ЕКОНОМІКО-МАТЕМАТИЧНЕ МОДЕЛЮВАННЯ БІЗНЕСОВИХ ПРОЦЕСІВ

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STUDY OF THE REVERSE LOGISTICS NETWORK IN INDUSTRY 5.0

ДОСЛІДЖЕННЯ МЕРЕЖІ ЗВОРОТНОЇ ЛОГІСТИКИ В ІНДУСТРІЇ 5.0

The article focuses on remanufacturing, the process of restoring the functionality of end-of-life products, which is considered an important link in reverse logistics systems to recover value. The aim of the paper is to prove that reverse logistics is important for business, as it allows to effectively manage returns, minimise losses, reduce waste and increase customer satisfaction. The market-based contractual system of reverse logistics for remanufacturing is studied. A mixed integer programming model is developed for making key tactical decisions, namely: setting up the systemic remanufacturing, production and inventory levels, purchasing and transporting the main components, as well as loading and balancing the remanufacturing line within the planning horizon.

Keywords: *remanufacturing, integer programming, reverse logistics, costs, solvency.*

Статтю присвячено ремануфактурингу – процесу відновлення функціональності продукції, що відслужила свій термін, який вважається важливою ланкою в системах реверсивної логістики для відновлення цінності. За останні два десятиліття проектування мереж зворотної логістики стало широко досліджуваною сферою як для науковців, так і для промисловців-практиків. Мета цієї статті – довести, що зворотна логістика важлива для бізнесу, оскільки дозволяє ефективно управляти поверненням, мінімізувати втрати, зменшити відходи та підвищити рівень задоволеності клієнтів. Досліджено ринкову контрактну систему зворотної логістики для ремануфактуризації. Розроблено модель змішаного цілочисельного програмування для прийняття ключових тактичних рішень, а саме: налагодження ремануфактуризації системи, закупівлі та транспортування основних компонентів, а також завантаження та балансування лінії ремануфактуризації в межах горизонту планування. На прикладі реверсної логістичної мережі між пунктами збору старих холодильників, а саме: Київ, Дніпро, Черкаси, доведено прибутковість такого підприємства. Розраховано мінімальний та максимальний дохід цього підприємства. Оскільки дохід є багатокритеріальним показником, було проаналізовано декілька факторів, а саме: кількість холодильників, вартість ремонту та вартість транспортування. Маршрути були оптимізовані для зменшення транспортних витрат. В роботі розраховано викиди шкідливих речовин в процесі експлуатації автомобільного транспорту, який є потужним джерелом забруднення довкілля. Розглядаються вуглецеві витрати, які впливають на вуглецеві податки, що виникають в результаті експлуатації об'єкта та транспортної діяльності. Витрати на викиди вуглецю враховуються для вуглецевих податків, що виникають в результаті експлуатації об'єкта та транспортної діяльності. Майбутні дослідження повинні зосередитися на розробці нових моделей і методів для кращого врахування впровадження технологій у рішеннях щодо проектування та експлуатації систем, щоб сприяти плавному промисловому і соціальному переходу.

Ключові слова: *ремануфактура, цілочисельне програмування, реверсивна логістика, витрати, платоспроможність.*

Problem statement. The solvency of Ukrainians is declining due to the beginning of the full-scale invasion of Ukraine. This was also influenced by the appreciation of the currency, which in turn led to an average 20–30% increase in prices for most imported goods. In the first three weeks of the war, according to the UN, almost 10 million Ukrainians were forced to flee their homes because of the war, of which 6.5 million were internally displaced and 3.2 million had already left the country.

Therefore, in this situation, remanufacturing, the process of restoring the functionality of products with an expired service life, is relevant.

This article investigates the market contractual system of reverse logistics for the remanufacturing of refrigerators. A model of mixed integer programming for making key tactical decisions is developed.

Analysis of recent research and publications. Reverse logistics is a concept that originated in the 1980s and describes the reverse flow of material compared to the forward flow.

