Improving Ecological Performance of Design Processes Accounting for Product Life Cycle

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Abstract:

To preserve favourable environment and natural resources with a high rate of technical development, a large-scale transition from anthropocentric positions to ecocentric ones in all spheres of economic activity, especially, at the design stage of new products is required as the decisions determining the necessary material base for the creation of products and having multiplicative effect of impact on the environment are made.

The new approaches to improve ecological performance of design processes accounting for the product life cycle were offered. The methods for assessing ecological safety of created products from the perspective of full ecological responsibility aimed at improving ecological safety of products in the life cycle and minimizing negative impact on abiotic resources were developed; these methods enable to set implicative dependences of engineering and ecological parameters and control over them to improve ecological performance of design processes.

The comprehensive ecological criteria for assessing ecological safety of technical products at the design stage based on the regressional dependences of ecological and engineering parameters of created products, algorithms and criteria for ecological safety of materials were given. The offered analysis methodology and methods for assessing ecological safety in the design by various ecological parameters can be used to study any engineering system being created.

Keywords: ecological safety, ecological design, technical products, ecological performance, life cycle, recycling, implicative relations, comprehensive ecological criterion.

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Introduction

The strategic goal of the state Russian Federation's policy in the environmental development is the solution of social and economic problems providing ecologically oriented economic growth, preservation of favourable environment, biological diversity and natural resources to meet the needs of present and future generations, to exercise each person's right for favourable environment, to strengthen law and order in environment protection and ensure ecological safety (Principles of State Policy in Environmental Development of the Russian Federation for the Period up to 2030; Dmitrishina and Uskov, 2015).

The authors opine that the achievement of objectives in ecological safety is possible only through science-based technical, economic and social compromises in the process of human economic activities, especially at the stage of design of new products. The main criteria for ecological performance of such decisions are saving the material and energy resources at the input and minimizing the negative environmental impact at the output of production systems.

At present, the scientific concepts in ensuring ecological safety are: the concept of control "in the end of the tube", the concept of "cleaner production", the concept of "design for ecology" and the concept of "comprehensive ecosystem approach". The implementation of the most modern concepts of "design for ecology" and "comprehensive ecosystem approach" requires making all technical decisions from a position of full responsibility for ecological safety of products being created in their life cycle.

The main disadvantage of the traditional system of ecological reasoning and choosing alternatives in the course of development of engineering systems 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 at earlier design stages as the decisions determining the necessary material base for the creation of products and having multiplicative effect of impact on abiotic resources are made in addition. Improving ecological safety of products can be achieved by improving the theory and methods for assessing competitive variants according to ecological criteria (Burkov *et al.,* 2002; Medvedeva *et al.,* 2015; 2016).

The assessment should be done on the basis of the analysis of implicative relations of functional and other technical characteristics of products and dependent ecological factors of negative effect using private and comprehensive ecological criteria to optimize and rationalize the solutions in choosing competitive alternatives. Such an approach will enable to control ecological performance indicators of project works and ecological safety of products and to reduce the intensity of environmental problems before they occur.

According to GOST R 14004-2007, in this work under ecological performance we understand the results of control measured by the organization through the ecological aspects (Theriou and Aggelidis, 2014; Thalassinos and Liapis 2014).

Methods

There are several directions to improve ecological performance of design processes accounting for the product life cycle. The offered methods were developed for design of technical products (TP).

I. **Assessment of TP criteria for subsequent recycling at the design stage**

The criteria used in the algorithms to improve ecological safety of designed products can be both quantitative and qualitative ones. For example, the quantitative criteria characterizing the possibilities for subsequent recycling should determine the efficiency of this process.

The efficiency of the recycling process depends on the following conditions:

- small dismantling of TP which is important in the process of products recycling in general;
- increase in the number of unified assemblies which is important in recycling of parts and assemblies;
- reduction in the number of used material brands and number of composite materials in products, which is important in recycling of construction materials.

Then ecological criteria for recycling should be of three types:

1. Ecological criteria for TP design by recycling of materials;
2. Ecological criteria for TP design by recycling of assemblies and parts;
3. Ecological criteria for the technological process of TP disassembling.
Taking into account the recommendations presented in (Goldberg *et al.,* 2001; Mushic and Müller, 1999), the authors developed the quantitative parameters for recycling. Such parameters may be:

By the first type:

1.1. Repeatability factor of construction materials in the TP structure:

$$K_{mr} = 1 / M_m, \tag{1}$$

where M_m – the number of types (brands) of construction materials used in the

product. The increase of this factor, and decrease of the number of material brands in the structure will allow raising efficiency of separation, sorting and subsequent processing of construction materials.

