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MODELING THE CAPACITY OF COLLECTION POINTS FOR ELECTRONIC HOUSEHOLD WASTE IN CITIES

Abstract. This paper presents guidelines for modeling the capacity of electronic household waste collection points. These points are used as infrastructure elements with a multi-stage logistic support scheme for the electronic waste disposal process. This paper includes theoretical and methodological information on the procedure for placing points of waste collection in cities using the processes of determining the parameters of waste accumulation, calculating the design capacity of warehouses at these points, and developing routes for the transportation of waste to the places of their disposal. We represent the dependence of the logistic support costs, including the costs of maintaining waste collection points, and waste disposal to utilization facilities, on the duration of the waste accumulation period. A mathematical model for optimizing the logistic support costs is developed, which takes into account the most important parameters of the waste disposal system, namely, the topology of the collection points, the intensity of waste accumulation, the configuration of the routes, and the vehicle carrying capacity. Using the example of the Vietnamese capital, the city of Hanoi, the required number of waste collection points is calculated, the volume of waste accumulation at each point is determined, the optimal period of waste accumulation, in which the total costs for logistic support for the disposal process will be minimal, is determined. Recommendations on the organization of waste transportation, depending on the actual level of filling the capacity of collection and accumulation points, are given.

Keywords: E-waste, electronic household waste, transport, waste collection points, recycling waste, waste recycling points, logistic support, modeling

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МОДЕЛИРОВАНИЕ ПРОПУСКНОЙ СПОСОБНОСТИ ПУНКТОВ СБОРА ЭЛЕКТРОННЫХ БЫТОВЫХ ОТХОДОВ В ГОРОДАХ

Аннотация. Рассматриваются методические рекомендации по проектированию вместительной способности электронных пунктов по сбору коммунально-бытовых отходов. Данные пункты используются как элементы инфраструктуры с многоступенчатой схемой материально-технического обеспечения процесса вывоза мусора. Работа содержит теоретическую и методическую информацию о процедуре размещения пунктов сбора отходов в городах с помощью установления параметров процесса накопления мусора, расчета проектной емкости мусорохранилищ в установленных пунктах, а также разработки маршрутов транспортировки отходов к месту их захоронения. Представлена зависимость затрат на материально-техническое обеспечение, которое включает затраты на содержание пунктов по сбору коммунально-бытовых отходов и их вывоз на полигоны, от длительности периода накопления отходов. Разработана математическая модель по оптимизации затрат на логистическую поддержку, принимающая во внимание наиболее важные параметры системы вывоза и захоронения мусора, такие как топология пунктов сбора, интенсивность накопления отходов, конфигурация маршрутов, грузовместимость транспорта. На примере столицы Вьетнама – г. Ханой – подсчитано необходимое количество пунктов сбора мусора и рассмотрен объем накопления отходов на каждом из них, установлен оптимальный период накопления мусора, при котором совокупные расходы на логистическую поддержку вывоза и захоронения бытовых отходов минимальны. Выработаны рекомендации по организации транспортировки бытового мусора в зависимости от непосредственного уровня наполняемости емкостей пунктов сбора коммунально-бытовых отходов.

Ключевые слова: логистическое обеспечение, моделирование, электронные отходы, электронные бытовые отходы, транспорт, пункты приема отходов, утилизация отходов, пункты утилизации отходов

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Introduction. In recent years, the improvement of the efficiency of the waste management process has been of great interest to the state and public structures. This problem is the most topical in large cities with high population density and concentration of industrial production facilities. Moreover, in modern conditions, the highest growth rates of electronic equipment waste (referred as electronic waste) in these territories are noted [1–3]. Electronic waste includes various objects with electrical or electronic components, nodes and consumables (computer equipment, monitors, motherboards and chips, peripherals, lamps, including mercury and luminescent ones, large home appliances, electronic and optical equipment and tools, etc.) that lost their consumer properties due to the failure, breakage, resource exhaustion, expiry, etc. [4–6].

