Optimizing the use of industrial wastes for sustainable spatial development within the framework of the eco-friendly concept

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Abstract. Addressing the issue of using wastes as secondary raw materials allows solving the problems of greening the environment, ensures sustainable development of territories and, at the same time, increases the potential of construction companies, contributes to reducing the area of ash dumps from heat and electricity production plants (HEPPs) and state district electricity production plants (SDEPPs). In view of this, the study proposes an optimized scheme of recycling secondary raw materials, which implies defining the effective radii of these products transportation and creating a demand between the manufacturing and prospective consumption of wastes from HEPPs and SDEPPs. Such a scheme solves the problems associated with the reduction of the area of ash dumps of HEPPs and SDEPPs; tactical level of development of the construction sector due to expanding the range of building materials; improvement of the territorial distribution of construction enterprises; and enhancement of the quality of construction and installation work. At the operating level, it implies using innovative resource-saving design, product and material technologies; creating an efficient structure of material resources of the construction sector; reducing cost of construction and installation work, etc.

To address the problem of using wastes from HEPPs and SDEPPs, the paper analyzes a model that accounts for the optimal capacity and specialization of the enterprise using secondary raw materials. The model provides for determining what types of materials and in what quantity should be produced by the enterprises included in the optimal plan, creating a rational scheme of recycling secondary raw materials that includes establishing the optimal radius of transportation. Moreover, with the help of the model, transport coefficients are obtained, and dependences showing the relationship between the transport costs and the optimal transportation distance for each type of construction product are composed. As a result of the calculations, optimized perspective schemes of recycling wastes from HEPPs and SDEPPs are created. The schemes involve defining the effective transportation radius, which is calculated as a weighted average volume of the freight transported. Furthermore, due to the usage of secondary raw materials, the balance of manufacturing and prospective consumption of the products considered is obtained.

Key words: ecosystem, greening of production, HEPPs and SDEPPs wastes, secondary raw materials, construction enterprises, linear model, matrix model, eco-friendly concept.

Оптимізація використання відходів промисловості для стійкості розвитку територій у рамках eco-friendly концепції

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Анотація. Розв'язання питання використання відходів як вторинної сировини дозволяє вирішувати завдання з екологізації довкілля, забезпечує стійкий розвиток території та, одночасно, підвищує потенціал підприємств будівельного комплексу, сприяє зменшенню площі відвалів золи теплоелектростанцій (ТЕС) і державних районних електростанцій (ДРЕС). У зв'язку з цим запропоновано оптимізовану схему виробництва та споживання вторинних сировинних ресурсів, яка визначає ефективні радіуси їх перевезення та створює попит між виробництвом і перспективним споживанням відходів виробництва ТЕС і ДРЕС. Така схема вирішує завдання зі зменшення площі відвалів золи ТЕС і ДРЕС, тактичного рівня розвитку будівельної галузі завдяки розширенню номенклатури будівельних матеріалів, вдосконалення територіального розміщення будівельних підприємств, підвищення якості будівельних і монтажних робіт. Оперативний рівень розвитку передбачає використання інноваційних ресурсозаощаджувальних конструкцій, технологій виробів і матеріалів, створення прогресивної структури матеріальних ресурсів будівництва, зниження собівартості будівельно-монтажних робіт та інше. Для вирішення питання використання відходів ТЕС і ДРЕС розглянуто модель, яка враховує оптимальну потужність підприємства, спеціалізацію підприємства, що використовує вторинні сировинні ресурси, тобто визначає, які види матеріалів і в якій кількості повинні виготовлятися підприємствами, що війшли в оптимальний план, раціональну схему транспортування матеріалів і встановлення
Introduction.

Nowadays, environmental problems arising in the ecosystem are of the greatest concern. Over the past years, people have begun to pay more attention to the importance of environmental problems at almost all levels, which is reflected in the United Nations Environment Programme (UNEP), namely: the destruction of the environment threatens the existence of life on the planet, the concept of sustainable development is the basis of the mankind future. In this regard, a necessary condition for solving this problem is respect for the environment and awareness of the consequences of ecosystem destruction. In recent years, the trend towards environmental friendliness, respect for the environment has been gaining momentum and becoming very relevant, therefore, presently, it is very popular and appropriate to use the eco-friendly («safe for the environment») concept. It aims to minimize and eliminate the damage to nature from human activities and can be manifested in technological advances.