1.2. Utilization factor of composite materials:

$$K_{cm} = (M_m - M_{cm})/M_m,$$
(2)

where M_{cm} – the number of composite materials. The composite materials do not regenerate so when making a structure, it's necessary to increase this factor by eliminating or reducing the number of composite materials.

By the second type:

2.1. The factor of disassembling the product assemblies:

$$K_{du} = N_{du}/N_c,$$
(3)

where N_{du} – the number of two-piece units,

N_c – the total number of assemblies in TP. Increasing this factor makes the structure more environmentally friendly in the life cycle as the permanent joints virtually eliminate disassembling and restoring assemblies.

2.2. Unification factor of the TP structure:

$$K_u = (E_u + D_u)/(E + D),$$
(4)

where E_u – the number of unified subassemblies in the TP structure,

D_u – the number of unified parts which are the components of the product and are not included in E_u;

E – the total number of subassemblies in the TP structure,
D – the total number of parts in the TP structure.

The increase of this factor and the number of unified subassemblies and parts will allow using the restored assemblies and parts as spare parts for similar TP.

By the third type the ecological parameters for recycling technological process can

be taken by analogy with the economic ones for technological processes. The possibility of TP recycling, for example, will be dependent on the economic parameter of the complexity of this process – *T*.

3.1. The complexity of the process

$$T = \sum T_i, \tag{5}$$

where T_i – the complexity of disassembling, restoring, quality control and testing of the i-th element of TP, in working hours. A significant increase of this parameter makes recycling counterproductive. Table 1 presents quantitative parameters for recycling.

Table 1. *Quantitative parameters for recycling*

Nomenclature of parameters	Designation of factors	Formula for factor calculation
1. Ecological parameters of the TP structure by recycling of materials	1.1. Repeatability factor of construction materials in the TP structure 1.2. Utilization factor of composite materials	$K_{mr} = 1/M_m$ $K_{cm} = (M_m - M_{cm})/M_m$
2. Ecological parameters of the TP structure by recycling of assemblies and parts	2.1. The factor of disassembling the product assemblies 2.2. Unification factor of the TP structure	$K_{du} = N_{du}/N_c$ $K_u = (E_u + D_u)/(E + D)$
3. Ecological parameters of the recycling technological process	3.1. Complexity of the recycling process	$T = \sum T_i,$

The analysis of existing practices (Bykov, 1993; Tang, Mak and Zhao, 2016; Mansour and Radford, 2016; Gu *et al.,* 2015; Ovchinnikov *et al.,* 2016; Angelakis *et al.,* 2015) and authors' research experience of their own (Grafkina, 2008; Grafkina *et al.,* 2016; Meskhi *et al.,* 2016; Albekov *et al.,* 2017; Havlíček *et al.,* 2013) allows providing high-quality ecological parameters of the TP structure with regard to subsequent recycling as follows:

- available materials being used and their eco-labeling;
- opportunity for available dismantling;
- opportunity for reusing particular assemblies in the structure;
- opportunity for restoring repeat assemblies in quality;
- identifying assemblies and parts which cannot be processed;

- available database on materials used, methods for dismantling, technologies for restoring assemblies for reuse, methods for collection and utilization, etc.;
- comparative assessments of different ways to joint parts from the perspective of load-bearing characteristics, complexity of assembling, disassembling and subsequent recycling.

II. Assessment and identification of implicative relation between the engineering and ecological parameters of TP

The assessment and optimization of TP at early development stages is the most effective tool for ensuring ecological safety of TP in the life cycle and achieving a goal of ensuring ecological safety of products and minimizing the negative impact on the environment not only by functional parameters but also by ecological ones. In spite of the fact that the methods for design and optimization of TP are rather profoundly developed they don't consider design opportunities for improving ecological safety in the full life cycle to the full extent yet.

The reason for it is that the analytical dependences of TP engineering and ecological parameters are difficult to be established, they have many factors, the environmental impact, as well as the ecological parameters, are not identified at early design stages. These problems are similar to problems of optimization of created products by engineering and economic criteria at the design stages (Faskhiev *et al.,* 2004).

