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Opportunities of Comprehensive Assessment of Ecological Safety of Various Engineering Systems at Their Development Stage.

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ABSTRACT

It is most efficient to solve the issues of ecological safety of engineering systems at the stage of their development. The basic objective of this research is the minimization or prevention of the negative impact on the environment in the lifecycle of engineering systems. To do so, a methodology, methods and means to choose competitive alternatives based on the analysis and comprehensive assessment of their ecological safety were offered. The authors opine that it is feasible to make a comprehensive assessment of ecological safety of engineering systems based on the analysis of implicative relations of technical characteristics and dependent negative ecological factors. The use of this method for the assessment of ecological safety will allow forecasting negative response to the environment upon the change of construction and engineering parameters of engineering systems. The offered method should be referred to the group of quality assessment methods of ecological safety. Meantime, it indicates the deviations of certain physical values and may serve as a basis for deterministic analysis methods enabling to work out corrective actions not only from ecological safety position, but to adjust engineering systems modernization. Such an approach was used by the authors in assessment of ecological safety and choosing the optimal alternatives of industrial sites, alternatives of electric machines being designed, optimal technological solutions. The use of the offered scientific and methodological approaches to ecological design will allow to preventively assess the ecological safety of created engineering systems, to control ecological safety parameters accounting for lifecycle and contribute to establishment of ecological responsibility of economic agents for decision making. The discussion section shows the need for improvement of engineering staff training in ecological design.
Keywords: ecological safety, engineering systems, comprehensive assessment, implicative relations, environment, technology-related effect, ecological factors.

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INTRODUCTION

The concept of improvement of ecological safety of engineering systems is changing depending on the ecological policy of the government. At the present development stage, one of the basic principles of the Russian Federation's policy in environment protection is the prevention of negative ecological results of commercial activity and accounting for remote ecological consequences. Therefore, many researches [1-15] are aimed at the development of a methodology, methods and means enabling to shift the concept of control *in the end of the tube* to the concept of *design for ecology*. Meantime, the main disadvantage of the traditional system of ecological reasoning and choosing alternatives in the course of development of various engineering systems (ES) is the lag of systematic analysis and comprehensive assessment of ecological safety behind the core technical decisions making. It is most efficient to do the analysis and comprehensive assessment of ecological safety of engineering systems at the development stage (especially, at earlier stages – conceptual idea, engineering study, research, etc.), as the material and engineering groundwork is laid at that time, identifying the multiplicative effect of negative impact on the environment.

Having some practices [16], the authors offer to do comprehensive assessment of ecological safety of ES via the analysis of implicative relations of technical/functional characteristics of ES being developed and dependent ecological factors of negative effect. Meantime, in each case the system of particular and comprehensive criteria is established to optimize and rationalize the solutions in connection with choosing competitive alternatives.

The basic objective achieved in the course of the implementation of this approach is the minimization or prevention of negative effect on the environment in a lifecycle of ES. Implementation of such an approach at early stages of development will allow to assess preventively the ecological safety of engineering systems being created, to control ecological safety parameters accounting for lifecycle and to assist in establishment of ecological safety in economic agents for their decision making.

METHODOLOGY

The methodology of this research is the systematic analysis of hierarchic levels of ES for the purpose of comprehensive assessment which enables to find the mutual relationships of internal design of ES with the level of negative impact on the environment.

The basic provisions of the offered methodology:

1. Opportunities for the improvement of ecological safety of ES being designed are identified via classifications developed on the basis of ecological-centrism and logical interrelations of engineering systems and the environment, using theoretical and empirical provisions of mathematics, physics, engineering, ecology and other sciences. The analysis and assessment of logically identified interrelations based on physical and mathematical models of ES enable to identify the alternatives with minimal negative effect on ES.
2. At every stage of ES development, a certain local technology-related effect ωi is input; its value depends on technical/functional characteristics of engineering systems; change and control of engineering characteristics of ES under development will enable to control their negative effect on the environment. Systematic features and negative impact factors of a particular stage of ES lifecycle arise on that particular level. The study of ecological safety of created ES in general goes via identification, analysis, generalizing and assessment of interrelations between ES at various stages of the lifecycle of ES and environment.
3. A developer's control actions for the purpose of improving the ecological safety of ES are taken on the basis of the analysis and assessment of information about the state of the environment and identified implicative relations between technical/functional parameters of ES under development and forecast of any possible changes in their interconnection and interrelation.
4. The physical model of the studied ES is a network of interrelations between ES and the environment based on the laws of conservation, transformation and transfer and balance of input and output materials and energy flows as well as on the laws of dynamic equilibrium conservation and environment stability.
5. Mathematical modeling and the concept of general description of ES behavior is theoretically a