Planning an effective reverse logistics system is an important and challenging task, where quantitative methods and operations research models have been intensively developed since the 1990s. Mixed integer methods are used to make decisions about nodes and arcs in strategic planning. Early studies developed models to minimise total cost or maximise total profit for used vehicle recycling networks. The incorporation of new technologies, such as big data, has become another emerging research area in this field. The following prominent scholars have addressed these issues: Abid, S., Mhada, F.Z. [1], H. Yu and X. Sun [2]. Among the works of Ukrainian scientists are M. Hryhorak [3], A. Dziubina [4]. However, at the same time, the issues of effective implementation of reverse logistics tools and its organisation at industrial enterprises, which have many features, require more attention in the context of scientific research.

Formulating the purposes of the article. The aim of the article is to determine the reverse logistics network in Industry 5.0.

Presentation of the main research material. At present, there are no high-quality refrigerators of our own production in Ukraine. The only refrigerators produced in Ukraine are Saturn refrigerators. This brand was registered in the Czech Republic in 1996. The company offered exclusive models and later began cooperation with factories in China, Turkey, and Taiwan. Several factories were built in Ukraine – in Kaniv and Cherkasy. The company that owns the Saturn brand has invested more than $30 million in the new plant. The price of household refrigerators is between UAH 9,000 and 13,000. The new plant produces about 300,000 units of refrigerators per year, using technologies from Chinese manufacturers.

It should be noted that in the 1970s and 1990s, the Dnipro Refrigerator Plant produced high-quality household electric refrigerators (Dnipro, Dnipro-2, Dnipro-2M, Dnipro-2MS). Nord refrigerators were also popular before the events of 2014. Today, due to the Russian invasion, Nord refrigerators are no longer available.

The Ukrainian home appliance market is flooded with imported goods. The best fridges are Samsung, LG, Bosch, Siemens (Fig. 1). Prices for these fridges range from 16000 UAH to 26000 UAH. The cheapest refrigerator with a freezer in Ukraine is Grunhelm VRM-S49M45-W, the price of which ranges from: 3932–3999 UAH.

In September 2024, inflation accelerated to 8.6% (+1.5% m/m) due to rising processed food prices, higher input costs, and ongoing pressure from the previous hryvnia devaluation. Let's build a reverse logistics network structure.

Let us consider an example. Let's mark a reverse logistics network on a map of Ukraine. The local collection points for old refrigerators will be Kyiv, Dnipro, Cherkasy (Fig. 2). Old refrigerators are sold for up to UAH 2000.

Let's write the objective function. The main fixed costs will be: transport costs, repair cost sand emission fees (Table 1). F is the fixed cost of organizing a regional collection center for old refrigerators (Table 2).

Using the salesman method, we optimize the cost of transporting refrigerators to recycling centers.

The travelling salesman problem is a shortest path problem (1).

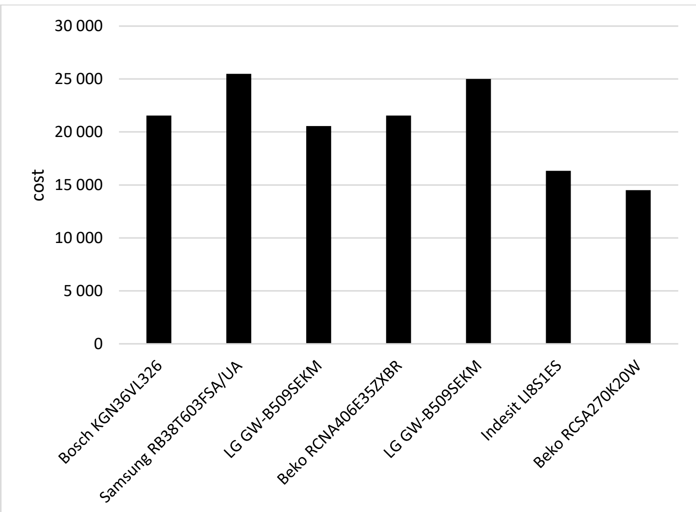

Figure 1. Cost of the most popular refrigerators

Source: built based on [6]