Success in the optimization of parameters primarily depends on the correct choice of optimization criteria. Currently, the effectiveness of TP design is defined by the fullest compliance of their constructive and functional parameters to operational requirements as well as by economic, first of all, cost parameters. Such an approach emerged in the anthropocentric ecology when all optimization criteria were taken from the perspective of a consumer.

At the same time, all the elements in the nature are interrelated and interdependent. The materials and energy flows required for the production of TP determine the technology-related impact on the environment at the input and output of production systems. Finally, almost all technical characteristics of TP affect their ecological parameter of negative impact within the life cycle. Therefore, the assessment, optimization and selection of design alternatives of created TP should be carried out in conjunction with engineering and ecological criteria.

The authors offer the method for improving ecological safety of TP based on the principle "What if?" which is applied to assess the reliability of TP and technology-related risk presented in (Akimov *et al.,* 2002). Applying 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 TP. This method should be referred to the group of quality methods for ecological safety

assessment. Meantime, it gives the idea on deviations of parameters for particular physical values and may serve as 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 TP modernization. The method uses intermediary parameters characterizing the state of TP at the development stages.

To assess the implicative relation between engineering and ecological parameters of TP the authors also developed:

- a model for comprehensive ecological criterion, the novelty of this approach lies in the fact that ecological criteria are calculated with regard to engineering parameters of designed TP used in their parametric optimization (using an electric starter machine as an example);
- ecological parameters of construction materials accounting for the life cycle.

Results

The procedure for selecting an optimal design solution includes the stages of synthesis, analysis and assessment of alternatives and decision-making. According to (Lopukhina and Semenchukov, 2009), in the synthesis the projects of technical objects or variations of them are created, in the analysis they are assessed and the choice of the final variant ends the procedure.

Thus, the overall efficiency of TP, which consists of their functional useful effect, reduction in expenditure for TP development and operation and reduction in the degree of their impact on man and environmental components, is identified. The task of designing is always a multicriteria one. The technical requirements are reflected in the parameters related to the parameters for technical quality (reliability, power, efficiency, speed, etc.).

The economic requirements are, first of all, competitiveness and reduction in expenditure for production and operation of TP. The ecological requirements are now determined by limits of negative impact (maximum permissible concentration, maximum permissible discharge, noise levels, vibration levels, etc.) established in the relevant regulations. However, from the standpoint of ecocentrism, the basic ecological criteria should be the improvement of TP ecological safety and minimization of negative environmental impacts in the life cycle.

It should be noted that the assessment of designed TP by ecological criteria accounting for the life cycle is a relatively new type of research (Graedel and Allenby, 2004; Zvonov *et al.,* 2001; Rezaei *et al.,* 2016); therefore, the system of ecological criteria related to the selection of an optimal variant of the engineering system accounting for the life cycle is virtually nonexistent to date. Many private ecological criteria have regressional dependence on the parameters of the designed system and can be calculated by appropriate mathematical models.

The authors offer a model for comprehensive ecological criterion calculated accounting for engineering parameters of TP being designed; these parameters are used in their parametric optimization (using an electric starter machine as an example). The integral (comprehensive) criterion should be applied at the final design stage to assess and choose the optimal variant.

The comprehensive ecological criterion includes:

- comprehensive criterion accounting for the negative impact on the atmosphere;
- comprehensive criterion accounting for the negative impact on the hydrosphere;
- comprehensive criterion accounting for the negative impact of the wastes formed;
- criterion accounting for the negative effect of noise on the environment;
- criterion accounting for the negative effect of vibration on the environment;
- criterion accounting for the negative impact of electromagnetic radiation on the environment;
- parameter accounting for probability of ignition in an electric network;

The assessment of the designed TP by several ecological parameters at once is a very challenging task. When solving the task of selecting alternatives with a few ecological parameters, different quantity and quality assessment methods are applied (Firescu and Popescu, 2015).

At the same time, applying all ecological parameters at early design stages is unfeasible as it will significantly increase the research time. Therefore, at each design stage it is necessary to choose via expert assessment the core ecological parameters dependent on the functional and constructive characteristics of designed object specified at a particular stage of design. The novelty of ecological design and ecological world view requires considering biosphere processes and all stages of the TP life cycle as events not isolated from each other but as elements of the whole system, i.e. in a deeply integrated way.

With such an approach, any of the TP influences the processes of natural resource use. Therefore, the comprehensive parameters of negative impact of construction materials on the environment were determined. The comparison of the obtained results with the ones of existing calculation methods "Ecoindicator-95" presented by the Netherlands University in Delft (*Eco-indicator 95*, 1996) was conducted. The parameters characterizing the negative impact of production processes of various construction materials obtained by different methods are shown in Table 2 and in Figures 1-2.

