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ENSURING THE ECONOMIC AND ENVIRONMENTAL EFFICIENCY IN MANAGING THE FLOWS OF CONSTRUCTION AND DEMOLITION WASTE BY USING TOOLS OF ECONOMIC AND MATHEMATICAL MODELING

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This paper argues that in the context of transformation from the linear to circular model of the economy, the issues of managing the flow of construction and demolition waste (C&DW) are becoming increasingly relevant, which is primarily due to the increase in prices for building materials, as well as resource saving and interest of stakeholders in the creation of eco-cities.

The tools and methods to manage C&DW flows have been examined in the context of simultaneous ensuring the environmental and economic efficiency of the process. It is substantiated that the expediency of implementing the C&DW flow management process exists only within the framework of the system of integrated management of waste flows from construction and demolition of real estate in compliance with logistical principles and coverage of the interests of all stakeholders of the process.

Tools, methods to forecast and plan C&DW volumes within IFMS have been proposed, which contributed to the construction of a model for forecasting the volume of C&DW formation and, therefore, determining the amount of total costs for the creation of appropriate technological capacities; the development of a model for assessing information risks in the process of logistics management of C&DW flows (based on solving the transport problem according to Kolmogorov's differentiated equations) and constructing an algorithm for its application, the introduction of which in practice will ensure the balancing of the interests of each stakeholder interested in the processing of C&DW; solving the problem of synthesis of reducing the cost of managing C&DW flows and reducing environmental pressure. In order to combine the goals of minimizing costs and minimizing environmental damage within the framework of SIWFM, a two-purpose dynamic optimization model is proposed, as well as restrictions on the possibility of its introduction and validation of this study's results. It is substantiated that the tools and methods of economic and mathematical modeling proposed in the current study could solve an important scientific and practical task to effectively manage C&DW flows

Keywords: construction and demolition waste, integrated management system, potential of secondary resources

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1. Introduction

In the context of transformation from the linear to circular model of the economy, the issues of managing the flow of waste from construction and demolition of real estate (hereinafter, C&DW) are becoming increasingly relevant, which is primarily due to the increase in prices for building materials, as well as resource saving and interest of stakeholders in the creation of eco-cities [1].

It is no secret that in most European countries up to 90 % of the formed C&DW are currently being processed [2, 3]. However, in Ukraine, these figures barely exceed 34 % [4] due to excessive costs of transportation and processing of C&DW. Thus, solving issues related to effective C&DW flow management should begin with the optimization of transportation costs, and therefore logistics costs, since their share in the total cost of C&DW flow management costs is constantly growing every day. This is due to the inevitable increase in obsolete houses (the service life of which is exhausted in the near future and the reconstruction of which is impractical), the significant remoteness of the infrastructure for their processing from the sources of formation, the complex routing of specialized vehicles by city streets and highways with limited traffic [5]. Instead, it should be remembered that waste flow management is carried out under the conditions of uncertainty, which is due, in particular, to the emergence of information risks, the consequences of which are undoubtedly losses, and, accordingly, a decrease in the efficiency of C&DW flow management.

2. Literature review and problem statement

The systematization of considered research on C&DW flow management shows its relevance due to the need for waste management, resource saving in the construction industry, its use as secondary raw materials, as well as environmental protection. However, most scientific studies [5–9] are aimed only at adjusting the policy of resource saving of construction companies while the issues of sustainable development of the industry through the re-inclusion in the economic cycle of C&DW are quite fragmented. Thus, paper [10] tackles the effective management of C&DW as a condition for minimizing the harmful effects on the environment, as well as factors that hinder its implementation [11]. Study [12] is aimed only at investigating the economic aspects of C&DW flow management, where, in the context of the cost of creating objects (technologies) of processing, the cost of materials, resources, and energy derived from the processing of C&DW, methodical approaches to determining the efficiency of using C&DW as secondary resources have been developed. The author summarizes the basic principles of construction and best practices of C&DW management throughout the construction value chain but does not take into consideration the conditions for ensuring the effectiveness of this process.

Noteworthy is paper [13] aimed at developing effective methods for managing C&DW flows but its disadvantage is the researcher's lack of consideration of the dynamism of the process itself. Study [14] considers innovative business models built on the key partnerships of those who appreciate the reduction of the negative impact on the environment but insufficiently reasons on the guidelines for ensuring economic efficiency, which limits the application of the submitted proposals in practice.

Interesting are the results reported in [15] where the author described findings from a comparative analysis of the best practices of C&DW management. However, a clear argumentation of vectors for improving the management of C&DW flows in Ukraine has not been determined.