Ecological and geographical studies of ecosystems are combined within the scope of geoeconomics that helps to solve the environmental problems. In order for environmental services to make an optimally correct management decision, they must have both environmental, geological and physical, geographical and technological information, which can be obtained in the course of systematic studies aimed at assessing and analyzing the state of the main components of the environment and natural complexes before they were affected by human activities. The negative anthropogenic impact suggests the need for special environmental measures. The most important tasks of environmental and economic research should be to harmonize business interests and environmental enhancement, which can be achieved through a management system focused not only on improving but also on greening industrial production. In the 21st century, experts and scientists from many countries of the world are showing increased interest and concern in the problems of environmental safety. Greening the economic development of countries is considered in works of many authors, including O. Prokopenko (Prokopenko, 2014), D. Bek (Bek, et al., 2017), D. Gibbs (Gibbs, & O’Neill, 2017), A. Heshmati (Heshmati, 2017). I. Feshchur (Feshchur, 2019), A. Voytsikhovska (Voytsikhovska et al., 2019), M. Ponomareva (Ponomareva, 2011), M. Tereshina (Tereshina, & Fedorova, 2012), O. Sushchenko (Sushchenko et al., 2019), A. Petrovska (Petrovska, 2019), I. Doronina (Doronina, 2020). Under modern economic conditions, environmental problems and their awareness by business entities are the impetus to reconsider the chain ‘production-consumption-utilization’ in view of the trend of environmental consciousness. Not only in Ukraine but also in many countries of the world, the environmental threat poses a danger to all living things due to the predominant development of the fuel and energy sector, the imperfection of the legal framework regarding environmental activities, the low environmental culture of people, and the limited use of environmentally friendly technologies as the key options of eco-modernization.

The strengthening of environmental requirements for modern production systems predetermines the expansion of using secondary raw materials including various types of wastes. In developed countries, such wastes are called a strategic product, since they are used in large quantities in the construction industry (as additives to concrete, cement, mortar and in the manufacturing of bricks and silicate products) and in road construction. World experience shows that the cost of the introduction of energy-saving measures is 3–5 times less than the cost of extraction and production of primary energy sources equivalent in the volume to those saved. According to the European Business Association, the level of ash and slag utilization in Ukraine does not exceed 8,3–11,7 %. This situation is fundamentally different from the practice of European Union countries. In the EU, 45–50 % of ash and slag materials are disposed off annually (Kibovska, 2021).

It should be noted that an important feature of the secondary raw materials market as a whole (on average by all its types) is a significant imbalance between supply and demand. In particular, the supply, which should be understood as all wastes generated annually and already accumulated earlier, significantly exceeds the demand for them. On the one hand, this is due to the fact that, under market conditions, the generation of wastes, in contrast to the production of goods, is not the goal of production, but just a consequence of the imperfection of the modern technological base. On the other hand, the current economic situation in Ukraine cannot yet ensure the utilization of all wastes.
generated as a result of economic activities, which exerts a negative impact on its ecosystem. However, the building materials industry employs a fairly wide range of materials produced from utility wastes. The best-known and popular building materials made of industrial by-products are slag concrete, ash concrete, fiberboard, tar roofing paper, gypsum fiber boards, fly ash cements, plastic containers for small architectural forms, textile wastes used in the production of nonwoven covering materials, etc. The main feature of using wastes in the production of building materials is addressing the environmental issue of halting land degradation by means of decreasing the area occupied by waste dumps of HEPPs and SDEPPs and also by employing an economic lever that implies a reduction in the cost of the final construction product, which, with large volumes of construction, plays an important role in the pricing and increasing demand for final products.

