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The Choice of a Set of Operations for Forest Landscape Restoration Technology

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Abstract: The study is intended for forest farmers who need to make a mathematically sound and objective decision on the choice of technological operations and technical means for forest restoration. Currently, in studies implementing the forest landscapes restoration approach from the point of view of technology and the use of technical devices (FLR technology), there is some discreteness and fragmentation of the issues. There is a need for a comprehensive study of FLR technology using frontier techniques and devices, and the construction of a single technological FLR algorithm. Preliminary analysis indicates a sharp increase in the number of operational sets from nine for the implementation of the classical technological FLR algorithm to 268 in the first approximation when implementing the proposed algorithm. The FLR algorithm construction is based on the algorithm's theory, and the verification of the similarity degree of operational sets is based on the cluster analysis by Ward and intra-group connections methods. The algorithm decomposition into six conditionally similar clusters will help plan new forest experiments taking into account interdisciplinary interaction, in addition to the modernization of plant propagation protocols for sustainable reforestation quality management. However, some questions remain for the future: which criterion should be used as a universal basis for choosing operational sets? How can the effectiveness of the FLR technology procedure be evaluated and predicted before its practical implementation?

Keywords: forest landscape restoration; FLR-algorithm; set operations; algorithm decomposition

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1. Introduction

According to Höhl et al. (2020), the following basic approaches to ecological restoration can be identified in world practice:

- Adaptive Forest Management (AFM approach) [1–3] as a "set of stand-related management concepts that are targeted to adapt existing forest stands to changing environmental conditions, e.g., due to climate change or changing societal demands [4]";
- Forest Landscape Restoration (FLR approach) [5–9] as a set of landscape-related management concepts that are "targeted to restore degraded or deforested landscapes, with a focus to restore forest functions [4]". There is an interpretation of the FLR approach based not on the restoration of the forest ecosystem functions, but on meeting the demand for wood supplies [10] (that is, the creation of plantation forests). At the same time, this interpretation of the FLR approach seems rather controversial, because it can "*lead to a wide range of adverse effects on soils and microorganisms, reducing soil organic carbon (24%) and total nitrogen (29%)* [11]";
- Complex approach as a set of management concepts combining the AFM and FLR approaches in "*different spatial scales* [2]", and allowing, for example, review of the concepts of functional zoning of forest landscapes in the context of climate change [12].

In addition to other approaches, "*the FLR-approach is relatively new (<20 years), complex due to its multifaceted nature* [13]". The term Forest Landscapes Restoration (FLR) entails culture and human interaction and backgrounds of the viewers [14]. Of undoubted importance in the design of reforestation approaches are the differences in the perceptions [15], "*engagement of local communities in decision making and implementation, equitable benefit sharing, and monitoring for adaptive management* [4]". Moreover, the FLR term is based on the intersection of environmental, anthropogenic, and technical barriers [4,16].

Modern technological studies of the implementation of the FLR approach are presented, in general, as strategic issues' articles (for example, [17]), research papers (for example, [18–20]), and reviews (for example, [21]). The presented papers do not contain mathematical justification and optimization of mathematical models aimed at the selection and consistency of a set of technological operations and technical means in FLR technology. The choice of the operation is carried out by a group of specialists based on their experience, without using the mathematical apparatus and the theory of algorithms. This, in turn, can affect the objectivity of the decision and lead to inefficient costs.

This study focuses on the case of the development of techniques to overcome the technological (technical) barrier. The study relates to the difficulty of rational choice of technological operations using mechanized and automated technical devices after making a decision regarding the restoration of the forest landscape (FLR technology); that is, the problem of choosing technological operations in FLR technology.

New methods are emerging [22] for implementing a set operations of FLR technology. Infocommunications [23] of all human activity areas and the widespread use of microelectronics products [24] have enabled:

- Information exchange [25] to be conducted between scientists from various fields, providing impetus to interdisciplinary research in the FLR-technology field [5]. This has resulted in new technical means [26–30] and new methods [22,31] in various scientific fields, including: study of heat and mass transfer during oscillating drying [32], immersion freezing [33] and polyacrylamide encapsulation [34] of seeds, study of biophysical methods [35] of non-destructive seed quality control [36] by autofluorescence spectral imaging [37], magnetic resonance imaging [38], study of navigation characteristics [39–43] of unmanned dynamical objects under disturbance conditions [44] (for example, when working under a forest canopy);
- The availability of electronic components, which in turn has made it possible for them to be widely used in research equipment and technical means. This has resulted in an increase in measurement accuracy; the emergence of new qualitative (not quantitative) methods for evaluating objects, including in forestry, for example, non-invasive determination of seed viability [45–50]; and the development of fundamentally new equipment in the field of seed sorting by spectrometric properties [51–53];
- The development of fundamentally new control systems for technical means. This has resulted in the use of unmanned aerial vehicles (UAVs) in the forest sector for remote sensing of stands [54,55] (including individual trees) and aerial seeding [56], in addition to robotic tools for forest nurseries [50,57].

However, classical methods of implementing FLR technology with an established set of technical means can also be used. The classical FLR-technology algorithm shown in Figure 1 is enlarged and shows the main operations: site preparation, tillage, and seeding or planting.