Study [16] contains practical aspects of designing the placement of recycling facilities, modeling the profitability of C&DW flow management, analyzing and implementing existing technologies for using the potential of C&DW secondary raw materials. However, the need for an integrated approach to C&DW flow management is not taken into consideration as a condition for the coherence of all components of the process in the context of ensuring efficiency.

Paper [17] outlines the global experience of effective management of C&DW and provides specifications for the use of secondary resources, but only in the context of environmental efficiency regulation. Article [18] stressed the need to implement integrated management systems under the conditions of weak C&DW monitoring but did not define the principles and mechanisms for improving such monitoring.

All this allows us to argue that it is expedient to find ways to create comprehensive C&DW flow management systems that can take these aspects into consideration and cover existing developments in a single system within dynamic management models.

3. The aim and objectives of the study

The aim of this study is to solve, using the tools of economic and mathematical modeling, an important scientific and practical problem of C&DW flow management. This will ensure not only the economic and environmental efficiency of the process of managing construction and demolition waste but will also balance the interests of stakeholders in the creation of eco-cities.

To accomplish the aim, the following tasks have been set:

– to construct a model for forecasting the volume of C&DW formation within SIWFM;

– to devise a model for assessing information risks in the process of logistics management of C&DW flows and the algorithm for its application;

– to resolve the task to synthesize a decrease in the costs for managing C&DW flows and reducing environmental pressure.

4. The study materials and methods

The object of our research is the C&DW flow management process. The subject of the study is the substantiation of the truth of the hypothesis – ensuring economic and environmentally efficient management of C&DW flows through the use of tools for economic and mathematical modeling of the logistics chain, taking into consideration the information risks characteristic of uncertainty conditions.

Accepted designations:

– C&DW – construction and demolition waste;

– IWMS – integrated waste management system;

Our study of the problems of substantiation of mechanisms and tools for managing C&DW flows was carried out on the basis of the analysis of scientific and practical information on this issue, analysis of the experience of successful implementation of certain management methods and tools in this area. The results of the original study provided for the use of methods of economic and mathematical modeling of management, forecasting and planning processes. The use of the logistics method contributed to a systematic consideration of the totality of processes and their integration into a single integrated system. The systematic approach to solving the problems of the original study was based on the assessment of quantitative indicators of C&DW management. The study also used two-target dynamical model and utility methods, as well as a combination of multicriterial functions with different units.

5. Results of studying the tools of economic and mathematical modeling of the efficiency of C&DW flow management

5. 1. Construction of a model for forecasting the volume of C&DW formation within IWMS

To determine the total amount of resources necessary for managing the flow of construction waste, with a controlling role in the system of the logistics center (information platform for IWMS), we propose a mathematical model formed on a cognitive approach with the following objective function (1):

$$TR_t^n = \sum_t \left(\begin{array}{l} \sum_{v\in V, n\in N, g\in G} CR_{(v,n,g,t)} * \sum_{g\in G} x_{(v,n,e,g,t)} + \\ + \sum_{v\in V, n\in N, g\in G} LR_{(v,n,e,t)} * \sum_{e\in E} x_{(v,n,g,t)} \\ + \sum_{v\in V, e\in E} SR_{(v,e,t)} * \sum_{n\in N} x_{(v,n,e,g,t)} \end{array} \right) = \min \cos t \quad (1)$$

where TR_t^n is the total volume of resources (costs, investments) required by the enterprise (n) in t – period;

$CR_{(v,n,g,t)}$ is the expenditure of resources for commissioning capacities for the recycling, sorting, disposal of construction waste of (v) form at an enterprise (n) by (g) technology in a certain period (t);

$LR_{(v,n,e,t)}$ is the logistics costs necessary for the transportation of construction waste of a certain (v) type from the producer of waste (e) to the enterprise (n) in a certain period (t);

$SR_{(v,e,t)}$ is the total volume of necessary resources (costs) to ensure the process of managing the volume of C&DW of form (v) by the producer of its formation (e) in a certain period (t);

$x_{(n,e,g,t)}$ is the total volume of construction waste directed from waste producer (e), of (v) type, to the processing enterprise (n), using (g) recycling technology.

If we talk about the necessary resources to ensure the smooth operation of this model, which may have different costs in time, then such an error can be taken into consideration by bringing cash flows to the base period (by discounting).