Figure 2. Network structure on the map of Ukraine

Source: author's development

$$z_{\min} = F + \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{c=1}^{C} d_{ij} x_{ji} s_{ic} + \sum_{i=1}^{N} \sum_{j=1}^{k} \sum_{g=1}^{g} u_{ij} x_{ji} s_{ig} + v \quad (1)$$

x_{ij}=1 if city *j* can be reached from city *i* and 0 otherwise; d_{ij} distance from city *i* to city *j*; s_{ic} price of transportation; u_{ij} which parts need to be replaced; x_{ij} number of parts; s_{ic}price of parts; N number of refrigerators; n number of cities; *k* number of parts; s_{ig} price of parts. *v* is the emission fee.

Constraints:

$$\sum_{i=1}^{n} x_{ij} = 1, i = 1, 2, ..., n, \qquad \sum_{j=1}^{n} x_{ij} = 1, j = 1, 2, ..., n, \quad (2)$$

x_{ij} =0 або 1.

$$\sum_{i=1}^{K} \sum_{j=1}^{N} \sum_{n=1}^{M} u_{ij} x_{ji} s_{ic} < \sum_{i=1}^{n} S_i \quad (3)$$

The route optimization results in savings of 22420 UAH (2)–(3).

The resulting profit can be written in the following formula:

$$z_{\max} = N * s - (F + \sum_{i=1}^{n} \sum_{j=1}^{n} \sum_{c=1}^{C} d_{ij} x_{ji} s_{ic} + \sum_{i=1}^{N} \sum_{j=1}^{k} \sum_{g=1}^{g} u_{ij} x_{ji} s_{ig} + v \quad (4)$$

where s is the price of the fridge.

Let's use a free tool from Google Trends, designed to compare and analyses trends in the popularity of certain products in a particular city or region. With its help, we get data on the demand for refrigerators (Fig. 3).

Among household appliances, Ukrainians are most interested in refrigerators, freezers and microwaves. Ukrainians are looking for refrigerators at a price of UAH 6,500. Let's assume that sales of refrigerators follow a uniform law of demand distribution Figure 5:

$$f(D) = \begin{cases} \frac{1}{(b-a)}, D \in (a;b) \\ 0, D \notin (a;b) \end{cases} \quad (5)$$

where a,b are the lower and upper bounds of the range. The lower bound is zero, and the upper bound is 2 thousand refrigerators per month (Fig. 4).

The next step is to transport the old refrigerators to the collection points. We have three collection points: Kyiv, Cherkasy and Dnipro. Let's analyses the cost of transportation from cities and towns in these regions. The Kyiv region, which covers 28,131 km², had a population of 1.8 million people as of the end of 2022. The distance to Kyiv from the largest cities and towns is 1516.34 km, and the cost of transportation is UAH 94870.35. Accordingly, the population of Dnipro region is 3.096 million, and the distance from Dnipro to the largest cities is 1443.014 km, with a transportation cost of UAH 10,7053. As of 1 January 2022, the population living in the region was 1160.7 thousand people. The cost of transportation in the Cherkasy region is UAH 44674, and the total distance to Cherkasy from small towns is 874.5 km.

