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A Two-Echelon Green Supply Chain for Urban Delivery

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Abstract. In recent years the urbanization to affect many countries of the world has made the significant changes to the material flow at all levels of the supply chain. The last mile logistics operating in the urban area has also changed notably. An increase in the volume of material flow within cities has led to a growth in the number of deliveries and the freight turnover, accordingly. The above-stated processes greatly reduce the sustainability of cities, which while keeping the urbanization trend, can lead to the serious negative results of the social and environmental nature not only for the cities, but also for the countries. One way to solve this problem is to create the green supply chains from the multi-echeloning principles. In the paper, the authors have presented a two-echelon green supply chain using the zero transport emissions within the second echelon. A multi-criteria function has been developed to assess the rational location of a transfer point in order to reduce the negative environmental impact from the transportation system. With the PTV Visum software product, a simulation has been conducted to evaluate the alternative scenarios for generating a green supply chain.

Keywords: supply chain, two-echelon system, sustainable effect, harmful substances

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Двухэшелонная зеленая цепь поставок для городских перевозок грузов

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Реферат. Процессы урбанизации, которые в последние годы затронули многие страны мира, внесли значительные изменения в продвижение материальных потоков на всех эшелонах цепи поставки. Особые изменения претерпела логистика последней мили, которая выполняется непосредственно на городской территории. Увеличение объема материального потока в пределах городов привело к росту количества поставок и соответственно транспортной работы. Эти процессы значительно снижают устойчивость городов, что при сохранении тенденции урбанизации может вызывать серьезные негативные последствия социального и экологического характера не только в городах, но и в странах. Одним из путей решения данной проблемы является построение зеленых цепей поставок на принципах мультиэшелонирования. В работе предложена двухэшелонная зеленая цепь поставок с использованием транспорта с нулевым выбросом CO_2 в рамках второго эшелона. Разработана многокритериальная функция оценки рационального расположения перегрузочного пункта для снижения негативного влияния на окружающую среду транспортной системы. Проведено имитационное моделирование в программном продукте PTV Visum для оценки альтернативных сценариев построения зеленой цепи поставки.

Ключевые слова: цепь поставок, двухэшелонная система, устойчивый эффект, вредные выбросы

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Introduction

The system of material support for cities with a tendency toward the population urbanization [1] requires a review of the main strategies for building the urban supply chains. In recent years, the number and frequency of deliveries to urban agglomerations have sharply risen resulting in a series of problems in the last mile logistics. The concentration of material flows without adapting the supply chain to the processes above can cause an increase in the goods final cost [2, 3], traffic flow deterioration [4] and, as a result, have a negative environmental impact on the urban territory [5, 6]. Removing the negative impact of freight transportation is possible with the efforts to change the delivery time, to make the off hours deliveries [7] or to create the two-echelon structures of urban material supply systems [8, 9].

So, the study considers the problem of building a two-echelon green supply chain to cut the negative transportation impact on the urban environment.

Literature review

Under the conditions of strict environmental protection and the increased business social responsibility, the need to implement the logistic functions determines the relevance of studying the green logistics. The paper [10] states the efficient green logistics operation through an interaction of its elements – warehouses, vehicles, intelligent transportation systems and financial mechanisms. In the research [11], there were the groups of techniques to increase a freight transportation decision making. These were the "air pollution-to-traffic congestion" correlation evaluation, off-hour freight deliveries and resource reallocation models. According to the author, the approaches are useful to minimize a negative environmental impact originated from the supply chain functioning. From the viewpoint of supply chain management, in order to convert the chain into green one, it is necessary to use the circular economy (CE) principle [12]. CE consists in improving the economic development while alleviating environmental and resource challenges. Within the CE levels (micro, meso and macro), the resourcing, purchasing, production, reprocessing are designed to consider environmental performance and human well-being.

The authors [13] consider the green logistics as the optimal combination of heavy duty, delivery truck and diesel rail CO_2 and PM emissions and transportation costs.

The authors of the study [14] suppose that the proper functioning of green logistics is possible only with the use of the present day software due to the complexity of the system organization (coordination of a large number of process participants, vehicles, considering the road and environmental conditions, delivery size etc.). This is to make this type of logistics flexible and applicable to successful supply task solution.

