Recycling of forestry waste

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Abstract. The article examines the current state of wood waste recycling in the interests of ensuring sustainable development and minimizing the impact on climate change. Classification of wood waste based on the stage of the life cycle of a wood product has been carried out. The problem of organization of wood waste disposal and processing is relevant both directly in the forest industry and in the process of using wood since this leads to the preservation of primary wood material and significantly reduces the volume of deforestation. During the study methods of wood waste recycling and options for complex recycling have been identified. A wood waste recycling scheme which includes such stages as collecting wood waste, deep wood processing and involvement in secondary circulation has been developed. An econometric analysis of correlation between current environmental costs and indicators of economic activity associated with the use of wood waste on innovative basis has been carried out. It has been concluded that there is a tight relationship between the costs of environmental protection and the selected factors. The research results can be used in the development of wood waste recycling schemes by various economic entities of timber and woodworking sectors.

1. Introduction

The relevance of woodland conservation and expansion is associated with the fact that forests help to preserve the climate. Waste from logging is the starting point in the forestry value chain. Further it is necessary to organize the collection and processing of wood waste at all stages of the life cycle of wood products [1]. Currently, there are no policy instruments that would help coordinate the processes of recycling of generated waste, taking into account the fact that recycling of wood waste supports the global goals of sustainable development [2].

The involvement of wood resources in recycling meets the requirements of resource conservation and natural resource management. The construction of a closed-loop economy model in the timber industry corresponds to the strategic trends of sustainable nature management and environmental protection. As it has been noted in the article by Kirchherr J, Reike D and Hekkert M, the implementation of the concept of resource recycling requires systemic changes [3].

Wood energy is viewed in various aspects of EEA (European Environment Agency) Joint Forestry and Timber Section work and specifically through the advisory work of Team of Specialists on Wood Energy, the Joint Wood Energy Enquiry (which is a comprehensive database on wood energy and wood fuel from EEA Member States) and publishing information on the wood energy market, such as a recurring chapter in Forest Products Annual Market Review [4].

The collected waste must be processed into new products and sold to the consumer. The economic advantage is increased employment in contrast to waste disposal in landfills and incineration.
Recycling can also be a viable response to the increasing demand for resources as it requires less energy than transforming new raw materials into a usable product. Material flows include internal consumption of materials and indicators of circular efficiency, namely, the cascade factor, the indicator of material circulation, processed resources, recovery rates [5].

The purpose of this study is to analyze the factors, to elicit of the tightness of correlation between ten quantitative indicators and current (operating) costs for environmental protection and to propose a toolkit for the implementation of the recycling model in the strategy for sustainable development of the timber industry complex.

The theoretical and methodological basis of the research is the general scientific empirical-theoretical methods of system analysis, abstraction, analysis and synthesis, induction and deduction, analogy, modeling, concretization, historical and logical research methods. Comparative, factor and correlation-regression analysis are used as specific scientific methods.

2. Methodology

To analyze the current state of forestry waste recycling quantitative indicators that affect the state of the environment and the costs of its protection have been determined. The right choice of the method of forestry waste disposal must reduce the costs of environmental protection. All costs associated with environmental protection and natural resource management that have been incurred by the enterprise and the government are classified as operating costs for environmental protection. To carry out a correlation analysis in order to determine the presence or absence of tight relations between the selected variables $X_1 \ldots X_{10}$ and the current (operating) costs of environmental protection $Y$ (table 1), statistical data on the timber industry complex for the period 2010-2019 were taken.