Terminal operators 1 and 15 (see Figure 1) indicate the beginning and end of the execution of FLR-technology operations. Data operator 2 indicates the need to know the main characteristics of the restored area (S)—geomorphology (especially slopes), soil type—in addition to the reasons for forest restoration. The operators of the predefined process 3 and 4 indicate the most expensive process in classical FLR technology, requiring up to 40% of energy and 25% of labor costs [56]. Because the classical FLR technology is shown in an enlarged manner, the designation of site preparation in the algorithm by the operator of a predefined process assumes the implementation of this operator in a separate module. Further, in the classical FLR algorithm, groups of conditional operators (criteria) 5 and 7 (bias) were used; if these were not met, the classical FLR technology could not be implemented. The success of the use of ground-based technical means and the associated costs depends on the slope of the site to a sufficiently high degree. Conditional operators

9 (soil type) and 10 (number of stumps per hectare) also had a significant impact on the choice and success of technological operations 13 and 14: tillage and seeding (planting).

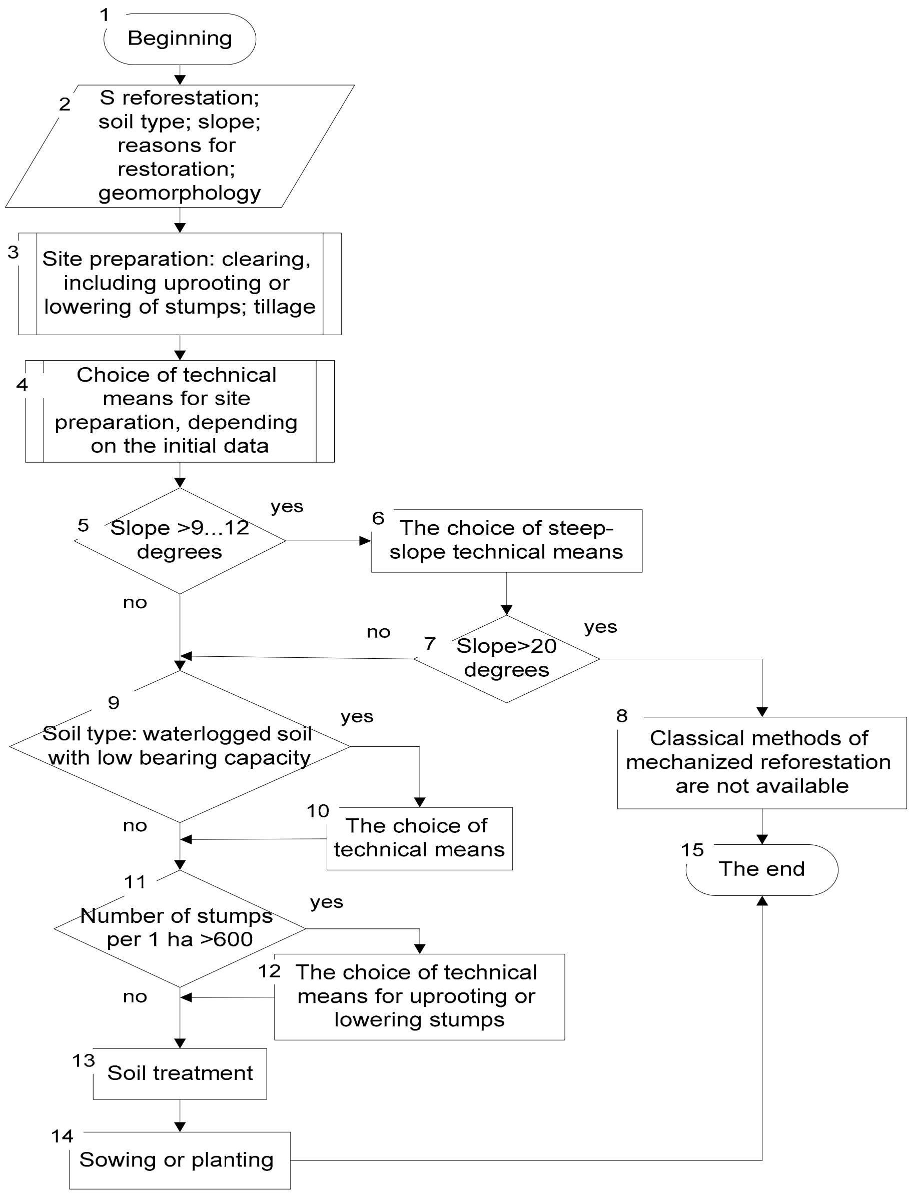

Figure 1. An algorithm using classical FLR technology. Adapted from [58].

This number of options with 15 operations (including the beginning and end of the algorithm) allows a complete search of technological operations to determine the optimal reforestation option. However, for a simplified algorithm (without taking into account: specific machines and aggregates with their performance; variation of soil types; causes of reforestation—after continuous logging, fires, etc.), the meaning of calculations is lost, because they will have a wide range of variation.