At the same time, the efficient supply chain operation is impossible without the participation of various transportation modes, among which the road transport is of great significance because of a series of advantages (high mobility, transportation speed, different carrying capacity etc.). However, the supply of this transportation mode is accompanied by a significant negative environmental impact to be decreased under the green logistic principles.

In this aspect, the multi-echelon supply chain organization is of great interest. In this field, literature refers to supply chain and inventory problems without studying the transportation system to optimize from the environmental viewpoint. In most recent works, the reduction of environmental pollution is towards to the problem of vehicles routing within the supply chain. The paper [15] deals with the routing issue to decrease the environmental and noise pollution in the first echelon through the Flow simulation product to generate a rational vehicle path. In the research [16], the routing problem consist in a vehicle assignment to serve the consumers in different echelons. M. Soysal et al. [17] consider a time-dependent routing problem and combine different objectives like distance traveled, travel time, vehicles and emissions in one weighted objective function. H. Li et al. [18] deal with a time constrained routing problem occurring in linehaul-delivery systems and consider an objective function consisting of different parts.

In recent years numerous papers have focused on environmental criteria as an additional objective in routing problems. These papers consider either emissions or fuel consumption [19–22].

Besides, external social criteria (noise, congestion, disturbance) are considered as a further objective by P. Nolz et al. (2014), B. Sawik et al. (2017) and J. Grabenschweiger et al. (2018) [23–25].

Thus, the above studies only partially reveal the problem of the functioning of supply chains. In the approach below, an attempt has been made to comprehensively estimate the technological (total vehicles' mileage in the supply chain) and social (emissions of harmful substances into the atmosphere) consequences from the green logistic principles in time of the urban supply chain operation.

Mathematical problem statement

The rational location of the transshipment point should guarantee the integrated efficiency of the transportation process at two levels of the supply chain. In this regard, it is suggested to determine the rational placement of the local depot from a multicriteria assessment:

$$RP = \\ = \text{opt}\left\{\left(\min\forall L_i^G\right)\wedge\left(\min\forall W_i^G\right)\wedge\left(\min\forall T_i^G\right)\right\}, \quad (1)$$

where RP – local depot rational placement; L_i^G – two echelon vehicle mileage, km; W_i^G – two echelon freight turnover, t-km; T_i^G – two echelon goods delivery time, h; i is the local depot placement option;

$$D^G = D^{1e} + D^{2e} = \sum_{j=1}^{A} d_j^{1e} + \sum_{h=1}^{K} d_h^{2e}, \quad (2)$$

D^{1e}, D^{2e} – vehicle total mileage within the first and second echelons, respectively, km; d^{1e}, d^{2e} – transportation cycle length within the first and the second echelons, km; A, K – number of the transportation cycles required to serve the freight flow in the first and the second echelons, units.

Similarly to (2), for each alternative local depot placement, an assessment of the total freight turnover and the delivery time should be made:

$$W^G = W^{1e} + W^{2e} = \sum_{j=1}^{A} w_j^{1e} + \sum_{h=1}^{K} w_h^{2e}, \quad (3)$$

where W^{1e}, W^{2e} – vehicle total freight turnover in the first and second echelon supply chain, t-km; w^{1e} – first echelon vehicle freight turnover, t-km; w^{2e} – second echelon cargo bike total freight turnover, t-km;

$$T^G = T^{1e} + T^{2e} = \sum_{j=1}^{A} t_j^{1e} + \sum_{h=1}^{K} t_h^{2e}, \quad (4)$$

t^{1e}, t^{2e} – transportation cycle duration in the supply chain first and second echelons, h;

Research object mathematical model

The local depot operates as a "from trucks-to-cargo bikes" transshipment point. Within the first echelon, these are the vehicle deliveries. In the second echelon, the delivery system is originated from the small lot supply technology. Due to this, the second echelon transportation cycles are created on the principle of multistop delivery routes. In the study, the generation of transportation cycles is performed according to the Clark and Wright algorithm in the second echelon.

The two-echelon green supply chain system should be presented as follows

$$GSC = \langle P, T\rangle, \quad (5)$$

where GSC – green supply chain; P – supply demand; T – supply transportation system.