Thus, modern technologies allow an effective use of the existing construction wastes for the production of high-quality building materials and reduce the consumption of materials in the sector, ensuring a significant economic and environmental benefit for business entities. The use of wastes as secondary raw materials facilitates solving the strategic task of harmonizing business interests and environmental enhancement and ensures an increase in the capability of construction enterprises by improving the efficiency of their activities in the context of the tactical and operational levels of management. In particular, at the tactical level, the expansion of building materials range is ensured, the territorial distribution of construction enterprises as well as the quality of construction and installation work are improved.

The operating level involves employing innovative resource-saving design, product and material technologies; creating an efficient structure of building material resources; reducing cost of construction and installation work, etc. Presently, the state of enterprises in the construction sector is characterized by high consumption of resources, fuel, and electricity, which is the main reason for the constant growth in prices for building materials and the final cost of construction. According to the Ministry of Finance of Ukraine, in recent years there has been a rapid rise in prices for building materials including primary products. The construction output price index has doubled compared to 2015 (Fig. 1). At the same time, the rates for freight transportation are also growing (Fig. 2).

This situation confirms the opinion about the need to find ways to minimize costs, one of which being the creation of an optimized scheme of using and transporting raw materials to ensure sustainable spatial development. Moreover, the search for ways to utilize secondary resources poses new challenges for the construction sector, with the focus on the development of the building materials industry, advancement of resource-efficient technologies and modernization of enterprises involved in the construction activity.

**Methodology**

To solve the problem of integrated use of raw materials and wastes from various industries, it
is necessary to create an optimized scheme of transportation considering for the geographical location. For this purpose, we analyzed the existing techniques presented in the works of O. Sokolov (Sokolov et al., 2020), V. Donenko (Donenko, 2011), M. Pedan (Pedan, 1977), O. Kostiuk (Kostiuk, 2006), T. Andreeva (Andreeva & Butenko, 2011), M. Pirigov (Pirigov, Sushok, & Zavalko, 1987). I. Balandin considers a model for assessing resource flows, with regard to the volume of construction resources and demand for them, as well as the price for similar resources (Balandina, 2013). As a rule, the models developed by other authors are intended for solving single-product tasks. While multi-product tasks are either limited to a single industry or imply a global approach that does not correspond to the goal set in this paper – to create an optimized scheme of recycling secondary raw materials by construction enterprises.

To solve the problem of using the raw material base, it is proposed to consider a mathematical programming model, which has the following form (Andreeva, 2014):

\[
Z(x, y) = \sum_{i,j} (C_{ij} + B_{ij} X_{ij}) \rightarrow \min
\]

\[
\sum_j X_{ij} = D_j \quad (j = 1, 2, ..., m)
\]

\[
\sum_i X_{ij} \leq A_i \quad (i = 1, 2, ..., n)
\]

\[
X_{ij} \geq 0; Y_{ij} \geq 0 \quad \sum_{j} Y_{ij} = Q_{ij} \quad (i = 1, 2, ..., n)
\]

where: \( X_{ij} \) is the volume of the \( i \)th industrial waste (incl. associated rocks) used in the manufacturing; \( Y_{ij} \) is the volume of the main raw material of the \( j \)th type of the \( i \)th deposit; \( X_{ij} \) is the volume of transportation of the \( j \)th industrial waste (incl. associated rocks) from the \( j \)th deposit to the \( k \)th consumer; \( Y_{ij} \) is the volume of transportation of the \( j \)th raw material from the \( i \)th deposit to the \( k \)th consumer; \( B_{ij} \) is the overall demand for the \( j \)th raw material; \( B_{ij} \) is the demand for the \( j \)th raw material of the \( k \)th consumer; \( B_{ij} \) is the size of the \( j \)th deposit of the \( k \)th deposit; \( C_{ij} \) is the cost of associated rocks of the \( j \)th industrial waste; \( D_{ij} \) is the cost of associated rocks of the \( j \)th industrial waste recovered at the \( k \)th deposit; \( K_{ij} \) is the relative capital investment in the manufacturing of the \( j \)th raw material at the \( k \)th deposit; \( Q_{ij} \) is the annual output of the \( j \)th industrial waste (incl. associated rocks) at the \( j \)th deposit; \( C_{ij} \) is the cost of the \( j \)th industrial waste (incl. associated rocks) at the \( j \)th deposit; \( K_{ij} \) is the relative capital investment in the recovery of the \( j \)th raw material at the \( k \)th deposit, per unit; \( T_{ij} \) is the cost of transportation of the \( j \)th industrial waste from the \( j \)th deposit to the \( k \)th consumer, per unit; \( T_{ij} \) is the cost of transportation of the \( j \)th raw material from the \( j \)th deposit to the \( k \)th consumer; \( E \) is the normative coefficient of investment efficiency.