All types of electronic waste contain hazardous substances, which, in non-compliance with the rules of disposal, can cause significant harm to the health of people and the environment. Therefore, it is necessary to ensure their complete disposal. However, nowadays, a significant part of electronic household waste (hereinafter referred to as EHW, E-Waste), generated by the population, is not disposed of properly and thrown away along with garbage – municipal solid waste (hereinafter – MSW). Such behavior is caused by the lack of EHW collection points (hereinafter – WCP) in cities. At the same time, the creation of WCP is associated with significant expenditures on logistic support for their activities – the maintenance and transport support of such points. Therefore, it is necessary to make economically reasonable decisions on the capacity of WCP, which provides minimal logistic support costs [7]. At the same time, the analysis of scientific works has shown that currently these issues are not studied enough. Therefore, it seems that the task of developing a method for substantiating the WCP capacity by the criterion of minimum logistic support costs is relevant.

Materials and Methods. To optimize the cost of collection, accumulation, and transportation of EHW, the methods developed on the basis of the theoretical and methodological provisions of logistics are used [8–11]. Logistic support for the EHW disposal process is to ensure the timely and cost-effective movement of e-waste on all links of the return logistics chain. To dispose of EHW, a two-stage logistic support scheme is used, which contains the following operations:

– collection and accumulation of EHW at WCP;

– transportation of EHW to EHW recycling points (hereinafter – WRP).

A single-stage logistic support scheme in which EHW moves from the population directly to the WRP, bypassing the WCP, is rarely applied in practice [12–15].

A typical WCP is an infrastructure facility in which there are rooms for staff placement, special equipment for collection and temporary storage of e-waste, tools for processing and preparing waste to transportation. Operations for collection and accumulation of EHW for subsequent transportation to the WRP are carried out at the WCP [16]. Collection means obtaining electronic waste from the population. The accumulation operation is the storage of waste from the population during the prescribed period of time for the formation of enlarged cargo lots in order to increase the efficiency of transportation. Transportation means the process of transporting the accumulated waste from the WCP to the WRP, which includes the operations of loading and unloading waste, vehicle movement along the route – empty mileage from the WRP to the first WCP, loaded trip through all WCPs included in the route and back to the WRP.

Each *i*-th WCP is created to serve the population within the boundaries of a specific section d_{Pi} ($i = 1,\ldots,D_P$) based on the rule "One section – one WCP" ($D_P = N_P$). The total number of sections D_P and, accordingly, the total N_P amount of WCPs placed within the borders of the section are set taking into account the local characteristics of the specific settlement, the social composition of the population, the configuration of the transport network, and other factors. At the same time, the parameters of the sections and the location of WCPs must provide the population with the convenient conditions for moving EHW to the WCP [17, 18].

This study was performed using the example of the Vietnamese capital, the city of Hanoi, in which only 5 official WCPs were created in three parts of the city: 2 points in the Cau Giay district, 2 – in the Ba Dinh district, 1 – in the Hoan Kiem district. According to the Report on the program Vietnam Recycles – 2019 "E-waste in Ha Noi Area", there are no WCPs in one of the largest urban areas – the Hoang Mai district. In this district, N_R = 423 thousand people live on the territory with a total area of F_R = 41 km^2, the population density thus being P_R = 10.3 thousand people / km^2. Due to the lack of WCPs, the total volume of EHW officially utilized in the Hoang Mai district is less than 1 %, and the main part of EHW is disposed of with MSW.

The survey of residents of the Hoang Mai district has shown that the long distance of WCPs from accommodation places reduces the motivation to comply with the EHW disposal rules. Based on the results of the survey of residents of the district, the permissible distance of the WCP from the people accommodation is determined: L_P = 0.9 km. This indicator sets the borders of the d_{Pi} sections to place WCPs. Each section is a square cell with a width L_B and a height L_H equal to the double value of L_P. The area of each site F_P amounted to:

$$F_P = L_B \cdot L_H = (2 \cdot L_P)^2 = 4 \cdot 0.81 = 3.24, \text{ km}^2. \quad (1)$$

Taking into account this parameter, thirteen sections are defined (N_P = 13 units) to place WCPs in the Hoang Mai district. The actual location of individual WCPs was determined taking into account the architectural and planning features of the terrain and the availability of the engineering infrastructure.

The potential average daily volume (Q_D, tons per day) of the EHW formation within the boundaries d_{Pi} of the section is determined taking into account the average daily intensity of the electronic waste generation W_D in the city, the area of the section F_P, and the population density in the area P_R:

$$Q_D = W_D \cdot F_P \cdot P_R = 7.4 \cdot 10^{-3} \cdot 3.24 \cdot 10.32 = 0.25 \text{ t/d}. \quad (2)$$

The following table shows the indicators of population density and the average daily intensity of the generation of electronic waste ($W_D = 7.4 \cdot 10^{-3}$ kg/people·day) for the Hoang Mai district. Values are set based on the official statistical data.