Transportation demand describes the goods average daily need of each consumer. From this, in the GSC equation it is of the following form

$$P = \langle\{l_c\},\ \{Q_c\}\rangle, \quad (6)$$

where l – consumer's location at the service area (graph vertex); Q – customer's delivery amount, t; c – number of customers at the service area, units.

The transportation system, in turn, consists of the following subsystems

$$T = \langle G,\ L,\ FV,\ CB\rangle, \quad (7)$$

where G – transportation network; L – local depots on the urban transportation network; FV – freight vehicle subsystem; CB – cargo bike subsystem.

The transport network graph is presented according to the widely used approach to creating a road network two-dimensional model [8, 26]:

$$G = \left\langle \left\{ e_g \right\}, \left\{ v_x \right\} \right\rangle, \quad (8)$$

where e – graph apex described from the two-dimensional coordinate system; v – graph arcs described by length, number of lanes, free flow velocity and road capacity; g – number of graph vertexes in the transportation network model, units; x – number of graph arcs in the transportation network model, units;

$$L = \left\langle e_{RP}, S_L, C_L \right\rangle; \quad (9)$$

$$L \equiv RP, \quad (10)$$

e_{RP} – vertex of the local depot rational placement; S_L – local depot area, m^2; C_L – local depot capacity, t.

The truck subsystem is as a connecting transport element between the shipper and the local depot subsystem.

In the first echelon, the use of simple transportation cycles does not improve the transportation process efficiency through the routing procedure. In this regard, one of the ways to increase the efficiency of transporting goods is to choose a rational rolling stock.

From the above-stated, the FV subsystem model is of the following form

$$FV = \left\langle \left\{ q_s^a \right\}, \left\{ u_s \right\}, \left\{ p_k \right\} \right\rangle, \quad (11)$$

where q^a – vehicle carrying capacity, t; s – number of alternatives for the vehicle capacity, units; u – number of vehicles for each s^{th} alternative, units; p – vehicle body type with a characteristic difference in the unloading technique and the equipment used; k – number of vehicle body types, units.

The cargo bike subsystem provides the services to end consumers in the second echelon. Last mile logistics chain ends with the cargo bike delivery under the trip chain supply technology.

In the local depot, the shipment deconsolidation is made under the condition that its total volume remains unchanged. In this case, the cargo bike subsystem should create the necessary shipment discreteness to fulfill the condition (1). This is achieved by combining the number of cargo bicycles of various carrying capacities when generating the transportation cycles. So, the cargo bike subsystem is presented as follows

$$CB = \left\langle \left\{ q_g^b \right\}, \left\{ z_g \right\} \right\rangle, \quad (12)$$

where q^b – cargo bike carrying capacity, t; g – series of cargo bike ranked by carrying capacity; z – number of cargo bikes of g^{th} type, units.

The models developed are the basis to create the alternative delivery systems, the efficiency of which is evaluated according to (1). The main components of functional (1) are presented in models (3)–(4) in a general form. To use them in experimental studies, it is necessary to provide the explanations on finding the model components (3) and (4). The results are presented below

$$w_{j(h)}^{ie} = \sum_{m=1}^{M} d_{j(h)}^{(m-1)-m} \cdot Q_{j(h)}^{m}, \quad (13)$$

where m – customer serial number in $j(h)^{\text{th}}$ transportation cycle; M – total number of customers served in the $j(h)^{\text{th}}$ transportation cycle; $d_{j(h)}^{(m-1)-m}$ – truck (cargo bike) distance travelled between the adjacent customers in one transportation cycle, km; i – echelon number.

Under a $m = 1$ condition, the delivery is done between the shipment point and the first customer at a $d_{j(h)}^{0-1}$ distance, which corresponds to half the length of the j^{th} transportation cycle in the first echelon.

The duration of transport cycles is determined in relation to the vehicle mileage and road speed. Obviously, in the second echelon, the delivery speed will be lower than in the first one. In addition, due to differences in the creating the transportation cycles at different levels of the model, the duration of transportation cycles will differ.