multitude approach (multitude of elements A and multitude of relationships R between them in connection with the selected objective of research – minimizing technology-related impact on the environment). In the general case, ES being designed – S is an ordered couple S = (A,R). To make that dependency practically useful, it should be specified and some hierarchical levels of ordered couples (A,R) should be put in, related to the solution of the task on minimizing negative impact on the environment. The hierarchical levels and ordered couples are brought using one of the two fundamental differentiating criteria:

a. identification of systems based on particular types of elements (parameters of engineering level of reliability, stability and quality of an object, ecological parameters, economic parameters, etc.), requiring various experimental methods and means to collect data – i.e., that classification has experimental basis;
b. identification of systems based on particular types of relations (interrelation of ES and its subsystems with each other and with the environment through the lifecycle) – such classification is related to data processing directly but not with data collection, its basis being mainly theoretical.

In the course of ES development, external design stages are distinguished when a system is regarded as a part of a higher hierarchical level – a natural and technical system, as well as internal design stages when a ES is regarded as a higher level for its subsystems (units, assemblies, parts, etc.).

The methodology is based on systematic research, analysis and assessment of the characteristics of various hierarchical levels of ES being developed for the purpose to obtain new information on interrelation of ES external and internal design parameters with the level of negative impact on ES within a lifecycle.

The basic principles and rules of systematic research, analysis and assessment of ecological safety of ES being developed are described by the authors to solve the tasks on minimizing negative impact on the environment within a lifecycle (Table 1).

Table 1: Basic principles and rules of systematic analysis and assessment of ecological safety of engineering systems within a lifecycle

Basic principles	Essence of the principle
1. Principle of ultimate goal	The priority of the ultimate goal of minimizing the negative impact of ES on the environment in a full lifecycle. Basic rules: - analysis should be conducted on the basis of understanding that any ES is interrelated with the environment and its technical/functional parameters cause the negative effects in a lifecycle; - in structural and parametric synthesis of ES and choosing the optimal solution any variant should be assessed regarding the ultimate goal
2. Principle of unit structure	Considering the ES under development as aggregate of subsystems. Basic rules: - to identify the interrelations of ES under development with the environment, subsystems by lifecycle stages are created along with production systems; - to identify technical/functional parameters of ES, control over which will cause minimizing negative impact on the environment and ecological safety improvement, structured ES systems are created
3. Principle of functionality	That principle is built on the statement that any hierarchical level of a structured system is connected with the functional purpose of ES under development while any hierarchical level of a production system is connected with the ES lifecycle stages. Basic rule: - ES lifecycle stages are connected with the establishment of input and output materials and energy flows. Technology-related effects comprise consumption of abiotic resources, ingredient and parametric (physical) impact on the environment
4. Principle of hierarchy	Introduction of subsystems hierarchy and ranking. Basic rule: - from ecological-centrism position, the environment is a system of the highest hierarchical level
5. Principle of connectivity	Analysis of ecological safety of subsystems comprised by ES implies procedure on identification of links between them and the system of a higher hierarchical level and finally with the environment. Basic rule: - ES being created should be decomposed to the level enabling to arrange respective mathematical modeling of their relations with the environment
6. Principle of unity	Joint consideration of ES as integral whole and aggregate of particulars. Basic rule: - ES are considered not as aggregates of isolated elements and objects but as a network of facts fundamentally interrelated and mutually dependent.

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RESULTS

During systematic study, analysis and assessment of designed ES and their operation conditions, implicative interrelations are identified between target parameters (first of all, functional, structural and construction) and input/output parameters on the basic levels of production system – manufacturing, operation and processing.

Production system means the aggregate of materially or energetically connected single processes which exercise one or more particular functions; structured system means the aggregate of technical elements (subsystems) with common parametric multitude [17].

To identify the ecological parameters of electric starter machine (ESM), possible ecological consequences of their functioning in a full lifecycle, i.e., materials and energy flows at the input and output of production system were studied.

