

UDC 164.035

DOI: <https://doi.org/10.30837/ITSSI.2020.14.113>

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## A MODEL OF CLOSED CIRCUITS FORMING IN A LOGISTICS SYSTEM WITH FEEDBACK

The **subject** of the research in the article is the reverse flows of material resources within the circular processes of closed supply chains of the logistics system with feedback. The **aim** of this article is to develop a model of the formation of reverse material flows using the processes of circular economy, which will achieve maximum efficiency of the logistics system. To achieve this aim it is necessary to solve the following tasks: to determine the essence and study the evolution of the circular economy through changes in the frameworks that form it; develop a graphical model of a logistics system with feedback, which is based on the implementation of circular processes; develop a mathematical model of the logistics system with feedback and conduct experimental calculations confirming its adequacy. **Methods** of systems analysis, operations research, namely linear programming (distribution problem is solved by the simplex method) are used to solve the tasks set in the study. The following **results** were obtained: the essence of the circular model of the economy, the evolution of its economic frameworks and the processes that are part of them were studied; the graphical model of the logistics system with feedback was presented by means of circular processes; a mathematical model of the logistics system with feedback was created. **Conclusions.** The concept of a circular economy is based on the principles and objectives of the concept of sustainable development and emphasizes the need to close logistics systems, i.e. to create logistics systems with feedback. The tools for the implementation of its concept are closed supply chains, which include direct and reverse material flows. Closed circuits are created through the use of circular processes, which create logistics loops that provide feedback between the participants in the chain and allow you to organize the reverse flow of products, their components, raw materials and materials. The application of operations research methods allows to create a mathematical model of the task of optimizing return material flows and to distribute material resources by loops, so that the total cash flows of the logistics system reach the maximum value and ecodestructive impact on the environment by creating return flows of secondary material resources was minimal.

**Keywords:** circular process; closed logistics chain; logistics loop; reverse material flow.

### Introduction

At the beginning of the XXI century, the problem of unsustainable development of modern civilization has acquired a new qualitative state and reached its limit. An economy built on the principles of technocracy and non-equivalent socio-natural exchange is incapable of ensuring long-term sustainable development for humanity. Today, the biosphere is unable to fight human activity, it has begun irreversible changes. Mankind produces 2,000 times more organic waste than all of nature [1]. It has already become clear that the contradictions between the ever-growing needs of society and the limited capabilities of nature threaten the continued existence of man as a species.

A harmonious alignment of the components of sustainable development that ensures economic growth, social stability and environmental balance in the long term can be achieved thanks to the introduction of the principles of circular economy, which has recently received increased attention from specialists around the world. The transition to a circular economy is becoming global, and the benefits of implementing this concept are becoming increasingly apparent. According to experts, in 2025, the circular economy can annually provide an increase in the income of the global economy of more than 1 trillion US dollars. In addition, the transition to a circular economy will create huge opportunities for modernizing production and introducing industrial innovations, ensuring annual GDP growth of 7% [2].

The existing linear model of the economy is not perfect, as it constantly requires the involvement of additional primary resources, which, passing through the man-made system, produce a large amount of waste. The circular economy takes into account the biological and

technical cycles of resource circulation and the potential benefits that can be obtained at different levels of these cycles, it involves the transition from a linear model of the economy to a closed cycle economy [3]. Ideally, the formation of a closed model of the circular economy should lead to compliance with the principle of zero waste, which is possible through the introduction of mechanisms of reverse (reverse) logistics and the creation of environmentally-oriented closed logistics chains.

### Analysis of recent research and publications

The study of the essence of the circular economy, its processes and business models is currently given some attention by scientists, but it cannot be considered sufficient, because this concept is not just a new direction of scientific thought within economics, but is an interdisciplinary approach, the main task of which is to create a theoretical basis for changing the worldview of mankind to a more humane in relation to the environment.