Characteristics and intensity of EHW generation in Hanoi districts*

Names of the city districts	Number of residents of the district N_R, thousand people	Area of the district F_R, km^2	Population density in the district P_R, thousand people / km^2	The average EHW generation intensity in the district W_D, 10^{-3}·kg/people·day
Hanoi, in total, including:	8053	3358.6	2.40	7.40
Hoan Kiem	147.3	5.29	27.84	7.26
Dong Da	430.05	9.95	43.22	6.99
Ba Dinh	247.1	9.21	26.83	7.12
Hai Ba Trung	321.5	9.62	33.42	6.58
Hoang Mai	423	41	10.32	7.40
Thanh Xuan	292.8	9.11	32.14	6.90
Long Bien	322.5	61	5.29	7.15
Nam Tu Liem	269.07	32.17	8.36	6.44
Bac Tu Liem	340.6	45.24	7.53	6.77
Tay Ho	171.2	24	7.13	7.21
Cau Giay	292.5	12.44	23.51	5.75
Ha Dong	402	49.64	8.10	6.42

End of table

Names of the city districts	Number of residents of the district N_R, thousand people	Area of the district F_R, km^2	Population density in the district P_R, thousand people / km^2	The average EHW generation intensity in the district W_D, 10^{-3}·kg/people·day
Chuong My	337.3	237.38	1.42	7.40
Dan Phuong	174.5	78	2.24	7.67
Dong Anh	405.7	185.62	2.19	7.81
Gia Lam	286.1	116.71	2.45	8.22
Hoai Duc	262.9	84.93	3.10	7.40
Me Linh	240.5	142.46	1.69	9.04
My Duc	199.9	226.25	0.88	7.40
Phuc Xuyen	213.9	171.1	1.25	9.73
Phuc Tho	184.02	118.63	1.55	7.40
Quoc Oai	194.41	151.13	1.29	9.04
Soc Son	343.43	304.76	1.13	8.77
Thach That	216.55	202.05	1.07	6.93
Thanh Oai	211.03	123.87	1.70	6.30
Thanh Tri	275.75	63.49	4.34	7.40
Thuong Tin	254.7	130.41	1.95	6.58
Ung Hoa	210.87	188.18	1.12	9.04
Ba Vi	290.58	423	0.69	6.85
Son Tay	145.86	117.43	1.24	7.12

* Source: authors' calculations.

For the disposal of e-waste, the transportation is organized from all WCPs, at least one ring route with a sequential visit of WCPs. The total number of routes N_M is established depending on the total e-waste generation volume at all points N_P of the serviced area and the carrying capacity of the vehicle used for e-waste transportation:

$$N_M = \frac{\sum_{i=1}^{N_P} Q_{Wi}}{q} = \frac{T_W \cdot Q_D \cdot N_P}{q}, \text{ un.,} \tag{3}$$

where q is the Load capacity of the specialized rolling stock, tons; Q_{Wi} is the volume of the accumulated e-waste in the i-th WCP.

The accumulation period T_W is used to assign the e-waste transportation intervals Y_{Mj} for each j-th route ($j = 1,\ldots,N_M$):

$$Y_{Mj} = T_W, \text{ days.} \tag{4}$$

The number of points N_{Nj} serviced by a separate j-th route is established taking into account the carrying capacity q of the specialized rolling stock used on the line, and the amount Q_W for the period T_W:

$$N_{Nj} = \frac{q}{Q_D \cdot T_W}, \text{ un.} \tag{5}$$

The total number N_{Tj} of cycles of the e-waste disposal for each route during a planning period T_Y (year) will be:

$$N_{Tj} = \frac{T_Y}{T_W}, \text{ un.} \tag{6}$$

The mileage of the rolling stock L_{Mj} for each j-th route is calculated as the sum of three types of mileages:

$$L_{Mj} = L_{BAj} + L_{Wj} + L_{ABj}, \text{ km,} \tag{7}$$

where L_{BAj} and L_{ABj} are initial and final mileages of the rolling stock following from the WRP to the first WCP on the route for loading and from the last WCP to the WRP for unloading, respectively, km; L_{Wj} is the mileage of the rolling stock between all WCPs of the j-th route, km.