| Designation | Factor (X) and resultant (Y) attributes | Unit of measurement |
|-------------|----------------------------------------|--------------------|
| $X_1$       | Total wood stock of forest stands on the lands of the forest fund and lands of other categories | million m$^3$ |
| $X_2$       | Volume of harvested timber            | thousand m$^3$    |
| $X_3$       | Average number of forestry workers    | people             |
| $X_4$       | Volume of marketable timber harvesting | thousand m$^3$ |
| $X_5$       | Wood pulp production volume           | thousand tons      |
| $X_6$       | Chipboard production volume           | thousand m$^3$    |
| $X_7$       | Plywood production volume             | thousand m$^3$    |
| $X_8$       | Pellet production                     | thousand tons      |
| $X_9$       | OSB$^a$ production volume             | thousand m$^3$    |
| $X_{10}$    | MDF$^b$ production volume             | thousand m$^3$    |
| $Y$         | Current (operating) costs of environmental protection in Russian Federation | million rubles |

$^a$Oriented Strand Board  
$^b$Medium-Density Fibreboard

Correlation between variables may occur as causal dependence of the resultant attribute (Y) on the variation of the factor attribute (X). Correlation analysis enables us to assess the correlation between variables and to separate the influence of specific factor attributes in a complex system of interactions. Moreover, the correlation analysis initially implies the presence of cause-effect relations between the
resultant attribute (Y) and the factor attributes (X). Correlation between resultant and factor attributes may be both direct and inverse. The general algorithm for applying the method of correlation analysis is shown in figure 1.

![Algorithm for the correlation analysis](image)

**Figure 1.** Algorithm for the correlation analysis.

Correlation between the resultant attribute (Y) and factor attributes (X) can be weak and tight (high). To assess the presence of a connection, the Chaddock scale is used, table 2.

| Degree of correlation | The value of the correlation coefficient, if available |
|-----------------------|-----------------------------------------------------|
|                       | Direct                          | Inverse                          |
| Weak                  | 0.1±0.3                         | -0.1±-0.3                        |
| Moderate              | 0.3±0.5                         | -0.3±-0.5                        |
| Salient               | 0.5±0.7                         | -0.5±-0.7                        |
| High                  | 0.7±0.9                         | -0.7±-0.9                        |
| Very high             | 0.9±0.99                        | -0.9±-0.99                       |

If the correlation coefficient is R = 0, then there is no relationship between the resultant and factor attributes. Moreover, if the correlation coefficient R = 1, then the correlation is direct, if the correlation coefficient is R = -1, the correlation is inverse. The source data for a sample consisting of 10 attributes under the study (n = 10) are shown in table 3.

| Year/ factor | X1     | X2     | X3     | X4     | X5     | X6     | X7     | X8     | X9     | X10    | Y      |
|--------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 2010         | 83386  | 173633 | 67818  | 173633 | 7510   | 5521   | 2716   | 500    | 2      | 1800   | 193463 |
| 2011         | 83106  | 196879 | 70357  | 196879 | 7661   | 6603   | 3090   | 630    | 7      | 2070   | 222598 |
| 2012         | 83022  | 191033 | 76770  | 191033 | 7658   | 6223   | 3150   | 850    | 30     | 1316   | 239170 |
| 2013         | 83013  | 193260 | 75889  | 193260 | 7211   | 6555   | 3303   | 916    | 101    | 1110   | 254377 |
| 2014         | 82825  | 202765 | 75602  | 202765 | 7537   | 6183   | 3540   | 878    | 547    | 1885   | 269838 |
| 2015         | 82791  | 205143 | 74986  | 205143 | 7875   | 6591   | 3607   | 939    | 618    | 2230   | 292074 |
| 2016         | 82734  | 213805 | 74504  | 128029 | 8208   | 6573   | 3759   | 1075   | 797    | 2595   | 306534 |
| 2017         | 82766  | 212382 | 73511  | 127901 | 8587   | 7460   | 3729   | 1429   | 1013   | 2970   | 320947 |
| 2018         | 82576  | 238581 | 73997  | 142774 | 8578   | 8400   | 4013   | 1445   | 1356   | 3147   | 345464 |
| 2019         | 82618  | 219153 | 73544  | 141200 | 8250   | 9986   | 4081   | 1636   | 1450   | 3250   | 374411 |

We find the value of the Pearson’s correlation coefficient $r_{xy}$ using the formula (1):
We construct a matrix of coefficients, table 4, based on the calculations of the Pearson’ correlation coefficients for the 10 attributes under the study.