There is no clear indication of specific models and brands of technical means in the classical FLR algorithm. The indication of specific technical means to sharply expand the implementation matrix and the study of the algorithm by an exhaustive method, which is impractical in the context of this paper. Despite this, the classical algorithm has an FLR-technology implementation of nine sets of technological operations (Figure 2).

The classical FLR algorithm (see Figure 1) was first proposed in the 1960s with the beginning of the development of complex mechanization; however, as a result of the modern level of the development of science, new equipment, machines and mechanisms, and software and hardware control systems for technical means have been developed, and the use of unmanned aerial vehicles and more has become possible. In such conditions, it is necessary to revise the classical technology by taking into account the current state of the issue.

1) 1-2-3-4-5-6-7-8-15—impossibility of artificial reforestation;
2) 1-2-3-4-5-6-7-9-10-11-12-13-14-15;
3) 1-2-3-4-5-9-10-11-12-13-14-15;
4) 1-2-3-4-5-6-7-9-11-12-13-14-15;
5) 1-2-3-4-5-9-11-12-13-14-15;
6) 1-2-3-4-5-6-7-9-10-11-13-14-15;
7) 1-2-3-4-5-9-10-11-13-14-15;
8) 1-2-3-4-5-6-7-9-11-13-14-15;
9) 1-2-3-4-5-9-11-13-14-15.

Figure 2. Possible sets of technological operations for the classical FLR algorithm.

Therefore, the aim of this study was the construction and examination of the FLR algorithm for selecting a set of technological operations of contemporary FLR technology.

2. Materials and Methods

The theory of algorithms was used to represent the sequence of operational technologies and to evaluate a possible set of technologies and technical means. The degree of similarity and difference in the variants of the set of operations was assessed using hierarchical cluster analysis, which estimates the distance of the algorithm's operations from the center based on the measure of the square of the Euclidean distance using the application software (IBM SPSS Statistics, ver. 25). Visualization of this method was carried out using Ward's [59] dendrogram and intra-group connections. The choice of software was due to the most frequent occurrence in Scopus (2497 cases, available 26 November 2021), in addition to convenient linguistic tools and an understandable adaptive interface for solving the necessary class of statistical problems.

Almost every step of the developed algorithm requires a mathematical justification of the choice. To "assess the necessity and possibility of site preparation (tillage)", a method of expert assessments is needed. Its application will ensure the objectivity, universality, complexity, and competence of practical decisions. For a comprehensive assessment of the site, to make a decision on the choice of machines and mechanisms, it is advisable to apply the theory of fuzzy sets.

A comprehensive assessment of the condition of the sites is based on taking into account the influence of all natural and climatic data and anthropogenic impacts. In order to take into account all of the indicators in the integral assessment of the state of the site, it is advisable to formalize the decisions of experts using the methods of fuzzy set theory. Then, the expert assessments will be presented in the form of linguistic variables. The assessment of the condition of the site will be presented in the form of a formalized set of such variables. This situation is called a fuzzy situation. If a possible threshold is set to include the existing situation in the acceptable options, then it is possible to make decisions about the inclusion of one or another existing technology during reforestation.

3. Results and Discussion

3.1. Constructing an FLR Algorithm

The variety of operational technologies (each of which includes its own set of technical means), types of areas to be restored, geomorphological and climatic data, and stand compositions generates a complex task of the optimal selection of a group of technological operations that take into account natural and climatic conditions that ensure cost reduction and energy efficiency of the reforestation process [60].

In an attempt to take into account current trends in reforestation and comprehensively approach the problem of reforestation, a reforestation algorithm was developed (Figure 3). This algorithm structurally consists of 32 technological operations, of which 31 technological operations or 31 blocks of the algorithm are significant (without the "Beginning" block). Almost every block of the algorithm can be described in more detail in terms of its practical implementation, technical means, equipment models, equipment performance, etc.

