https://doi.org/10.21122/2227-1031-2022-21-6-517-524

UDC 656.021.8

Organization of Logistics Operations for Transportation of Household Electronic Waste in Cities

D. V. Kapskiy[1], O. N. Larin[2], Nguyen Thi Thu Huong[3], L. V. Khmelnitskaya[1]

[1]Belarusian National Technical University (Minsk, Republic of Belarus),
[2]Russian University of Transport (Moscow, Russian Federation),
[3]Plekhanov Russian University of Economics (Moscow, Russian Federation)

Abstract. The paper presents the methodological provisions for the organization of logistics operations during the transportation of household electronic waste in large cities. Human activity is accompanied by the formation of waste, the amount of which has recently increased. In modern conditions, households actively use electronic and electrical devices. Therefore, a lot of household electronic and electrical waste is generated, which is hazardous to the environment and must be disposed of in accordance with legal requirements. The efficiency of disposal of household electronic waste depends on the organization of logistics operations for the collection, accumulation and removal of such waste. The main methodological stages of logistical support for the recycling process include the formation of a hierarchy of territorial formations (taxons), standardization of waste generation indicators for taxa of each level in the hierarchy, designing the configuration of a network of collection points for acceptance and temporary storage of waste within the boundaries of the service area, substantiating the rational storage capacity of each point and deadlines for waste storage; planning the transportation of waste from accumulation points to objects of their further processing. When planning the transportation of waste, the actual volume of waste accumulation at each collection point is taken into account, transportation routes are designed for the shortest distances, taking into account the capacity of vehicles. The main feature of the developed method of waste removal is the operational adjustment of routes so that the car drives only to those accumulation points where the actual volume of waste has reached the maximum storage capacity. This approach ensures timely waste collection and lower transportation costs compared to existing methods that organize waste collection at a specified frequency. The developed methodology was tested on the basis of statistical data from Hanoi (Vietnam). The results of numerical experiments show that the application of methods provides a reduction in transport costs for the removal of household electronic waste, and also increases the level of their collection and disposal.

Keywords: recycling, logistics operations, household electronic waste, waste collection points, waste disposal

For citation: Kapskiy D. V., Larin O. N., Nguyen Thi Thu Huong, Khmelnitskaya L. V. (2022) Organization of Logistics Operations for Transportation of Household Electronic Waste in Cities. *Science and Technique*. 21 (6), 517–524. https://doi.org/10. 21122/2227-1031-2022-21-6-517-524

Организация логистических операций при перевозке электронных бытовых отходов в городах

Докт. техн. наук Д. В. Капский[1], докт. техн. наук, проф. О. Н. Ларин[2], асп. Нгуен Тхи Тху Хыонг[3], Л. В. Хмельницкая[1]

[1]Белорусский национальный технический университет (Минск, Республика Беларусь),
[2]Российский университет транспорта (Москва, Российская Федерация),
[3]Российский экономический университет имени Г. В. Плеханова (Москва, Российская Федерация)

Реферат. В статье представлены методические положения организации логистических операций при перевозке электронных бытовых отходов в крупных городах. Жизнедеятельность человека сопровождается формированием

Адрес для переписки
Капский Денис Васильевич
Белорусский национальный технический университет
ул. Я. Коласа, 12,
220013, г. Минск, Республика Беларусь
Тел.: +375 17 293-95-70
oapdd_atf@bntu.by

Address for correspondence
Kapskiy Denis V.
Belarusian National Technical University
12, Ya. Kolasa str.,
220013, Minsk, Republic of Belarus
Tel.: +375 17 293-95-70
oapdd_atf@bntu.by