Table 2. *Parameters characterizing the negative impact of processes of obtaining various construction materials*

Materials	Specified mass of emissions, kg/kg of materials (Grafkina)	"Eco-indicator – 95", point/kg of materials (data of the University in Delft)
Aluminium	2,975.84	18.1
Copper	22,720.6	133
Plastic	1,375.12	5.29
Lead	4,126.88	6.94
Steel	998.367	4.88

Figure 1. *Parameter for the specified mass of emissions in making 1 kg of construction materials*
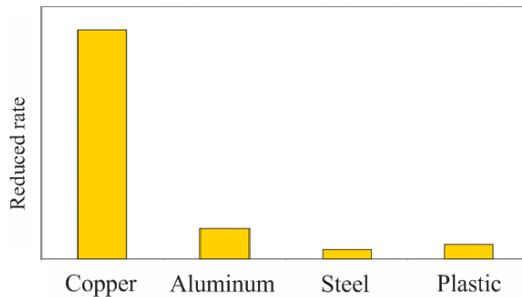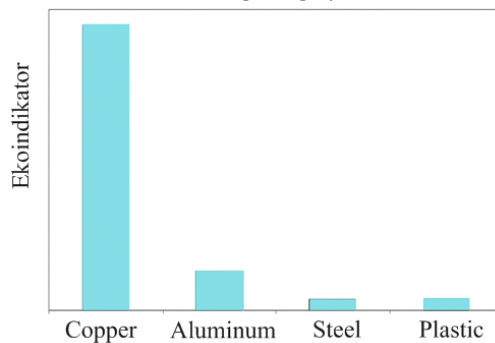

Figure 2. *"Eco-indicator – 95" in making 1 kg of materials*

The comparison shows that the results are comparable. The offered methods for determining the negative impact at the stages of production and recycling of materials have the following main advantages:
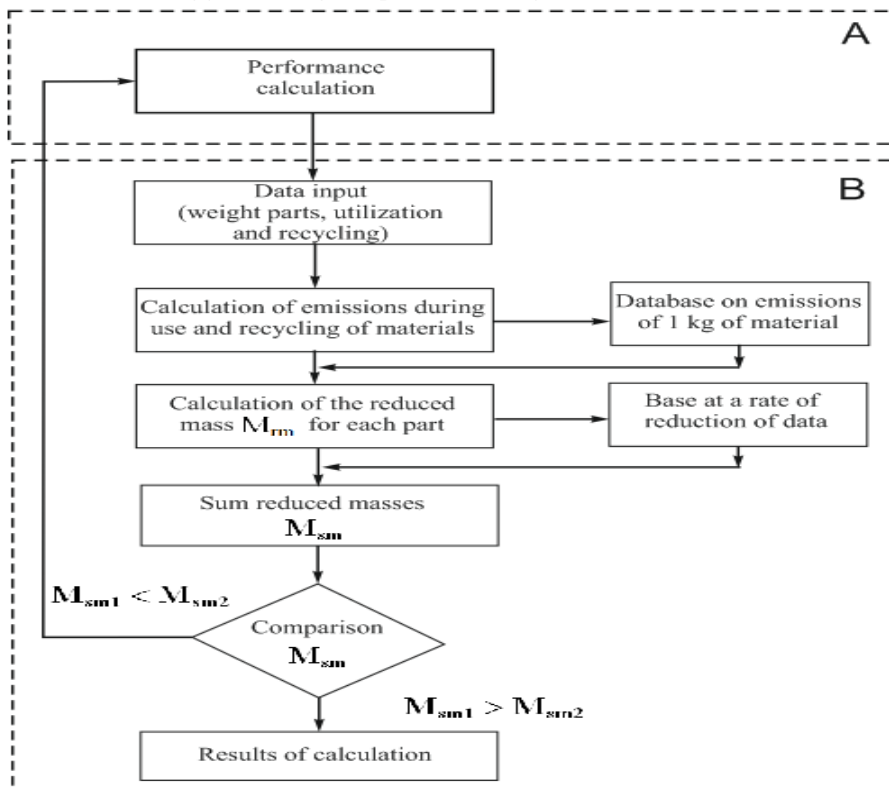
- are adapted to Russian conditions,
- reduce the number of parameters used in the calculations greatly.
To assess the ecological safety of TP accounting for the negative impact at the stages of production and recycling of construction materials, the following algorithm was

developed: small variations of values of design parameters used in the traditional block of calculation of electrical machines – A are calculated; calculation of ecological parameter of the negative impact on the atmosphere accounting for ecological parameters of construction materials in block B (Figure 3) is conducted.