As part of this study, the initial L_{BAj} and the final L_{ABj} mileages for all routes can be taken equal and amount to half of the longest length L_D inside the boundaries of the district (for example, diagonally or diameter):

$$L_{BAj} = L_{ABj} = \frac{L_D}{2}, \text{ km.} \tag{8}$$

For a uniformly distributed network of sections through the district territory, the length L_{Wj} between any neighboring WCPs is also taken equal to L_{FL} and calculated by the formula:

$$L_{FL} = \sqrt{F_P} = 2 \cdot L_P, \text{ km.} \tag{9}$$

Then the mileage L_{Wj} of the rolling stock between the adjacent WCP along the j-th route will be:

$$L_{Wj} = L_{FL} \cdot (N_{Nj} - 1) = 2 \cdot L_P \cdot \left(\frac{q}{Q_D \cdot T_W} - 1 \right), \text{ km.} \tag{10}$$

The general mileage L_{Mj} of the rolling stock on the route as a whole will be:

$$L_{Mj} = \frac{L_D}{2} + 2 \cdot L_P \left(\frac{q}{Q_D \cdot T_W} - 1 \right) + \frac{L_D}{2} = L_D + \frac{2 \cdot L_P \cdot q}{Q_D \cdot T_W} - 2 \cdot L_P, \text{ km.} \tag{11}$$

It is important to note that when the amount of accumulation Q_W in each WCP for the period T_W is larger than the carrying capacity q of the rolling stock, then the pendulum routes should be generated, one route to each WCP. On the pendulum routes, there are no mileages L_{Wj} between adjacent WCPs, and the total mileage along the route L_{Mj} is the length from the WRP to some WCP and back:

$$L_{Mj} = L_{BA} + L_{AB} = L_D, \text{ km.} \tag{12}$$

Results. The design capacity Q_{Bi} of the warehouse of each i-th WCP should be sufficient to store the EHW in the amount of Q_{Wi} accumulated during the period T_{Wi}. Since the e-waste generation volumes Q_D and the accumulation periods T_W for all WCPs in the served district are set as the same, the design capacity Q_{Bi} of warehouses in all WCPs will also be the same and equal:

$$Q_{Bi} = Q_{Wi} = Q_D \cdot T_W, \text{ tons.} \tag{13}$$

With the well-known capacity of the i-th point Q_{Bi} within the district area, it is possible to determine the capacity Q_{RB} of the entire WCP network:

$$Q_{RB} = \sum_{i=1}^{N_P} Q_{Bi} = T_W \cdot Q_D \cdot N_P, \text{ tons.} \tag{14}$$

The minimum warehouse capacity $Q_{B\min}$ corresponds to the average daily volume of e-waste generation Q_D:

$$Q_{B\min} = Q_D, \text{ at } T_W = 1 \text{ day.} \tag{15}$$

With $Q_{B\min}$, costs S_{CB} for the maintenance of all WCPs (rental, operating costs, etc.) will be minimal. However, in this case, it is necessary to ensure the daily removal of small e-waste batches, which will lead to high transport costs S_{CT}. Increasing the accumulation period ($T_W > 1$) will require an increase in the capacity of WCP warehouses, which will lead to an increase in the cost S_{CB} for the maintenance of the infrastructure object. With $T_W > 1$, the e-waste transportation intervals will also increase, and the cost of transporting S_{CT}, as a result, will decrease. The dependences of the costs S_{CB} and S_{CT} on T_W make it possible to formulate a statement regarding the capacity Q_B of the WCP warehouse. Firstly, the capacity Q_B should be sufficient to accommodate the entire volume Q_W of the accumulated EHW for the period T_W, and therefore should be calculated based on the established duration T_W. Secondly, when choosing a design value of capacity Q_B, it is necessary to take into account the cost criterion – the total costs S_{BT} for logistic support for the EHW disposal process (costs calculated in Vietnamese dongs, VND):

$$S_{BT} = S_{CB} + S_{CT}, \text{ VND.} \tag{16}$$

Since the maintenance costs of all infrastructure objects S_{CB} is in direct dependency on their capacity (Q_B), and the cost of removal S_{CT} is reduced as this capacity increases, such a value of Q_B can be found, in which an increase in S_{CB} will be overlapped with a decrease in S_{CT}, the total S_{BT} costs will be minimal.