For the first time, the circular economy was recognized as a promising direction of economic development in the Report of the Club of Rome "The Limits to growth" [4], published in 1975 and contains the results of analysis of possible civilization potential population growth, scale of use of natural resources, environmental problems.

In 2015, the European Commission addressed the European Parliament and the Council of Europe, socio-economic and regional committees with a report "Closing the loop – An EU action plan for the Circular Economy" [5], in which the concept of circular economy was substantiated. The modern concept of logistics, which is actively developing and has recently been influenced by greening, taking into account the principles of the circular

economy, is the management of supply chains (logistics chains) - Supply Chain Management.

Such scientists as Yu. V. Varenko, M. Yu. Hryhorak, L. M. Zaretska, E. V. Krykavsky, I. I. Mukhina, A. V. Smirnova, C. Comtois, Robert D. Klassen, Su-Yol Lee, J.-P. Rodrigue, B. Slack, etc. disclose the issues of applying an ecological approach to logistics chain management in their works. Models of the logistics chain with reverse material flows are presented in the works of such researchers as: S. S. Ali, V. V. Bezkorovainy, E. M. Bukrinskaya, D. O. Gobov, M. N. Grigoriev, K. O. Dzyubina, A. V. Dzyubina, O. P. Dolgov, D. A. Karkh, O. V. Myasnikova, S. V. Potapova, A. Tambovtsev, T. Tambovtseva, S. O. Uvarov, V. A. Falovich, S. A. Shahnazaryan etc.

The importance of taking into account environmental requirements in the optimization of logistics structures by solving in conjunction with traditional logistics problems of optimizing return material flows from consumers to places of production or disposal within the reverse logistics is noted in [6]. In [7], the scope of activity, which is identified as logistics of recycling and utilization, is defined within logistics, and its goals and main logistic functions are outlined. In [8] the necessity of transition to the closed-loop economy is noted and the issues of transformation of logistics systems are considered, the conditions of realization of logistics of interaction of system participants in the conditions of construction of circular economy are revealed, the structure of closed supply chain is developed. In [9] the peculiarities of direct and reverse material flows are considered, the expediency of introduction of reverse logistics tools into the logistics activity of the enterprise is substantiated, the basic models of reverse material flows functioning in modern economic conditions are formed, the peculiarities of return and utilization recycling are revealed. In [10] the key parameters of the closed loop of the supply chain are investigated, the need to coordinate the reverse logistics strategy with the life cycle of the product, seasonality of demand for it, with the pricing strategy for refurbished goods and the level of after-sales service; the conditions for allocating part of the closed loop of the supply chain for outsourcing are outlined. In [11] an integrated and generalized scheme of logistics network with feedback, due to which it is possible to reach a compromise between costs in this network and eco-destructive impact on the environment, presents a mathematical model for solving integrated multicriteria multi-link direct and inverse logistics. The paper [12] presents mathematical models and methods for solving problems of transport route optimization in closed logistics systems, taking into account many topological and logistical constraints, including a proposed solution for network optimization for transporting direct and reverse product flows, which will increase the efficiency of closed logistics systems.

Despite the existing research on the organization of direct and reverse flows within the reverse logistics, traditionally these tasks are considered separately, which does not allow for general optimization of material flows and achieve a synergistic effect for participants in the logistics system.

The **aim** of this article is to develop a model of the formation of reverse material flows using the processes of circular economy, which will achieve maximum efficiency of the logistics system. To achieve this aim it is necessary to solve the following tasks:

1. Define the essence and explore the evolution of the circular economy through the change of frameworks that form it.
2. Develop a graphical model of the logistics system with feedback, which is based on the implementation of circular processes.
3. Develop a mathematical model of the logistics system with feedback and conduct experimental calculations confirming its adequacy.

### Task solving

#### Circular processes in the model of circular economy.

There are two approaches to defining the essence of a circular economy: resource-oriented (flow-oriented) and economic-oriented (systemic).

According to the flow approach [13-16], the circular economy is based on the use of closed flows of materials, energy and waste, which can be achieved through the reuse of product, components, raw materials and supplies.