Table 4. Paired correlation coefficient matrix.

|     | X1  | X2   | X3   | X4   | X5   | X6   | X7   | X8   | X9   | X10  | Y    |
|-----|-----|------|------|------|------|------|------|------|------|------|------|
| X1  | 1   |      |      |      |      |      |      |      |      |      |      |
| X2  | -0.850 | 1   |      |      |      |      |      |      |      |      |      |
| X3  | -0.595 | 0.352 | 1   |      |      |      |      |      |      |      |      |
| X4  | 0.471 | -0.582 | 0.106 | 1   |      |      |      |      |      |      |      |
| X5  | -0.673 | 0.817 | 0.033 | -0.825 | 1   |      |      |      |      |      |      |
| X6  | 0.691 | 0.732 | 0.181 | -0.544 | 0.647 | 1   |      |      |      |      |      |
| X7  | 0.965 | 0.467 | 0.757 | 0.781 | 1   |      |      |      |      |      |      |
| X8  | 0.853 | 0.361 | 0.805 | 0.889 | 0.921 | 1   |      |      |      |      |      |
| X9  | 0.850 | 0.847 | 0.361 | -0.708 | 0.855 | 0.819 | 0.942 | 0.934 | 1   |      |      |
| X10 | 0.676 | 0.801 | -0.142 | -0.766 | 0.921 | 0.730 | 0.781 | 0.790 | 0.909 | 1   |      |
| Y   | -0.930 | 0.899 | 0.386 | -0.650 | 0.794 | 0.855 | 0.982 | 0.967 | 0.967 | 0.823 | 1   |

To assess the statistical significance of the correlation we find the value of the t-test using the formula (2):

\[ t_r = \frac{r_{xy} \sqrt{n - 2}}{\sqrt{1 - r_{xy}^2}} \]  (2)

To find the critical value of the t-criterion we use the Student’s table, where for the number of degrees of freedom \( f = n - 2 = 8 \) and the chosen level of significance \( p = 0.01 \) value \( t_{criteria} = 3.355 \).

3. Results

Let us assess the values of the paired correlation coefficients from table 5 for the presence of correlation between the variations of the factor attribute (X) and the effective attribute (Y). To assess the tightness of correlation we will use the Chaddock scale (table 4).

Table 5. Paired correlation coefficients.

| Factor attribute | \( r_{xy} \) | \( t_r \) |
|------------------|-----------|--------|
| \( X_1 \)       | -0.930    | -7.15  |
| \( X_2 \)       | 0.899     | 5.80   |
| \( X_3 \)       | 0.386     | 1.18   |
| \( X_4 \)       | -0.650    | -2.42  |
| \( X_5 \)       | 0.794     | 3.69   |
| \( X_6 \)       | 0.855     | 4.66   |
| \( X_7 \)       | 0.982     | 14.70  |
| \( X_8 \)       | 0.967     | 10.73  |
| \( X_9 \)       | 0.967     | 10.73  |
| \( X_{10} \)    | 0.823     | 4.10   |

The values of the Pearson’ correlation coefficients of the changing variables \( X_1 (-0.930) \) and \( X_4 (-0.650) \) have a negative value on the Chaddock scale, which indicates the presence of an inverse
relationship between the variables and the resultant attribute $Y$, table 6. To achieve this we will use a method of constructing a scatter diagram and confirm the presence of inverse relationship between the two changing variables $X_1$ and $X_4$, figures 2 and 3.

