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SUBSTANTIATION FOR ENHANCEMENT OF ENVIRONMENTAL SAFETY OF WASTE MANAGEMENT SYSTEMS THROUGH FORECASTING EFFICIENCY OF SPECIALIZED EQUIPMENT

The article deals with actual problems of ecological safety of waste management in small settlements, modern aspects of mathematical modeling of technical support of waste management systems. Well-known examples of methods of ecological and economic evaluation and forecasting of expediency of functioning of branch technical systems were analyzed. An automated simulation mathematical model of dynamic prediction of the ecological effect from long-term exploitation of specialized equipment for waste management systems in small settlements was proposed.

Keywords: forecast, waste, equipment, ecological safety, small settlements, efficiency, evaluation, mathematical model

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ОБҐРУНТУВАННЯ ПІДВИЩЕННЯ ЕКОЛОГІЧНОЇ БЕЗПЕКИ СИСТЕМ ПОВОДЖЕННЯ З ВІДХОДАМИ ПРОГНОЗУВАННЯМ ЕФЕКТИВНОСТІ СПЕЦІАЛІЗОВАНОГО ОБЛАДНАННЯ

У статті розглянуто актуальні проблеми екологічної безпеки поводження з відходами в малих населених пунктах, сучасні аспекти математичного моделювання технічного забезпечення систем поводження з відходами. Проаналізовано відомі приклади методів екологічної та економічної оцінки і прогнозування доцільності функціонування галузевих технічних систем. Запропоновано автоматизовану імітаційну математичну модель динамічного прогнозування екологічного ефекту від довгострокового експлуатування спеціалізованого обладнання для систем поводження з відходами в умовах малих населених пунктів.

Ключові слова: відходи, обладнання, екологічна безпека, малі населенні пункти, ефективність, оцінювання, математична модель

Problem and its connection with scientific and practical tasks. The issue of accumulation waste for a long time does not lose its relevance for Ukraine.

The most acute problem is the crisis of waste for small settlements. Lack of moral and technical obsolescence service vehicles (deterioration by more than 70%) [1], no waste processing companies and organized, technically equipped, hydro isolated landfills for waste storage, the presence of abandoned warehouses and cemeteries hazardous, radioactive and biological substandard materials, lack regular control (monitoring) environment in places of waste accumulation, very limited funding waste management – all these factors led to substantially reduce of the environmental safety of waste management in terms of small settlements.

It is also relevant to carry out modernization and deindustrialization of individual regions of the country for the improvement of the ecological situation [2, 3].

The process of scientifically grounded, high-tech deurbanization, compatible with the technical and environmental modernization of existing settlements, is one of the possible ways to increase their environmental safety [1, 3].

One of the most popular and up to date forms of small ecologically effective settlements is the development of ecological settlements as a direction of organization of living space with the ability to minimize the formation and accumulation of waste. In a number of countries around the world, the practical implementation of the concept of eco-settlement is becoming more and more relevant in Ukraine.

Today in the world there are about 2000 ecological settlements. But up to current situation the approach og our country to achieve a comprehensive solution of environmental problems has a rather low level of development [2]. But the need for a quick restoration of the destroyed infrastructure in the east of Ukraine opens up new directions for the implementation of projects of environmentally effective small settlements. Such an approach to the implementation of future restoration work in the Donbass may allow not only to develop the most effective projects for the restructuring of a damaged or destroyed urbanized human habitat, but will also provide an unprecedented opportunity for a radical solution to a whole range of basic environmental problems of the industrial region [3].

In order to attract investments, a comprehensive scientific substantiation of the feasibility of investing in the development of such basic elements of infrastructures as waste management systems in small settlements is necessary. All this makes it particularly important to develop methodological foundations for the formation, forecasting and evaluation of the ecological and economic efficiency of specialized technical support for such systems.

Analysis of the research and publications. The main general principles of the system-dynamic paradigm of simulation modeling were developed by J. Forrester, D. and D. Meadowes, W. Berens, M. Goodman, J. Randers, J. Stermann and others [4].

