Ecological Safety of Progressive Technologies in the Life Cycle

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Abstract. The article is devoted to the analysis of the impllicative (according to the “What-If?” principle) interaction of all decisions on the organization and implementation of technological processes and providing them with material and energy resources, machines, units, equipment, technological equipment, technological structures and materials at various stages of the life cycle response in the environment, which allows you to identify and formulate recommendations for improving the environmental safety of technological processes in the life cycle.

Introduction

The development of advanced technologies is a response to the needs of the market for highly efficient production, constant updating of products and requirements for environmental protection and reducing environmental tensions. The technologies being developed must meet both technical, economic and environmental requirements, therefore the task of choosing the best option will always be multi-criteria. Recently, environmental requirements during the development of technical systems are becoming increasingly important.

The progressive and most significant modern technological processes include electron-beam, laser, membrane technologies, powder metallurgy, etc. Technologies have undoubted technical advantages, for example, the quality and accuracy of the products obtained. The performance of laser welding machines, the strength of the joints obtained is higher than that of modern automatic arc welding machines, and the use of laser welding avoids deformation of the welded parts. Technologies make it possible to increase the utilization rate of construction materials at the expense of the accuracy of the operations performed. Distinctive environmental features of advanced technologies are their focus on the best available technologies and, above all, their focus on combating emissions into the environment and reducing the consumption of material and energy resources, introducing closed (waste-free) technological cycles (regeneration of solutions used, energy recovery, recycling of materials used, rational water consumption), the introduction of modern systems for the cleaning of ventilating gases and waste gases in.

However, at present, not all opportunities for minimizing the industrial environmental impact of technological processes in the life cycle are used effectively. Technological processes as well as industrial products have their own life cycle, and the organization of processes is more costly, both economically and from the standpoint of use and the constant need for significant amounts of natural, material and energy resources, the cycle stages take a considerable time period, therefore environmental consequences will have a larger scale, multiplicity, a certain inertia, and may eventually meet more stringent environmental requirements.

Analysis of impllicative (according to the “What-If?” principle) interaction of all decisions on the organization and implementation of technological processes and providing them with material and energy resources, machines, units, equipment, technological equipment, technological compositions and materials at different stages of the life cycle with a response in the environment will allow to identify and formulate recommendations for improving the environmental safety of technological processes in the life cycle. When choosing the best solutions, you should use both qualitative and quantitative methods for evaluating alternatives.
Results and discussion
To analyze the environmental safety of technological processes, we can consider various stages of the life cycle, in this paper we will focus on the following:

- project design;
- stage of scientific work;
- implementation of the process and provision of it with all necessary resources;
- direct operation of the technical process (main and auxiliary operations);
- repair and adjustment processes;
- modification of technological processes;
- recycling, disposal or destruction.

The generalization of existing developments [1-5] to improve the environmental safety of technical systems allows us to formulate the main directions for reducing the negative impact on the environment that are applicable at all stages of the life cycle of the technological process include:

- reduction of consumption of raw materials, material and energy resources at all stages of the life cycle (including intermediate technological losses, losses during storage and transportation, etc.);
- reduction of the use of extremely hazardous and highly hazardous substances and materials (including taking into account the long-term prospects for restrictions on the use of certain substances and materials);
- improvement of the main and auxiliary technological operations in order to eliminate or reduce the sources of formation of pollutants, wastes and other negative factors affecting the environment;
- recycling (regeneration of technological compositions, recycling and reuse, recovery) of raw materials, materials, reagents, water, energy;
- processing and use of waste products by creating by-products based on the integrated use of raw materials and waste;
- coordination and cooperation with other industries (business partners) in the field of saving and saving raw materials and energy resources, using secondary resources, processing and using waste, transferring environmental information about processes, machines, aggregates of materials, etc.;
- reduction of situations with increased environmental risk and the risk of occurrence and development of emergency situations;
- preparation for environmental mitigation activities under conditions of emergency impact on the environment;
- environmental education and awareness of the organization’s personnel to prevent negative environmental impacts;
- development of effective industrial environmental monitoring and control (including monitoring and control of the use of all types of resources, emission sources of polluting emissions, etc.);
- reflected in the policy, goals and objectives of the organization of the relationship of the main production and environmental activities of the enterprise;
- active use of various internal qualitative and quantitative environmental indicators, characteristics, including those developed independently by the enterprise;
- effective planning and organization of environmental activities in accordance with accepted goals and objectives;
- rational and effective use of all the opportunities and means at the enterprise (primarily cost-free and low-cost) to solve environmental problems;
- use of an independent performance measurement (environmental audit);
- development of a “green” accounting system for the movement of material resources in the course of technological operations, etc.