**Table 6.** Selection of factor attributes and identification of the relationship between them according to the Chaddock scale.

| Degree of correlation | Factor attribute of the correlation coefficient if relationship is observed |
|-----------------------|------------------------------------------------------------------------|
| Weak                  | $X_3$ Average number of forestry workers, people                        |
| Moderate              | $X_4$ Volume of marketable timber harvesting, thousand m³               |
| Salient               | $X_5$ Wood pulp production volume, thousand tons                        |
| High                  | $X_6$ Chipboard production volume, thousand m³                          |
|                       | $X_{10}$ MDF production volume, thousand m³                             |
| Very high             | $X_7$ Plywood production volume, thousand m³                            |
|                       | $X_8$ Pellet production volume, thousand tons                           |
|                       | $X_9$ OSB production volume, thousand m³                                |

In figure 2 may observe a negative (inverse) linear relationship between the two variables $X_1$ and $X_4$, which indicates the following tendencies: with an increase of attribute “Total wood stock of forest stands on the lands of the forest fund and lands of other categories”, attribute “Current (operating)
costs of environmental protection in the Russian Federation” will reduce.

In figure 3 may observe a negative (inverse) non-linear relationship between the two variables $Y$ and $X_4$. The calculated correlation characterizes the degree of non-linear statistical dependence of two variables. Therefore, there is no statistical significance of two variables “Current (operating) costs of environmental protection in the Russian Federation” and “Volume of marketable timber harvesting”.

The values of the Pearson’ correlation coefficients of changing variables $X_2$, $X_3$, $X_5$, $X_6$, $X_7$, $X_8$, $X_9$ and $X_{10}$ have a positive value on the Chaddock scale, which indicates the presence of a direct relationship between the variables and the resultant attribute $Y$. The correlation coefficient $X_3$ (0.386) has moderate connection with the resultant attribute $Y$. Correlation coefficients $X_2$ (0.899), $X_5$ (0.794), $X_6$ (0.855) and $X_{10}$ (0.823) have a high correlation with the resultant attribute $Y$. Correlation coefficients $X_7$ (0.982), $X_8$ (0.967) and $X_9$ (0.967) have a very high correlation with the resultant attribute $Y$.

The results of the study of the relationships between the variable $Y$ “Current (operating) costs of environmental protection in the Russian Federation” and changing variables $X$ enabled us to determine the following (figure 4). An increase in the production of plywood, pellets, and OSB boards will be followed by a very high increase in operating costs for environmental protection in Russian Federation. Growth of the volume of harvested timber and production of wood pulp, chipboard, and MDF will be followed by a very high increase in operating costs for environmental protection in the Russian Federation. The average number of forestry workers will have a moderate impact due to the increase in growth of operating costs for environmental protection in the Russian Federation.

The use of correlation analysis enabled us to assess the relationship between the changing variables $X_1$-$X_{10}$ and the resultant attribute $Y$ “Current (operating) costs for environmental protection in the Russian Federation” and to separate the influence of specific factor attributes in a complex system of relationships.

4. Discussion

Wood waste is understood as biomass which is generated during the processing of timber in various production processes. Waste and wood losses are generated at all stages of wood processing. The reasons are both natural factors (the inconsistency of the shape and size of the raw material or its semi-finished product with the final parameters of the product, for example, the inconsistency of the shape
of the logs with the sections of sawn timber and workpieces), and technological factors, in particular, the cutting modes and the quality of the cutting tools used [6].

Wood waste is divided into several categories:

- sawmill waste (sawdust, wood chips, and lump waste), which is used mainly for panel production, production of pellets, briquettes, etc.;
- wood obtained as a result of the maintenance of green areas in parks, forest parks, along roads and railways etc., which is used by regional municipal power plants and boiler houses, mainly as fuel chips and in agriculture and industry, for example, in the form of mulch;
- “old wood” – industrial wood waste and second-hand wood products: euro pallets, furniture, old railway sleepers and poles, formwork, packaging, wood waste from construction work etc.

