Technocenosis paradigm sustainability management of a forest enterprise

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Abstract. The relevance of the study is associated with the need to provide an effective methodology for the implementation of information technologies in forestry management. The article substantiates for the first time the application of a technocenological approach to enterprise sustainability management in the forest industry. This approach is effective in a variety of products and equipment, provides an account of the important laws of their optimal construction and operation. The technocenological approach allows us to design the structural architecture of the main subsystems of the enterprise, describing it as a certain standard form of the statistical distribution of elements within the boundaries of mathematical stability. This allows using the model as a guide for various management decisions. It is assumed that the proposed formal model will not only increase the manageability of individual enterprises, but also accelerate the digitalization of the entire industry.

1. Introduction
Forests are the planet's most important life-sustaining ecosystems. In addition, they provide economic and social services to society, which creates contradictions in the formation of key management paradigms. Numerous approaches have already been developed, for example, ‘sustainable forest management’, ‘ecosystem management’, ‘multifunctional forestry’ and others. A wide variety of management approaches and paradigms must be built into the supporting structure that unites them, which is provided by modern information technologies and various methods of simulation modeling [1].

Modern authors especially point out several methodological problems that need to be addressed by the scientific community in areas related to forestry modeling. Here are some of them below.

Firstly, these are problems caused by the growth of biodiversity and the complexity of modern logging technology, which are considered in the article from the standpoint of forest species diversity as a source of ecosystem sustainability [2]. Thus, a number of publications based on achieving the
goals of preventing negative trends in climate change indicates the need to ensure the diversity of cultivated types of land and forest funds, which is achieved through the formation of the most optimal microclimate [2-4]. Using an approach called ‘enhancing structural complexity’, scientists from the University of Vermont showed that the result is high logging productivity, reduced losses, and increased natural sustainability of the forest [5]. The problem of the wide distribution of this technology is the growth of control elements and parameters, which requires the development of appropriate tools.

The second group of problems is caused by the widespread use of digital technologies in management practice. Forestry lagged behind most industries in the adoption of digital technology. This trend, however, is finally starting to change. Studies already show productivity growth in general agriculture by 5-25 percent per year, and the return on investment in digital technologies is from one to two years (of course, depending on many factors, such as farm size, crop choice and other conditions) [6]. As McKinsey’s experts testify, similar benefits are not only on the horizon for forest products, but are also being realized by some pioneers today [7]. The size of these benefits is only comparable with the transition from livestock to mechanized processes and, in the food industry, to the 1960s Green Revolution.

However, in the field of forestry management, digital solutions are currently confronted with a system that still operates largely based on the principles developed by Hans Karl von Karlovitz more than 300 years ago, who consider sustainability from the standpoint of long-term preservation of economic results, productivity.

However, inspired by progress in agriculture, foresters Europe and North America have begun introducing advanced technologies to improve forest management results. In the industry, this approach is commonly referred to as ‘accurate forestry’. Natural pioneers are those who plant forestry and have a rich track record of innovation and continuous improvement focused on productivity. This management style is closest to agriculture with monocultures, selectively bred tree species and a relatively high degree of automation - indeed, these forests are often called tree farms’ [7].

However, accurate forestry is not just the introduction of digital technology. For forest managers, this implies a paradigm shift: from a fully manual and analog system with extensive management instructions to a system with digital data’s collection and scheduling, detailed management requirements and strict operational control, as well as relevant system management technologies.

The third group of problems is due to the complexity of the entire system of consumption of forest products [1, 4]. For example, bioenergy, which has a lot to offer in terms of reducing greenhouse gas emissions, especially when using waste, but it also poses risks and consequences for a small selection of wood biomass and feedstock. In cases where environmental and social requirements are the main goal, there is a need to develop complex models based on sustainability requirements. Hence, the need arises to develop probabilistic methods for predicting and designing such systems that they are trying to solve within the framework of interdisciplinary approaches, such as, for example, in the format of the so-called provisions ‘Post normal science’, which is aimed at overcoming contradictions in complex systems [4].

The fourth group of problems is due to the need to implement a number of modern technologies, such as phenotyping, the effectiveness of which is associated with the development of wireless sensor networks, and the possibility of targeted exposure to forestry facilities and increase labor productivity. The deployment of such systems is limited by the lack of simple analysis and design tools, the lack of a basic paradigm for their implementation [8].