отходов, количество которых в последнее время возрастает. В современных условиях домохозяйства активно используют электронные и электрические устройства. Поэтому образуется много электронных и электрических бытовых отходов, которые представляют опасность для окружающей среды и должны быть утилизированы с соблюдением законодательных требований. Эффективность утилизации электронных бытовых отходов зависит от организации логистических операций по сбору, накоплению и вывозу таких отходов. Основные методические этапы логистической поддержки процесса утилизации включают: формирование иерархии территориальных образований (таксонов), нормирование показателей генерации отходов для таксонов каждого уровня в иерархии, проектирование конфигурации сети сборных пунктов для приемки и временного хранения отходов в границах обслуживаемой территории, обоснование рациональной складской емкости каждого пункта и предельных сроков хранения отходов, планирование перевозки отходов от пунктов накопления до объектов их последующей обработки. При планировании перевозки отходов учитывается фактический объем накопления отходов в каждом пункте сбора, проектируются маршруты перевозок по кратчайшим расстояниям с учетом вместимости транспортных средств. Главная особенность разработанной методики вывоза отходов заключается в оперативной корректировке маршрутов, чтобы автомобиль заезжал только в те пункты накопления, в которых фактический объем отходов достиг предельной емкости складирования. Данный подход обеспечивает своевременный вывоз отходов и снижение затрат на перевозку по сравнению с существующими методами, которые организуют вывоз отходов с установленной периодичностью. Разработанная методика апробирована на основе статистических данных г. Ханой (Вьетнам). Результаты численных экспериментов показывают, что применение методик обеспечивает снижение транспортных затрат на вывоз электронных бытовых отходов, а также повышает уровень их собираемости и утилизации.

Ключевые слова: утилизация, логистические операции, электронные бытовые отходы, пункты сбора отходов, вывоз отходов

Для цитирования: Организация логистических операций при перевозке электронных бытовых отходов в городах / Д. В. Капский [и др.] // *Наука и техника*. 2022. Т. 21, № 6. С. 517–524. https://doi.org/10.21122/2227-1031-2022-21-6-517-524

Introduction

Sustainable economic development is one of the seventeenth Global Goals. Therefore, governments started paying more attention to environmental pollution issues, including electronic household waste (e-waste) pollution. Where e-waste is various forms of electric and electronic equipment (EEE) that have ceased to be of value to their users. E-waste also contains various toxic components such as lead, mercury, cadmium, barium, etc. that can be dangerous to the environment and human health in case of incorrect collecting and treatment. A big amount of recent research indicates broadening of the e-waste amount because of expanding the scale of EEE usage, devices breaking down, short product life cycle, etc. [1–4].

Logistic support for e-waste management (LSEWM) is to ensure the contemporary and cost-effective waste movement along all stages of the reverse logistics chain, such as:

– generation sources of the waste stream (GSWS) located within the boundaries of certain territorial areas (taxa);

– the collecting points (CP) of e-waste acceptance and temporary storage;

– transportation from the CP to the points of accumulation and treatment (PAT);

– further redistribution to the points of e-waste disposal (DP) by the established technology of use (recycling, regeneration, recovery, etc.).

Disadvantages of LSEWM cause low e-waste disposal efficiency [5–7]. Therefore, studying negative factors and improving organizational approaches for LSEWM is an up-to-day scientific objective. The research aim is to study negative factors and to improve organizational and economic conditions for effective LSEWM. The scientific novelty is to develop theoretical approaches for organizing the LSEWM and to create methodological recommendations for increasing LSEWM efficiency.

Methods

The main functions of LSEWM are:

– creating the territorial areas (taxa) hierarchy for LSEWM;

– standardizing generation indicators of e-waste for taxa of each hierarchy level;

– designing the network configuration of e-waste transfer from GSWS within service area boundaries to CP;

– substantiation for the rational storage capacity of each CP and relevant deadlines for e-waste storing there;

– planning of e-waste removal with minimal transportation costs from the CP to PAT.

The LSEWM system contains:

– a complex of standardized regulation of e-waste management;

– licensing of activities for the e-waste disposal;

– the institutional environment of the e-waste disposal;

– interaction models among participants of disposal activities.

Analysis of e-waste management in Vietnam enables us to point out the negative reasons for the lack of disposal efficiency:

– the access of commercial facilities to disposal has not been regulated and the efficiency of its implementation has not been controlled;

– measures have not been taken to develop the infrastructure for e-waste collection;

– economic incentives have not been used to motivate stakeholders to increase the collection of e-waste and reduce the cost of logistics operations such as e-waste shifting to the resource recovery facilities.