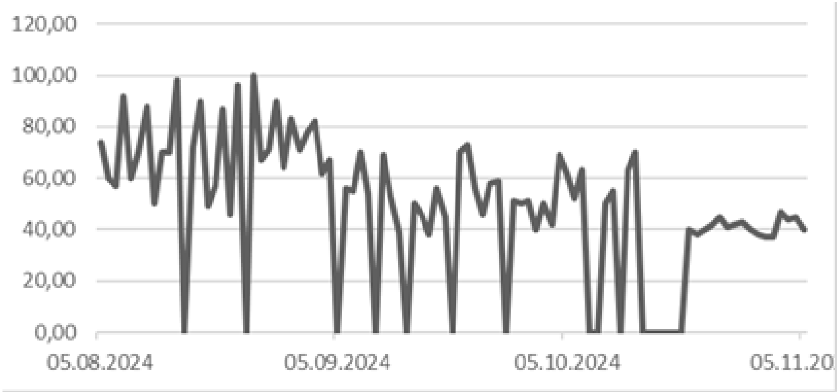

Figure 3. Requests for refrigerators in Ukraine in 90 days

Source: compiled by the authors

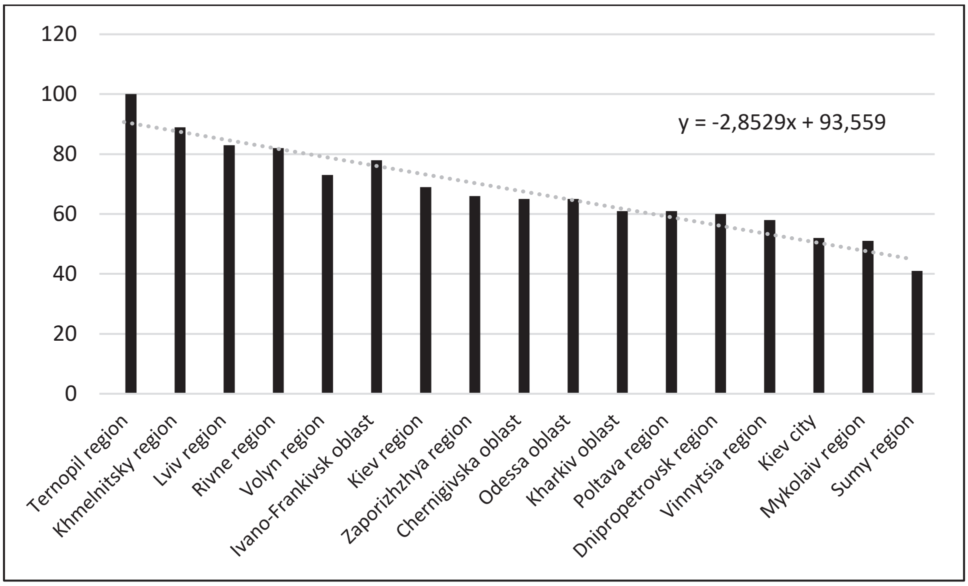

Figure 4. Popular queries by territorial units of Ukraine for 90 days

Source: built based on [6]

Table 1

Costs of repairing a refrigerator

Title	Price
Freon for refrigerators and air conditioners	3 065
Sensors, sensors for refrigerators	335
Doors for refrigerators	3 860
Fasteners for refrigerators	325
Sensors, sensors for refrigerators	335
Compressors for refrigeration systems	7920

Source: built based on [6]

Carbon emission costs are determined by formula (6), which is used to account for carbon taxes arising from facility operations and transport activities.

Vehicles are powerful sources of environmental pollution. Every year, a large amount of toxic and aggressive substances are released into the air of settlements from engine exhaust gases (EGR).

For the purposes of reporting on air protection, assessing the level of pollution from mobile sources, and stimulating the implementation of environmental protection measures, it is necessary to calculate the mass emissions of harmful substances released into the atmosphere from vehicle exhaust gases.

During the operation of motor vehicles, emissions of harmful substances (HS) change significantly. In order to assess the toxicity of vehicles during operation objectively, it is necessary to take into account a large number of factors that determine the number of pollutants released into the environment. Numerous studies have shown that all of these factors accurately characterize vehicle fuel consumption. Therefore, the calculation of mass emissions of HS is based on information about the mass of fuel consumed by a car over a certain period of time. This value depends on operational factors and therefore takes into account their influence.

Mass emissions are calculated based on the specific emissions of HS per unit mass of fuel consumed by a vehicle with an engine of a given type. Specific emissions are set for engines that are in good working order and properly adjusted.