General ecological characteristic and safety of EMS in lifecycle $\omega_o\left[X(A_i)\right]$ is an aggregate of negative effects in input and output of production system:

$$\omega_0\left[X(A_i)\right]=\sum_{j=1}^{m}\sum_{i=1}^{n}\omega_{input}\left[X(A_i)\right]+\sum_{j=1}^{m}\sum_{i=1}^{n}\omega_{output_j}\left[X(A_i)\right], \quad (1)$$

where j, i – respective indices of identification of natural object (j =1…m) and engineering characteristics of object (i=1…n);

$\omega_{input_j}\left[X(A_i)\right]$ – negative effect at the production system input or lifecycle stage of object X, characterized by technical parameters Ai;

$\omega_{output_j}\left[X(A_i)\right]$ – negative effect at the production system output or lifecycle stage.

We consider ecological safety of EMS accounting for decomposing by lifecycle and functional decomposing.

At the stage of materials manufacturing, ecological safety of EMS at production system input depends on the consumption of abiotic resources and energy:

$$\omega_{input}^{cm}\left[X(A_i)\right]=f\left(\sum_{k=1}^{n}(M_k^{cm}m_k^{cm}),\sum_{k=1}^{n}(M_k^{cm}E_k^{cm})\right), \quad (2)$$

where M_k^{cm} – mass of k-th construction material used for ES construction, kg;

m_k^{cm} – specific consumption of raw materials to get 1 kg of k-th construction material, kg/kg of construction material;

E_k^{cm} – specific consumption of energy to get 1 kg of k-th construction material, MJ/kg of construction material.

Negative output flow depends on the ecological parameters related to making materials:

$$\omega_{output}^{cm}\left[X(A_i)\right]=f\left(\sum_{k=1}^{n}(M_k^{cm}m_{output_k}^{cm}),\sum_{k=1}^{n}E_{output_k}^{cm}\right), \quad (3)$$

where $m^{cm}_{output_k}$ – specific mass characterizing the wastes formed (emission, discharge, solid waste) in making 1 kg of k-th construction material, kg/kg of construction material;

$E^{cm}_{output_k}$ – energy negative impact in making k-th construction material, MJ.

The analysis of the obtained regressions shows that the decrease of negative effect at this stage depends on the decrease of consumption of mass of each k-th construction material contained in the structure which is widely used at present time and causing, in particular, decrease of the total mass of EMS structure. Also, in the course of design, at the structural synthesis stage it is required to seek for materials with the best manufacturing ecological characteristics while during parametric optimization it should be noted that the total negative effect on the environment depends on the optimal ratio of various construction materials (their masses). It may be an intermediate criterion for assessment of ecological safety of alternatives of EMS being designed.

At the manufacturing stage of EMS, negative effect is found mainly depending on

$$\Delta\omega_{manuf} = \omega_T - \omega_{prot}, \qquad (4)$$

where ω_T – level of technology-related effect of complex of technologies;

ω_{prot} – level of engineering protection of environment:

$$\omega_{prot} = \sum_{i=1}^{n} \omega_{prot_i}, \qquad (5)$$

where ω_{prot_i} – contribution in the decrease of negative effect by methods, means and devices of ventilation exhausts, sewage, recycling waste in manufacturing EMS.

$$\Delta\omega_{manuf} \prec \omega_{\max}, \qquad (6)$$

where $\omega_{\max}$ – for an enterprise, maximal permissible emissions in the atmosphere, standards waste formation and sewage.

In a general case, decrease of negative effect from industrial enterprises is achieved via introduction of more clean technologies and compensation abilities of engineering protection of the environment via implementation of environment protection measures [18].

At the stage of EMS maintenance, it is feasible to consider two variants of EMS operation as independent objects and elements of higher hierarchical level systems.

In the first case, at the stage of maintenance we will consider negative effect from X object (electric engineering system) characterized by Ai, first of all related to energy transfer which directly depends on the functional characteristics of EMS. At the input, it is:

$$\omega^{oper}_{input}\left[X(A_i)\right] = f(E_{input}), \qquad (7)$$

where E_{input} – energy consumed by ES, MJ.