It is especially effective to think over all the environmental consequences of the technologies used, machines, units, energy, materials at the initial stages of the life cycle of the process - the design and scientific work concept, that is, before material and energy resources are involved in the process, that is, the material base is laid, possessing a huge multiplicative effect on the life-supporting resources of the earth.

Environmental safety analysis and assessment of alternatives should be carried out using the “What-If” method, which is used both to assess the reliability of technical systems and to assess environmental risks. The use of the method involves the assessment and analysis of the implicative relations of technical and environmental indicators of the technological process and allows you to predict
the negative response in the environment when changing any process parameters. This approach will allow you to manage the indicators of environmental safety of processes and reduce the tension of a number of environmental problems even before they occur. This method is most often used to assess qualitative changes, but it also gives an idea of the deviations of indicators of specific physical quantities and can serve as a basis for deterministic assessment methods, and allows you to develop corrective effects not only from the standpoint of improving the functioning of the system but also environmental safety.

At the stage of implementing the process and providing it with all the necessary resources, a qualitative and quantitative assessment of the environmental safety of the process equipment when choosing alternatives can be carried out on the basis of the following criteria:

- indicators of mass and volume of equipment;
- indicators of the number of construction materials in processes and equipment;
- energy efficiency;
- reliability and service life of the equipment;
- application of eco-labeling of materials and products;
- volumes of consumables during operation, repair and maintenance of the process and equipment;
- the possibility of using recycled materials;
- the possibility of regeneration, recycling, recovery of material and energy resources.

These indicators primarily ensure the saving of material and energy resources, as well as an increase in the efficiency of their reuse.

The maximum task in the implementation of technological processes is the transformation into finished products of all the involved material resources. The assessment of the environmental safety of a technological process requires consideration not only of the environmental characteristics of the main process itself, but also of the characteristics of auxiliary processes that precede or follow it [2]. For example, the welding process requires preliminary preparation of the blanks: it is necessary to carry out a mechanical cleaning from rust and other contaminants, as well as to degrease and dry the parts being welded. The soldering processes require subsequent operations to clean up the flux.

To improve the environmental safety of the stages of repair, adjustment processes, modification of technological processes and recycling, it is necessary to provide for the possibility of optimal disassembly, unification of components, marking of materials. This will allow reuse of some nodes, provided they meet their quality requirements, and facilitate their disassembly at the end of the life cycle. In general, the same requirements for environmental safety of the life cycle as for technical products are applied to equipment of technological processes.

When analyzing the environmental safety of technological processes, it is necessary to strive for the collection of environmental information and, above all, quantitative information. The transition to quantitative assessment methods is most effective at the stages of implementation and operation of the process and the involvement of all the necessary resources, as well as carrying out repair and commissioning works and modification of technological processes. Here it is advisable to use the developments that are used in assessing the environmental safety of products.

The authors propose a number of criteria for assessing the environmental safety of machines and units used in the process, the choices and decisions on which are applied at earlier stages, and the environmental consequences are manifested at the stage of utilization and destruction, equipment that has served its life, equipment and accessories (Table 1).

The following criteria are proposed:

1. The coefficient of repeatability of grades of materials in the design:

\[ K_{rg} = \frac{1}{M_m}, \]  

where \( M_m \) – the number of brands of materials used in the product.

Reducing the number of materials in the design will improve the efficiency of sorting and subsequent processing (recycling) of materials.