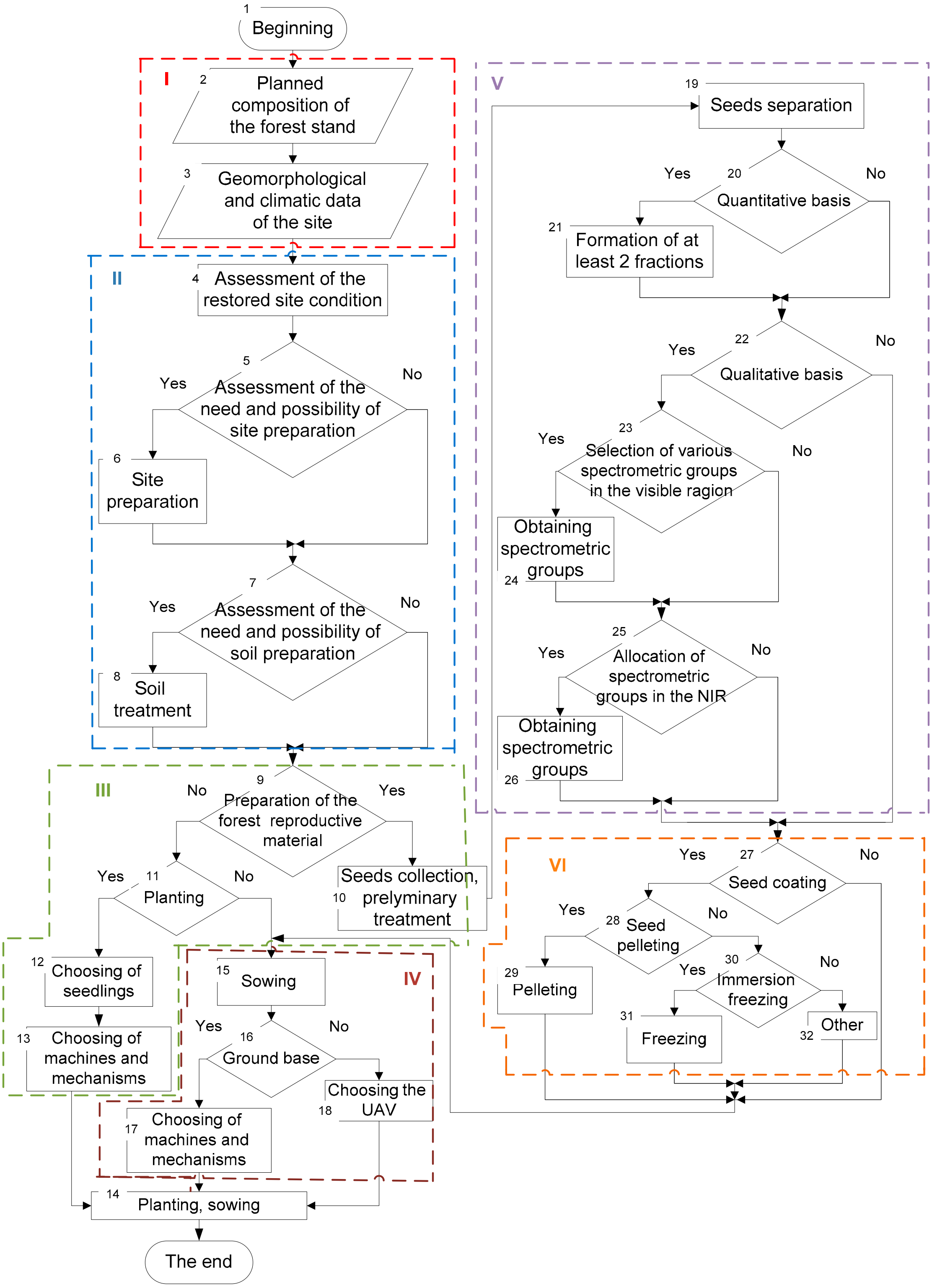

Figure 3. The developed algorithm that takes into account current trends in FLR technology.

Based on a more detailed description of each of the blocks, it is possible to develop a mathematical apparatus for each block that will determine the optimal solution to the problem of the algorithm block. For example, for the block "Assessment of the need and possibility of site preparation", the need for soil preparation is determined based on the type of condition of the area (after logging—the volume of felling residues, the number and height of stumps; after fires (riding or grassroots)—the depth of burning of the soil, the number of trunks per hectare; after biotic exposure—the nature of the damage to the stand (bark, bast) etc.), and the possibility is determined from the purposes of reforestation: natural or artificial; the composition of rocks; the existing fleet of machines and mechanisms, etc. Given the impossibility of numerical calculation for all parameters that determine "need and possibility", the main method here is the method of expert assessments. The use of the method of expert assessments will ensure objectivity, versatility, complexity, and competence in solving this problem. The basis of this method will be to obtain qualitative group expert assessments according to particular criteria, according to which a decision on "need and possibility" can be made. In this study, the task of collecting expert opinions and calculating group expert assessments was not set, because this topic deserves separate consideration in the future.

Thus, almost every block of the algorithm carries a separate task, for the solution of which it is necessary to apply a specific apparatus (to develop a mathematical model specifically for the task; to apply the method of network planning; to collect expert opinions and apply the method of expert assessments; to develop an algorithm for choosing the optimal set of equipment; etc.). Therefore, in order not to complicate the algorithm even more and to make the visualization of the algorithm understandable, the blocks (technological operations) shown in the algorithm are not presented in detail.

The reforestation process contains a set of technological operations (a set of algorithm blocks). For the developed algorithm (Figure 3), there are 268 solutions or 268 different sets of technological operations (Appendix A); this number was obtained in the first approximation by a complete search.

Based on the presented algorithm (Figure 3) (without taking into account: specific machines and aggregates with their performance; variation of soil types; causes of reforestation—after continuous logging, fires, etc.), we see that such a task is multi-criteria in nature and if a mathematical model is developed based on minimizing downtime of equipment and people, then with a high probability such a task will be NP-complete [61], requiring either a complete search of all possible options, or additional development of a heuristic algorithm to solve it.

3.2. Interpretation an FLR Algorithm

The frequency characteristics of the occurrence of technological operations in 268 sets of operations of the FLR algorithm were analyzed (Figure 4).