Modern technologies allow the collection and processing of large amounts of data, providing valuable information for various industries, including forestry, where machines and equipment equipped with numerous sensors are actively introduced [9]. Such data can be extracted and transferred to computers using special forest protocols, such as StanForD, where they can be analyzed. As a result, it is possible to study yields using thousands of records, rather than several hundred as would be possible using traditional methods (visual inspection or shooting). However, traditional analytical methods for processing this information, such as linear regression, are not able to work with
this amount of data (or at least not use the data’s potential to the full), therefore, new approaches are required, such as clustering algorithms, simulation models.

Another group of problems caused by economic requirements is associated with the shortcomings of the variational programming of value chains in forestry, which occur due to the large species’ of diversity of machinery and equipment. For example, the work of Canadian experts on the material of freight transportation of forests showed that the use of a heterogeneous fleet of trucks increases the uncertainty of optimization scenarios [10]. ‘Unfortunately, there exists no study on the probability distributions of such events in the forest industry. Conducting such a study is challenging given that it is hard to get historical data. This is, however, an avenue for future research since many forest companies are investing in log-trucks with onboard computers, positioning systems, and communication technologies that can be used to collect accurate data on disruptions’ [10].

The modern forestry enterprise has evolved to the complication of its technological and technical complexity, which has led to the need for multidisciplinary approaches [11]. The structural elements of such a coenosis are either the totality of all technical objects, logging objects, qualification structure, etc. Thus, the task of model formalization of this approach is set in order to improve the quality of management. Considering the place of a person in the technical cenosis, the authors adhere to the approach according to which management should be built taking safety into account, which can become an additional optimization criterion in modeling [12]. It should be noted that the approach considered in the article is applicable only to forestry enterprises with a high proportion of labor mechanization, where the number of machines and equipment exceeds hundreds.

Thus, we believe that the solution to these problems can be the integration of two methodological approaches to the study of complex systems - technocenological theory and fuzzy-multiple analysis, as a mechanism for determining the key parameters of the technical objects under study (capacity, productivity, cost, etc.). The second section of the article will consider the concept of designing control systems for intellectual production. The third section is devoted to the formalization of the managerial model, where the parameter of optimization is system stability, and the criteria are cenological patterns. In conclusion, the main direction of development of the proposed methodology will be determined.

2. Methods and materials
The theoretical basis of the proposed study is the adaptation of one of the theories in the field of scientific systematics - cenology to the tasks of modeling the ‘ideal technological structure’ of the technical complex of forestry, which is a certain numerical counterpart of it. To determine the basic prerequisites for the study, data from forestry objects of the Rostov region of the Russian Federation are used [13]. The consistency of the proposed approach makes it possible to translate it to other subsystems: financial, resource labor, etc., providing the necessary synergy and innovation. This approach will provide a new impetus for increasing productivity and introducing modern information management technologies, including the Internet of Things. [14].

Thus, the need for intensive creation of not only biotechnology products in forestry that can provide a breakthrough in stimulating innovative processes and policies in traditional sectors, as well as in innovative areas aimed at preserving biological diversity and reproduction of highly productive forest resources, but also development of management tools based on the most modern technologies, including the Internet of things is evident. Today this idea is supported by many experts in the modeling sphere, such as, for example, the ‘ecosystem synthesis’ model, which involves the interconnection of various subsystems of forestry enterprises within the economic optimality framework [14]. Then the methodology for adapting the technocenological approach to the tasks of the forestry enterprises management improving in the context of structural complexity will be considered.

The tools used to analyze and predict this type of coenosis are based on the fundamentals of the technoevolution theory and the science of technical reality - the so-called 'technetics' [15], which make it possible to describe complex structures with system-wide indicators within the framework of the laws of information selection, which determines the evolutionary vector of such systems. The
listed set of results can be adapted to research of complex intelligent systems of an interdisciplinary nature management in forestry, namely, for forecasting, designing the technical objects architecture and their permanent monitoring from the standpoint of optimal resource consumption.