Costs S_{CB} for the maintenance of the WCP network depend on the overall capacity of points and are calculated by the formula:

$$S_{CB} = Q_B \cdot U_B \cdot T_Y = T_W \cdot Q_D \cdot N_P \cdot U_B \cdot T_Y, \text{ VND,} \tag{17}$$

where U_B is the rate of the cost of maintaining a single tank at the WCP, i. e. 1 ton per day, VND/t·d.

Costs S_{CT} on the removal of e-waste from the WCP to the WRP are calculated by the formula:

$$S_{CT} = Q_{CT} \cdot U_T, \text{ VND,} \tag{18}$$

where Q_{CT} is the volume of the transport work performed when removing a planned Q_{CY} number of EHW, t·km/year; U_T is the Cost rate per unit of the completed transport work, i. e., 1 t·km, VND/t·km.

The calculation of transport costs is based on the following assumptions: all sections within the boundaries of the district have the same area F_P, the number N_R and the density P_R of residents; all WCPs have the same capacity Q_B; there are transport communications between all WCPs; routes are built along the shortest distance through the sequential transport stops at the adjacent WCPs. Then the value of costs Q_{CT} planned to export from all WCP during the year is determined by the formula:

$$Q_{CT} = \sum_{j=1}^{N_M} (N_{Tj} \cdot Q_{Mj} \cdot L_{Mj}), \text{ t} \cdot \text{km,} \tag{19}$$

where Q_{Mj} is the volume of EHW removed from all WCPs included in each j-th route, tons.

The amount Q_{Mj} of the transported e-waste for each route is established taking into account the carrying capacity q of the specialized rolling stock used on the line. With full use of the carrying capacity of the rolling stock we have $Q_{Mj} = q$.

Taking into account the above-mentioned formulas for the calculation of variables, the total volume of the transport work Q_{CT} will be:

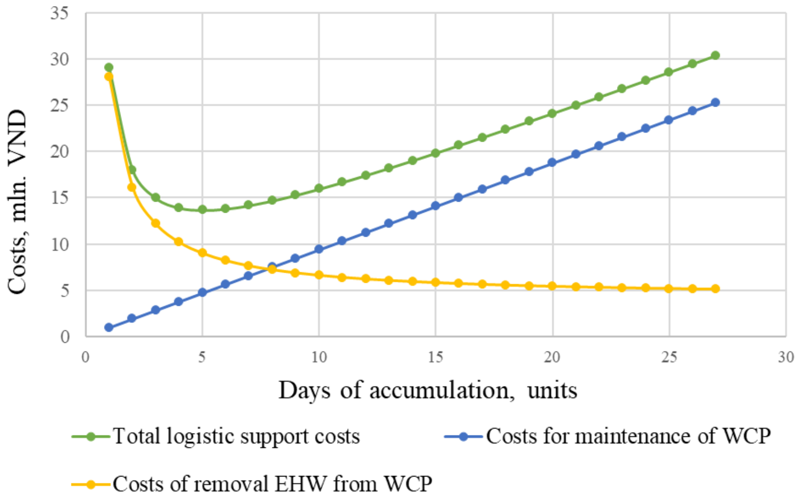
$$\begin{aligned} Q_{CT} &= \frac{T_Y}{T_W} \cdot \frac{T_W \cdot Q_D \cdot N_P}{q} \cdot q \cdot \left(L_D + \frac{2 \cdot L_P \cdot q}{Q_D \cdot T_W} - 2 \cdot L_P \right) = \\ &= T_Y \cdot N_P \cdot Q_D \cdot L_D + T_Y \cdot N_P \cdot Q_D \cdot \frac{2 \cdot L_P \cdot q}{Q_D \cdot T_W} - T_Y \cdot N_P \cdot Q_D \cdot 2 \cdot L_P = \\ &= \frac{T_Y \cdot N_P \cdot 2 \cdot L_P \cdot q}{T_W} + T_Y \cdot N_P \cdot Q_D \cdot (L_D - 2 \cdot L_P), \text{ t} \cdot \text{km.} \end{aligned} \tag{20}$$