The efficiency of using E_{input} depends on the basic characteristics of systems being designed (efficiency factor η, power factor cosφ, specific mass per unit of net power, etc.). Meantime, during operation some energy loss is inevitable expressed at the output as follows:

$$\omega_{output}^{oper}\left[X(A_i)\right]=f(\sum_{i=1}^{n}Ke_i)\,, \qquad (8)$$

where Ke_i – parametric characteristics of ecological impact.

During intermediate stages design, it is necessary to check functional and constructive characteristics of EMS affecting the main energy flows: heat loss, electromagnetic emission, noise/vibration levels, etc. To reduce the negative effect of material flows, cut-down and non-waste use of consumables should be ensured [19].

In the second case, when EMS are one of the elements of higher level systems, materials and energy input and output flows falling to the share of EMS are identified.

To improve the ecological safety at the stage of EMS maintenance it is required to follow the general principles: enhancement of reliability and useful life, usability of service and repair, use of module-type construction, cut-down of consumables, etc. The level of negative effects at the input and output will depend on materials and energy flows imperative to maintain EMS operation.

At the stage of EMS recycling, the recycling opportunities of particular subsystems, units, parts, materials should be considered. For materials, negative effect will be found at the input as follows:

$$\omega_{input}^{r}[X(A_i)]=f\sum_{k=1}^{n}(M_k^r E_k^r)\,, \qquad (9)$$

where M_k^r – mass of k-th construction material of ES expected to be recycled, kg;

E_k^r – energy consumption for recycling of 1 kg of k-th construction material, MJ/kg of construction material.

The recycling technology should be chosen with minimal energy consumption and minimal technology-related impact on the environment. At the output, negative effect is found as follows:

$$\omega_{output}^{r}[X(A_i)]=f(\sum_{k=1}^{n}(M_k^r M_k^{red}\},\sum E^{output})\,, \qquad (10)$$

where M_k^{red} – reduced mass of waste from recycling 1 kg of k-th construction material, kg/kg of construction material;

$\sum E^{output}$ – negative energy effect on the environment from recycling (energy loss), MJ.

To reduce that effect at the structural synthesis stage, it is required to ensure choosing of recyclable materials, use of recycled materials, possible dismantling of EMS structures after decommissioning and use of its elements for restructure of similar or other EMS. Also, it is of urgency to consider in the course of parametric optimization that general negative effect at that stage depends on the optimal ratio of the masses construction materials.

Assessment of ES being designed by many criteria, including ecological, is a rather comprehensive task. In the performance of the task on choosing alternatives using several ecological parameters, various quality and quantity assessment methods are applied. Meantime, applying all the ecological parameters at early design stages is unfeasible as it greatly increases the research time. Therefore, at each stage of design the basic ecological parameters dependent on the engineering characteristics of ES being designed should be chosen via expert assessment.

The authors apply for assessment of ecological safety of EMS being created the method based on implicative relations of engineering and ecological characteristics of ES, or the principle *What if?* The method utilizes intermediary parameters characterizing the state of EMS and is conductive to enhancement of ecological safety at the stage of the development of the system.

The novelty of that approach is that ecological characteristics are calculated with due regard to engineering characteristics of EMS being designed used in their parametric optimization.

The application of this method for the assessment of ecological safety will allow forecasting negative effect to the environment in case of change in construction and functional parameters of EMS. That method should be referred to the group of quality methods for assessment of ecological safety. Meantime, it gives the idea on deviations of parameters of particular physical values and may be a basis for deterministic analysis methods, also enabling to develop corrective actions not only from the positions of ecological safety but also in connection with EMS modernization. The method utilizes intermediary parameters characterizing the state of EMS at the development stages.

Figure 1 displays the scheme of utilization of intermediary parameters of EMS to improve the ecological safety of systems being designed.

