation and the third is evaluation of the effectiveness. In addition, the methodology provides the relationship between the RW and EW production.

The detailed structure of the block “Energy wood production” is shown in figure 2. Elements of the “Data” module are following: “Biomass yield” is the element for input and storage the information about the volumes of WBat each individual harvesting site; “List of harvesting sites” is an element that allows the user to choose from the entire set of harvesting sites those that will also be integrated with energy wood production; “Characteristics of energy wood harvesting teams” is an element for input and storage the information about the set of machines used for EW harvesting and transportation and their features; “Required wood fuel moisture” shows the maximum humidity level of WBt to control the drying process; and “Energy wood consumers” is designed for input and storagethe information about consumers, which includes the location of the consumer and the types of EW consumed as well as monthly consumption plans.
Figure 2. Structure of the block “Energy wood production”.

Elements of the “Simulation” are following: “Calculation of the biomass volume” estimates the amount of energy wood at each site in any time period; “Calculation of moisture” evaluates the moisture content of WB at each site in any time period; “Simulation of energy wood harvesting and delivery” means the implementation of a simulation model of machinery and equipment for harvesting and transportation of WB and chips; “Optimization of harvesting sites mastering by harvesting teams” provides the optimal order of the harvesting sites for each of available harvesting teams, as well as the optimal set of these teams at each site; and “Optimization of energy wood deliveries” links each harvesting site with the optimal consumer to minimize transportation costs.

The structure of the proposed methodology (see figures 1 and 2) requires the development of a number of models.

2.1. The model for WB volumes calculating

The model for WB volumes calculating is based on the use offirewood and logging residues outputspecificfor a given forest plot by species as a percentage of the stock:

\[ V_b = V_o + V_f = \sum_{i=1}^{n} h_o \cdot V_i + \sum_{i=1}^{n} h_f \cdot V_f, \quad (1) \]

where, \( V_b \) – EW volume, m^3; \( V_o \) – volume of logging residues, m^3; \( V_f \) – volume of firewood, m^3; \( n \) – number of tree species; \( h_o \) – the share of logging residues in the volume of RW for the \( i \)-th species; \( V_i \) – RW volume for \( i \)-th species at the harvesting site, m^3; \( h_f \) – the share of firewood in the volume of RW for the \( i \)-th species.

The algorithm for WB volumes calculating is included in the simulation model of the wood harvesting. Volumes of wood are added at the end of the model day on all harvesting sites where logging is currently active and are determined in accordance with the estimated productivity of the machinery set on this site and with the specified distribution of this volume by type of products. For example, for FT machinery set, the daily output of firewood on a harvesting site will be:

\[ B_f = n_s \cdot t_s \cdot k_e \cdot \min(P_{fb}; P_s; P^*) \cdot \frac{V_f}{V}, \quad (2) \]

where, \( n_s \) – number of shifts; \( t_s \) – duration of the shift, h; \( k_e \) – effective utilization rate; \( P_{fb} \) – average hourly productivity of the feller buncher, m^3/h; \( n_s \) – number of skidders used; \( P_s \) – average hourly
productivity of the skidder, \( m^3/h \); \( P_p \) – average hourly productivity of the processor, \( m^3/h \); \( V_f \) – total volume of the firewood on the harvesting site, \( m^3 \); \( V \) – total volume of RW on the harvesting site, \( m^3 \).

2.2. Moisture content calculation model

In the supply of EW, its moisture content is very important. It significantly affects the calorific value, and consequently the amount of energy received. The drying of logging residues is influenced by a large number of factors, many of which are related to weather conditions. Therefore, it is not possible to accurately predict the drying intensity for a certain period of time. To estimate this value, a statistical method based on long-term observations is used. To date, there is no information about such researches in Russia. Therefore, the model for calculating the moisture content is based on researches provided in Scandinavia [7-9], which are similar to the conditions of northwestern Russia.