2. The coefficient of disassembly of units of the product:

\[ K_{du} = \frac{N_{sn}}{N_i}, \]  

(2)
where \( N_{sn} \) – number of split nodes,
\( N_t \) – total number of nodes in the product.

Increasing this ratio makes the design more environmentally friendly, as permanent connections virtually eliminate the disassembly and restoration of components.

3. The coefficient of unification of the design:
\[
K_u = \frac{E_u}{E},
\]
where \( E_u \) – number of unified assemblies in the structure;
\( E \) – total number of subassemblies in a structure.

4. The possibility of recycling materials and nodes will also depend on the economic indicator of the complexity of this process - \( T \), which is defined as:
\[
T = \sum T_i,
\]
where \( T_i \) – the complexity of the disassembly, restoration, quality control and testing of the \( i \) - component of the machine, in hours.

Table 1. Criteria for assessing the environmental safety of machines and units

| № | The name of the criterion, units measurements | Designation | Formula for calculating |
|---|---------------------------------------------|-------------|------------------------|
| 1. | The coefficient of repeatability of grades of materials in the design | \( K_{rg} \) | \( K_{rg} = \frac{1}{M_{m}} \) |
| 2. | The coefficient of disassembly of units of the product | \( K_{du} \) | \( K_{du} = \frac{N_{u}}{N_{t}} \) |
| 3. | The coefficient of unification of the design | \( K_r \) | \( K_r = \frac{E_u}{E} \) |
| 4. | The complexity of the disassembly process, in hours | \( T \) | \( T = \sum T_i \) |

Thus, when choosing alternative variants of machines, units, and tooling, it is necessary to evaluate not only their technical characteristics, but also environmental indicators in the life cycle. To obtain the necessary environmental information, it is advisable to establish interaction with suppliers of the necessary products.

Special attention should be paid to the environmental assessment of the materials used. On a geographic and geopolitical scale, a certain imbalance between demand and supply of materials, especially metals, has already been noted. The work [1] characterized the criticality of 62 metals and metalloids in a three-dimensional “criticality space”, consisting of supply risk, environmental consequences, and vulnerability to supply restrictions. Factors contributing to the occurrence of extreme situations include a high geopolitical concentration of primary production, the lack of available suitable substitutes and political instability. For example, the results show that the restrictions for many metals important to developing electronics (for example, gallium and selenium) are largely related to the risk of supply. The growth of technological innovation over the past decades has been partly made possible by the fact that an increasing number of metals in the periodic table are used to perform specialized functions. However, concerns are growing regarding the reliability of the supply of some of these metals. The main reason for these concerns is the fact that many of these metals are extracted only as a by-product from a limited number of geopolitically concentrated ore deposits, which makes their stocks incapable of responding to rapid changes in demand. Dependence of accessibility of the associated metal on the production of base metals introduces a new aspect of the risk of supply for modern technologies [2]. In these works, the environmental safety of materials is mainly assessed using expert ball methods.

There are also methods for quantitative assessment of the environmental safety of materials [6-12]. The most frequently cited information is on atmospheric pollution during the production and recycling of structural materials, which is justified from the standpoint of assessing the overall scale of
the pollution of the biosphere, including the atmosphere, since it accounts for more than 80% of anthropogenic pollution. The generalization of these data allows us to estimate the emissions of harmful substances into the atmosphere during the production and recycling of various materials. As an example, in Figure 1. The results of generalizations on the negative effects on the atmosphere of certain substances released during the production of copper are presented. The estimated amount of emissions in grams per kilogram of material produced was estimated.

Figure 1. Emissions in the production of copper (g/kg)

It also summarizes the energy consumption in the production and recycling of steel, aluminum, copper and lead. The specific indicators of electricity consumption in kW per one kilogram of metal produced are shown (Figure 2).