Within the framework of the integrated management of construction waste flows, analysis of the dynamics of the volume of production of finished products from secondary raw materials (based on statistical methods and forecasting techniques) directly affects the efficiency of IWMS. This is achieved by optimizing the cost of creating and maintaining operational capacities; estimates of the amount of additional value creation. In addition, the method of forecasting and planning the volume of construction waste is the key to the validity of determining all indicators of the system. Namely: the effectiveness of each stakeholder of the system, forecasting the required volume of resource costs for the processing of construction waste, as well as planning and forecasting the volume of finished products from secondary raw materials. Accordingly, the C&DW volume forecasting and planning objective function will take the following form (2):

$$\sum_{v=1}^{V} W_{gen} = \sum_{v=1,n=1}^{V,N} W_{in} + \left(\sum_{v=1,e=1}^{V,E} W_d + \sum_{v=1,e=1}^{V,E} W_{ne} \right) * k, \quad (2)$$

where W_{gen} is the projected (total) amount of construction waste that can be involved in the re-economic cycle; v is the type of waste of construction to be processed; V is the total number of types of waste to be recycled, according to the capabilities and existing technologies within IWMS at present, respectively, the purpose of the system: $V\rightarrow$max; its achievement is possible through the introduction of new technologies and the expansion of processing capacities.

W_{in} is the total volume of each type of construction waste (v) involved in IWMS, which was not recycled and disposed of at the beginning of the period, which are located at each stakeholder of the waste management system (n), ($n\in N$) at the regional level;

W_d is the total volume of construction waste, of each type (v), formed as a result of planned demolition of structures and buildings at the level of each producer of waste (e), among all waste producers involved in the system (E);

W_{ud} is the total amount of construction waste, of each type (v), formed as a result of unplanned demolition of structures and buildings at the level of each producer of waste (e), among all waste producers involved in the system (E);

W_{ne} is the total volume of construction waste, of each type (v), formed as a result of new construction at the level of each producer of waste (e), among all waste producers involved in the system (E);

k is the coefficient of reuse of construction waste that does not require additional processing, or recycling can be carried out locally (at the place of waste generation).

It should be noted that determining this coefficient by the ratio of the entire volume of construction waste supplied to processing enterprises to the total volume of construction waste, as indicated in [19], is not entirely correct. This definition does not take into consideration the volume of waste during recycling, so it is more appropriate to determine this coefficient as (3):

$$k = \frac{W_{gen} + W_l - W_f}{W} \leq 1 \rightarrow \max, \quad (3)$$

where W_l is the volume of waste recycled locally;

W_f is the volume of waste received from the recycling process (potential waste for disposal), to the total volume of waste of the construction industry (W) at the level of the region (state).

Accordingly, it is proposed to determine the coefficient of processing of construction waste (k) as the ratio of the volume (W_{gen}) of the projected (total) volume of construction waste, which can be involved in the re-economic cycle and is aimed at processing enterprises and (W_l) volume of waste recycled locally. Minus (W_f) of the waste received from the recycling process (potential waste for disposal) to the total volume of waste of the construction industry (W) at the level of the region (state).

5. 2. Building a model for assessing information risks in the process of logistics management of C&DW flows and the algorithm for its application

We believe that the functioning of any system of material flows is associated with the influence of risk factors, which must be taken into consideration in the process of managing waste flows because this directly affects the efficiency and, accordingly, the feasibility of IWMS.

Information risks are associated with the flow of information directed from producers of construction waste – the volumes and types of construction and demolition waste. Processors send information about technical capabilities and technological capacities to a single information platform. Accordingly, in the opposite direction – information on the optimization of logistics costs, the distribution of material flows, the forecast volumes of resources. The condition for deciding on the direction of construction waste flows will be economic feasibility and minimization of environmental damage from the management process (transportation, recycling, disposal, etc.). This involves the choice of at least two alternatives: sorting and directing waste to an enterprise-recycler (return to the re-economic cycle), or export to the landfill for disposal (it is a negative scenario for managing C&DW flows).

Therefore, in this case, we shall consider the volume of losses as an information risk, provided that the first option is impractical. And accordingly, this requires the development of a mathematical model for assessing information risk, by solving a transport problem based on Kolmogorov's differentiated equations [20].

The problem statement stipulates that the logistics costs of directing waste flows to recyclers (LR_{pr}) should be either less or equal to the logistical costs of directing flows to waste disposal landfills (LR_b). $LR_{pr} \le LR_b$.

$LR_{pr} > LR_b$ is considered negative, with maximum damage ($D_{\max}$) as the maximum possible difference between LR_{pr} and LR_b. Accordingly, determining the acceptable level of risk (IR_a), which will not critically affect the overall efficiency of C&DW flow management, the decision to direct the waste flow will be made on the basis of determining the actual level of risk (IR_f) and comparing them.