In model (14), the components being common for two echelons are represented as *j(h)*, while the components assigned only to the second echelon are described with the index h

$$t_{j(h)}^{ie} = \sum_{m=1}^{M} t_{j(h)}^{(m-1)-m} + t_{j(h)}^{M-0} + t_{j(h)}^{load} + + t_{j(h)}^{unload} + \sum_{m=1}^{M} t_{h\_dwell}^{m}, \quad (14)$$

where $t_{j(h)}^{(m-1)-m}$ – loaded truck (cargo bike) travel time between the $(m-1)-m$ customers, h; $t_{j(h)}^{M-0}$ – empty truck (cargo bike) travel time when moving back to the departure point, h; $t_{j(h)}^{load}$ – loading time per one transportation cycle, h; $t_{j(h)}^{unload}$ – unloading time per one transportation cycle, h; t_{h_dwell} – additional cargo bike technological downtime for customer service in the second echelon, h.

From the models and criteria presented, at the next stage of the study, an experimental assessment of the *GSC* system alternatives will be done.

Research object experimental study

Experimental studies on the creation of a *GSC* system rational option have been fulfilled on the example of town of Brovary, Kiev region (Ukraine).

The urban area is 34 km^2, the population is 107000 people. To create the *GSC* system, the delivery of dairy products through the urban retail network has been chosen. The echelon system is created as follows: in the first echelon, the dairy products are transported by refrigerated vehicles with a carrying capacity of 1.5 t. The isothermal boxes of cargo bikes with a capacity of 0.2 and 0.3 t are used in the second echelon.

Using the local depot transshipment system should generate the sustainable effect and reduce the negative consequences of the transport industry operation.

When constructing the two echelon *GSC* structures, the main task is to find a rational local depot placement on the urban core borders.

Alternative local depot options are indicated with the green triangles in Fig. 1.

Potential consumers (35 facilities) are located in the cultural and historical town core and are presented as the red dots in Fig. 1. In the first echelon, the goods shipping point is indicated with the yellow circle in Fig. 1.

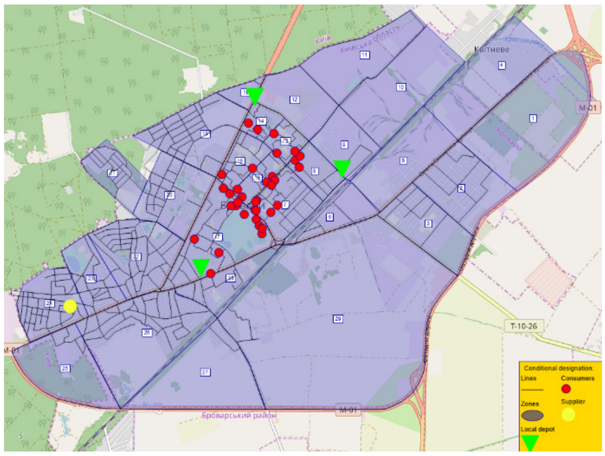

Fig. 1. Transportation network design

According to the criteria developed (1)–(4), to evaluate the local depot rational distribution, it is necessary to simulate the alternative options for the supply of goods within the second echelon. Each alternative second echelon system will be characterized by a set of delivery routes and a combination of the cargo bike types involved. Route modeling is performed from the Clark and Wright algorithm, which is resulted in a distance gain matrix. In this regard, it was decided to build a transport network local graph for displaying the road network of the urban core. The results of the construction are presented in Fig. 2.