Table 2

Transportation of refrigerators to markets

Title1	Title2	Distance	Price 1 km	Cost of transport (UAH)
Kyiv	Cherkasy	203,4	46	9356,4
Kyiv	Dnipro	449	47	21103
Cherkasy	Dnipro	321,6	45	14472
Total				44931,4

Source: built based on [6]

Table 3

Mathematical expectation of income

F	The price of an old fridge		Transport costs		Repair costs		Demand		Revenue		Realisation price (UAH.)	
max	min	max	min	max	min	max	min	max	min	max	min	max
10^6	1000	2000	246597	227881	3500	7920	100	134000	4658471	4828334	6500	8000

Source: compiled by the authors

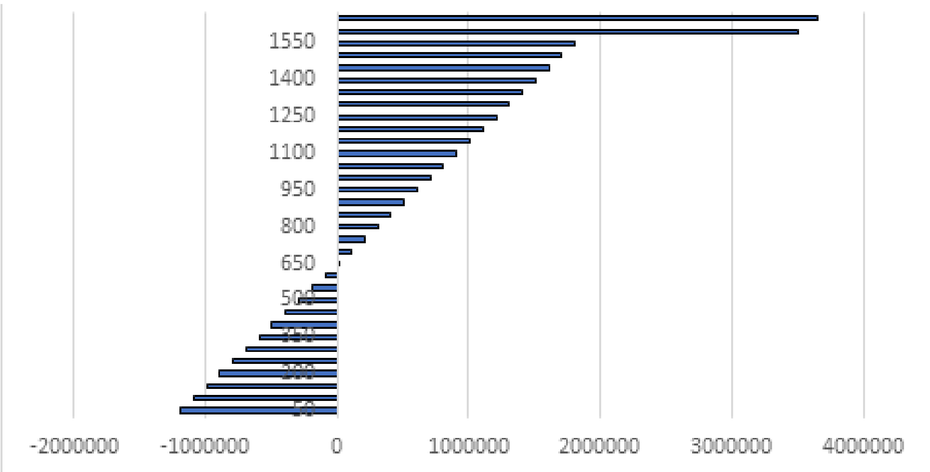

Figure 5. Revenue of the enterprise depending on the number of repaired refrigerators

Source: compiled by the authors

The calculation of the mass of emission of the *i*-th HS by the rolling stock of road transport, which has n groups of vehicles of the *k*-th type, for a certain period of time t is carried out depending on the information on fuel consumption and the number of vehicles of a certain type and group.

Types of harmful substances to be calculated:

– *CO* – carbon monoxide;
– *CH* – hydrocarbons;
– NO_2 – nitrogen oxides;
– *PM* – particulate matter (should be divided into two types.

They are calculated as follows:

Mass emissions of individual harmful substances, calculated according to dependence (6), t/year:

$$M_i = \sum_{m=1}^{m} g_{icj} G_j K_{Tikj} k_j \qquad (6)$$

where g_{icj} is the average specific emission of the *i*-th harmful substance per unit mass of the *j*-th fuel type, kg/t; G_j – is the consumption of the *j*-th vehicle fuel for a certain period, t/year; K_{Tikj} – is a coefficient that takes into account the impact of the technical condition of a vehicle of the *k*-th type consuming the *j*-th fuel on the value of specific emissions; k_j – is the coefficient of reduction to the environmental class of the vehicle.

During operation, changes in the technical condition of the vehicle and violations of its regulations are possible, which cause an increase or decrease in emissions of individual GHG components. In the calculations, these changes are taken into account by introducing the correction factor K_{Tikj} , which is selected depending on the HS (j), the mass of which is calculated, the type of vehicle *(k)* and the type of fuel consumed *(i)*. The values of the coefficients K_{Tikj} are given in Table 4.

Fuel consumption is calculated using formula (7), t/year:

$$G_j = m_k \cdot S_k \cdot G_i \cdot \rho_i \cdot 10^{-5} \qquad (7)$$

where m_k is the number of vehicles of the *k*-th type, S_k is the mileage of one vehicle of the *k*-th type per year, thousand km/year; G_i is the fuel consumption of the vehicle of the *k*-th type, l/100 km; ρ_i is the density of the *i*-th type of fuel, kg/l.