It is assumed that the information and logistics system (centrally) should solve the problems of collection, transportation, and distribution of waste flows from construction and demolition, respectively, the transport task is an important component of the information and logistics system [21]. In this case, the transport problem should solve the problem of waste delivery as potentially secondary raw materials to the processing plant. The condition for this is the technological capabilities, capacities, and demand of consumers (at a certain time) for a certain type of products from recycled waste (at a specific place and a certain time).

The maximum possible damage is $D_{\max}$. It is determined by the excess of the cost of logistics costs for the delivery of waste from the producer to the processing plant over the logistics costs to the site of waste disposal (without sorting and disposal). $D_{\max}$ is the maximum possible loss to ensure the optimal level of efficiency of the waste flow management process as a potentially secondary raw material for producer (E_{man}).

The decision will involve an alternative to accepting, or rejecting, orders for the supply of waste as potentially secondary raw materials.

The algorithm for constructing and calculating a mathematical model that involves assessing and taking into consideration information risk in the process of managing C&DW, within IWMS, consists of four stages. Consider it on a specific example illustrated in Fig. 1, 2, *a*, *b*.

Formalization of the problem suggests that there are N points where the flows of construction and demolition waste (processing enterprises, waste disposal sites, etc.) that are part of IWMS can be directed.

One point is the point of departure (waste production), and all other N–1, delivery points (respectively, these can be processing enterprises, sorting stations, landfills). If necessary, it is necessary to consider k points of departure (which is objective for IWMS), the problem should be solved k times).

The directions of possible movement (one-way or two-way) are also taken into consideration, the throughput function between vertices (points) is $f_{\text{throughput}}\ ij(t)$), the values of which are dimensionless values in the range from 0 to 1.

This assumes that if a certain producer has a certain volume, a certain type of C&DW, and according to the information of a single logistics center, there is a request for this volume by the enterprise (several) for the processing of this volume. Clearly defined parameters of shipment and delivery time to n points ($n<N$) are provided. It also takes into consideration the permissible level of information risk (IR_a), consistent with the target level of efficiency of C&DW (E_{man}) flow management process. Based on this, the producent must decide on the feasibility of directing these volumes of waste to processing enterprises.

This is the solution to such a problem, which involves the formation and calculation of a mathematical model in several stages.