The systems approach [17-19] presents the circular economy as a model of the economic system, which is an element of the man-made system and is based on the reuse of materials, which will preserve natural resources, and considers creating value for system elements.

The most commonly used and taking into account the above approaches to determining the essence of the circular economy is the interpretation of the circular economy provided by experts of the Ellen MacArthur Foundation [2], according to which *the circular economy is an economy that has a renewable and closed character, provides for the creation of a continuous development cycle that preserves natural capital and increases its value, increasing the return on resources by optimizing their use.*

The circular economy is an alternative to the traditional linear economic mechanism, as it is characterized by a closed nature of resource use and recovery. Unlike the traditional model of economy, which works on the principle of "take, make, use, waste", the circular economy offers a fundamentally new sustainable model based on the principle of "take, make, use, repair or recycle, reuse". The circular model is a good way to save resources and materials, reduce the negative impact on the environment and sustainable economic growth.

In modern conditions, the transition to a circular economy is possible due to the closure of the resource cycle and the creation of closed supply chains. This opportunity first appeared due to the introduction of recycling – the process of returning waste to the production process, which was one of the first processes of the circular economy. In the process of developing the concept of circular economy, the framework conceptual structures were formed - frameworks, which as the ideas of circularity were transformed: "3R", "4R", "6R" and

"9R" [20; 21]. Stages of evolution of the circular economy and their corresponding circular processes are presented in table 1 [13].

**Table 1.** Characteristics of circular economy framework processes

The level of circulation of the economy [20]	Framework	Process characteristics
First level - useful use of raw materials	4R, 6R, 9R	<i>Recover</i> (recovery, refund) – the process of collecting products and components at the end of use, disassembly, sorting and cleaning for use in subsequent life cycles.
	3R, 4R, 6R, 9R	<i>Recycle</i> (recycling, processing) – the process of returning waste, discharges and emissions into the processes of techno genesis. Reuse of waste for the same purpose, as well as the return of waste after appropriate treatment in the production cycle.
The second level is the extension of the service life of the product and its parts	9R	<i>Refurbish</i> (update, repair) - restore and update an old but serviceable product.
	6R, 9R	<i>Remanufacture</i> (update, modification) - the process of restoring the product to bring it into working order by replacing or repairing major units or components.
	9R	<i>Repurpose</i> (reorientation) - repurposing, using a product that has failed and its parts in a new product with a second purpose.
	9R	<i>Repair</i> (repair, correction) – repair and maintenance of a defective product for use in accordance with the original purpose.
	3R, 4R, 6R, 9R	<i>Reuse</i> implies that a certain product is reused for original or new purposes in its original form or with some changes and minor improvements.
The third level - smart production and use of products	3R, 4R, 6R, 9R	<i>Reduce</i> (reduction, diminution) involves the reduction of the use of resources and energy at the stages of planning and production of the product, and the reduction of emissions and waste at the stage of its use.
	9R	<i>Rethink</i> (rethinking) – increasing the intensity of product use (for example, sharing).
	9R	<i>Refuse</i> (refusal) – reduction of excessive consumption of products by completely abandoning their functionality by transferring their functionality to other products.
	6R	<i>Redesign</i> – the process of developing next-generation products that would use components, materials and resources extracted from the previous lifecycle or products of the previous generation (redesign to use as many extracted components and parts as possible without losing functionality).

Implementation of circular economy frameworks involves the transformation of business interactions, in particular, through the implementation of economic strategies of industrial symbiosis and industrial metabolism, according to which the interaction between elements of the man-made system can be carried out at the micro, meso and macro levels in cascade resources, when waste from one production is a raw material for another, thus ensuring the reduction of eco-destructive impact on the environment.