The values of specific emissions of SE g_{icj} , by modern vehicles are given in Table 5.

Based on the mass emissions of individual components, the total mass emissions of SE by the vehicle fleet are calculated.

For the calculation of Euro-0 vehicles, k_j is equal to 1. For the calculation of Euro-1 to Euro-5 vehicles, conversion factors are used, which are multiplied by the value of mass emissions of pollutants (Table 6).

Average vehicle fuel consumption in liters per 100 km for trucks with petrol engines is 25 liters of petrol per 100 km. The average density of A92 petrol is 0.715–0.760 kg/l. The average cost of 1 liter of petrol is UAH 53.

The calculation of the total economic loss is carried out in accordance with the EU methodology. In accordance with Directive 2009/33/EC of the European Parliament and of the Council, the amount of damage should be calculated using the formula (8) in EUR, taking into account the coefficients shown in Table 7.

$$K = \sum_{j=1}^{m} \varphi_j M_j 10^{-6} \quad (7)$$

where φ_j is the value that determines the emission fee per unit of the j-th harmful substance, EUR/g (Table 8); M_i is the mass of the j-th pollutant emitted by cars for a certain period, t/year.

Table 4

Values of the coefficient K_{Tikj}

Vehicle groups	K-values of K_{Tikj} i for different SR			
	CO	CH	NO_x	PM
Trucks with engines powered by petrol or LPG	1,7	1,8	0,9	–
Trucks with diesel engines	1,5	1,4	0,95	1,8
rucks and buses with LNG-fuelled engines	1,7	1,8	0,9	–

Source: built based on [5]

Table 5

Average specific vehicle emissions of harmful substances

Type of fuel	Specific emissions of SE, kg/t of fuel			
	g_{CO}	g_{CH}	g_{NOx}	g_{PM}
Trucks with engines powered by petrol	196,5	37,0	21,8	–
Trucks with diesel engines	36,0	6,2	31,5	3,85
Trucks and buses with LNG-fuelled engines	87,5	22,4	27,6	–

Source: built based on [5]

Table 6

Conversion factors for k_j to Euro

Pollutants	Environmental classes of vehicles					
	Євро-0	Євро-1	Євро-2	Євро-3	Євро-4	Євро-5
CO	1	0,4	0,32	0,17	0,12	0,12
NO_x	1	0,55	0,49	0,34	0,24	0,13
C_nH_m	1	0,46	0,46	0,28	0,2	0,2
PM	1	0,51	0,21	0,14	0,03	0,03

Source: built based on [5]

Table 7

Calculation of emission charges in Euros

Pollutants	M_i	g_{icj}	G_j	K_{Tikj}	k_j	φ_j	K(EUR)
Co	22207,64	196,5	554	1,7	0,12	0,0001	0,002220764
CH	8855,136	37	554	1,8	0,24	0,001	0,008855136
No	2173,896	21,8	554	0,9	0,2	0,004	0,008695584
PM	0				0,03	0,087	
Total	33236,68						0,019771484

Source: built based on [5]

Table 8

Emission charge per unit of the *j*-th AR, EUR/g

Pollutants	*CO*	*CH*	NO_x	*PM*
Payment for emissions per unit of the *j*-th SE	0,00011	0,001	0,0044	0,087

Source: built based on [5]

Conclusions. This paper discusses remanufacturing, the process of restoring the functionality of products with an expired service life. Over the past two decades, the design of a reverse logistics network has become a widely researched area for both academics and industrial practitioners. An integer model was used for calculations.

An example of an enterprise that refurbishes old refrigerators is considered. The minimum and maximum income of this enterprise is determined. Since income is a multicriteria indicator, several factors were analyzed, namely the number of refrigerators, the cost of repair, and the cost of transportation. The routes were optimized to reduce transportation costs.

The paper also examines the carbon costs, which affects the carbon taxes arising from the operation of the facility and transport activities.

There is a great deal of uncertainty in the paper, so future work should focus on developing new models and methods to better incorporate technology adoption into system design and operation decisions to facilitate a smooth industrial and social transition.

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