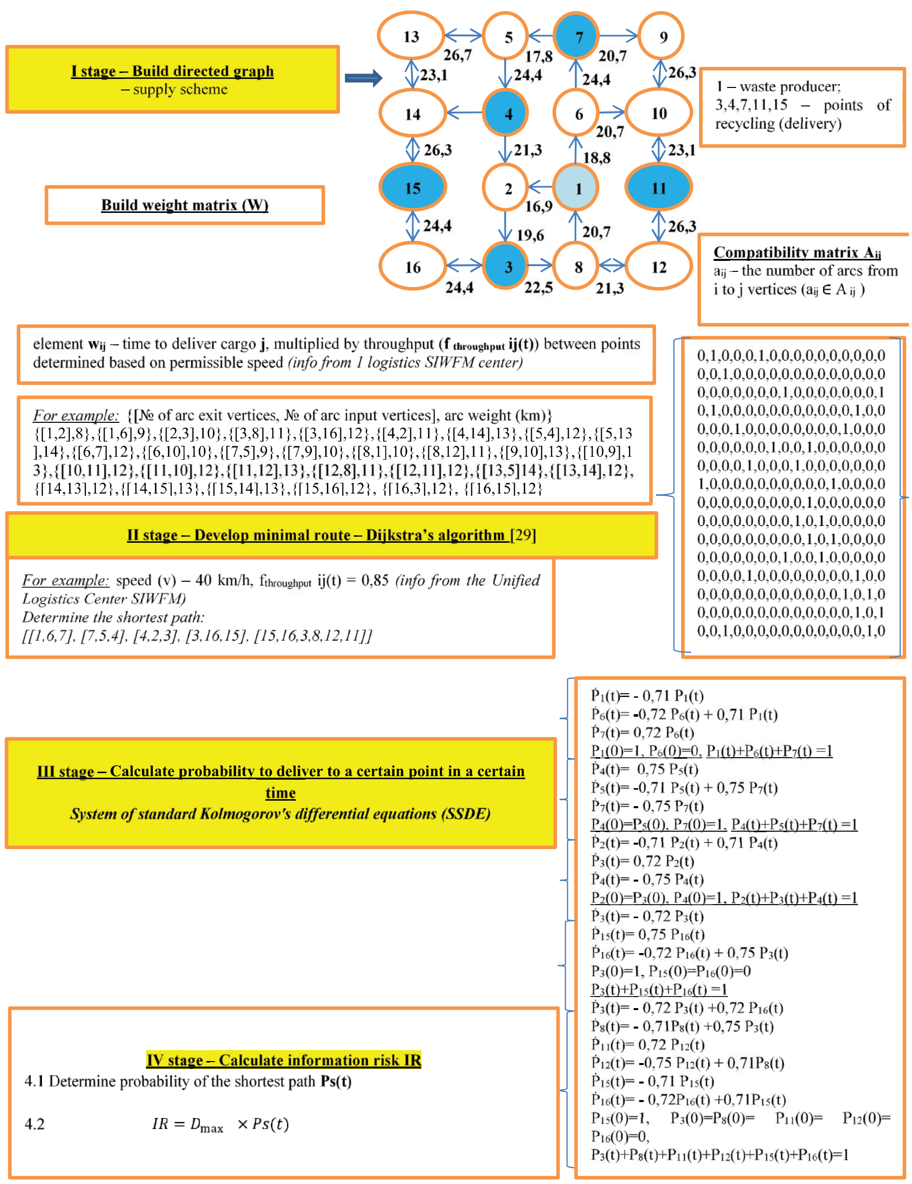

Fig. 1. Stages of the algorithm for assessing and taking into consideration information risk in the process of managing C&DW

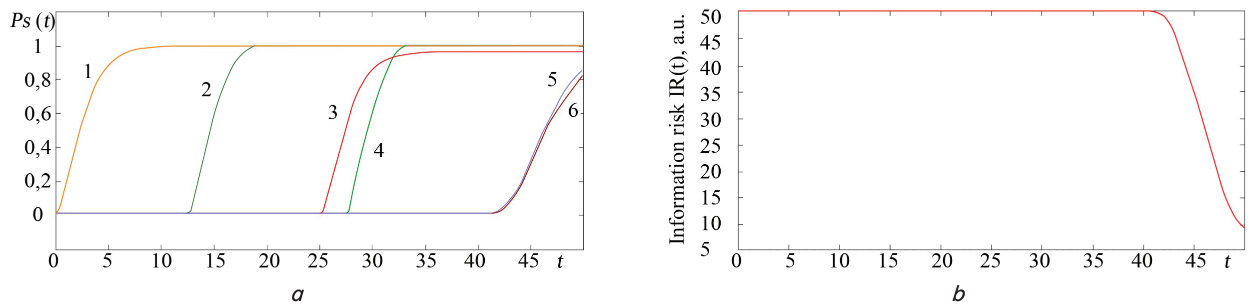

Fig. 2. Algorithm for assessing and taking into consideration information risk in the process of managing C&DW: *a* – a plot of the probability of reaching the destination and the overall probability depending on time; 1 – point 7; 2 – 4; 3 – 3; 4 – 15; 5 – 11; 6 – total probability; *b* – dependence of information risk on the time of the route

5. 3. Solving the synthesis of reducing the cost of managing C&DW flows and reducing environmental pressures

Another aspect that also affects the overall efficiency of the C&DW flow management process is environmental, assessed by determining the environmental pollution indicator associated with the distribution, processing, and placement of C&DW. This indicator increases linearly with the increase in C&DW volumes and decreases with the distance of points and objects of waste processing and disposal [19].

This causes existing contradictions in the functioning of the C&DW logistics system because increasing the distance from the place of environmental impact, on the one hand, increases the environmental effect, on the other hand, increases logistics costs. Therefore, it is necessary to use a model formulated using multidimensional linear programming to simultaneously minimize the total volume of resources for managing C&DW flows and the indicator of environmental damage from the functioning of IWMS [22].

The objective function (1) should be clarified by taking into consideration the total costs of IWMS. It is necessary to include costs for each object of possible direction of C&DW: regional collection and transportation points (*d*), local processing facilities (*l*), processing enterprises (*pr*), landfills for disposal (*b*). We obtain the following objective function of model (4):

$$\begin{aligned}&\min cost = TR_t^n = \\&=\sum_1^t\sum_1^d\left(CR_{d(t)}+(LR_{d(t)}+TC_{d(t)})\times W_{d(t)}\right)+\\&+\sum_1^t\sum_1^l\left(CR_{l(t)}+(LR_{l(t)}+TC_{l(t)})\times W_{l(t)}\right)+\\&+\sum_1^t\sum_1^{pr}\left(CR_{pr(t)}+(LR_{pr(t)}+TC_{pr(t)})\times W_{pr(t)}\right)+\\&+\sum_1^t\sum_1^b\left(CR_{b(t)}+\left(LR_{b(t)}+TC_{b(t)}\right)\times W_{b(t)}\right).\end{aligned} \quad (4)$$

In other words, the total volume of resources (including investments) (*TR*) is necessary for the functioning of all (*n*) objects of IWMS. These objects are involved in the process of collection and sorting (*d*), local processing (*l*), disposal (recycling) (*pr*), burying (*b*), in a certain period (*t*). (*TR*) must have an optimal minimum cost. It is the sum of the cost of commissioning resources (*CR*) and the volume of logistics costs (*LR*) and the costs of the C&DW management process, taking into consideration the volume of waste involved in IWMS (*W*).