#### Graphic model of a logistics system with feedback

To create a model of a closed logistics system (logistics system with feedback), which includes closed (complete) logistics chains; we use participants and processes used in the model of circular economy, which is proposed by the Ellen McArthur Foundation [2]. According to this model, the main participants in closed circuits are: *resource provider*, (RP), *parts manufacturer* (PM), *product manufacturer* (PM), *service provider* (SP), *consumer / user* (CU), *collection center* (CC), *repair center* (RC), *sort center* (SC), *utilization center* (UC).

Eco-oriented closed logistics chain consists of two chains: forward and reverse, depending on the direction of material flow. Participants in the direct chain may not be in the reverse, and vice versa. There are participants in both the forward and reverse chains. The conditional link that divides the complete chain into direct and reverse is the consumer / user of the product. Within a complete logistics chain, the direct chain begins with the natural environment and the resource supplier and ends with the

consumer / user of the product, the reverse chain begins with the consumer / user of the product and ends with the recycling center and the natural environment.

The implementation of the concept of a circular economy, which is based on the creation of closed logistics systems, which requires the closure of logistics chains by creating feedback systems, has led to the use of processes that are not typical of linear logistics chains. Among the processes of circular economy should be noted processes related to reverse logistics and involved in the organization of reverse flows to create feedback in a closed logistics chain: recover, recycle, refurbish, remanufacture, repurpose, repair, reuse. Due to these processes, which can be called circular, there are logistic loops between the participants in the logistics chain, providing feedback in closed logistics chains (fig. 1).

The largest number of logistics loops is created by the process of recycle (recycling, recycling) – ten loops. The process of returning waste, discharges and emissions into the production cycle can be carried out by almost all elements of the environmental chain.

The *repair* process (repair, maintenance) creates a single logistical loop, as the repair and maintenance of a faulty product for use in accordance with the original purpose requires the participation of the repair center.

The *repurpose* process creates three logistic loops, as the path of the failed product to the product manufacturer goes through the collection center or collection center and

repair center, and parts of the product move through the disassembly center.

The *recover* process creates two loops in the logistics chain, because after disassembling the products, the products and their components can go to the parts manufacturers and product manufacturers.

The processes of *refurbish* (update, repair) and *remanufacture* (update, modification) create two loops, as products from consumers can come to the repair center through the collection center, and directly.

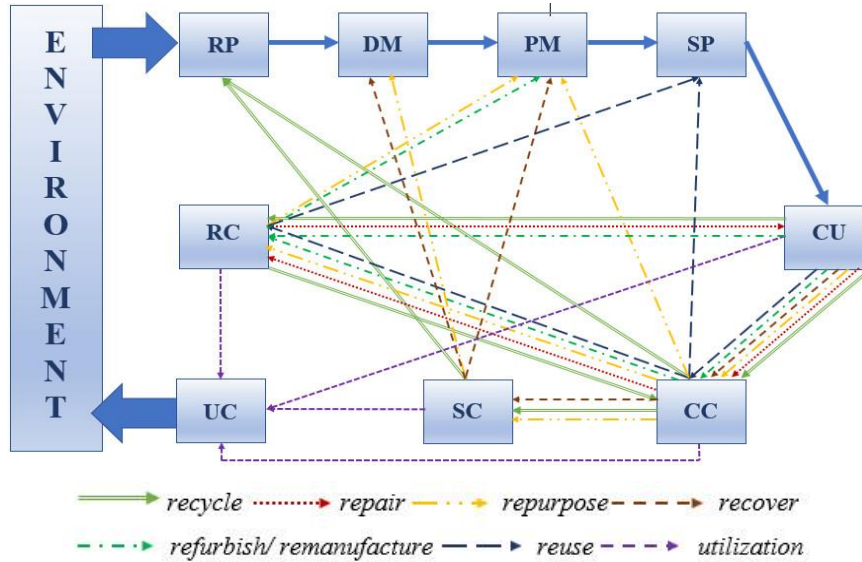


Fig. 1. Logistics system with feedback

The *reuse* process creates two loops because it involves reusing the product for original or new purposes in its original form or with some changes and minor improvements.