It is necessary to organize the interaction among all participants of the reverse logistic chain by the Vietnam administration for planning LSEWM and increasing its efficiency. Where clear separation of power, rights, and duties are implied [8, 9].

For the organization of LSEWM, data on the average daily volumes of e-waste generation in the regions Q_{RD}, t/day, and their districts Q_{PD}, t/day, are required. However, these indicators are not usually known or precise. Statistical analysis on e-waste generation data in various territorial entities reviles statistical relation among scopes of adjacent taxa hierarchy levels. Correlation analysis on the relation between e-waste generation scopes in Hanoi and its districts and the number and density of population has been conducted. Such analysis allows justifying the feasibility of using the calculated data on the average daily volumes of taxon e-waste generation (a city Q_{CD}, e. g.) and subtaxon (lower level of taxon hierarchy, a region Q_{RD}, e. g.) that is possible due to accounting current population. It is feasible through converting average daily volumes in cities Q_{CD}, t/day, into specific indicators by population. Such a specific indicator is an average daily intensity of e-waste generation W_{CD}, kg/capita/day, for an urban area that is calculated as the ratio of the average daily volume of e-waste generation in a city to the number of citizens N_C (thousand people)

$$W_{CD} = \frac{Q_{CD}}{N_C}. \tag{1}$$

The possibility of using the value of intensity indicators of e-waste generation of higher taxa in the hierarchy to determine the generation scale of the adjacent lower taxa is substantiated due to a comparative analysis of the statistical characteristics of e-waste generation indicators for Hanoi and its regions. For instance, the calculated value of the city's density W_{CD} is used for assessing the amount of e-waste in a region Q_{RD}, and the calculated value of the region density W_{RD} is used for assessing the amount of e-waste in a district Q_{PD}. The following are the equations for such cases:

$$Q_{RD} = W_{CD} F_R P_R; \tag{2}$$

$$Q_{PD} = W_{RD} F_P P_P, \tag{3}$$

where F_R, F_P – areas of a region or a district relevantly, km^2; P_R, P_P – population densities of a region or a district accordingly, people/km^2.

To organize a CP network, it is necessary to ensure a high level of accessibility of these points for the population, which is feasible by locating the CP within the acceptable indicator value of their remoteness L_P from the locations of potential GSWS – citizens and households. The value of the L_P indicator is determined by various factors, mainly of a social nature (such as the population age, lifestyle, leisure time, etc.). It is advisable to conduct a direct survey of the population to assess the preferred value of L_P. The value of L_P defines the area boundaries D_i ($i \in P$), which are supposed to be served by one e-waste collection point.

Each service area (SA) is a square cell with the same width L_B, height L_H and area F_P

$$F_P = 4L_P^2. \tag{4}$$

When forming the network for CP, a settlement is divided into a set of R “characteristic districts” in such a way that all of them have the same population density P_{Ri} ($i \in P$). Where the “characteristic district” notion indicates that several “characteristic districts” can be created within or along the boundaries of a regulated administrative area.

District division makes it feasible to improve the accuracy of estimating the volumes of e-waste accumulation at each CP, which is crucial for planning the parameters of e-waste disposal at the PAT.

The planned number of the SA by the territorial boundaries (M_P) is calculated by the equation:

– for cities M_{PC}, U:

$$M_{PC} = \frac{F_C}{F_P}; \quad (5)$$

– for regions M_{PR}, U:

$$M_{PR} = \frac{F_R}{F_P}. \quad (6)$$

The planned number of the SA for Hoang Mai district is (for L_P = 0.9 km, that was determined on the survey data of GSWS with accounting varies economic stimulations)

$$M_{PR} = \frac{F_R}{F_P} = \frac{41}{3.24} = 12.65 \approx 13 \text{ U}. \quad (7)$$

It is necessary to determine the Q_{PD} indicator of the average e-waste daily volume within the boundaries of the area for planned CP by formula (3). The obtained values Q_{PD} are assigned to all CP within the "characteristic region". The value Q_{PD} reviles the potential e-waste volume that can be collected at one CP per day, provided that all GSWS send e-waste for disposal through the official CP network.