The scientific literature review showed that it is the design of corporate and industrial architecture in the complexity context that is still a fairly new concept, interpreted in various ways that cannot be called completed ones. Interdisciplinary approaches to the formation of a management architecture are of great interest. The ‘ADACOR-holonic (ADaptive holonic COntrol aRchitecture for Distributed Manufacturing Systems)’ model inspired by biological and evolutionary theories [16]. The authors consider the possibility of using an adaptive production management mechanism balancing between two states: a hierarchically stationary and a decentralized transitional one, which largely corresponds to the ideas of coenosis, to be important for the design of the forestry architecture [17].

Moreover, taking into account the digital technologies’ influence on the process of production systems designing, a special place is occupied by such concepts as ‘TOGAF (The Open Group Architecture Framework)’ [18] and its invariants, like ‘FEAF (Federal Enterprise Architecture Framework)’ [19], based on fundamental principles of system design, such as the systems’ life cycle, recursion of life cycle relationships systems and systems modeling [20].

Implementation of the approaches is complicated by the fact that various scientific schools codified their industrial experience in the design of complex production systems in the form of various architectural frameworks, such as PERA (Purdue Enterprise Reference Architecture) and CIMOSA (Computer Integrated Manufacturing Open System Architecture), GERAM (Generalised Enterprise Reference Architecture and Methodology). Such diversity is a scientific problem, since it forms general uncertainty, narrow concepts, inconsistent terminology and taxonomy, fails to present the whole picture and results in limited management tools [21]. All the above is reflected in the superficial conceptualization of the problems and it hinders the development of theory and methodology.

Various principles of designing the structure of sociotechnical systems are used, which also differ significantly. So, for some of them it is important to create values, cationic contexts such as data management [22], for others it is security management [23]. Others are limited only by the process of abstract design, in isolation from real practice [24].

The general idea that should form the basis of the proposed model is that the only design task is to reduce the complexity and uncertainty of such a system and manage complexity, i.e. control the complexity itself, not the parameters and elements [25].

Design will mean, in this case, a re-combination of technical forestry facilities and the process with the help of which this project is implemented when configuration procedures and specifications are included that reflect, for example, trends in technology, prototype testing, etc. [26].

These restrictions are also considered from the standpoint of ‘technoethics’, which justifies the need for socially responsible design and equipment operation, the consideration of environmental consequences, the need to save resources, etc., which imposes additional restrictions on the formation of a new understanding of control systems under such conditions [27].

This activity does not answer a number of questions related to the nature of the formation and dynamics of the structure of complex intellectual systems of an interdisciplinary nature, it does not provide the possibility of interdisciplinary synthesis; such activity causes difficulties in structuring intra-paradigmatic problems (narrow domain, lack of mathematical tools, linear development); characterized by problems in matching research models. The theory of coenosis partially overcomes these shortcomings.

The effective interdisciplinarity of the cenological approach is due to the confirmed universal properties of coenosis or special systems localized in a certain framework of time and space as a whole, which is observable, statistically countable and consists of elements that do not have rigid connections, different in their characteristics and not statistically modeled in categories ‘Average.’ Being a ‘collective concept’, from the point of view of the logic of understanding within the framework of the general theory of systems, these sets can be considered within the boundaries of the
categories ‘uniformly-heterogeneously’, ‘stably - unstably’, ‘orderly- chaotically’, ‘concentrated-scattered’, ‘holistically - amorphous’, ‘entropy-limited entropy’, etc.

In addition, the interdisciplinarity of the theory of coenosis is due to the general features of statistical formalization, which can characterize the structure of any considered totality (species distribution) and its content (rank or status distribution). For example, the structure of machines ordered by power gives a rank distribution; distribution by characteristics is a species one. Similar distributions can be created for coenosis of any nature: organic, inorganic, social, sign and informational.

The interdisciplinarity of the theory of communities is manifested in the choice of a mathematical model that describes the behavior of coenotic distributions. As such, in the vast majority of cases, the formula used is the non-equilateral hyperbola (H-distribution). Various interpretations of this formula (Zipf, Pareto, Lotka, Willis, Kudrin, etc.) are used in a long list of theories and are tested on a wide variety of empirical material (economic, biological, scientific, technological, etc.).