In addition to the reverse processes in the circular economy model, there is a process of *utilization*, which aims to safely recycle waste that cannot be used in another, more efficient way.

**Mathematical model of a logistics system with feedback**

The essence of the mathematical model is the formation of reverse material flows, which allow to close the supply chain through the organization of circular processes and achieve the maximum value of the total cash flow from their implementation. To solve this problem, the method of linear programming of economic and mathematical modeling (distribution problem) is used.

Assume that the movement of material flow is carried out from link *i* to link *j* of the logistics chain. The designations of the chain links are as follows:  $i = \{I_E; I_{RP}; I_{DM}; I_{PM}; I_{SP}; I_{CU}; I_{CC}; I_{SC}; I_{RC}; I_{UC}\}$ ;  $j = \{J_E; J_{RP}; J_{DM}; J_{PM}; J_{SP}; J_{CU}; J_{CC}; J_{SC}; J_{RC}; J_{UC}\}$ , where  $\{I_E; I_{RP}; I_{DM}; I_{PM}; I_{SP}; I_{CU}\}$ ,  $\{J_E; J_{RP}; J_{DM}; J_{PM}; J_{SP}; J_{CU}\}$  – sets of participants in the direct logistics chain,  $\{I_{CU}; I_{CC}; I_{SC}; I_{RC}; I_{UC}\}$ ,  $\{J_{CU}; J_{CC}; J_{SC}; J_{RC}; J_{UC}\}$  – sets of participants in the reverse logistics chain. Chains begin and end with the following elements:  $I_{RP} (J_{RP})$  – first participant in the direct logistics chain (resource provider),  $I_{CU} (J_{CU})$  – last direct chain participant and first reverse chain participant (consumer / user),  $I_{UC}$  – last participant in the reverse

logistics chain (utilization center),  $I_E$  – natural environment.

The objective function of the mathematical model is the total cash flows from the organization of the reverse (recycling and utilization) flow of material resources in the logistics chain

$$CF = \sum_{i=I_{CU}}^{I_{UC}} \left( \sum_{j=J_{RP}}^{J_{RC}} \sum_{p=1}^P \sum_{l=1}^L cf_{ij}^{pl} \cdot x_{ij}^{pl} + cf_i^u \cdot u_i \right) \rightarrow \max, \quad (1)$$

where  $x_{ij}^{pl}$  – the amount of product (material flow) coming from the link *i* ( $i = \overline{I_{CU}; I_{RC}}$ ) and enters the link *j* of the logistics chain ( $j = \overline{J_{RP}; J_{RC}}$ ) through the loop *l* ( $l = \overline{1; L}$ ) of the circular process *p* ( $p = \overline{1; P}$ );  $cf_{ij}^{pl}$  – cash flows generated by the movement of a unit of material flow from the link *i* ( $i = \overline{I_{CU}; I_{UC-1}}$ ) to the link *j* of the logistics chain ( $j = \overline{J_{RP}; J_{RC}}$ ) through the loop *l* ( $l = \overline{1; L}$ ) of the circular process *p* ( $p = \overline{1; P}$ );  $u_i$  – the amount of products that are disposed of from the link *i* ( $i = \overline{I_{CU}; I_{RC}}$ ) of the logistics chain;  $cf_i^u$  – cash flows generated by the disposal of a unit of material flow in the chain *i* ( $i = \overline{I_{CU}; I_{RC}}$ ) of the logistics chain.

- Restrictions:
- for the return or utilization of all products entering the links of the reverse logistics chain, taking into account that

$$\sum_{i=ICU}^{IRC} \sum_{p=1}^P \sum_{l=1}^L x_{ij}^{pl} = a_j, \quad (2)$$

where  $a_j$  – the number of products that arrive in the link  $j$  ( $j = \overline{J_{CU}; J_{RC}}$ ) of the reverse logistics chain, we will accept that  $a_j = b_j$ ;  $\forall i = j$ , then

$$\sum_{j=JRP}^{JRC} \sum_{p=1}^P \sum_{l=1}^L x_{ij}^{pl} + u_i = b_i, \quad (3)$$

where  $b_i$  – the number of products that come out of the link  $i$  ( $i = \overline{I_{CU}; I_{RC}}$ ) of the reverse logistics chain.