The proposed model allows considering the problem of utilization of raw materials, with regard to the factors of their transportation and location of the production facilities. Moreover, it can be used for various types of secondary sources, since it takes into consideration both raw materials inventory and consumer demand. The disadvantage of the model proposed is that it does not account for the qualitative characteristics of some types of waste. However, depending on their chemical and technological properties, they can be used in different materials. Also, the model is cumbersome and time consuming. Therefore, a step-by-step solving of the problem of this type is proposed.

**Stage One.** At this stage, the problem of distributing secondary raw materials including different types of industrial wastes (by-products of power generation, metallurgy, mining, etc.) is fulfilled. The task is formulated as follows: it is necessary to determine the value of the variable \( X_{ij} \), which minimizes the linear function represented as the total costs:

\[
L_i = \sum_{j=1}^{m} \sum_{j=1}^{n} 3_{rij} X_{ij} \rightarrow \min
\]

with the following constraints:

\[
\sum_{j=1}^{m} X_{ij} \leq D_j \quad (j = 1, 2, ..., m)
\]

\[
\sum_{i=1}^{n} X_{ij} \leq A_i \quad (i = 1, 2, ..., n)
\]

\[
X_{ij} \geq 0 \quad (i = 1, 2, ..., n)
\]

where: \( X_{ij} \) is the amount of the \( i \)th raw material required for manufacturing the \( j \)th building material; \( 3_{rij} \) is the total costs of manufacturing the \( j \)th building material from the \( i \)th raw material; \( D_j \) is the demand for the \( j \)th building material in the region under the study; \( A_i \) is the maximum output of the \( i \)th raw material; \( j \) is the number of the building material (\( j = 1, 2, ..., n \)); \( i \) is the number of the raw material \( i = 1, 2, 3, ..., m \).

The formulated problem belongs to linear programming problems. Its solution with consideration for geographical location is possible upon the following:
– calculation of costs associated with the processing of certain types of raw materials;
– converting natural units of measurement of various resource types into common ones;
– determination of coefficients for converting all types of resources considered to a single unit of measurement characterizing their main consumer properties.

The choice of interchangeable raw materials, with regard to their quantity and the justification of their processing cost is made on the basis of technical and economic information (production, reporting, experimental data).

The consumer properties of interchangeable materials are accounted for with the help of the conversion factor $k_i$. This makes it possible to aggregate various building materials according to consumer criteria and consider the possibilities of meeting the demand due to employing both natural raw materials and industrial wastes.

The conversion factor is closely connected with determining the indicator $\alpha$ – consumption of $i^{th}$ resources (wastes) per unit of the $j^{th}$ building material and can be calculated by the formula:

$$k_i = \frac{\gamma_i \sum a_j}{n},$$

where: $\gamma$ is the share of the raw material into which all the rest $i^{th}$ resources considered are converted; $\gamma_i$ is the share of the $i^{th}$ raw material for manufacturing the $j^{th}$ material; $a$ is the consumption of the $i^{th}$ raw material for manufacturing the $j^{th}$ building material.

The proposed first stage involves implementing a problem of optimal planning of the output volume of one or several types of products under conditions when the capacity of suppliers is known, and it is planned to increase the production (Volontir et al., 2020), but it is adjusted with regard to the problem under the study. The matrix model of the problem (Fig. 3), except for the main variables, includes a number of additional ones, which are conventionally introduced into constraints 8, 9 and are a part of the objective function 7.

$$k_i = \frac{\gamma_i \sum a_j}{n},$$

where: $\gamma$ is the share of the raw material into which all the rest $i^{th}$ resources considered are converted; $\gamma_i$ is the share of the $i^{th}$ raw material for manufacturing the $j^{th}$ material; $a$ is the consumption of the $i^{th}$ raw material for manufacturing the $j^{th}$ building material.