Currently the mathematical tools for economic modeling of various technological processes (including waste management systems management systems) and various models of anthropogenic impact assessment on the environment are sufficiently developed [5]. Modern methodological developments in this field can be divided into the following main groups, such as:

– highly specialized research methods – systems for estimating and forecasting the efficiency of technological processes of handling individual types or fractions of waste. (Such as well-known studies on ecological and economic assessment of utilization of rubber-technical waste in secondary raw materials [6], optimization of biofuel production systems [7] and prediction of biogas output and solid waste landfill temperature based on mathematical modeling) [8];

– general methodological recommendations – models of optimized systems of work with waste in the conditions of separate settlements. (Such as developed within the framework of the "Development of the Model and Technologies of Logistics of the Communal Waste Transport" project, the MSW utilization management scheme for the city of Nish (Republic of Serbia) [9], the specialized solid waste utilization infrastructure modeling complex in Florida (USA) [10], and a study on optimal deployment of receiving systems and processing of secondary raw materials) [5, 11];

– research models – methods and devices that in practice simulate the technological physic-chemical processes characteristic of various stages of waste management with a view to their study. (Such as an installation for studying the air migration of waste chemicals in the simulation of natural ultraviolet irradiation) [12].

However, due to the complexity and too deep profile (economic or environmental) specificity, the overwhelming majority of known simulation models for forecasting and evaluating the technological processes of the waste management system require the user to have substantial specialized training, applied knowledge necessary for effective solving of practical tasks. This greatly reduces the efficiency of the implementation of mathematical models for the development of scientific substantiation of specialized systems.

At the same time, all the existing methods of modeling of the ecological and economic effect of technological processes of equipment do not take into account the factor of dynamics of innovation development and modernization of mechanisms. This leads to a narrowing of the range of accounted risks for investment capital and a decrease in the reliability of long-term forecasting. As a result, such additional methodological tools as the mathematical models of optimal innovation development and investment in production systems are known today [13]. This complicates the design work and significantly reduces the average speed of execution of the settlement and analytical parts of the process of forecasting environmental and economic efficiency.

The important issue for complex modeling of the effective waste management systems is to take into account the specificity of the priority of the development of a specific locality. But today known methods of forecasting the effectiveness of the development of small ecologically efficient settlements [12] are generalizable, reflecting only the economic profitability of the settlement. Due to the over-general approach to the evaluation of a complex project and the recognition of secondary essential characteristics and properties of service subsystems of an alternative small settlement, similar applied and auxiliary studies do not provide sufficient information for using simulation results in the process of designing the optimal infrastructure for small towns, including the waste management system.

Setting up the research tasks. The purpose of the work is to develop a convenient methodological tool for estimating and forecasting economic profitability and environmental impact of technical support (equipment) for a waste management system at the initial stage of designing or improving infrastructures of small settlements for the rapid, scientifically substantiated adjustment of the composition of specialized technological lines.

The urgency of the work is the acute necessity of increasing the ecological safety, development and modernization of the technical support of the waste management system in the conditions of various forms of small settlements due to the excessive accumulation of various non-conventional materials.

The novelty of this paper is to propose new basic equations of the mathematical model of index prediction of complex ecological efficiency and comparative analysis of long-term exploitation of various modifications of technological units (equipment for collection, transportation, sorting of storage and processing of non-standard materials) with the possibility of increasing the ecological safety of handling systems waste in the process of environmentally efficient modernization of settlements. The obligatory indicator of the quality of the model is taking into account the change of safety parameters of the branch technical system, in this work – the environmental parameters [14].

Material presentation and results. On the basis of the analysis of the function and the main disadvantages of known systems of mathematical expressions [12], the basic provisions of the criteria for constructing a mathematical model of the predicted efficiency of the technical support of this service subsystem are formed.

The main provisions are the complexity of the set of features of the research object. The model is formed with the involvement of the maximum number of parameters characterizing the object being studied. Among the quality scores is a safety parameter for a branch technical system, in this design, environmental parameters

An important indicator of the study is the dynamism of the values of the characteristics of the model. The model introduces features of the object, the values of which can be adjusted in the process of long-term forecasting of the development of a settlement under the influence of factors of dynamic changes in its infrastructure.

Additionally one of the main requirements for the study is the universality of the method – the possibility of using a mathematical model for predicting the ecological and economic efficiency of the operation of various equipment without the need for significant change in the modeling system.

In developing of the modeling method, the following requirements were taken into account:

– practicality of results (the possibility of using simulation results to correct the formation of an ecologically efficient technosphere);

– simplicity of the model (availability of the model for the work of specialists without additional training).

These provisions form the basis for the formation of an optimal mathematical tool for forecasting the specified practical purpose.