- on non-exceeding the capacity of the links of the reverse logistics chain

$$\sum_{i=ICC}^{IRC} \sum_{p=1}^P \sum_{l=1}^L x_{ij}^{pl} \leq g_j, \quad (4)$$

where  $g_j$  – the number of return products in which there is a need for the link  $j$  ( $j = \overline{J_{CC}; J_{RC}}$ ) of the logistic chain.

- for the needs of the links of the direct logistics chain in the reverse material flow

$$\sum_{i=IRP}^{ICU} \sum_{p=1}^P \sum_{l=1}^L x_{ij}^{pl} \leq h_j, \quad (5)$$

where  $h_j$  – the number of return products in which there is a need for the link  $j$  ( $j = \overline{J_{RP}; J_{CU}}$ ) of the logistic chain.

- for the maximum volume of product utilization in the links of the direct logistics chain

$$u_j \leq k_{dj} \cdot x_{ij}, \quad (6)$$

where  $k_{dj}$  – utilization coefficient in the link  $j$  of material flow ( $j = \overline{J_{RP}; J_{CU}}$ ) received from the link  $i$  of the direct logistics chain ( $i = \overline{I_E; I_{SP}}$ ).

- for the maximum volume of product utilization by the links of the reverse logistics chain

$$\sum_{j=JCU}^{JRC} u_j \leq k_r \left( x_{IE} - \sum_{j=JRP}^{JSP} u_j \right), \quad (7)$$

where  $k_r$  – utilization coefficient in the reverse logistics chain.

Due to the use of the proposed mathematical model it is possible to solve the problem of optimization of reverse recycling and utilization of material flows in the logistics system, which will achieve the maximum value of total cash flows from the introduction of circular processes.

Experimental calculations of the corresponding distribution problem, which were performed by the simplex method, confirmed the adequacy of the model and allowed to distribute the material flows in the same way as presented in table 2.

**Table 2.** Logistics loops of reverse logistics chains

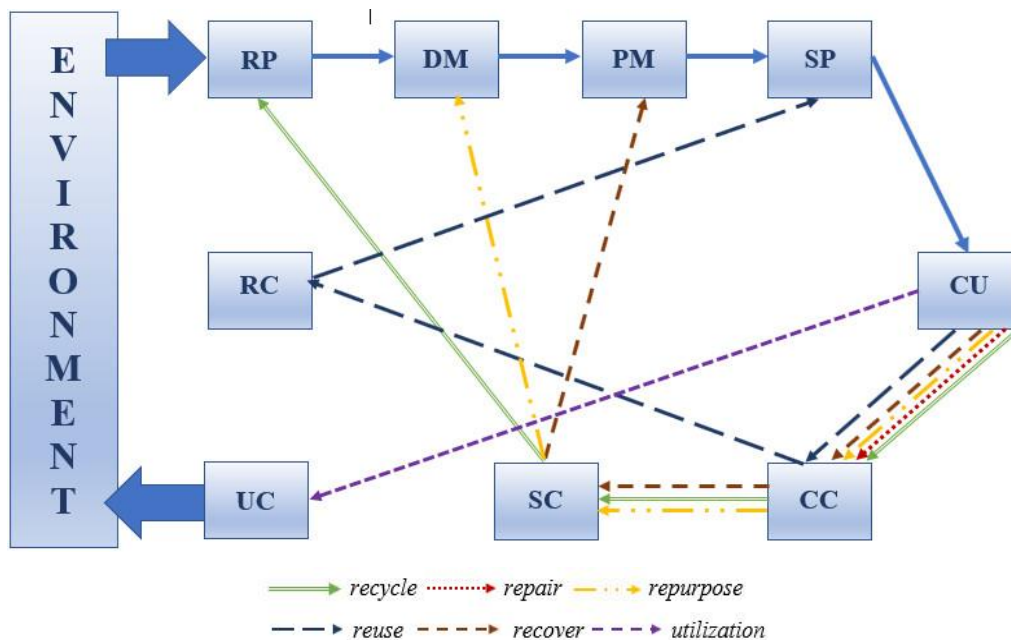
Circular process	Logistics loop	Reverse material flow (tone)			
1 recover	11	CU	CC	SC	PM
		600	600	600	600
	12	CU	CC	SC	DM
		0	0	0	0
2 refurbish/remanufacture	21	CU	RC	PM	
		0	0	0	
	22	CU	CC	RC	PM
		0	0	0	0
3 reuse	31	CU	CC	SP	
		0	0	0	
	32	CU	CC	RC	SP
		1000	1000	1000	1000
4 repurpose	41	CU	CC	PM	
		0	0	0	
	42	CU	CC	RC	PM
		0	0	0	0
	43	CU	CC	SC	DM
		600	600	600	600