The most common operations: 2, 3, 4, 5, 7, 14 (1—"Beginning" is not taken into account, because it is a structural part of the algorithm, which in this case does not carry a semantic load). The high frequency of occurrence of operations 2, 3, and 4 (268 out of 268, or 100% occurrence) is due to the need for a complete set of initial data for each variant of the set of operations during reforestation. The volume and completeness of information can affect the number of possible options; the less the amount of information about the object of reforestation, the more options need to be considered to find the optimal and effective set of technological operations. The frequency of occurrence of 5 and 7 (100%) is due to the fact that reforestation and afforestation, firstly, is carried out in areas accessible to machines and mechanisms used in the "classical" technology of reforestation; secondly, in general, they are not carried out in hard-to-reach areas (swampy soils of South America, mountainous terrain, or permafrost of the North of Russia) due to economic inefficiency—logging makes a profit here and now, and reforestation and afforestation requires enormous costs that will pay off, at best, in 40–60 years; thirdly, the complete absence of technological operations 5 and 7 is advisable when using UAVs, and the use of UAVs in reforestation is only gaining momentum. The occurrence of 14 operations is 100% due to the fact that it was believed that if the reforestation process is started, then it should have a positive outcome in terms of planting and sowing.

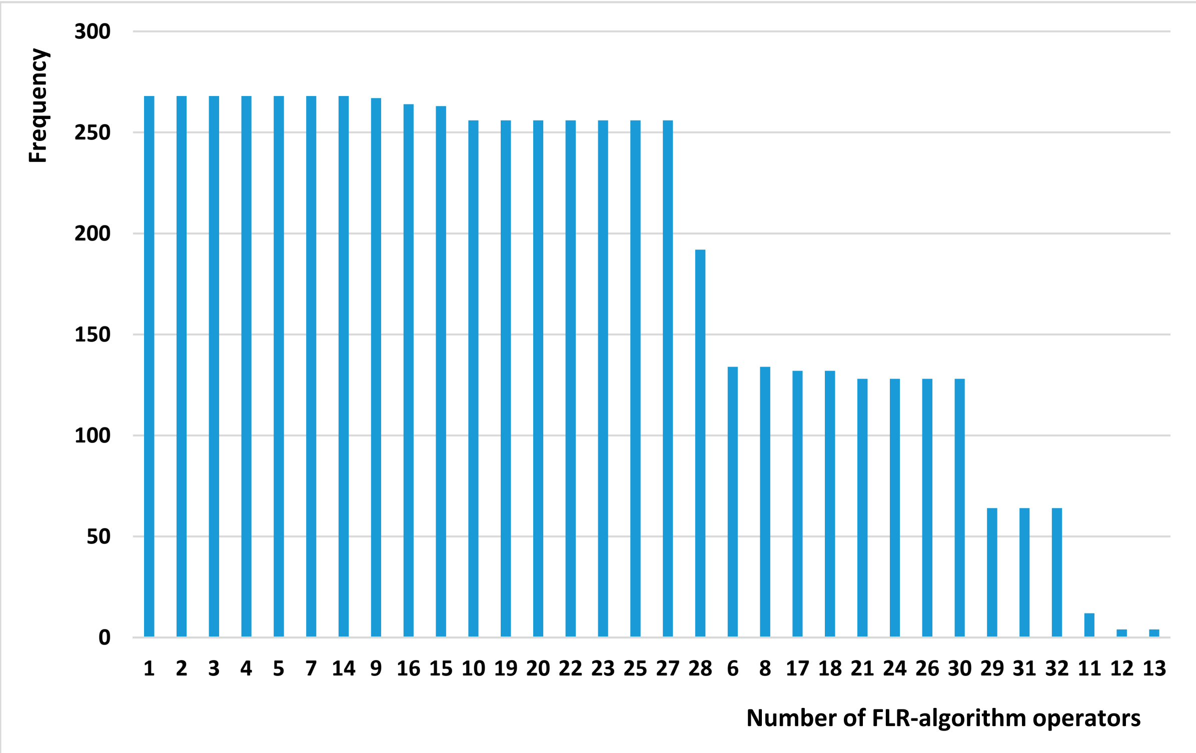

Figure 4. Frequency plot of the FLR technological operations in the FLR algorithm implementation.

The most rarely encountered operations are 11, 12, and 13. This is due to the fact that if reproductive material prepared by third-party organizations is planted, the number of technological operations decreases, but the question arises of the cost and quality of the purchased reproductive material.

There is a dilemma: while a detailed consideration of each technological operation with its decomposition is necessary, a comprehensive global approach to the entire reforestation process is also needed, taking into account current trends in the development of technologies and tools used in reforestation. The solution to this dilemma, in our opinion, can be the decomposition of the algorithm into six enlarged groups—I, II, III, IV, V, and VI (in Figure 3, a dotted line of different colors is highlighted). The decomposition was carried out based on the generality of operations and their belonging to a certain stage. Thus, the possibility of detailed consideration of individual operations within a small block remains but, at the same time, enlarged groups can easily be joined together for an extensive analysis of the situation on reforestation.

For a detailed analysis of the set of operations during reforestation, a binary matrix with a size of 32 × 268 (Figure 5) was compiled based on the developed algorithm.

The binary matrix formed the basis of hierarchical cluster analysis by the Ward method (Figure 6) and intra-group relationships (Figure 7) to create groups of similar objects. Ward's method is aimed at combining closely spaced clusters.