It was found that a stable reduction of the logging residues moisture content is observed only in the summer months and in September, and the average intensity of this process is not the same in different parts of this period. A piecewise linear model of moisture content changes was applied with different intensity in different months and constant intensity within one month:

\[
\Delta M = \sum_{i=6}^{10} k_{Mi} \cdot n_i, \tag{3}
\]

where, \( \Delta M \) – moisture content change, \%; \( i \) – month number (January – 1, February – 2 etc.); \( k_{Mi} \) – model coefficients (-0.13% for June; -0.33% for July; -0.20% for August; -0.07% for September and 2.00% for October); \( n_i \) – the number of days of the logging residues storage period within the month \( i \).

2.3. Energy potential calculation model

Energy potential calculation model:

\[
Q = \frac{1}{36 \cdot (100 - M)} \cdot \sum_{i=1}^{n} V_i \cdot P_i \cdot \left( Q_{ui} \cdot \left( 1 - \frac{M}{100} \right) - 0.02441 \cdot M \right), \tag{4}
\]

where, \( Q \) – energy potential, MWh; \( P_i \) – density of wood of species \( i \) in absolutely dry condition, kg/m\(^3\); \( Q_{ui} \) – net calorific value of wood of species \( i \), MJ/kg.

2.4. A simulation model of EW harvesting and delivery

A simulation model of EW harvesting and delivery is implemented in a specially computer program and allows to do simulation of all stages of the production processes [10].

A report containing prospective harvesting and transporting plans is prepared by the computer program as the results of the simulation of EW harvesting and delivery. In the report, for each model day and machinery set, the following information is provided: date; name of the machinery set; kind of technology; the harvesting site where operations are performed on this date; machine operating time (chipper, bundler); machinery utilization rate; volume of processed WB (logging residues, firewood); the volume of EW produced and delivered (chips, WB logs); EW moisture content; energy potential of delivered EW; destination (optimal consumer to whom the EW is supplied); transportation distance; the optimal number of vehicles involved; total operating time of machines; number of runs; total mileage. In addition to data on individual machinery set, daily sums of the given indicators, sums for each machinery set for the entire planning period and sums for all machinery sets for the entire planning period are output.

The machinery utilization rates are determined as:

\[
k_s = \frac{T_u}{n_n \cdot T_d} = \frac{T_u}{n_n \cdot n_s \cdot t_i}, \tag{5}
\]
where, $T_o$ – total time worked by machine(s) per day; $n_m$ – number of machines; $T_d$ – daily fund of working time for one machine.

The time worked by the chipper within the day is defined as the product of the number of loads by the average loading time. The number of loads is equal to the total number of runs completed by trucks per day:

$$T_{oc} = n_r \cdot t_l,$$

where, $n_r$ – total number of runs completed by trucks per day; $t_l$ – loading time.

The time worked by the bundler is:

$$T_{ob} = \frac{V_{wb}}{P_b \cdot k_o},$$

where, $V_{wb}$ – volume of WB logs produced during a model day; $P_b$ – average hourly productivity of the bundler; $k_o$ – effective utilization rate for the bundler.

The total time worked by all trucks includes driving time, loading time and unloading time:

$$T_o = n_r \cdot (t_r + 2 \cdot t_t + t_u) + m \cdot n_r \cdot (t_{el} + t_{g2} - t_r),$$

where, $t_r$ – driving time from the current harvesting site to the optimal consumer; $t_u$ – unloading time; $m$ – optimal number of trucks for transporting wood chips or logging residues; $t_{el}$ – driving time from the garage to the current harvesting site; $t_{g2}$ – driving time from the optimal consumer to the garage.

3. Conclusion
The practical application of proposed approach provides an increase in the efficiency of wood harvesting due to the optimal medium- and long-term planning of WB procurement and EW production. By comparing the values of effectiveness indicators calculated for different technologies, machinery sets and organizational features, the approach allows to reasonably determine the most effective technological schemes for use in specific conditions. At the operational level, the approach allows to optimize the current plans for the harvesting, initial processing and transportation of EW for available production capacities, taking into account the RW production providing at the same time. An effective solution to these problems should become a real tool in the hands of wood harvesting companies for ensuring profitability and sustainable growth of the EW production, which, ultimately, will stimulate the development of bioenergy in Russia.

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