A prerequisite for the use of this mathematical model is the complete processing or disposal of all volumes of C&DW formed in a certain period. This involves the maximum inclusion of C&DW flows in IWMS and, accordingly, taking into consideration all the costs of logistics and operational management of this volume.

Accordingly, the purpose of ensuring the efficiency of the C&DW flow management system is to minimize the total costs (cost) for such management, including total investments, logistics and operating costs, which will ensure the maximum inclusion of all C&DW flows in IWMS.

The next goal of creating IWMS should be to ensure minimal damage to the environment, and to minimize damage from the processes of recycling and disposal of C&DW, for the population living within the territories of influence, determined from the following equation (5).

$$\min damage = ED_t^n = \\ =\sum_1^t\sum_1^z P_{z(t)}\left(\begin{aligned}&\sum_1^d\frac{IEP_{d(t)}*W_{d(t)}}{S_{\frac{d}{z}}}+\sum_1^l\frac{IEP_{l(t)}*W_{l(t)}}{S_{\frac{l}{z}}}+\\&+\sum_1^{pr}\frac{IEP_{pr(t)}*W_{pr(t)}}{S_{\frac{pr}{z}}}+\\&+\sum_1^d\frac{IEP_{b(t)}*W_{b(t)}}{S_{\frac{b}{z}}}-\sum_1^{ft}\sum_1^n\frac{IEP_{ft(t)}*W_{n(t)}}{S_{\frac{ft}{z}}}\end{aligned}\right), \quad (5)$$

where *ED* is the environmental damage from the pollution of each object and, accordingly, the process providing this object, taking into consideration the number of inhabitants in the territory of influence and the distance of the object from residential points;

IEP is the indicator of environmental pollution per unit C&DW;

$W_{d(t)}$ is the volume of C&DW transferred to collection and sorting centers;

$W_{l(t)}$ is the volume of C&DW processed locally;

$W_{pr(t)}$ is the volume of C&DW formed by producers minus those processed locally;

$W_{b(t)}$ is the total volume of C&DW temporary accommodation;

$W_{n(t)}$ is the volume of C&DW to be buried.

ED increases linearly with the increase in the volume of C&DW involved in IWMS and decreases with an increase in the distance of the IWMS facility from the impact zone (settlement), as well as the creation of environmental protection facilities and the introduction of technological modernization of treatment plants, environmental barriers, etc.

Accordingly, the adjustment of these factors of influence on the environmental damage indicator makes it possible to improve the indicator and determine the target guidelines for reducing the risks of environmental impact for each IWMS facility.

As noted above, the purpose of IWMS should be a combination of goals of minimizing costs and minimizing environmental damage. This task uses different measures of units of two objective functions, so to solve it, the utility method developed by Nema & Gupta, United States [23], and the method of combining multicriterial functions with different units are used [24].

For each of the indicators, an indicator of importance is defined, which implies a certain priority between minimizing the total costs of the system (I_{TR}) and minimizing the negative impact on the external environment (I_{ED}).

The relationship between them is determined by function (6):

$$I_{ED} = 1 - I_{TR} \quad (6)$$

The model is formed using multiperiod linear programming to simultaneously minimize the total cost of the system and the damage (pollution level) to the environment, which are objectively related to the C&DW flow management process, which is determined from the ratio $\frac{cost\ objective\ TR_t^n}{\min\ cost\ TR_t^n}$ and $\frac{damage\ objective\ ED_t^n}{\min\ damage\ ED_t^n}$.

The optimal solution for simultaneous minimization of C&DW flow management costs and minimization of environmental damage from its functioning can be obtained by solving the objective linear function (7):

$$\min objective = I_{TR} * \frac{TR_{\text{cost objective}}}{TR_{\min cost}} + I_{ED}\frac{ED_{damage\ objective}}{ED_{\min damage}}, \quad (7)$$

where $TR_{cost\ objective}$ is the objective (actually possible taking into consideration actual volumes and capacities) cost of the total resources for C&DW management processes;

$TR_{\min\ cost}$ is the minimum cost (target);

$ED_{damage\ objective}$ is the objective (actually possible taking into consideration the actual volumes, capacities of IWMS facilities, capacities of treatment and protective structures, distance to environmental impact objects) volume of environmental damage;

$ED_{\min\ damage}$ is the lowest possible environmental damage.