Analysis of the dendrogram based on Ward's method (Figure 6) shows the following pronounced clusters in the upper part of the dendrogram I (1-4, 6, 8, 13, 14, 31), II (9, 17, 18, 20, 21, 23, 25), III (11, 12, 10), and IV (19, 22, 24), and a large number of clusters in the lower part of the dendrogram. There are differences between them, but they are insignificant. If we compare the blocks obtained by decomposition of the algorithm and the clusters obtained on the dendrogram by Ward's method, we see that cluster I approximately reflects the decomposed blocks I and II, which relate to the analysis and input of initial data and preparation and tillage. Otherwise, cluster I can be characterized as the simplest variant of a set of operations for reforestation. Cluster II reflects the process of seed preparation and can be correlated with the decomposed block V. Cluster III practically corresponds to the decomposed block III. From cluster IV onwards, the clusters practically coincide with the algorithm blocks (technological operations). However, the Ward method dendrogram shows a significant difference between clusters I, II, and the rest; that is, it can be concluded that cluster analysis has identified a group of basic operations and a group of operations related to the involvement of new methods and technical means for reforestation.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
1																																	
2		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
3	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	2	1	1	1	1	1	0	1	1	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	3	1	1	1	1	1	1	1	0	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	4	1	1	1	1	1	0	1	0	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	5	1	1	1	1	1	1	1	1	1	0	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	6	1	1	1	1	1	0	1	1	1	0	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	7	1	1	1	1	1	1	1	0	1	0	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	8	1	1	1	1	1	0	1	0	1	0	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	9	1	1	1	1	1	1	1	1	1	0	1	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	10	1	1	1	1	1	0	1	1	1	0	1	0	0	1	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
262	260	1	1	1	1	1	0	1	0	1	1	0	0	0	1	1	1	0	1	1	1	0	1	1	1	1	1	1	1	0	1	1	0
263	261	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	0	1	1	0
264	262	1	1	1	1	1	0	1	1	1	1	0	0	0	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	0	1	1	0
265	263	1	1	1	1	1	1	1	0	1	1	0	0	0	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	0	1	1	0
266	264	1	1	1	1	1	0	1	0	1	1	0	0	0	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	0	1	1	0
267	265	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0	1	1	1	0	1	1	0	1	1	1	1	0	1	1	0
268	266	1	1	1	1	1	0	1	1	1	1	0	0	0	1	1	1	0	1	1	1	0	1	1	0	1	1	1	1	0	1	1	0
269	267	1	1	1	1	1	1	1	0	1	1	0	0	0	1	1	1	0	1	1	1	0	1	1	0	1	1	1	1	0	1	1	0
270	268	1	1	1	1	1	0	1	0	1	1	0	0	0	1	1	1	0	1	1	1	0	1	1	0	1	1	1	1	0	1	1	0

Figure 5. Part of the 32 × 268-dimension binary matrix of the implementation of the FLR algorithm.

The dendrogram by the method of intra-group connections (Figure 7), almost as well as the dendrogram by the Ward method, identified the first two clusters I and II with the same set of operations, which confirms the importance and prevalence of these technological operations. Further on in the diagram, clusters almost combine the remaining technological operations in pairs. This shows the existence of differences between technological operations; however, significant differences are observed between a cluster with operations (5, 7, 16) responsible for the choice of preparation, tillage, and the choice of machines for planting or sowing and a cluster with operations (10, 27, 30, 29), ensuring the preparation of seed material.

Based on the results obtained by Ward's methods and intra-group relationships, it can be unequivocally said that there are significant differences between technological operations that provide different stages of reforestation. Moreover, these methods indirectly confirm the feasibility of decomposing the developed algorithm into six blocks based on the technological and technical generality of operations.

What needs to be done in the future? The developed FLR algorithm, taking into account the promising directions of the industry development, contains 31 significant technological operations. Analysis of the algorithm showed 268 different operational reforestation sets. Theoretically, a network model can be built and optimized for groups of similar variants. However, then the question arises—what parameters should be used to look for a critical path? If related to cost, then such optimization will reduce the costs of reforestation, but without taking into account technical and technological indicators. If according to equipment performance, then there is a possibility of using machines and mechanisms for the purpose of "machines and mechanisms" (inefficient use of a chain of machines and mechanisms). There are other optimization criteria, but they all show only one side of the reforestation process. Therefore, it is possible to approach the problem of comprehensively choosing a group of technological operations only on the basis of the proposed algorithm, having developed an optimization model in the future. However, such a task is of a multi-criteria nature, and if a mathematical model is developed based on cost, minimizing downtime of equipment, and personnel, taking into account a large set of source data options, then such a task will be NP-complete. In this case, another problem arises—the solution of this NP-complete problem and the development of a heuristic algorithm. Therefore, it is necessary to decompose the algorithm into six blocks, each of which can be calculated mathematically and, having the final results, combined into a single technological pipeline.