The calculation of the matrix will allow obtaining data characterizing the rational consumption of different types of resources for the prospective production of the material $Q_{ij}$, in common units. To convert the obtained values into natural units, the formula for calculating the conversion factor $k_i$, (11) is used. The proposed methodology for solving the problem is aimed at building a general structure of waste utilization and can be presented in the form of a block diagram (Fig. 4), which makes it possible to visualize the sequence of steps.
Fig. 4. The sequence of solving the multi-sector problem of building the general structure of using secondary raw materials

Stage Two. This stage implies determining the maximum processing capacity for each type of wastes, with regard to their quality characteristics and demand in the region under consideration. In this case, at determining the maximum capacity of each enterprise engaged in processing secondary raw materials into building materials the value of the total costs will be minimized. The mathematical model will have the form:

\[ L_2 = \sum_{f=1}^{F} \sum_{\varphi=1}^{b} \sum_{j=1}^{n} c_{\varphi j} X_{\varphi j}^f \rightarrow \text{min}, \]  

(12)

With the following constraints:

\[ \sum_{j=1}^{n} X_{\varphi j}^f = B_{\varphi}^f (\varphi = 1,2,...,b), \]  

(13)

\[ \sum_{f=1}^{F} X_{\varphi j}^f = Q_j^f (j = 1,2,...,n), \]  

(14)

\[ X_{\varphi j}^f \geq 0 \]  

(\( \varphi = 1,2,...,b; j = 1,2,...,n \))  

(\( f = 1,2,...,F \))

where: \( X_{\varphi j}^f \) is the amount of the \( f^{th} \) secondary raw material required for manufacturing the \( j^{th} \) building material; \( B_{\varphi}^f \) is the total costs when using the \( f^{th} \) waste product at the \( \varphi^{th} \) enterprise for manufacturing the \( j^{th} \) building material; \( B_{\varphi}^f \) is the amount of the \( f^{th} \) waste product at the \( \varphi^{th} \) enterprise; \( Q_j^f \) is the amount of the \( f^{th} \) waste product required for manufacturing the \( j^{th} \) building material; \( f \) is the number of the \( f^{th} \) secondary raw material; \( \varphi \) is the number of the enterprise manufacturing building materials from wastes (\( \varphi = 1,2,...,b \)).

Constraints 13 and 14 should be equal and form a closed system, which has the following form:

\[ \sum_{f=1}^{F} \sum_{j=1}^{n} Q_j^f = \sum_{f=1}^{F} \sum_{\varphi=1}^{b} B_{\varphi}^f \]  

(16)

The most rational method for solving the problem is using a closed transport problem, which is confirmed by the closed system (16). A single-product transport model is built for each \( f^{th} \) secondary raw material, its implementation requiring supplementary information on the capacity of enterprises engaged in waste recycling (Fig. 5).
Fig. 5. Matrix model of the problem of building the scheme of recycling secondary raw materials at enterprises (with regard to the quality characteristics)

As a result of solving the problem, we obtain the limiting values of the load of the $\phi^\text{th}$ enterprise at manufacturing the $f^\text{th}$ amount of the $j^\text{th}$ building material but without accounting for the transport costs and competing products from natural raw materials. These factors will be calculated at the third stage of drawing up a comprehensive plan for processing and using secondary raw materials. Stage Three. This stage implies solving the following issues:

- determining the distance from the manufacturer to the consumer;
- calculating the cost of transport per unit of secondary raw materials;
- determining the aggregate costs of manufacturing and supply of materials (matrix coefficients);
- calculating the prospective demand of individual consumers;
- justifying the enterprise’s long-term capacity for the processing of natural raw materials into corresponding building materials.