To solve the tasks the following algorithm is offered. To form a conceptual model, the cenological approach by B Kudrin is used, the approach was not previously used in the design of forest industry facilities, but it showed a high research result in various branches. The suggested approach provides support for the entire life cycle of analytical systems as well as unique opportunities for their dynamic adaptation.

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The analysis of modern approaches to the design of complex systems of an interdisciplinary nature showed that the solution of mathematical problem of developing adequate tools for expert evaluation of signals about the status of all subsystems, which are also characterized by complexity, a probabilistic nature of functioning and high dynamism, is also required [28]. Since the proposed technocenological approach involves the use of a number of integrated indicators that reflect the state of enterprise subsystems of various nature (technical, intellectual, informational, etc.), they can be used to characterize these systems’ stability, survival, efficiency, self-organization as management parameters for intellectual forest production models.

Such categories as ‘supercomplexity’ and ‘uncertainty’ are integral characteristics of modern models of intellectual production, which determines their coenosis characteristics: weak connections, structural dynamics and self-organization.

The projected models are based on the category of sustainability, which according to Bergstrom’s review overcomes the shortcomings of the ‘engineering’ approach to the design of intellectual production, which prevailed earlier in science and practice [29]. Here is important the authors position, which justifies the causal relationship between risk and adaptation as a starting point for studying the stability [30].

The process of technological standardization can be implemented through the technology of patterns, denoting the logical regularity found in nature, technology and society, as well as a repeating pattern, an example of solving a design problem in the framework of frequent problem environments. There are design patterns, programming patterns and others [31]. The pattern of forestry organization should be projected onto a specific management object, regardless of ownership, type of activity, size and other parameters of the enterprise or organization. After the development of such a pattern (an abstract model based on the laws of the theory of coenosis) of the organization and a software platform based on it, improving the quality and efficiency of the introduction of new technical objects and their system management will become possible.

Organization means any entity that is the subject of the operation and is characterized by integrity, emergence and homeostasis. Similar to the definition of an organization, we introduce the concept of a resource. Resource is any entity that is the object of the operation. The definition of an organization is more stringent than that of a resource. In other words, any organization can be considered as a resource in some operations, but not every resource can be considered as an organization.

Thus, we have an operational definition of an organization and a resource, which, on the one hand, include a universal absolute feature with respect to the operation in cosideration - activity, and on the
other hand, can change places depending on which operation we are considering. This assumption was the basis for the formalization proposed below.

3. Results and discussion

As it was stated above, the minimum structural unit of an enterprise subsystem is a functional element that combines a person, 'active' technical devices and software services that can recognize a signal and respond to it. Therefore, in the proposed pattern, the features and formats of receiving and processing signals in a functional element (e.g. mulching process) \( F \) by a person (technical object user) \( P \), a technical object (e.g. feller and skidders) \( T \) and a software service \( S \) are taken into account and integrated into a single whole. The perception, processing, and propagation of signals by \( P, T, \) and \( S \) differ in distance, transmission rate, physical fundamentals, and many other parameters.

In general, \( F \) is a combination of \( P, T, S, P + T, P + S, T + S, P + T + S \).

And then we can describe the organization as a system that combines functional elements \( F \), implementing the program in cooperation with each other (goal) and acting according to certain procedures or rules. Procedures and rules can be written in textual, graphical, mathematical, software and other forms that the components of functional elements can perceive.

Now it is possible to construct a pattern that has invariant, resource and structural attributes of the organization, which is understood in three aspects:

1) as a system, an association of people jointly implementing a program (goal) and acting according to certain procedures or rules;

2) as a process, actions to create and improve the relations between the parts and the whole;

3) as an attribute of material and abstract systems to detect the interdependent behavior of parts of the system within the framework of the whole.

The first meaning of organization is described by an autopoietic system model that is invariant with respect to any associations of people.

Therefore, the first feature of the constructed pattern is that it is an autopoietic system that in the course of its development reproduces the following characteristics: integrity, system differentiation, organization as an open system, reduction of complexity, operational isolation, self-reference, ability to communicate, and the meaning of its existence.

Depending on the situation, the autopoietic system can be considered as a functional element, a cluster, an organization, a coenosis.