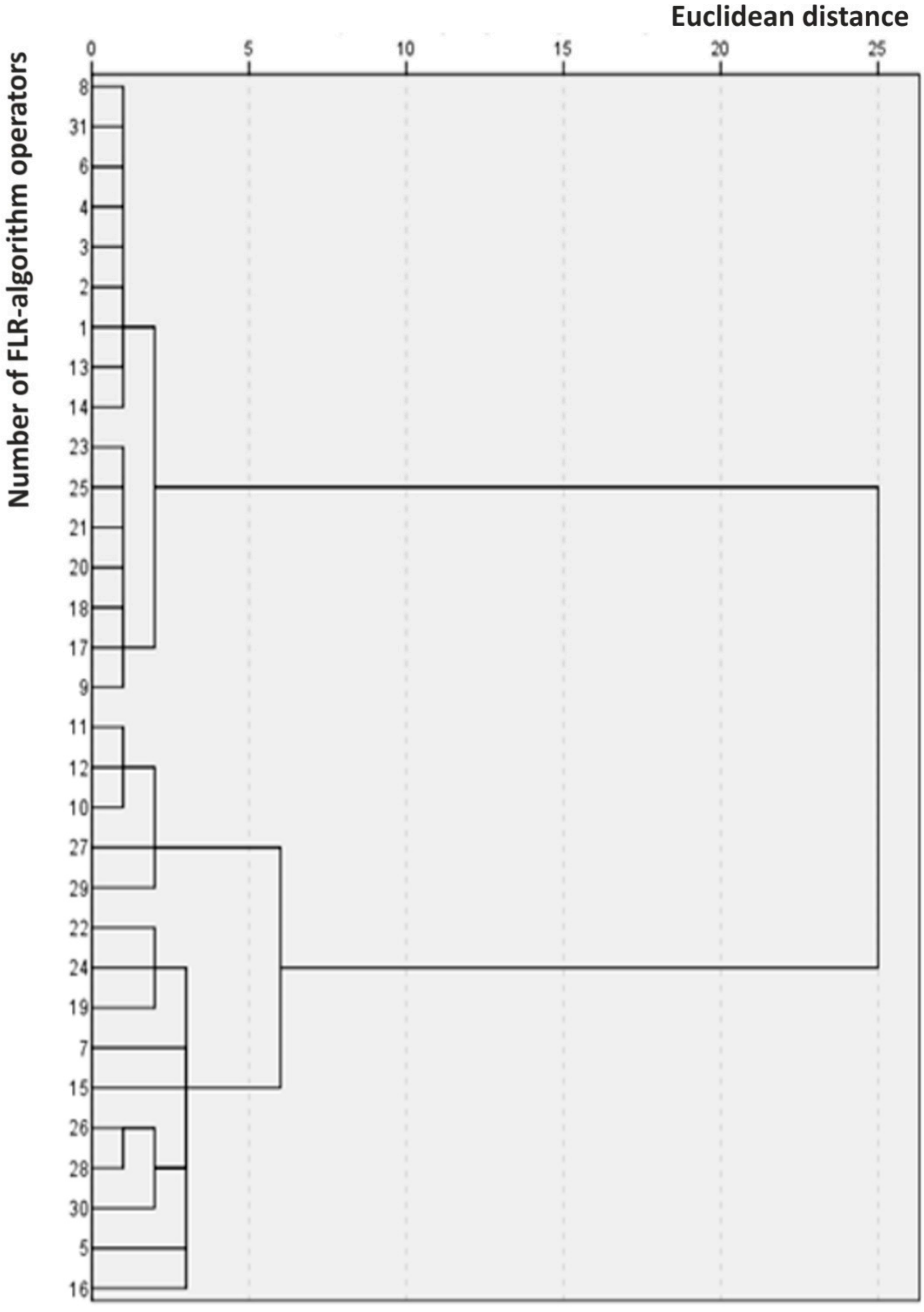

Figure 6. Ward's dendrogram for the FLR algorithm.