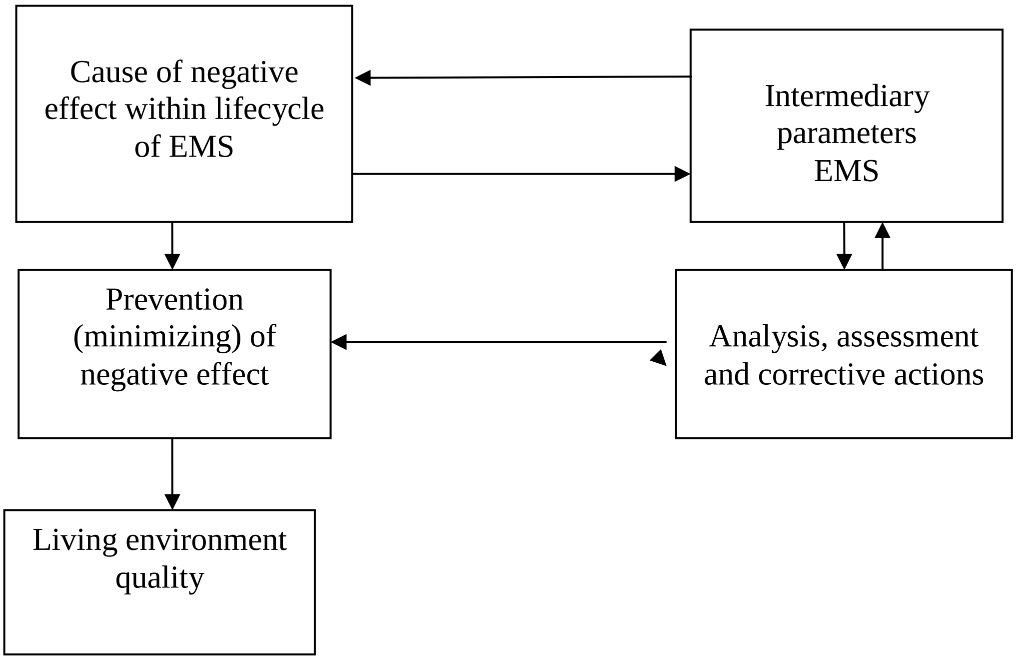

Figure 1. Model of implicative relations of engineering and ecological parameters to improve ecological safety of engineering systems

Table 2 displays the general criteria for *ecologically safe engineering system*.

Table 2. General criteria for *ecologically safe engineering system*

Elements of the system	Ecological safety criteria
1. Materials	1.1. Materials supplies are unlimited 1.2. Materials are not or are not expected to be legally limited 1.3. Low energy costs and natural resources for extraction, production and use of materials 1.4. Minimal negative effect on the environment in mining, production, maintenance and recycling 1.5. Recycling opportunity 1.6. Minimal negative effect on the production environment, etc.
2. Engineering systems	2.1. ES mass and volume decrease 2.2. Use of same grade materials to improve further recycling efficiency when applicable

	2.3. Restriction on the use of composition and combined materials in ES 2.4. Improvement of energy efficiency factor 2.5. Enhancement of reliability and life 2.6. Minimizing negative effect within lifecycle 2.7. Ecological marking of products 2.8. Cutting consumables in maintenance, repair and service 2.9. Recycling opportunity 2.10. Choosing ES assembly method accounting for future dismantling, etc.
3. Technological processes	3.1. Cutting the period of consumption of material and energy sources 3.2. Decrease of ecological and production risks 3.3. Minimizing extra processes 3.4. Minimizing negative environment effects 3.5. Minimizing treatment facilities, etc.

For quantity and quality analysis of ecological safety of EMS the authors offered a model based on mathematical regressions in order to identify the implicative relations of engineering and ecological parameters of EMS. Identification of particular and comprehensive ecological criteria for assessment and choosing alternatives goes according to the following scenario:

1. Comprehensive ecological lifecycle analysis of the structured system of a designed object and the range of engineering characteristics is carried out.
2. Functional target of engineering systems is analyzed and the basic range of ecological parameters at lifecycle stages of an object is identified.
3. Interdependency of engineering characteristics of a designed system with ingredient negative impact throughout the lifecycle is found.
4. Within the selected range of engineering parameters, the indicators of ingredient and technological impact throughout the lifecycle (particular ecological parameters) are found. If required, corrective actions are implemented to change the engineering characteristics of ES.
5. Integral (comprehensive) engineering and ecological indicator of engineering systems to complete the process of optimization of the structure of a designed system and choosing the most balanced solution is identified.

Assessment of an engineering system being designed by several ecological parameters is a rather comprehensive task. While solving the task on selecting alternatives with a few ecological parameters, different quantity and quality assessment methods are applied [20].

Meantime, the use of all ecological parameters at early design stages is not feasible as it will greatly increase the research time. Therefore, at every stage of design it is necessary to choose via expert assessment the basic ecological parameters dependent on the functional and construction characteristics of designed object specified at a particular stage of design.