Figure 2. Energy consumption in the production and recycling of materials (kW/kg of material)

However, by absolute indicators of emissions of harmful substances into the atmosphere, as well as by the volume of consumption of water and energy resources in the production and recycling of construction materials, it is impossible to conduct a comparative analysis and draw a conclusion about the degree of complex (integral) negative impact on the components of the production environment and recycling of various materials.

The method developed by the authors, as well as a comparison of the results obtained with the results of other researchers, allows us to identify materials with the lowest environmental impact [7]. The method is based on formalized requirements for an integrated (integrated) environmental indicator of technical systems, which can be represented as a functional:
\[ K(e) = f \left[ \varepsilon_{A} \left( \sum_{i=1}^{n} e_{i} \right) \right] = f \left[ \sum_{j=1}^{m} \sum_{i=1}^{n} \omega_{j} [X(A_{i})] \right], \] (5)

where \( \varepsilon_{A} \left( \sum_{i=1}^{n} e_{i} \right) \) – a vector characterizing the parameters of the natural-technical system that are manageable;

\( e_{i} \) – the level of negative changes;

\( j, i \) – corresponding indexes of the nomenclature of the object of nature \( (j = 1 \ldots m) \) and technical indicators of the object \( (i = 1 \ldots n) \);

\( \omega_{j} [X(A_{i})] \) – technogenic impact throughout the life cycle of object X, characterized by technical indicators \( A_{i} \).

This functional does not necessarily contain additive relations in the expression of the integral criterion. In this case, it only does not exclude the possibility of a linear approximation of the integral criterion from its constituent parameters \( e_{i} \). Controllable parameters include those that characterize technical solutions to improve the environmental safety performance of a technical system in the life cycle.

Table 2 shows the results of a quantitative assessment of the environmental safety of some structural materials obtained by the method of the authors in comparison with other methods [8].

| Materials | Environmental indicator (Grafkina M.V.) [7] | EcoIndicator score / kg of material (Kozlov A.V.)[8] |
|-----------|-----------------------------------------------|--------------------------------------------------|
| Aluminum  | 2975.84                                       | 0.564                                            |
| Copper    | 22720.6                                       | 3.148                                            |
| Plastic   | 1375.12                                       | 0.2983                                           |
| Lead      | 4126.88                                       | 0.769                                            |
| Steel     | 998.367                                       | 0.222                                            |

This method is applicable to the assessment of environmental safety of technological processes; the efficiency of calculations is enhanced by using data from "green" accounting. Calculation example:

\[ \Delta \omega_{pr} = \omega_{t} - \omega_{p}, \] (6)

where \( \omega_{t} \) – level of technological impact of the process;

\( \omega_{p} \) – level of engineering protection of the environment, taking into account the work of cleaning devices:

\[ \omega_{p} = \sum_{i=1}^{n} \omega_{pi}, \] (7)

where \( \omega_{pi} \) – contribution to the reduction of anthropogenic impact from the use of methods, tools and devices for cleaning ventilation emissions, wastewater, reuse of waste production of technical systems.

\[ \Delta \omega_{pr} < \omega_{s}, \] (8)

where \( \omega_{s} \) – maximum permissible emissions for the enterprise, waste generation standards and wastewater quality standards [13].

Quantitative methods for assessing the environmental safety of processes, equipment, and materials allow us to simplify the choice of developers, whose main efforts should be focused on the technical and functional characteristics of the processes.

To analyze and assess the environmental safety of technological processes in the life cycle (in different space-time coordinates), it is necessary to develop the skills of strategic environmental thinking and environmental responsibility for decision-making among process developers.
Conclusion

Despite the fact that advanced technologies are being created including in response to environmental protection requirements, not all opportunities are currently used to improve their environmental safety in the life cycle. It is most effective to conduct thinking about environmental aspects in the early stages of the life cycle of technological processes, before the involvement of material and energy resources in the process begins. Such an approach makes it possible to reduce and in some cases eliminate the negative impact on the environment. To analyze environmental safety at the early stages of the life cycle, it is advisable to apply qualitative assessment methods, whereas at subsequent stages the application of quantitative methods seems to be more effective and simplifies the choice of the necessary process components for developers.

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