Based on the obtained value of Q_{CT}, let us define the annual costs S_{CT} of the e-waste transportation:

$$S_{CT} = \frac{T_Y \cdot N_P \cdot 2 \cdot L_P \cdot q}{T_W} \cdot U_T + T_Y \cdot N_P \cdot Q_D \cdot U_T \cdot (L_D - 2 \cdot L_P), \text{ VND.} \tag{21}$$

Now the total cost of logistic support for the disposal process S_{BT} can be determined:

$$\begin{aligned} S_{BT} = S_{CB} + S_{CT} = T_W \cdot Q_D \cdot N_P \cdot U_B \cdot T_Y + \frac{T_Y \cdot N_P \cdot 2 \cdot L_P \cdot q}{T_W} \cdot U_T + \\ + T_Y \cdot N_P \cdot Q_D \cdot U_T \cdot (L_D - 2 \cdot L_P), \text{ VND.} \end{aligned} \tag{22}$$



Graphs of changes in the costs of logistic support (S_{CB}, S_{CT}, S_{BT}, VND) for different values of the accumulation period T_W (days). Source: authors' calculations

Analysis of expression (22) shows that all indicators, except T_W, are constant values. Therefore, it is possible to find such a value of T_W^*, for which the cost of logistic support S_{BT} will be minimal:

$$S_{BT} \xrightarrow[T_W]{} \min. \tag{23}$$

Let us differentiate function S_{BT} (22), equate the resulting expression to zero and find T_W^*, with which the minimum cumulative costs S_{BT} for logistic support for the disposal process are ensured:

$$T_W^* = \sqrt{\frac{2 \cdot L_P \cdot q \cdot U_T}{U_{PB} \cdot Q_D}}, \text{ days.} \tag{24}$$

Using the source data in the Hoang Mai district, we define the optimal period of accumulation T_W^*. The following values were used for calculations: $T_Y = 365$ days; $L_P = 0.9$ km; $q = 5$ t; $U_T = 560$ VND/t·km; $N_P = 13$ units; $U_B = 790$ VND/t·d; $Q_D = 0.25$ t/d:

$$T_W^* = \sqrt{\frac{2 \cdot 0.9 \cdot 5 \cdot 560}{790 \cdot 0.25}} = 5.05 \approx 5, \text{ days.}$$

Using formula (22), let us define the summary costs for logistic support S_{BT} for the calculated value of $T_W = 5$ days, with $L_D = 8.1$ km: $S_{BT} = 13\,653\,738$ VND/year. At $T_W^* = 5.05$ days, the total costs will be $S_{BT} = 13\,653\,238$ VND/year, which is less than the calculated for $T_W = 5$ days by 499 VND. Thus, rounding caused a slight increase in costs – less than 0.01% of the optimal option. Table 2 shows the results of the calculation of the total costs of logistic support S_{BT} for various values of the accumulation period T_W (from 1 to 30 days).

Based on the obtained data, graphs (Figure) of changes in logistic support costs (S_{CB}, S_{CT}, S_{BT}) are built for various values of the accumulation period T_W.

Discussion and conclusions. The developed method of planning the WCP capacity is based on determining the optimal value of the period T_W^* of e-waste accumulation. One should bear in mind that the process of EHW accumulation is caused by random factors that affect the performance of various types of electronic and electrical equipment. This means that with an average intensity W_D of EHW generation during the period T_W, the volume Q_W will accumulate at the i-th WCP. However, this process will be uneven, and it is possible that the volume of Q_W will be accumulated before the end of the period T_W. Consequently, at $T_W^* > 1$, situations of a deficit in the WCP capacity may occur until the planned removal of e-waste in accordance with the interval Y_{Mj}. With a shortage of WCP capacity, the population will not be able to send e-waste for disposal, which is unacceptable. Therefore, when $T_W^* > 1$, it is advisable to organize the removal of EHW according to the “actual level of filling the WCP capacity” on the days when the volume of accumulation Q_W reaches the capacity of the point Q_B.

It should also be noted that when calculating transport costs, we used the values of indicators (in particular, the number of routes, the number of waste collection points in one route, etc.), which characterize not the factual but the potentially necessary volume of transport work for the disposal of EHW. Therefore, the values of some indicators (for example, in formulas (3), (5), (6), etc.) can take non- integer values. However, when organizing work of vehicles on routes, it is necessary to use indicators with integer values, which should be calculated on the basis of the factual data of speed vehicles along routes, the length of routes, the duration of the drivers’ working hours, etc.

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