The required storage capacity Q_{PB} of CP for temporary storing of e-waste received from the population is calculated based on the Q_{PD} indicator. The minimum CP's capacity corresponds to the average daily generation volume ($Q_{PB\min} = Q_{PD}$), and it is set at the daily removal of e-waste, which corresponds to the value of the accumulation period T_W per day.

Since the daily removal of small batches of e-waste is accompanied by high costs for the transportation S_{TB}, to reduce them, it is possible to set intervals for the e-waste removal with a longer duration ($T_{Wm} \geq 1$). However, in this case, it is necessary to increase the storage capacity of the point Q_{PB}, t, to store the stock of e-waste to the size

$$Q_{PB} = Q_{PD} T_{Wm}, \quad (8)$$

that causes an increase of cost S_{CB} on CP maintaining.

The cost S_{CB} for the maintenance of all infrastructure facilities directly depends on their capacity Q_{PB}, while the removing cost S_{TB} decreases as this capacity increases. This makes it possible to find such value Q_{PB}^* that the total costs S_{CBT} is minimal. This also determines the value of the capacity Q_{PB}^*, in relevance with the optimal length of the T_W^* period.

The costs S_{CB} of the maintenance of the CP network depend on the total capacity of the collecting points S_{CB}, CU (currency units), and are calculated by the formula

$$S_{CB} = Q_{PB} U_{PB} T_Y = T_W Q_{PD} N_P U_{PB} T_Y, \quad (9)$$

where U_{PB} – cost rate for the maintenance of a single capacity of the CP, CU/capita/day.

The cost S_{CT}, CU, for removal e-waste from CP to PAT is determined by the formula

$$S_{CT} = Q_{CT} U_T, \quad (10)$$

where Q_{CT} – amount of transport work for transportation the planned e-waste scope Q_{CY}, t-km/year; U_T – cost rate per unit of transport work performed, CU/t-km.

The amount Q_{Mj} of the transported e-waste for each route is set taking into account the carrying capacity of the specialized rolling stock q_A, used on the line. With full use of the carrying capacity of the rolling stock, it is equal: $Q_{Mj} = q_A$.

The formula for calculating the S_{CBT} of the total cost for LSEWM is as follows:

$$S_{CBT} = T_W U_{PB} T_Y \sum_{i=1}^{R} \left(Q_{PDi} M_{PRi} \right) + \\ + \frac{T_Y 2 L_P q_A U_T}{T_W} \sum_{i=1}^{R} M_{PRi} + T_Y U_T \sum_{i=1}^{R} \left(M_{PRi} Q_{PDi} L_{Di} \right) - \\ - T_Y U_T 2 L_P \sum_{i=1}^{R} \left(M_{PRi} Q_{PDi} \right), \quad (11)$$

where R – region number; L_{Di} – longest path within the boundaries of i^{th} region, km.

Analysis of the formula (11) shows that all indicators are constant values, except for T_W. Therefore, it is possible to find such a value of T_W^* to minimize the cost function of S_{CBT} for LSEWM

$$S_{CBT} \xrightarrow[T_W]{} \min. \quad (12)$$

Let us differentiate the equation S_{CBT} (12) concerning T_W, days, by equating the result to zero and find T_W^*

$$T_W^* = \sqrt{\frac{2L_P q_A U_T \sum_{i=1}^{R} M_{PRi}}{U_{PB} \sum_{i=1}^{R} \left(Q_{PDi} M_{PRi}\right)}}, \quad i = 1, 2, ..., R. \quad (13)$$

Based on the dataset on Hanoi May region the optimal period of accumulation for all CP T_W^* equals to 5 days. The following values are used for calculation: T_Y = 365 days; L_P = 0.9 km; q_A = 5 t; U_T = 560 ruble/t-km; M_{PR} = 13 U; U_{PB} = 790 ruble/capita/days; Q_{PD} = 0.25 t/days.

In relation to the equation (21) total costs S_{CBT} for LSEWM equals to 13653238 ruble per year, where L_D = 8.1 km and estimated optimal value T_W^* = 5.05 days. If T_W is rounded value to 5 days S_{CBT} = 13653738 ruble/year.