The model is two targeted, and provides optimization capabilities for the creation and improvement of the C&DW flow management system. This is achieved through the introduction of new facilities, capacities, and innovative recycling technologies that can ensure the maximum inclusion of C&DW in the re-economic cycle and minimally harmful impact on the environment.

There are several restrictions that determine the feasibility of the model, namely:

– the volumes of C&DW involved in certain IWMS facilities may not exceed their powerful capabilities for regional centers for collecting, sorting, and temporary placement of equation (8), which is solved by planning C&DW volumes:

$$W_{d(t)} \le \max Op_{d(t)},\ \text{for}\ 1,\ldots,d,1,\ldots,t; \quad (8)$$

– the volumes of all transported C&DW from producers (e) must be equal to the volumes involved in the collection, sorting, and temporary placement centers, in a certain period ($W_{d(t)}$). As well as the total volume of C&DW formed by producers ($Wp_{e(t)}$), minus those volumes that are processed locally ($W_{l(t)}$) (for example, a crushing plant on a construction site), equation (9):

$$\sum_1^e Wt_{d/e(t)} = \sum_1^d W_{d(t)} = \sum_1^e Wp_{e(t)} - \sum_1^l W_{l(t)},\ \text{for}\ 1,\ldots,d,1,\ldots,t. \quad (9)$$

Compliance with such a restriction provides for the mandatory consideration of the above planning of C&DW volumes, which is possible only in the case of full coverage of all construction and demolition projects by IWMS. This is solved by covering the information platform of all participants in the process. As well as the use of organizational and technological solutions aimed at minimizing C&DW and forecasting its volumes as a result of the implementation of projects, to increase the opportunities for attracting C&DW as secondary raw materials.

On the one hand, exceeding the actual volumes of C&DW over the technological capacities of disposal, temporary placement and disposal facilities creates waste residues that cannot be included in IWMS. On the other hand, unused capacities, for which certain volumes of investment were spent, become economically unreasonable and increase the operating costs of reserve capacities, while reducing the efficiency of the system as a whole.

That is, the planning of C&DW volumes ensures the validity of the application of this mathematical model.

Similar is the restriction (10), (11), on the local processing of certain types of C&DW, which provides for the assessment of future volumes, which directly affects the feasibility of investments in C&DW mobile processing equipment and technologies at the facility of their formation.

$$W_{l(t)} \le \max Op_{l(t)},\ \text{for}\ 1,\ldots,l,1,\ldots,t, \quad (10)$$

$$W_{l(t)} \ge \min Op_{l(t)},\ \text{for}\ 1,\ldots,l,1,\ldots,t. \quad (11)$$

Restrictions (12), (13) determine that all C&DW volumes directed to processing plants cannot be greater than the technological capabilities of such enterprises but unused technological capacities will also lead to a decrease in the efficiency of investments and the system as a whole.

$$W_{pr(t)} \le \max Op_{pr(t)},\ \text{for}\ 1,\ldots,pr,1,..,t, \quad (12)$$

$$W_{pr(t)} \ge \min, Op_{pr(t)},\ \text{for}\ 1,\ldots,pr,1,..,t. \quad (13)$$

According to constraint (14), those volumes of C&DW that were transported to processing enterprises ($Wt_{e/pr(t)}$) must be equal to the volumes that were recycled at them using certain technologies in a certain period.

$$\sum_1^e Wt_{e/pr(t)} = W_{pr(t)},\ \text{for}\ 1,\ldots,pr,1,..e,1,..,t. \quad (14)$$

The limitation of the technological capacity of the C&DW waste disposal landfills (15) stipulates that the total volumes of C&DW directed from producers to these facilities should be less than the maximum possible capacity of such landfills.

$$\sum_1^e W_{b(t)} \le \max Op_{b(t)},\ \text{for}\ 1,..b,1,..t. \quad (15)$$

The restriction on the minimum possible volumes of C&DW disposal should be considered impractical. This contradicts the environmental direction of such a mathematical model and the strategic goal of IWMS. Ideally, C&DW volumes directed from producers to landfills for disposal purposes, without the use of their secondary raw material potential, should approach min, or zero (16):

$$Wt_{e/b(t)} \to \min. \quad (16)$$

And all volumes of transported C&D from producers to landfills should be buried on specialized and authorized for a certain level of safety types of C&DW (17):

$$\sum_{1}^{e} Wt_{e/b(t)} = W_{b(t)}, \text{ for } 1,..b,1,..,t. \quad (17)$$

$$\sum_{1}^{e}\left(Wt_{e/d(t)} + Wt_{e/pr(t)} + Wt_{e/b(t)} + Wt_{e/l(t)} \right) =$$
$$= \sum_{1}^{n} W_{t(n)}, \text{ for } 1,\ldots d,1,.., pr,1,\ldots b,1,\ldots,l,1,..t. \quad (18)$$

The restriction (18) stipulates that the logistics system of IWMS should cover all volumes of C&DW that were directed from producers to regional collection and sorting centers, local processing facilities, processing enterprises, authorized disposal sites.