In block A, the constructive and functional parameters of TP being designed are calculated. The variant recognized as the optimal one ("base model") without accounting for a new ecological criterion is selected. Then a group of experts identify engineering parameters which at this stage of design through implicative relationship will reduce the negative effect accounting for ecological parameters of materials. The constructive parameters altering the functional performance of designed TP insignificantly vary. The obtained alternatives of designed TP go to block B. The ecological parameters of several alternatives are compared and assessed. The best one is returned to block A and is checked for compliance with functional technical characteristics specified in the beginning of design. As a result of using this method, the ecological assessment of alternatives can be conducted and choosing of the design solution not only from the standpoint of TP functionality and reliability, etc. but also from the positions of ecological safety can be rationalized.

Figure 3. *Algorithm for assessment of TP ecological safety (electric starter machine) accounting for ecological parameters of construction materials*

The final choice of the variant of the designed engineering system is made by the designers and technologists on the basis of comprehensive analysis of the system parameters by technical, economic and ecological criteria. Meantime, the analysis and assessment of ecological safety of TP at early design stages allows improving ecological safety of TP and minimizing the negative impact on the environment.

Discussion

The authors believe that the transition from anthropocentrism to ecocentrism requires significant changes in the approaches to the design of technical products and the shift to design with full ecological responsibility which requires improvement of the staff training system.

Training of engineering staff and engineers' awareness of ecological problems emerging in the interaction of man with the environment is one of the core conditions for the global shift towards sustainable development and solution of problems of mankind future survival. In the world educational practice, this kind of education is called "environmental education".

It's necessary to train future specialists in preventive methods for the assessment of environmental threat of TP depending on the decisions being made and to control over ecological characteristics of engineering systems being designed with regard to the life cycle. As each created engineering system has significant differences in its functional purpose and technical characteristics it is advisable to introduce disciplines on the fundamentals of ecological design reflecting common approaches to solving this problem to the basic standards.

In contemporary world, education should be considered as a framework factor. The rate of reducing negative human impact is dependent on the level of formation and development of the system of higher and secondary vocational education, retraining, advanced training of engineering staff, in-house education and certification of specialists and heads of executive authorities and organizations in the environmental problems and ways of their solution. The education system should be a multilevel one with the fundamental goal of forming ecological consciousness in each person's mind. The basic principles of ecological education are: consistency, continuance and generality.

Currently, in the national education system, the mechanisms, aimed to form graduates' strategic ecologic worldview, enabling them to assess ecological safety of designed systems accounting for the life cycle proactively and form ecological responsibility for technical decisions making which is especially important for implementation of the concept of sustainable development, are not fully developed.

Meantime, the increasing scale of ecological catastrophe is so large that the future paradigmatic changes in the education system should be built on the scenarios which are based on the principles of control over ecological safety. To harmonize the relationship between man and nature, it is necessary to change the paradigm of culture, science and education. Speaking about the possibility of implementing the decision on the shift towards sustainable development in Russia made by the government, it is feasible to formulate five basic areas in which consent must be achieved in the near future:

- rational use and restoration of natural resources;
- solution of scientific and engineering problems in such a way that irreversible alterations in the nature should be excluded;
- providing the total population of the country with commodity products according to the standards of the civilized society;
- accumulation of optimal decisions on the number and location of the population which eliminate problems of hunger and infringement of national traditions;
- organizing systems of objective monitoring of the country territory and informing the population of the state and alterations due to anthropogenic activities.

Conclusion

1. The methods for assessing ecological safety of created products from ecocentric positions and full ecological responsibility aimed at improving ecological safety of products in the life cycle and minimizing the negative impact on the environment were offered; these methods enable to set the implicative dependences of engineering and ecological parameters and control over them to improve ecological performance of design processes.
2. The comprehensive ecological criteria for assessing ecological safety of technical products at the design stage based on the regressional dependences of engineering and ecological parameters of products being created were developed.
3. The algorithms and criteria for ecological safety of materials to assess the ecological safety of created technical products were developed.
4. The offered analysis methodology and methods for assessing ecological safety in the design by various ecological parameters can be used to study any engineering system being created.

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