The second approach to the organization as to actions for creating and improving the relations of parts and the whole can be considered in functional elements, clusters and coenosis. In functional elements the meaning of the organization is determined by a person himself, in accordance with his understanding of the situation, and it is described by job descriptions and characteristics of the person himself (competence, gender, age, and other non-formalized parameters). A functional element is modeled as a point object with rigid connections.

A cluster is modeled as a spatial object, which can be described by simulation models and Gaussian distributions. Upon reaching a certain level of complexity, it is necessary to use a rank analysis and a technocenological model.

As mentioned before, the properties of coenosis are described mainly in a mathematical way. The fundamental law is the optimal construction of technocenosis, according to which the parameters are technical objects and their rank distributions, and the designed extension for coenosis, where the total parametric resource of all types \( F \) consists of combinations \( P, T, S, P + T, P + S, T + S, P + T + S \) will be equal to the product of the total number of \( V \) types and the total parametric resource of each type \( P, T, S, P + T, P + S, T + S, P + T + S \) can be formalized by the formula:

\[
\sum_{k=1}^{j=\infty} \left( \int_0^\infty W_j^k (X) dx \right) = \sum_{k=1}^{j=\infty} \left( \int_0^\infty V^k (y) dy \right) \sum_{j=1}^{k=\infty} \left( \int_0^F F_j^k (x) dx \right) = F_\Sigma = \text{const} \quad (1)
\]
$K$ - type of functional element ($F$) as one choice of seven combinations: $P, T, S, P+T, P+S, T+S, P+T+S$. $F_j^k(r)$ - wound parametric distribution of functional elements of the k-th type, according to the parameter wound parametric distribution of functional elements of the k-th type, according to the j-th parameter $\nu^k_j(y)$ - species distribution of functional elements of the k-th type, $\eta^k_i$ - parametric rank of the k-th type, i-th type in the j-th parameter, $x$ and $y$ - continuous rank analogues, $F_{\Sigma}$ - total parametric resource ($F_{\Sigma_i}$ for the i-th type).

Thus, we can say that the set of measures for coenosis optimization means actions for creation and improving the relations between the parts and the whole, it reveals the second aspect of the definition of an organization as well as homeostasis. At the cluster and functional levels, it is achieved by classical methods.

Thus, the constructed pattern is a coenosis, which is described mathematically by parametric-energy connection (between continua of parameters and functional elements of the k-type $k$, $\Sigma_{k,j=1}^{k=7,j=\infty} \left\{ \int_0^\infty W_j^k(x)dx + \int_0^\infty M_j^k(x)dx \right\} = \Sigma_{k,j=1}^{k=7,j=\infty} \left\{ \int_0^\infty W_j^k(x)dx \right\} (2)$

and related software.

The third meaning of the pattern, as an attribute of material and abstract systems, is to detect the interdependent behavior of parts of the system within the framework of the whole through formalization into a management model, which is graphically presented as a five-level structure of the control system, where the final element is a functional element, which is usually described by job description in specific organization.

The peculiarity of the resulting management pattern is that its elementary basis is not only computationally and mathematically structured, but also self-reproduces its functions when interacting with the environment. Then the resulting control system takes the form of a VariableSystemModel (VSM), or understanding it as a digital twin of all technical objects, as an aggregate - VSM ForestryCenose. This name suggests that a digital model based on the laws of technical coenosis is used for management.

The principles of autopoiesis are reflected in the requirement that the pattern should reproduce itself. Then the universal VSM ForestryCenose organization pattern can be defined as a self-reproducing cenological forestry organization with a VSM-like management system.

The VSM ForestryCenose pattern is described by text principles, graphical images, mathematical formulas, and software. It is this approach that allows us to ensure constantly improving interaction between people, technical devices, and software services in the process of processing information in a situational center using organization models. We list the features of the formal model.

1. Invariant characteristics of the VSM ForestryCenose Pattern.

1.1. In the VSM ForestryCenose pattern, the invariant characteristics of the organization are self-reproduced: 1) integrity, 2) system differentiation, 3) organisational openness, 4) reduction of complexity, 5) operational isolation, 6) self-reference, 7) communication and 8) meaning.