End the **Table 2.**

5 repair	51	CU	CC	RC	CU
		2000	2000	2000	2000
6 recycle	61	CU	CC	SC	RP
		500	500	500	500
	62	CU	CC	RP	
		0	0	0	
	63	CU	RC	CC	SC
		0	0	0	0
	64	CU	RC	CC	RP
		0	0	0	0

When solving the problem, all the restrictions were met and the maximum value of the objective function (total cash flows) was reached - 43602.5 USD. At the same time, logistics loops were created, providing

feedback within closed logistics chains, within five circular processes: recover, reuse, repurpose, repair, and recycle. The utilization process is also taken into account (fig. 2).



**Fig. 2.** Experimentally obtained closed logistics system

### Conclusions

The concept of a circular economy is based on the principles and objectives of the concept of sustainable development and emphasizes the need to close logistics systems, ie to create logistics systems with feedback. The tools for implementing the concept of a circular economy are closed supply chains, which include direct and reverse material flows. There are closed chains due to the use of circular processes: recover, recycle, refurbish, remanufacture, repurpose, repair, reuse, which create logistics loops between the participants in the logistics chain. Logistics loops provide feedback between the

participants in the chain and allow you to organize the reverse flow of products, their components, raw materials and materials.

The use of economic and mathematical modeling methods allows you to create a mathematical model of the problem of optimizing return material flows and distribute material resources in loops that are created within the circular processes of the logistics chain, so that the total cash flows of the logistics system reach the maximum value, and the eco-destructive impact on the environment due to the creation of return flows of secondary material resources is minimal.

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Received 24.11.2020

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## МОДЕЛЬ ФОРМУВАННЯ ЗАМКНУТИХ ЛАНЦЮГІВ В ЛОГІСТИЧНІЙ СИСТЕМІ ЗІ ЗВОРОТНИМ ЗВ'ЯЗКОМ

**Предметом** дослідження в статті є зворотні потоки матеріальних ресурсів в межах циркулярних процесів замкнутих ланцюгів постачань логістичної системи зі зворотним зв'язком. **Метою** даної статті є розробка моделі формування зворотних