The transportation route of e-waste is a motion scheme of a vehicle along the street and road network of the city that is obtained by the coherent or consistent visiting all required by route CP. The set of routes is supposed to be optimal within minimal common vehicle mileage L_M. The route charts of vehicles along a route are designed in relevance with the time consumption on technological operations such as movement among CP, e-waste acceptance, etc.

Results

Standard procedure for planning e-waste transportation in the cities provides for determination of some parameters such as:

– frequency (intervals) of e-waste transport according to the cyclical nature of its accumulation;

– the shortest vehicle path among CP that provides with cost minimization on transport;

– the calculation of the required number of rolling stock A_M relevant to the full e-waste transportation of the volume Q_{PBi} from each CP that is accumulated in optimal period T_W^*.

The first parameter is crucially important as incorrect intervals can cause a deficit of free space in CP that leads to reducing the e-waste disposal level. There are two prime approaches relevantly to the cyclical waste generation parameter:

– "by the set frequency" approach;

– "by the actual filling" approach.

Frequency property is inherent in the accumulation of all waste categories. For instance, in cities, municipal solid waste is accumulated regularly and, as a rule, evenly in all CP that is due to the peculiarities of the everyday products' consumption by the population. Therefore, the removal of MSW, especially in large cities, is carried out according to the principle "by the set frequency", as a rule, daily, covering all the route networks of all CP in each district. However, this approach does not apply to the organization of e-waste disposal, since such waste is characterized by cyclicity with less regularity and uniformity of volume accumulation.

The actual values of the e-waste generation parameters are determined by the reliability of the functioning of electronic products, which end-of-life, as a rule, occurs randomly. Consequently, even with known values of the e-waste generation intensity, it is difficult to predict the moment when each electronic product breaks down and enters a specific CP. This circumstance means that if you plan the removal of e-waste according to the principle "by the set frequency" at intervals T_W^*, then the storage capacity of individual CPs can be exhausted ahead of schedule. That means if the storage capacity is exhausted, the CP will not be able to receive e-waste which is unacceptable.

To avoid such undesirable situations, it is proposed to plan the removal of e-waste "by the actual filling" of the CP storage capacity. This methodological principle allows the formation of e-waste disposal routes for individual days within the T_W^* period, when the actual accumulated volume of e-waste in individual CP reaches the established export rate Q_{PB} (point capacity limit), calculated by the formula (8) taking into account the duration of T_W^*

$$Q_{PW} = Q_{PB}. \quad (14)$$

The following algorithm is proposed for planning the removal of e-waste "by the actual filling" of the CP capacity with a minimum total mileage of vehicles LM:

– providing with a list of CP for the upcoming planned e-waste removal;

– providing with a matrix of the shortest paths among all CP and PAT;

– providing with a system of optimal routes according to the criterion of the minimum total mileage;

– calculation of the required number of rolling stock units to service all routes during the day.

For the timely removal of e-waste in each CP, the current filling level of the storage capacity should be monitored. If condition (8) is satisfied CPs are included in the plan for the upcoming removal. To implement this approach, a numerical experiment was carried out for the CPs in the Hoang Mai area, which is located on D_i sites (one site – one CP).

With an average daily volume of waste generation, Q_{PD} = 0.25 t/day and the optimal accumulation period T_W^* = 5 days, the storage capacity of each collecting point is Q_{PW} = 1.25 t. Using the program module "random number generation" MS Excel, for each t^{th} day of the planning period $T_D = T_W^*$, the distribution of CP is simulated where the actual level Q_{PWt} of accumulated e-waste reaches the established limit Q_{PB} of the capacity of the point. The results of one of the options for generating random numbers are presented in Tab. 1.