The object of the study is the specialized technical support for waste management systems. The choice of the object (for example, the model of aggregate for grinding solid waste) is based on the appropriateness of the appointment of a well-known branch equipment to the technological needs of the system of handling non-conforming materials, using open sources of information and (or) through a laboratory study of technical samples (aggregates, technological lines, etc.).

The subject of the study is the impact on the environment and the economic profitability of a technical solution (device or system of devices) known from the state of the art and aimed at working with non-conforming materials (their collection, transportation, sorting, recovery or utilization).

Thus, the task of simulation mathematical modeling is to carry out long-term forecasting of the complex efficiency of using different types of technical support (models, types, etc.) in order to optimize the selection of equipment for waste management in the conditions of technologically developed settlements. Taking into account the formulated provisions, a mathematical model of index prediction of ecological and economic efficiency of equipment in the field of waste management in conditions of ecologically efficient modernization of small settlements is proposed.

In calculating the average annual ecological and economic effect of branch equipment, which provides optimized processes for handling industrial waste in the territory of an alternative settlement, it is proposed to use two main subgroups of the initial signs of the modeling object – units of equipment:

No. 1 Environmentally significant subgroup (a set of basic parameters of the 1st unit of the predicted equipment, characterizing its averaged baseline negative impact on the natural environment);

No. 2 Economically significant subgroup (set of basic parameters of the 1st unit of the predicted equipment, characterizing the cash flows generated during its operation and forming the average economic effect).

Averaged performance indicators in the simulation process are proposed to be expressed in the effect on the quantitative unit (kg. or t.) processed (transported, processed or destroyed nonconventional materials).

As ecologically significant features of equipment, by eliminating secondary factors, the following main indicators of the influence of technogenic equipment on the environment are selected and proposed for use: emission of pollutants into the atmosphere and discharges of pollutants into the hydrosphere from the unit of equipment. An economically significant subgroup is basically based on the revenue and cost characteristics of the operation of the unit of the intended equipment.

For the scientific substantiation of the selection of specialized equipment for the purpose of forming the technical support of waste management systems in a small settlement, it is proposed to use the following mathematical model of environmental and economic efficiency (Formula 1) [15]:

$$\left.\begin{array}{l} \mathbf{X1} = (X4 + X5) \cdot h1 \cdot h2^{365d} / h3 \\ \quad X6 = (F1 - F2) / h2^{1095d} \\ \mathbf{X2} = (X6 + X7) \cdot h1 \cdot h2^{365d.} / h3 \\ \mathbf{X3} = (Z1 + Z2 + Z3 + Z4) \cdot h1 \cdot h2^{365d.} / h3 \end{array}\right\} \quad (1)$$

where: **X1 –** index of ecological effect (coefficient of pollutant substances per ton of recycled waste / amount of unit equipment per year), (log index);

X2 – index of economic effect (log index);

X3 – index of the technical and economic effect, (log index);

X4 – release of pollutant substances in the atmospheric airborne equipment existing equipment (g/hour);

X5 – dumping of contaminant substances in the hydrosphere unite quipment, which index (g/hour.);

X6 – hourly Profit Unit Equipment that Induce (UAH/hour);

X7 – the sum of the market price of functions the production of equipment is indexed (based on the value of the work of the mono-functional equipment, which generates each function of the unit equipment) **-** commercial cost of services rendered to order (UAH/hour.);

h1 – number of operating units of equipment that index;

$h2^{365d}$ – number of hours of operation of the unit of equipment, which is indexed in a year (hour/year);

$h2^{1095d}$ – number of hours of unit operation of the indexing equipment in the constant period (3 years), (hour/year);

h3 – the amount of treated waste by the total number of units of equipment that index (t/year.);
F1 – cash flow from the operation of the unit equipment, which is indistinguishable, in a constant period – 3 years (direct profit from realization of products of processing waste) (UAH/year);
F2 – prime cost (the volume of the purchase) 1 unit equipment that indicate (for the first year of forecasting) (in subsequent years – the cost of enterprises, with the renovation of the technology park, or value 0, at the expense cost) (UAH/year);
Z1 – pay for personnel necessary for the operation of the unit of equipment that index (UAH/hour);
Z2 – the cost of the area occupied by the unit of equipment that indexes (based on the average region cost of renting 1 m^2 of industrial sites and taking into account the dimensions of the equipment unit), (UAH/hour);
Z3 – the cost of energy consumed when the unit of equipment is indexing (UAH/hour);
Z4 – cost of elimination of predicted problems and maintenance of unit of equipment that index, in the period of 1 year (per hour of operation of a unit of equipment) (UAH/ hour).