The tasks addressed at the third stage are also linear programming ones and should be considered as a manufacturing and transport multi-product problem.

$$L_3 = \sum_{\phi=1}^{b+b_{r-1}} \sum_{j=1}^{r} \sum_{\gamma=1}^{n} 3^\phi_{\gamma j} X^\phi_{\gamma j} + \sum_{\phi=1}^{b+b_{r-1}} \sum_{j=1}^{r} \sum_{\gamma=1}^{n} T^\phi_{\gamma j} X^\phi_{\gamma j} \rightarrow \min,$$  \hspace{1cm} (17)

With the constraints:

$$\sum_{j=1}^{n} \sum_{\gamma=1}^{r} X^\phi_{\gamma j} \leq F^\phi_j (j = 1, 2, \ldots, b+\ldots+b_{r-1}),$$  \hspace{1cm} (18)

$$\sum_{\phi=1}^{b+b_{r-1}} X^\phi_{\gamma j} = D^\gamma_j (j = 1, 2, \ldots, r),$$  \hspace{1cm} (19)

$$X^\phi_{\gamma j} \geq 0 (j = 1, 2, \ldots, n; \gamma = 1, 2, \ldots, b+\ldots+b_{r-1}),$$  \hspace{1cm} (20)

where: $X^\phi_{\gamma j}$ is the volume of manufacturing the $j^\text{th}$ building material at the $\phi^\text{th}$ enterprise, demanded by the $\gamma^\text{th}$ consumer; $T^\phi_{\gamma j}$ is the cost of transportation of the $j^\text{th}$ material from the $\phi^\text{th}$ enterprise to the $\gamma^\text{th}$ consumer; $F^\phi_j$ is the capacity of the $\phi^\text{th}$ enterprise for manufacturing the $j^\text{th}$ building material; $D^\gamma_j$ is the demand of the $\gamma^\text{th}$ consumer for the $j^\text{th}$ building material; $\gamma$ is the number of the consumer ($\gamma = 1, 2, \ldots, r$); $\phi$ is the number of the enterprise supplying interchangeable raw materials for manufacturing building materials.

The condition (17) is limited by the existing capacity of the $\phi^\text{th}$ enterprises but allows for their prospective development aimed at satisfying the demand of the consumer for the $j^\text{th}$ building material. The condition (18) is limited by the determined demand $D$ of the $\gamma^\text{th}$ consumer for the $j^\text{th}$ material, and the condition...
(19) considers only positive values of the demand for the distributed product. The task of this stage can be presented in the form of an open transport problem for each \( j^{th} \) building material \((j = 1, 2, \ldots , n)\), which includes addressing a number of additional issues including:

1. determination of the distance from the manufacturer to the consumer;
2. calculation of the costs of transportation per output unit (transport coefficients \( T_{n\phi\gamma} \));
3. determination of the total costs of manufacturing and transportation of materials (matrix coefficients);
4. justification of the enterprise’s long-term capacity for the processing of natural raw materials into building materials under consideration;

\[
T_{n\phi\gamma} = W_{\phi} + V_{\phi} \cdot L_{\phi} \quad (\phi = 1, 2, \ldots, r; \gamma = 1, 2, \ldots, n; j = 1, 2, \ldots, n),
\]

where: \( W_{\phi}, V_{\phi} \) are the correlation coefficients for the \( j^{th} \) building material at transporting it from the \( \phi^{th} \) manufacturer to the \( \gamma^{th} \) consumer.

The obtained formula for each \( j^{th} \) building material considerably facilitates and speeds up the calculation of transport coefficients.

The determination of the aggregate costs, i.e., the final matrix coefficients, is carried out using matrix tables according to the following formula:

\[
3_{n\phi\gamma} + T_{n\phi\gamma} = P_{\phi\gamma} \quad (\phi = 1, 2, \ldots, b + \ldots + b_{r-1}; \gamma = 1, 2, \ldots , r; j = 1, 2, \ldots, n),
\]

As a result of converting the total costs into one indicator, the function \( L_3 \) (Fig. 6) can be presented as follows:

\[
L_3 = \sum_{\phi=1}^{b} \sum_{\gamma=1}^{r} \sum_{j=1}^{n} P_{\phi\gamma} X_{\phi\gamma} \rightarrow \text{min}.
\]

In addition to addressing issues related to the distribution of various building materials, the open transport problem accounting for a conditional consumer allows:

– determining optimal capacity of the enterprise; optimal specialization of the enterprise using secondary raw materials, i.e., establishing the types and quantities of materials to be produced by the enterprises included in the optimal plan;
– creating a rational scheme for transporting materials and establishing the optimal transportation radius.