The volume of accumulated waste Q_{PWt}, t, in each T_{Dt} day is

$$Q_{PWt} = Q_{PW} N_{PDt},\ t \in T_D, \qquad (15)$$

and for the entire period T_D, the total removal volume Q_{RW}, t, for all sections of the district is

$$Q_{RW} = \sum_{t=1}^{n} Q_{PWt},\ n = 1, 2, ..., T_D. \qquad (16)$$

The matrix of the shortest paths among all CPs and PATs is developed taking into account the actual data of GIS systems on the locations of these objects and the configuration of the transport network [10]. To design the optimal routes, standard mathematical methods developed for the "Traveling salesman problem" [11–15] have been used. For instance, the evolutionary algorithm that has been implemented in the "Solution Search" software module MS Excel. Tab. 2 presents the prime characteristics of the optimal "global" route, covering all CPs.

The information presented in Tab. 2 shows that the vehicle starts moving in the PAT (number "0"), then passes through the CP in the following sequence: 1–3–4–8–9–10–11–12–13–7–6–5–2, and returns to PAT (number "0"). The total length of the global route equals LM = 35.61 km. The global route is used to organize waste collection according to the approach "by the set frequency" when the vehicle regularly bypasses all CPs. in sequence. The volume of W_{RG} transport work for the removal of e-waste along the global route is

$$U_{RG} = N_{MT} Q_{RW} L_M = \frac{365}{5} \cdot 16.25 \cdot 35.61 = \\ = 42242.36 \text{ t} \cdot \text{km}, \qquad (17)$$

where N_{MT} – the total cycle number of detour cycles of the global (number of removals) for the period T_Y (a year),

$$N_{MT} = \frac{T_Y}{T_W} = \frac{365}{5} = 73 \text{ U}. \qquad (18)$$

When calculating U_{RG}, the value Q_{RW} is used, and the products' Q_{PW} volumes and the length of individual sections of the route have not been summed up, since the work of the vehicle is paid regardless of the degree of its filling. Costs S_{RG} for the removal of all waste during the T_Y period along the global route is equal to:

$$S_{RG} = U_{RG} s_T = 42242.36 \cdot 7.43 = \\ = 313860.73 \text{ USD}. \qquad (19)$$

where s_T – cost rate per unit of transport work performed, and equals to 7.43 USD/(t·km).

However, in practice, global routes cannot always be implemented due to the limited vehicle load capacity (q_A). If the total amount of waste accumulated at all points exceeds the carrying capacity of the vehicle $Q_{RW} > q_A$), then the global route is divided into several additional routes N_{MS}, U (sub-routes), and their number is determined by the formula

$$N_{MS} = \frac{Q_{RW}}{q_A}. \qquad (20)$$

Table 1

The results of the distribution of e-waste accumulation in D_i points by days T_D of the period T_W

D_i, number of CP	1	2	3	4	5	6	7	8	9	10	11	12	13
T_D, day number of period T_W	1	2	5	2	2	4	5	4	3	4	2	3	3

Table 2

Characteristics of the optimal global route

The visiting order of CP, number of CP	0	1	3	4	8	9	10	11	12	13	7	6	5	2	0
The distance to the following point, km	12.0	1.7	0.7	1.1	0.7	0.9	0.7	0.7	0.8	0.7	0.7	0.7	1.2	13.0	0

At the same time, all sub-routes are served on the same day, regardless of the actual amount of accumulation. The cost of servicing sub-routes is greater than that of servicing one global route, and is 330226.6 USD.

When planning the export "by the actual filling", a system of local routes is developed to connect the PAT only with those CPS in which the actual amount of accumulation Q_{PW} has reached the limit value according to condition (8). The total number of N_{MZ} local routes is in the range from 1 to TD and corresponds to the number of days on which e-waste is removed.

Based on the data on the days of actual accumulation of waste (Tab. 1), five local routes have been developed with a traffic pattern between CP along the shortest paths (the same methodology is used as for the global route). Information about the total length L_{Mz} ($z \in T_D$) and volumes Q_{MWz} of waste removed by each route is presented in Tab. 3.

The volume of transport work of U_{TZ}, t·km, for the removal of e-waste along the z-th number of local routes with a length of L_{Mz} and with the volume of removal Q_{PWz} with the total number N_{MT} cycles of bypassing all routes during the year is determined by the formula

$$U_{TZ} = N_{MT} \sum_{z=1}^{m} \left(Q_{PWz} L_{Mz} \right), \ z = 1, 2, ..., N_{Mz}. \quad (21)$$

In formula (21), the volume of transport work is defined as the product of the total volume of e-waste that is removed from all CPs of each route by the length of the route, and not as the sum of the products of the volumes removed from individual CPs but by the length of the corresponding sections of the route, since the operation of the vehicle is paid regardless of the degree of filling.