1.2. Characteristics 1-3 are formalized by the resource balance equation

$$r_i^t = \sum_{n, k, i, t} R_{n, k, i} \beta_{n, k, i}$$ (3)

Where $\beta_{n, k, i}$ coefficient determining the share of the input resource and used in the production of this product. In this formula, the final result is taken into account, even if the process was multi-stage.

1.3. Property 4 is formalized graphically by the allocation of counterparties in the outside world (figure 1).
Figure 1. The scheme of interaction of the organization with the external environment.

1.4. Characteristic 5 is formalized by the description of the resource and structural features of the VSM ForestryCenose pattern.

1.5. Characteristic 6 is formalized by standards and software designed as plugins.

1.6. Characteristic 7 is formalized by the interaction of employees, technical devices, and software with the outside world.

1.7. Characteristic 8 is formalized by the organization’s existence strategy, environmental, social and other requirements.

2. Resource characteristics of VSM ForestryCenose Pattern.

2.1. The resource characteristics of the pattern are described by a system of integro-differential equations, within the framework of which the conditions of a theoretically optimal state of the organization are formulated according to the nomenclature and parameters. It is possible if there is a necessary set of personnel, technical devices, software services and any their combinations that by their combined functional indicators ensure the fulfillment of tasks, and on the other hand, the total energy resources embodied in the personnel ($P$) at the process of training and technical devices ($T$) and software services ($S$) at the process of production, are distributed evenly among $P$, $T$, and $S$ populations.

3. Structural characteristics of the VSM ForestryCenose pattern.

3.1. The structural characteristics of the pattern are created graphically and represent the VSM model (figure 2).

Figure 2. VSM model of a forestry enterprise.
The main advantage of preventive management based on the VSM ForestryCenose pattern model is that it uses the ability of decision makers (DM) to predict the course of events before they occur, and theoretically provides the opportunity to implement an optimal type of management that takes into account numerous requirements. However, the proposed methodology requires high-quality information on the structure of the subsystems under consideration. It implies a thorough knowledge of production, environmental and social processes. The disadvantage is that the output of the model may not coincide with the target values, which are determined by external stakeholders who do not use the technocenological approach for the normalization (standardization) purpose. At the same time, our study showed that direct-link management combined with the VSM ForestryCenose pattern complement each other, since serious problems can be detected before they affect the system, and technocenological diagnostics can overcome many of the shortcomings of direct-link management associated with their immeasurability or the fact they have not been measured yet. An example of the implementation of such technology in other industries is presented in the work of the authors [29].

The proposed sustainability management format in forestry enterprises allows using all possible methods of cenological theory to analyze the dynamics and stability of subsystems.

4. Conclusion

The proposed cenological management system is relatively simple and takes into account numerous standards, both technological and social in nature, however, it does not replace classical control methods: it supplements them. The question regarding the technology of cenological management concerns the types of indicators that it is desirable to use for a specific purpose (level of decision-making). For example, absolute process indicators (technological parameters) are best suited for making decisions about a process because they provide effective process control. Cenological indicators are effective in making decisions aimed at increasing the resource optimality of the enterprise subsystems, the operational search for structural imbalances, designing the content of equipment, products. When developing a set of sustainable development indicators, the application of the proposed approach can be useful, since it helps to formulate standard values by the number of elements in the subsystems, their proportions, ensuring maximum economic efficiency through the development of standard structural models. However, it should be noted that the authors do not fully support the technocentric nature of the cenological theory. In the proposed paradigm, the role of human is understood as the most important, especially speaking about the biological significance of forests. Thus, we proceed from the position that the technocenosis is a kind of digital model that can be adjusted taking into account human interests.

The requirements for a good indicator are known to be as follows: target orientation, comparability, measurability (access to data), significance (scientific certainty or analytical validity), integrity (ability to correlate with other indicators), continuity, clarity and effectiveness. Coenological characteristics provide all of the above requirements, and their combination with the existing management parameters will allow us to assess sustainability, both in environmental and social contexts.

As reference materials, it is preferable to use international systems for assessing the effectiveness of sustainable development, for example, the Global Reporting Initiative. It will help any enterprise to develop a functional and effective system for assessing the effectiveness, fully reflecting its values and needs.

Thus, the proposed cenological model of sustainability management of the forestry enterprise provides the necessary level of information and analytical support for decision-making processes for more efficient activities of forestry enterprises.

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