6. Discussion of results of studying the tools of economic and mathematical modeling of the efficiency of C&DW flow management

The peculiarity of our results is the integration of individual indicators of the effectiveness of C&DW management and the use of an integrated approach, the absence of which is a disadvantage of most studies on this topic.

The proposed tools, methods of forecasting and planning C&DW volumes within IWMS contributed to:

– building on a cognitive approach the model of forecasting the volume of formation of C&DW, which can be involved in the re-economic cycle (2), and therefore determining the volume of total costs for the creation of appropriate technological capacities;

– development of a model for assessing information risks in the process of logistics management of C&DW flows (based on solving the transport problem according to Kolmogorov's differential equations) and building an algorithm for its application (Fig. 1, 2, *a, b*), the introduction of which in practice will ensure balancing the interests of each of the stakeholders interested in the processing of C&DW;

– solving the problem of synthesis of reducing costs for managing C&DW flows and reducing environmental pressure. In order to combine the goals of minimizing costs (4) and minimizing environmental damage within the framework of IWMS (5), a two-purpose dynamic optimization model (7) is proposed, the application of which in practice will ensure long-term planning of the volume of C&DW formation; expansion of its potential as secondary raw materials; planning costs and necessary investments to ensure the maximum involvement of C&DW in re-business turnover.

The implementation of the submitted proposals in practice will ensure solving an important scientific and practical task for effective management of C&DW flows and balancing the interests of stakeholders in creating eco-cities through the tools of economic and mathematical modeling.

There are restrictions that determine the feasibility of introducing the proposed model (8) to (18):

– the volumes of C&DW involved in certain IWMS facilities may not exceed their capabilities for regional collection, sorting, and temporary accommodation centers;

– the volumes of all transported C&DW from producers must be equal to the volumes involved in the collection, sorting, and temporary placement centers, in a certain period;

– the volumes of C&DW directed to processing enterprises may not be greater than the technological capabilities of such enterprises but unused technological capacities will also lead to a decrease in the efficiency of investments and the system as a whole;

– C&DW volumes that have been transported to processing plants ($Wt_{e/pr(t)}$) should be equal to the volumes that have been recycled at them using certain technologies in a certain period;

– C&DW volumes directed from producers to these facilities should be less than the maximum possible capacity of such landfills;

– C&DW volumes directed from producers to landfills for disposal purposes, without the use of their potential of secondary raw materials, should approach min, or zero;

– the volumes of C&D transported from producers to landfills must be buried in specialized and sanctioned for a certain level of safety C&DW types;

– the IWMS logistics should cover all C&DW volumes sent from producers to regional collection and sorting centers, local processing facilities, processing plants, and authorized landfills.

Further research on C&DW flow management will focus on tackling low-carbon recycling of construction and demolition waste.

7. Conclusions

1. We have proposed, formed according to the cognitive approach, a model for predicting the volume of C&DW formation that can be involved in the repeated economic cycle. Unlike existing ones, due to the saturation of its model and information tools, it is based on lateral understanding of the clarity of the formation of C&DW flows, taking into consideration their adjustment by the share of reuse of construction waste that does not require additional processing, or the recycling of which can be carried out locally (at the site of waste). The introduction of the proposed model in practice will ensure the obtaining of realistic results and the adoption of balanced decisions on the management of C&DW flows, the creation of appropriate technological capacities, as well as the introduction of innovative technologies for the processing of construction and demolition waste.

2. The model of assessment of information risks in the process of logistics management of C&DW flows (based on solving the transport problem according to the differential equations of Kolmogorov) and the algorithm of its application, the introduction of which in practice will ensure balancing the interests of each of the stakeholders interested in the processing of C&DW, have been developed. This is convincingly evidenced by each of the defined stages of the algorithm implementation: the first is the creation of a C&DW supply scheme

and the development of a route's directed graph; the second is determining the most optimal way to supply C&DW flows; the third is the calculation of the probability of supplying C&DW flows at a certain time and certain points; the fourth is the definition of information risk.

3. We have solved the problem of synthesizing the cost reduction of C&DW flow management and reducing environmental pressure by developing a two-goal dynamic optimization model based on the utility method and the method of combining multicriterial functions with different units.

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