The removal coats S_{TZ}, CU, is calculated on the equation

$$S_{TZ} = U_{TZ} s_T. \quad (22)$$

The volume of transport work for the removal of e-waste along five local routes is U_{TZ} = = 42,549.9 t·km, and the cost of removal is S_{TZ} = = 316145.76 USD.

The comparison of the obtained results reviles that the transport costs for servicing the local routes (S_{TZ}) and the global route (S_{TG}) are almost on the same level. Costs for local routes increase by 2285.03 USD (less than 1 %). At the same time, the costs for local routes are 4.5 % less than the costs for servicing sub-routes (S_{TGs})

$$\Delta S_{RTs} = 330226.6 - 316145.76 = = 14080.84 \text{ USD}, \quad (23)$$

that indicates the effectiveness of the proposed model of e-waste removal "by the actual filling".

Table 3

Local route characteristics

Local route							Q_{MWz}, t	L_{Mz}, km
First								
The visiting order of CP	0	1.0	0	–	–	–	1.25	–
The distance to the following point, km	12	12	0	–	–	–	–	24
Second								
The visiting order of CP	0	4	11	5	2	0	5	–
The distance to the following point, km	16.0	2.2	2.5	1.2	13.0	0	–	34.9
Third								
The visiting order of CP	0	9.0	12	13.0	0	–	3.75	–
The distance to the following point, km	17.0	1.8	0.7	20.0	0	–	–	39.5
Fourth								
The visiting order of CP	0	8.0	10.0	6.0	0	–	3.75	–
The distance to the following point, km	17.0	1.2	1.2	18.0	0	–	–	37.4
Fifth								
The visiting order of CP	0	3.0	7.0	0	–	–	2.5	–
The distance to the following point, km	15.0	2	19	0	–	–	–	36
Total number							16.25	171.8

CONCLUSIONS

1. Increasing the efficiency of LSEWM is feasible by increasing the volumes of received e-waste for disposal through official channels, as well as by reducing the cost of collecting and transporting e-waste to special facilities for disposal. The process of disposal of household electronic waste is accompanied by active interaction among public authorities (state and municipal), commercial structures and the population. For high efficiency and safety of the recycling process, such interaction should include procedures for establishing measures for economic incentives for participants in this process, competitive selection of logistics companies to organize the collection and removal of waste, monitoring the volume and quality of services performed.

2. For planning LSEWM, it is necessary to use data on the volumes of household e-waste generation within the boundaries of the respective administrative-territorial regions. For the case when there is no statistical data on such volumes for districts of cities and sections of districts, it is proposed to determine the volumes of generation by calculation using indicators of the intensity of waste generation and the number of people living in the area or on the site. This proposal is based on established dependencies between the pointed indicators.

3. The methodology for planning the removal of household e-waste from the collecting points based on the actual level of filling of their storage capacity provides for the inclusion in the routes for the arrival of vehicles only those points where the accumulated volume of waste has reached the maximum storage volume. The use of the methodology provides a reduction in the cost of transport operation when visiting points with an empty container, and also eliminates situations of refusal to accept waste at overcrowded points.

4. The research results are recommended to be used to improve the organizational and economic mechanisms of the LSEWM, including to adjust the system and structure of participants and the functions they perform, to clarify the powers of the competent state bodies to standardize the costs of collecting and removal of e-waste products.

5. The use of the methodological recommendations presented in the work is supposed to contribute to the achievement of sustainable development goals because of:

– recycling of waste products and minimizing the volume of their disposal;

– increasing recycling rates by creating a convenient infrastructure of the waste collection for the population;

– organizing proper administration and control of spending financial resources on LSEWM;

– reducing the negative impact of waste products on the environment.