матеріальних потоків з застосуванням процесів циркулярної економіки, що дозволить досягти максимальної ефективності функціонування логістичної системи. Для досягнення поставленої мети необхідно вирішити наступні **завдання**: визначити сутність та дослідити еволюцію циркулярної економіки через зміну фреймворків, що її утворюють; розробити графічну модель логістичної системи зі зворотним зв'язком, яка базується на впровадженні циркулярних процесів; розробити математичну модель логістичної системи зі зворотним зв'язком та провести експериментальні розрахунки, що підтверджують її адекватність. Для вирішення поставлених завдань в дослідженні використовуються **методи** системного аналізу, дослідження операцій, а саме лінійного програмування (розподільна задача вирішується симплекс-методом). Отримано наступні **результати**: досліджено сутність циркулярної моделі економіки, еволюцію її фреймворків та процесів, що входять до їх складу; за допомогою циркулярних процесів представлено графічну модель логістичної системи зі зворотним зв'язком; створено математичну модель логістичної системи зі зворотним зв'язком. **Висновки**. Концепція циркулярної економіки базується на принципах та цілях концепції сталого розвитку та наголошує на необхідності замикання логістичних систем, тобто створенні логістичних систем зі зворотним зв'язком. Інструментом реалізації концепції виступають замкнуті ланцюги поставок, до складу яких входять прямі та зворотні матеріальні потоки. Виникають замкнуті ланцюги завдяки використанню циркулярних процесів, які створюють логістичні петлі, які забезпечують зворотний зв'язок між учасниками ланцюга та дозволяють організувати зворотний потік продуктів, їх компонентів, сировини та матеріалів. Застосування методів дослідження операцій дозволяє створити математичну модель завдання оптимізації зворотних матеріальних потоків та розподілити матеріальні ресурси за петлями, таким чином, щоб загальні потоки грошових коштів логістичної системи досягли максимального значення, а екодеструктивний вплив на навколишнє середовище завдяки створенню зворотних потоків вторинних матеріальних ресурсів був мінімальним.

**Ключові слова**: циркулярний процес; замкнутий логістичний ланцюг; логістична петля; зворотний матеріальний потік.

## МОДЕЛЬ ФОРМИРОВАНИЯ ЗАМКНУТЫХ ЦЕПЕЙ В ЛОГИСТИЧЕСКОЙ СИСТЕМЕ С ОБРАТНОЙ СВЯЗЬЮ

**Предметом** исследования в статье есть обратные потоки материальных ресурсов в рамках циркулярных процессов замкнутых цепей поставок логистической системы с обратной связью. **Целью** данной статьи является разработка модели формирования обратных материальных потоков с применением процессов циркулярной экономики, что позволит достичь максимальной эффективности функционирования логистической системы. Для достижения поставленной цели необходимо решить следующие **задачи**: определить сущность и исследовать эволюцию циркулярной экономики путем изменения образующих ее фреймворков; разработать графическую модель логистической системы с обратной связью, которая базируется на внедрении циркулярных процессов; разработать математическую модель логистической системы с обратной связью и провести экспериментальные расчеты, подтверждающие ее адекватность. Для решения поставленных задач в исследовании используются **методы** системного анализа, исследования операций, а именно линейного программирования (распределительная задача решается симплекс-методом). Получены следующие **результаты**: исследована сущность циркулярной модели экономики, эволюции ее фреймворков и процессов, входящих в их состав; с помощью циркулярных процессов представлена графическая модель логистической системы с обратной связью; создана математическая модель логистической системы с обратной связью. **Выводы**. Концепция циркулярной экономики базируется на принципах и целях концепции устойчивого развития и подчеркивает необходимость замыкания логистических систем, то есть создания логистических систем с обратной связью. Инструментом реализации концепции выступают замкнутые цепи поставок, в состав которых входят прямые и обратные материальные потоки. Возникают замкнутые цепи благодаря использованию циркулярных процессов, которые создают логистические петли, которые обеспечивают обратную связь между участниками цепи и позволяют организовать обратный поток продуктов, их компонентов, сырья и материалов. Применение методов исследования операций позволяет создать математическую модель задачи оптимизации обратных материальных потоков и распределить материальные ресурсы по петлям, таким образом, чтобы общие потоки денежных средств логистической системы достигли максимального значения, а екодеструктивное влияние на окружающую среду благодаря созданию обратных потоков вторичных материальных ресурсов было минимальным.

**Ключевые слова**: циркулярный процесс; замкнутая логистическая цепь; логистическая петля; обратный материальный поток.

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