The total volume of wood waste generation in the Russian Federation is estimated at 15 000 000-20 000 000 solid m³ and the volume of use is 8 000 000-13 000 000 m³, mainly due to the use of large lumpy waste. The largest volume of waste is generated in the process of harvesting spruce timber 0.43 m³ per 1 m³, followed by pine timber 0.26 m³ per 1 m³ and birch timber 0.18 m³ per 1 m³. Thus 2/3 of the volume of wood waste comes from construction work, demolished old wooden buildings, second-hand wooden products, etc. This kind of waste is subject to primary preparation (cleaning from impurities, sorting, etc.), after which it is burned to obtain energy used for production of a number of new materials, for combustion in thermal power station plants with the main fuel as a fuel substitute and disposal in waste incineration plants.

Use of wood waste for energy purposes may be attributed to negative activity due to emissions of harmful substances (fine particles and nitrogen compounds) into the atmosphere during their combustion. Therefore, it is necessary to promote the reduction of wood waste use (pellets, briquettes, fuel chips) for energy purposes by all means of legislation [7].

The main factors of negative impact of timber industry waste on the life of the population and the environment include the following:

- wood waste contaminates populated areas and their surroundings;
- spontaneously combustible and smoldering wood waste acts as a source of air smoke with the soot formation;
- wood waste contaminates forests and poses a threat of forest fires;
- being a source of methane and carbon emissions decomposed wood waste poisons rivers and lakes;
- wood waste dumps are changing the landscapes of municipalities, hindering the development of agriculture, recreation and nature tourism [8].

Therefore, the traditional approach to logging, where woody biomass which remains after logging is treated as waste, increases the cost of harvested timber. Today in developed forestry countries such as Finland, Sweden, Germany, Canada, USA, etc. woody biomass is not considered as waste. On the contrary, woody biomass is considered as a related raw material that may be used to obtain useful products. This approach does not only reduce the cost of harvesting, but also brings additional income to the logger. Today bioenergy is becoming the main consumer of woody biomass which remains after harvesting in developed forestry countries [9-11].

The recycling system of forestry waste includes the processes associated with the collection of waste from logging, woodworking, as well as their involvement in the secondary production process and complete processing (figure 5).

As you can see, recycling of forestry waste organizes production chains where wood waste is converted into products with high added value that are in demand on the market. Waste-free production can be organized both in large timber and woodworking companies and in small and medium-sized businesses specializing in the collection and processing of wood waste. In this regard, the need to form an independent industry sector for wood waste processing arises. The sector must be provided with sites for temporary accumulation and sorting of industrial waste and wood products.
5. Conclusion
The results of the study have revealed a correlation between the costs of environmental protection and volumetric indicators which reflect the possible options for recycling forestry waste. The volume of harvested wood, the volume of wood pulp production, the volume of chipboard production, and the volume of MDF production have a high tightness of connection with the resultant attribute. A very high tightness of connection is noted for such attributes as plywood production volume, pellet production volume, OSB production volume.

Taking into account the global trend of the predominance of use of forest industry waste for fuel and energy purposes, our proposals are related to an integrated approach to solving this problem. Different countries have specific structures of forest industry waste, but a common characteristic is that the recycling process involves, first of all, sawmilling and woodworking waste, followed by low-quality and small-scale wood. Relatively new technologies used in Russian and foreign practice allow us to develop the production of plate and other products used in the furniture, construction, chemical
and cellulose–paper industries. Recycling shall allow meeting the growing demand for wood resources without increasing the energy consumption required to obtain and transform new raw materials.

The results obtained allow us to develop recommendations for choosing a method for recycling forestry waste:

1. Use of recycled wood resources as part of raw materials for the production of panel products, plywood, pellets, and cellulose.
2. Introduction of a system for separate collection of wood waste in order to optimize the system for their further recycling.
3. Complete disposal of secondary wood resources along with minimizing the volumes of burials that are harmful to the environment.
4. Increased use of recycled biofuels for heat and power generation.
5. Legislative prohibitive measures against two methods of waste disposal, namely, incineration and burial, must be taken.

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