Integral (comprehensive) criterion is feasible at the final stage of design for assessment and choosing the optimal variant.

A typical specific feature of new systems development process is the need to choose alternatives [21]. Improvement in design tasks in connection with some parameters may cause worsening other. Currently, enhancement of the functional characteristics of ES via structural or parametric optimization should be with regard to overall comprehensive ecological assessment of alternatives at various development levels. The assessment should be done including identification and comparison of ecological parameters of alternatives by quality or deterministic expression of some particular and – at the final stage – comprehensive criteria accounting for the level of ecological requirements brought to the system of ecological requirements being created.

For assessment and calculation of ecological parameters of the starter being designed, a software was developed to create, store and ensure quick access to information and data store used for ecological assessment; calculation of ecological parameters; analysis and assessment of ecological state of engineering systems being designed with graphic diagrams; graphic interpretation of ecological analysis results and assessment of systems being designed; transfer of data both in electronic form and via information networks to ensure control over design process.

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DISCUSSION

The shift to design with full ecological responsibility will require, besides the changes in the institutional responsibility system, a more comprehensive system of ecological management and staff training. The worldview aspect of design as a kind of engineering activity is related to the gradual transition from strictly determined formalized assessment schemes to probability models, which is especially characteristic for the analysis and assessment of technology-related effects on the environment.

It should be noted that a designer's role is of special importance as the complexity of design tasks put forward by the practice is growing much faster than the capacities of computers, which requires their contemplation and creative solutions by the developer as well as deep scientific knowledge and intuition.

Therefore, for the complete analysis and assessment of technical, economic, social and ecological characteristics of the system being created it is feasible to make a research team comprising various specialists. Such an approach was applied by the authors in the course of the assessment of ecological safety of ES and choosing the optimal site/point for an industrial object, ecological assessment of electric machines being designed and seeking for optimal technological solutions.

Training of engineering staff and engineers' awareness of ecological problems emerging in the interaction of man and man-made ES with the environment is one of the core conditions for the global shift towards sustainable development. As the authors opine, staff training should be introduced which ensures establishment of strategic ecological worldview aimed to seek preventive measures and solutions for mitigation of negative effect on the environment and control over ecological characteristics of ES being created. The basic principles of ecological education are consistency, continuance, and generality.

The improvement of scientific and methodological approach to the change and establishment of strategic ecological worldview and ecological responsibility for making project decisions is based on the following principles:

– development of strategic ecological thinking and training analytical skills and assessment of comprehensive ecological safety of ES created in various spatial and time coordinates (from choosing engineering concept and analysis of local pollutions during operation to assessment of ecological behavior of ES in general and global impacts with due regard to lifecycle);

– use of the methodology offered for assessment of ecological safety of ES being created for formalization of technology-related response in the environment (establishment of implicative relations of functional and ecological parameters characterizing the effect on geospheres at various stages of lifecycle).

Theoretical objectives of ecological training in that context are as follows:

– analysis of design and development processes for various ES to integrate ecological parameters at early stages of design;

– making multilevel energy and materials balances to seek for dependencies and enhancement of ecological safety of systems being created on the local and global levels;

– learning methods of quantity and quality assessment of ingredient and parametric effects of ES in a lifecycle and seek for comprehensive ecological criteria of assessment;

– use of tools and instruments of ecological control system in design processes.

CONCLUSION

1. At each stage of ES development, a particular local technology-related effect influencing the general level of ecological safety of ES in a lifecycle is set up. The significance of technology-related effect depends on structural, construction and functional parameters of the ES being developed; change and control of engineering characteristics of ES systems being developed will enable to control their negative effects.
2. Identification of dependencies of implicative relations of engineering (functional, structural and construction) parameters of ES being developed and dependent negative ecological factors within a lifecycle will make it possible to develop multifactor regression equations which may be used for

comparative analysis of ecological safety of competitive alternatives.

3. After generalization, quality and quantity methods were offered for the assessment of ecological safety of ES based on particular and comprehensive ecological criteria.
4. The algorithm for the study of the ecological safety of ES and the required software for the assessment of parametric optimization at earlier stages of design were developed.
5. Scientific and methodological approaches were offered to control over ecological design, change and establishment of strategic ecological worldview and ecological responsibility for making project decisions.

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