The values of the indicators X4 and X5 are selected taking into account the ratio of the degree of danger of pollutants emitted when working counterparts analogues of the necessary equipment that is indexed. In the case of significant differences in the total composition of pollutants that are formed when working on technical analogues, in view of the simulation model of the proposed method, take into account the quantitative indicators of individual pollutants, relatively close to the degree of danger for humans and the environment.

The considered formulas of the model (1) are basic and may contain additional values. In mathematical expressions, the following (taken by the minor in this variation of the model), the significant features of equipment, such as:

– water consumption (quantity of water required for the implementation of the technological process);

– noise level (vibration) when operating equipment;

– traumatic work of equipment (coefficient of risk of occupational injury by workers, etc.)

Ecologically significant signs of a primary nature can be replaced by secondary ones (in the absence of values of X4 or X5).

The model can be transformed into a system of models, with the introduction of additional restrictions on the specificity of its operation.

The choice of the research object and the collection of the source data about the object of forecasting is carried out using open sources of information and (or) by means of laboratory examination of technical samples (aggregates, technological lines, etc.).

In order to take risks into account and increase the realism of index modeling of the ecological and economic effect of equipment in the field of waste management, the basic indexes of annual indexation should be calculated multiple times. This creates the basis for simulating a longer period of operation of index able equipment, taking into account the correction of the following values:
h1 – (correction on the background of predicted dynamics of waste formation taking into account the production capacity of the unit of indexing equipment);
$h2^{365d}$ – (correction against background of predicted dynamics h1 and h3);
h3 – (correction against the background of projected dynamics of development of the industrial sector of the settlement);
Z1 – (correction against the background of the projected dynamics of the minimum wage in the region);
Z3 – (correction on the background of projected dynamics of the cost of energy resources in the region);
X2 – (correction against the background of projected dynamics of the cost of renting 1 m^2 of industrial sites in the region);
X6 – (correction against the background of the end of the projected period of self-sustainment of the units of the initial composition of the thematic park and the commissioning of additional units of equipment or reduction of the number of previously operated).

When introducing into the model additional signs of the investigated object, the list of corrected values can be expanded.

Visualization of annual modeling results (indexes X1, X2, X3) as a graphical representation of data, allowing to quickly evaluate the ratio of several values, makes it possible to correct the technical parameters of the technical equipment at a certain stage of the projected period in order to increase the further ecological and economic efficiency of the operation of specialized equipment without the need for a practical experiment. Through visualized analysis, it is possible to quickly substantiate the need for correction of the number of units of equipment, their capacity, number of hours of work, etc., in order to increase the environmental safety and economic profitability of using one or another technical support. This is done by improving the efficiency of branch technical system safety with the consideration of its safety parameters per recycled waste (in tones / year).

There are examples of both manual and automated calculations. However, because the inclusion in the article of a numerical example will require the description of the "legend" for correcting the values for several objects of the study by years during the forecasted period of justifying the demonstration dynamics of the annual index values (and this is several pages of text + diagrams), it was decided to allocate calculations in a separate publication, so as not to overload this article. Now the preparation of a test version of a specialized computer program for the automated calculation of environmental efficiency indexes is being completed according to the model described in the article. After this, there will be published examples of calculations performed with the use of own software. After testing, registration of copyrights and registration of the act of program implementation, 2-3 more publications with calculations are planned.

The duration of the projected period (for example, t = 10 years is accepted conditionally and can be adjusted depending on the modeling tasks when designing a specific project of an eco-efficient municipality.

After calculating the main averaged indices for the forecast period (as an example, 10 years), it is necessary to calculate their average values, which are convenient for further comparative analysis of the efficiency of equipment. For this purpose, the consolidated indices of ecologically and economically meaningful subgroups are formed by the characteristics of the investigated object (equipment) according to the following formulas 2-3:

$$\mathbf{Y1} = \sum X1 / t \tag{2}$$

$$\mathbf{Y2} = ((\sum X2 - \sum X3) - \%W) / t \tag{3}$$

where: **Y1** – the final index of the ecological effect (average value of the equipment's environmental impact on 1 ton of treated waste in the forecast period), (log index);

Y2 – the final index of the economic effect (average profit from equipment per year per 1 ton of treated waste in the forecast period), (log index);

ΣX1 is the sum of annual indexes X1 for the forecast period;

ΣX2 is the sum of annual indexes X2 for the forecast period;

ΣX3 is the sum of annual indexes X3 for the forecast period;

%W – forecasted percentage of inflation in the region in the forecast period (%);

t – duration of the projected period (number of years).