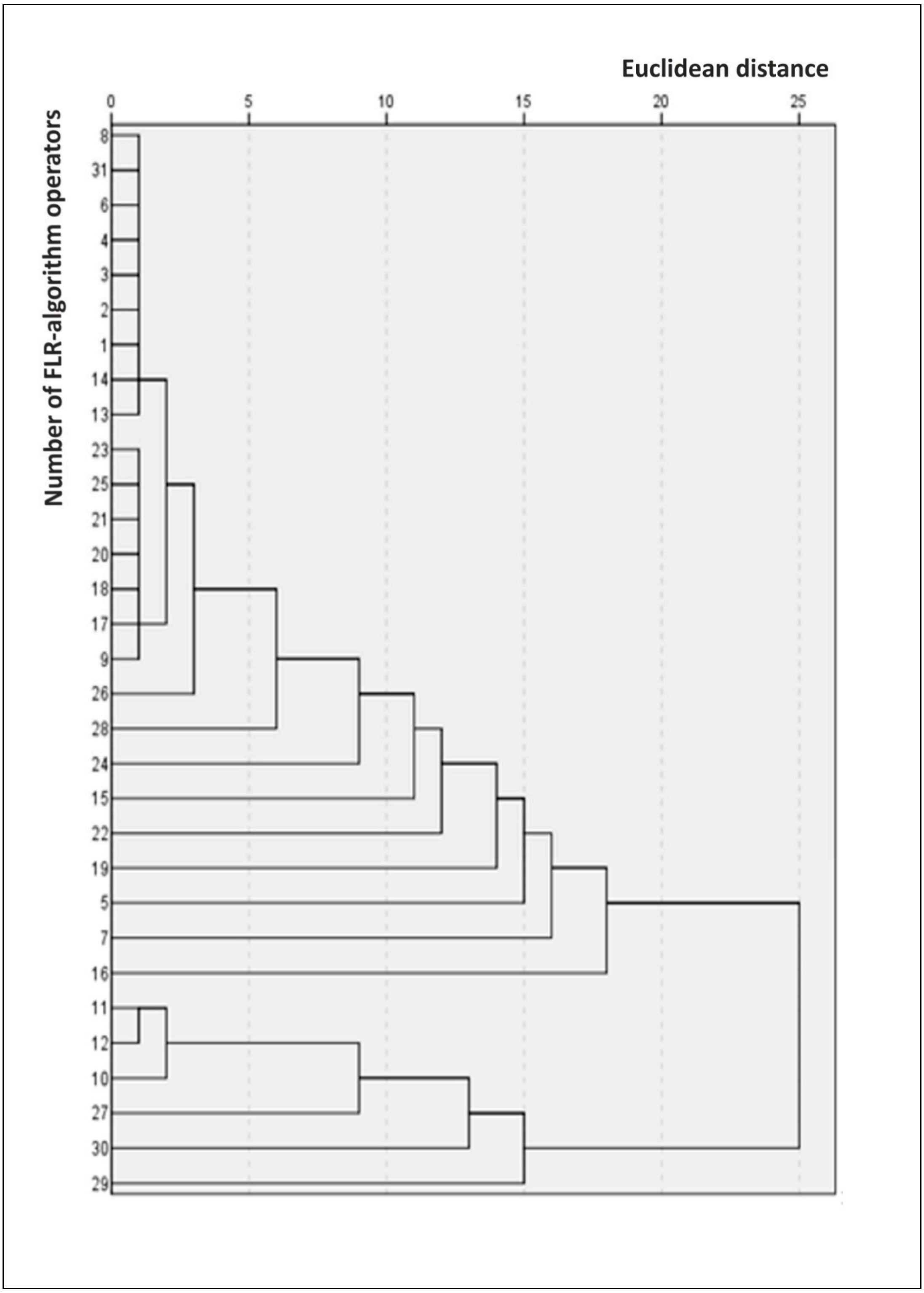

Figure 7. Intra-group connections dendrogram for FLR-algorithm.

Today, in general, the FLR approach implementation is considered by scientists of different fields from three perspectives:

1. Technical and technological—the study of a separate set of technological processes, machines, and mechanisms for the preparation of forest seed material, soil preparation, planting, sowing [62], and crop care;

2. Biological (ecophysiological, genetic, etc.)—study of the ontogenesis of seedlings, the influence of external factors on young forest stands, biomass accumulation [11,63–69], and patterns between phenotypic and genetic variations of forest trees [70];
3. Socio-economic—a study of ways to reduce costs [71] in the implementation of the supply chain [72] during reforestation and a questionnaire analysis showing that "*the majority of respondents believe that national and European legislation on seed transition is not adapted to climate change* [1]".

Very often, the results of research on each of the three points are not consistent and sometimes contradict each other. In the future, for the integrity of the picture, the author has planned an ambitious goal—to trace the path of each technological operation from the selection of technical means to implementation, taking into account expert opinions on all three points; that is, in fact, to create a "FLR-approach passport" in each reforestation initiative. This will allow an objective assessment of the effectiveness and expediency of using certain technical means, and a set and sequence of operations in FLR technology'

4. Conclusions

1. There is an interdisciplinary disparity in the study of the main technological processes of forest landscape restoration.
2. For a comprehensive study of FLR technology, it is desirable to use a combined FLR algorithm, containing 268 sets of operations only in the first approximation.
3. The FLR algorithm must be decomposed into six blocks, partially confirmed using Ward's and intra-group connections methods.
4. The developed FLR algorithm and the optimization mathematical model planned in the future will form the basis of software that will allow for a rational choice of technological operations and technical means with minimal costs.

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Appendix A. Implementation Options for the FLR Algorithm (Operational Sets)

(1) 1-2-3-4-5-6-7-8-9-11-12-13-14;
(2) 1-2-3-4-5-7-8-9-11-12-13-14;
(3) 1-2-3-4-5-6-7-9-11-12-13-14;
(4) 1-2-3-4-5-7-9-11-12-13-14;
(5) 1-2-3-4-5-6-7-8-9-11-15-16-17-14;
(6) 1-2-3-4-5-7-8-9-11-15-16-17-14;
(7) 1-2-3-4-5-6-7-9-11-15-16-17-14;
(8) 1-2-3-4-5-7-9-11-15-16-17-14;
(9) 1-2-3-4-5-6-7-8-9-11-15-16-18-14;
(10) 1-2-3-4-5-7-8-9-11-15-16-18-14;
(11) 1-2-3-4-5-6-7-9-11-15-16-18-14;
(12) 1-2-3-4-5-7-9-11-15-16-18-14;
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