REFERENCES

1. Widmer R., Oswald-Krapf H., Sinha-Khetriwal D., Schnellmann M., Böni H. (2005) Global Perspectives on E-Waste. *Environmental Impact Assessment Review*, 25 (5), 436–458. https:// doi.org/10.1016/j.eiar.2005.04.001.
2. Ho S. T., Tong D. Y. K., Ahmed E. M., Lee C. T. (2012) Factors Influencing Household Electronic Waste Recycling Intention. *Advanced Materials Research*, 622–623, 1686–1690. https://doi.org/10.4028/www.scientific.net/amr.622-623.1686.
3. Babu B. R., Parande A. K., Basha C. A. (2007) Electrical and Electronic Waste: A Global Environmental Problem. *Waste Management & Research*, 25, 307–318. http://dx.doi.org/10.1177/0734242X07076941.
4. Bartoleto P. (2015) *Waste Prevention Policy and Behaviour, New Approaches to Reducing Waste Generation and Its Environmental Impacts, Routledge Studies in Waste Management and Policy*. Routledge, London.
5. Yoshida A., Terazono A., Florencio Ballesteros Jr. C., Nguyen D. Q., Sunkandar S., Kojima M., Sakata S. (2016) E-Waste Recycling Processes in Indonesia, the Philippines, and Vietnam: A Case Study of Cathode Ray Tube TVs and Monitors. *Resources, Conservation and Recycling*, 106, 48–48. https://doi.org/10.1016/j.resconrec.2015. 10.020.
6. Chiang T., Che Z. H., Cui Z. (2014) Designing a Multistage Supply Chain in Cross-Stage Reverse Logistics Environments: Application of Particle Swarm Optimization Algorithms. *The Scientific World Journal,* 2014, https://doi.org/10.1155/2014/595902.
7. Nguyen T. T. H., Larin O. (2022) Improving Organizational and Economic Conditions for E-Waste Logistics Support. *Ekonomika, Predprinimatelstvo i Pravo = Journal of Economics, Entrepreneurship and Law*, 12 (1), 333–348. https://doi.org/10.18334/epp.12.1.114117 (in Russian).
8. Manuel V., Miguel A., Natalia K., Guillermo F. (2021) Reverse Logistics for Solid Waste from the Construction Industry. *Advances in Civil Engineering*, 2021, 1–11. (2021). https://doi.org/10.1155/2021/6654718.
9. Nguyen T. V. (2012) Solid Waste Separation at Source: Necessary and Sufficient Condition for Waste Management in Ho Chi Minh. *Int. J. Environ. Sci. Sustain. Dev,* 1, 1–9.
10. *Vietnam Environment Monitor 2004. Solid Waste*. Available at: https://documents1.worldbank.org/curated/en/724701468308959503/pdf/331510rev0PAPER0VN0Env0Monitor02004.pdf (accessed 10 May 2021).
11. Kallel A., Serbaji M. M., Zairi M. (2016) Using GIS-Based tools for the Optimization of Solid Waste Collection and Transport: Case Study of Stax City, Tunisia. *Journal of Engineering*, 10, 1–7. https://doi.org/10.1155/2016/4596849.
12. MacGregor J. N., Chu Y. (2011) Human Performance on the Traveling Salesman and Related Problems: A Review. *The Journal of Problem Solving*, 3, (2), 1–29. https://doi.org/10.7771/1932-6246.1090.
13. Korte B., Vygen J. (ed.) (2018) *Combinatorial Optimization. Theory and Algorithms*. Springer-Verlag Berlin Heidelberg. https://doi.org/10.1007/978-3-662-56039-6.
14. Larin O., Tarasov D., Mirotin L., Rublev V., Kapski D. (2021) Resilient Supply Chain Management Model. *SHS Web of Conferences,* 93, 03005. https://doi.org/10.1051/shsconf/202193 03005.
15. Brunner P. H., Rechberger H. (2015) Waste to Energy-Key Element For Sustainable Waste Management. *Waste Management*, 37, 3–12. https://doi.org.10.1016/j.wasman.2014.02.003.

Received: 16.06.2022
Accepted: 20.09.2022
Published online: 30.11.2022