The resulting values of the final indices are summarized in the summary table for comparative analysis with the indices computed for equipment similar to the indexing (similar to the intended purpose), and the choice of types (or modifications) of the equipment most commonly used for exploitation in small settlements, based on priorities of their development (Table 1).

Table 1

Table of comparative analysis of the final indices "Y1" and "Y2" (not filled)

Title of the equipment	**Index Y1** (log index)	↓ *	**Index Y2** (log index)	↑ **
Equipment "A"				
Equipment "B"				

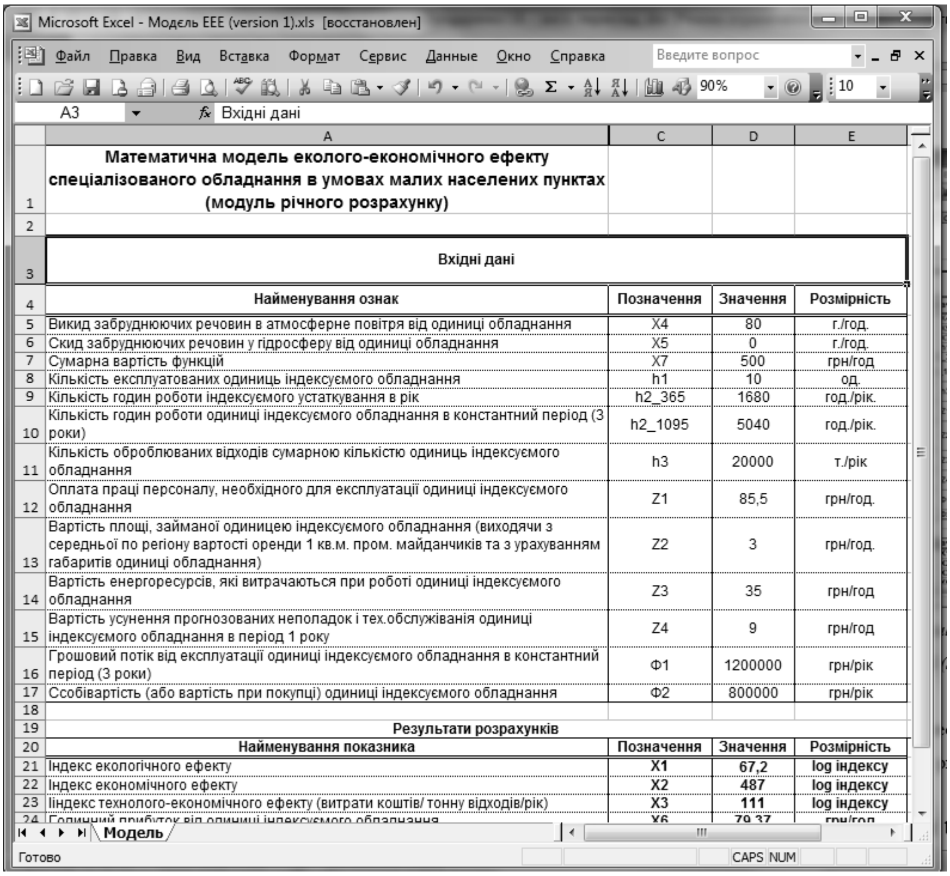
, * ↓ / ↑ - *priory tasks of measurement of the index (increasing/decreasing)*

In order to increase the effectiveness of the results of the forecasting of ecological and economic processes in the proposed mathematical model, it is expedient to introduce commonly accepted mathematical tools of the procedure for obtaining a problem assessment based on the opinion of experts (experts) for further decision making (selection) based on expert evaluation. Subjective experience of using different equipment in the field of agriculture in its classical form may be the basis for the formation of optimal technical support for waste management system in the territory of a modernized small settlement.

Taking into account the specifics of the possible composition of the technological complex of this area (the heterogeneity of the purpose of this or that equipment is required), the methodology of the expert evaluation is determined. In the form of the implementation of this study, the best collective assessments are based on the use of the collective opinion of experts, which can be based on the well-known method of the vectors of preferences T. Saati [16] (expert analysis of the whole set of alternative options, which allows you to choose the most desired). The results of peer review as one of the main criteria for selecting specialized technical support can increase the reliability of simulation.