The work on the elaboration of the optimal option for transporting and processing fly ash or other types of resources involves solving successive tasks, each of which ensuring the fulfillment of the following goals:

– defining general directions for the use of various resources (waste and natural raw materials);
– determining rational volumes of recycling wastes at the enterprise, with regard to their quality characteristics;

5) calculation of the prospective demand of individual consumers.

The determination of the distance and calculation of the transport coefficients is carried out using matrix tables, similar to those considered earlier. However, first, we need to find the values of the matrix coefficients. It is proposed to perform a correlation analysis and calculate the cost of transporting 1 ton of various building materials from the supplier to the consumer.

As a result of changing the analysis data, we obtain straight-line dependences, which have the form:

\[
\text{Results}
\]

The application of the proposed methodology makes it possible to balance the use of each type of resources, including all types of industrial wastes. The calculations made at the first stage resulted in determining the marginal rational costs of various types of resources for the prospective production of materials with their consequent conversion from common units to natural ones. The defined general directions of using various types of resources are the constraints for solving the problems of the following stage. However, they do not present the final result since they are refined at the second and third stages of calculation.
### Fig. 6. The matrix model of the problem of determining the rational volume of manufacturing and distribution of the \( i \)th material

When solving the problems of the second stage, namely, determining the directions of processing secondary raw materials at particular enterprises, the technological conditions, chemical composition of slags and ash are considered, which helps to calculate the quality coefficient. For example, the slags with a high medium activity index are required for production of granulated slag, and, when using fly ash as an additive to cement, ashes obtained from the combustion of high-quality fuel (Lviv-Volyinsk and Donetsk coal) should be used.

To account for all the factors, the decomposition method is employed. It implies filling the matrix cell, into which a certain type of secondary raw materials is to fall, with the maximum negative value (in our case – 9). Matrix coefficients are calculated by the formula:

\[
B_i = C + E_n K,
\]

where: \( B_i \) is the matrix coefficient of the cost of manufacturing the \( i \)th material from secondary raw materials;  
\( C \) is the cost of the \( i \)th product; \( E_n \) is the normative coefficient of investment efficiency, 0.15;  
\( K \) is the investment in manufacturing the building materials.

At filling in the matrix, for the limiting values \( B_1 \) and \( Q_1 \) (13, 14), data on the output of slag and ash and their amount required for manufacturing various types of products are used. The value of \( B_1 \) is obtained using the enterprise’s statistical data, and the limiting value \( Q_1 \) is calculated at the first stage. After filling in the matrix (Fig. 3), we perform the calculations, the results of which make it possible to determine the maximum volume of processing ash-slag wastes. The value obtained will be used as the limiting one to implement the task of the third stage, which implies filling in the matrix (Fig. 5). At this stage, transport coefficients are determined and dependences demonstrating relations between the transport costs and the optimal transport distance for each type of building products are composed (Tabl. 1).
Table 1. Formulas for calculating transport costs per 1 t of freight

<table>
<thead>
<tr>
<th>Product</th>
<th>Calculation formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crushed stone</td>
<td>( T=0.61+0.002l )</td>
</tr>
<tr>
<td>Expanded clay aggregate</td>
<td>( T=0.65+0.003l )</td>
</tr>
<tr>
<td>Lump pumice</td>
<td>( T=0.69+0.005l )</td>
</tr>
<tr>
<td>Cement</td>
<td>( T=0.55+0.002l )</td>
</tr>
<tr>
<td>Ash</td>
<td>( T=0.34+0.008l )</td>
</tr>
<tr>
<td>Granulated slag</td>
<td>( T=0.33+0.002l )</td>
</tr>
<tr>
<td>Sand</td>
<td>( T=0.4+0.002l )</td>
</tr>
</tbody>
</table>

To solve the problem at this stage, the number of matrices built should be equal to that of directions of using secondary raw materials considered by the enterprise.