The process of calculating the mathematical model of index prediction of ecological and economic efficiency of equipment in the field of waste management in conditions of environmentally efficient small settlements can be simplified. Simplification is realized through appropriate software that automates and accelerates work with the model.

The basic principles of the considered mathematical model are implemented in the computer program for working with spreadsheets "Microsoft Office Excel" (Figure 1).



Математична модель еколого-економічного ефекту спеціалізованого обладнання в умовах малих населених пунктах (модуль річного розрахунку)

Вхідні дані

Найменування ознак	Позначення	Значення	Розмірність
Викид забруднюючих речовин в атмосферне повітря від одиниці обладнання	X4	80	г./год.
Скид забруднюючих речовин у гідросферу від одиниці обладнання	X5	0	г./год.
Сумарна вартість функцій	X7	500	грн/год
Кількість експлуатованих одиниць індексуємого обладнання	h1	10	од.
Кількість годин роботи індексуємого устаткування в рік	h2_365	1680	год./рік.
Кількість годин роботи одиниці індексуємого обладнання в константний період (3 роки)	h2_1095	5040	год./рік.
Кількість оброблюваних відходів сумарною кількістю одиниць індексуємого обладнання	h3	20000	т./рік
Оплата праці персоналу, необхідного для експлуатації одиниці індексуємого обладнання	Z1	85,5	грн/год.
Вартість площі, займаної одиницею індексуємого обладнання (виходячи з середньої по регіону вартості оренди 1 кв.м. пром. майданчиків та з урахуванням габаритів одиниці обладнання)	Z2	3	грн/год.
Вартість енергоресурсів, які витрачаються при роботі одиниці індексуємого обладнання	Z3	35	грн/год
Вартість усунення прогнозованих неполадок і тех.обслужівания одиниці індексуємого обладнання в період 1 року	Z4	9	грн/год
Грошовий потік від експлуатації одиниці індексуємого обладнання в константний період (3 роки)	Ф1	1200000	грн/рік
Ссобівартість (або вартість при покупці) одиниці індексуємого обладнання	Ф2	800000	грн/рік

Результати розрахунків

Найменування показника	Позначення	Значення	Розмірність
Індекс екологічного ефекту	**X1**	**67,2**	**log індексу**
Індекс економічного ефекту	**X2**	**487**	**log індексу**
Ііндекс технолого-економічного ефекту (витрати коштів/ тонну відходів/рік)	**X3**	**111**	**log індексу**
Годинний прибуток від одиниці індексуємого обладнання	X6	79,37	грн/год

***Figure 1** – Form of the automated version of the mathematical model of prediction of efficiency in the program Microsoft Office Excel (screenshot)*

Using shown in pic. 1 automated forms of the model reduces the duration of calculating the values of annual indexes X1, X2, X3 to 1 minute (in the presence of input data) and does not require special training from the user.

The efficiency of the model can also be increased by jointly analyzing the results of computing its final indices and the results of specialized computer programs that simulate the spread of pollutants in the environment. Such an additional tool may be known program EOL 2000 [17], which implements the methodology for calculating concentrations in the air of harmful substances, "OND-86" to assess the impact of emissions of harmful impurities into the atmosphere from sources at the design stage and existing enterprises (reconstructed) on the surface layer of air. According to the process of modeling equipment with a complex operation algorithm and with the involvement of a large number of service personnel, it is appropriate to combine the work of the index prediction model with known mathematical tools for modeling the probability of life safety in production [14, 18], which will increase the level of awareness and objectivity of the final decision regarding the ecological and economic efficiency of use one or another specialized technical support of a waste management system under conditions of various forms of small settlements points.

Conclusions. The proposed system of mathematical expressions allows to predict and evaluate the complex ecological-economic effect from the long-term exploitation of the expected technical support of the waste management system and to adjust the composition of the required industry techno sphere, using the results of mathematical modeling at the initial stage of engineering design of small settlements with the possibility of significantly increasing their ecological security. It reduces the risks and volumes of exposure to non-conforming materials to the environment and provides a comprehensive scientific basis for the economic feasibility of investing in the modernization of the material and technical base in the projected period in the practical implementation of the improvement of existing small cities of the traditional urban type and in the process of creating other modern forms of ecologically balanced infrastructure of human living space.

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