**Conclusion**

The proposed model allows a comprehensive analysis of the problem of increasing the efficiency of using raw materials with consideration for the transportation and geographical location factors. Moreover, it can be used for various types of secondary resources, since it accounts for the inventory of various types of raw materials and the consumer demand. For the successful implementation of the economic-mathematical model, its step-by-step solution is proposed. As a result of the calculations, we create the optimized perspective schemes of recycling secondary raw materials including the determination of an effective transportation radius, which is calculated as the weighted average volume of freight transportation. Furthermore, we obtain the balance of manufacturing and prospective consumption of products due to using secondary raw materials as of 2020 (Tabl. 2).

Table 2. Balance of manufacturing and prospective consumption of products due to using secondary raw material resources

<table>
<thead>
<tr>
<th>Type of product</th>
<th>Demand, %</th>
<th>blast furnace slag, %</th>
<th>converter slag, %</th>
<th>open-hearth furnace slag and steelmaking slag, %</th>
<th>fly ash, %</th>
<th>crushed stone, %</th>
<th>plain cement, %</th>
<th>mining waste, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>100</td>
<td>62</td>
<td>-</td>
<td>-</td>
<td>28</td>
<td>-</td>
<td>10</td>
<td>-</td>
</tr>
<tr>
<td>Clinker-free binder</td>
<td>100</td>
<td>9</td>
<td>57</td>
<td>-</td>
<td>34</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lightweight aggregates</td>
<td>100</td>
<td>0.15</td>
<td>-</td>
<td>-</td>
<td>2.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Heavy aggregates</td>
<td>100</td>
<td>2.5</td>
<td>-</td>
<td>15</td>
<td>59</td>
<td>-</td>
<td>37</td>
<td>-</td>
</tr>
<tr>
<td>Fillers for asphalt concrete</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

As a result of the calculations, it has been determined that it is expedient to transport slag crushed stone over a distance of up to 145 km, expanded blast furnace slag – up to 269 km, fly-ash aggregate – up to 337 km, fly ash – 50 km, granulated slag – 500 km; while expanded clay aggregate and some other materials are advisable to use at the place of their formation.

It has been established that raw materials for the production of cement can comprise blast furnace slags (62 %), ash from HEPPs and SDEPPs (28 %), and clinker (10 %). Clinker-free binders based on slags (66 %) and fly ash (34 %) are recommended for wide application.

Depending on the consumer demand of construction enterprises and the technological process employed, we can single out enterprises and production facilities located near raw material regions, e.g., those that specialize in the extraction and processing of raw materials. This type of production includes the manufacturing of cement, lime, gypsum. The largest centers for the production of building materials are Kyiv, Kharkiv, Odesa, Dniprop, Kryvyi Rih, Zaporizhzhia, Mariupol. The main factors affecting the operation of construc-
tion enterprises are the territorial concentration of production, availability of building mineral raw materials, labor resources, and transport communications. Manufacturing industries are mainly concentrated in large industrial centers and hubs, settlements with a significant volume of housing and civil construction.

The further development of the building materials industry should be consistent with the state environmental and economic policy, apply tools to stimulate the use of industrial wastes, take into consideration the geographical location of production wastes and construction enterprises, ensuring sustainable spatial development, and be coordinated with the reconstruction of the technical base, active introduction of mechanization and automation of technological processes, expansion of the range of building materials and prefabricated building elements, light and economical structures, and products of improved quality.

Thus, under modern economic conditions, solving environmental problems allows not only to take a fresh look at reality but also to determine new guidelines and directions for the development of enterprises and search for new technologies for the interaction of production with nature. At the same time, strengthening the environmental component in enterprise activities is the key objective of environmental economics, within the framework of the eco-friendly concept as a factor in the sustainable spatial development.

References