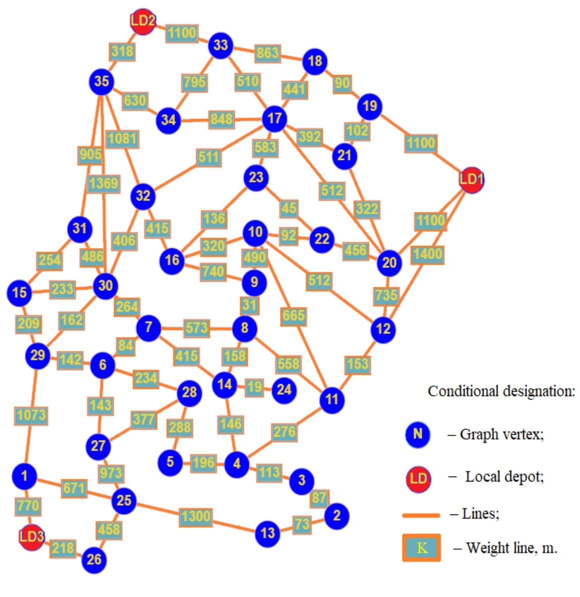

Fig. 2. Urban core network graph

The creation of the transportation volume database has been done using the apparatus of simulation modeling based on a preliminary assessment of the end consumers' delivery volume distribution. It has been established that this indicator is distributed according to the exponential law with a mathematical expectation of 0.02 t.

Upon completion of the simulation procedure for the three alternative supply systems in the second echelon, the first echelon transportation cycles have been added to each of the *GSC* systems.

The systems have been obtained from the proposed local depot placement options (green triangles in Fig. 1) and the main shipper stationary location (yellow circle in Fig. 1). The first echelon transportation cycles have been formed from the optimal shipper assignment procedure using minimal transportation links to consider the traffic conditions on the urban road network.

The results to obtain the alternative *GSC* systems are presented in Tab. 1. The alternative local depot options are given as LD1, LD2 and LD3. The numbers of the delivery points correspond to the numbers of the graph vertexes on the road network of the urban core (Fig. 2).

Table 1

Alternatives for green supply chain systems

GSC system options	Routes	Transportation mode
1	Supplier–LD1–Supplier	Truck
	LD1–6–27–25–26–1–15–31–35–34–LD1	Cargo bike 2
	LD1–12–11–24–14–8–9–10–16–23–22–20–LD1	Cargo bike 2
	LD1–13–2–3–4–5–28–7–30–32–LD1	Cargo bike 2
	LD1–19–18–33–17–21–LD1	Cargo bike 1
2	Supplier–LD2–Supplier	Truck
	LD2–6–28–5–7–27–25–26–1–29–LD2	Cargo bike 2
	LD2–22–10–12–11–4–3–2–13–9–8–14–24–LD2	Cargo bike 2
	LD2–31–15–30–32–16–23–20–21– 19–18–17–33–LD2	Cargo bike 2
	LD2–34–35–LD2	Cargo bike 1
3	Supplier–LD3–Supplier	Truck
	LD3–1– LD3	Cargo bike 1
	LD3–2–3–24–9–8–14–4–11–12–5–LD3	Cargo bike 2
	LD3–21–17–16–10–23–22–20–19–18–33–34–35–31– LD3	Cargo bike 2
	LD3–25–13–29–30–32–15–7–6–28–27–LD3	Cargo bike 2
	LD3–26– LD3	Cargo bike 1

At the next stage of finding a rational *GSC* option, the road network load has been simulated in case of goods delivery by cargo bikes. The simulation has been done in the PTV Visum software. For this, each end-user was allocated to a separate transport area. In the case of proximity, the customers were merged into one area.

The task of compiling the freight destination matrices (demand model) was solved by adding the volumes of goods moving from one transport area to another area.

The size of the resulting matrix is 28×28, where 27 transport areas with customers and one area that correspond to an alternative local depot placement were allocated.

The freight flow simulation results are presented in Fig. 3–5.

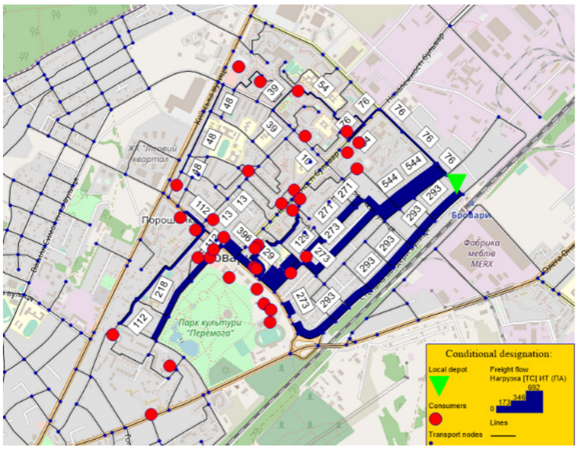

Fig. 3. The second echelon *GSC* freight flow chart, 1st option

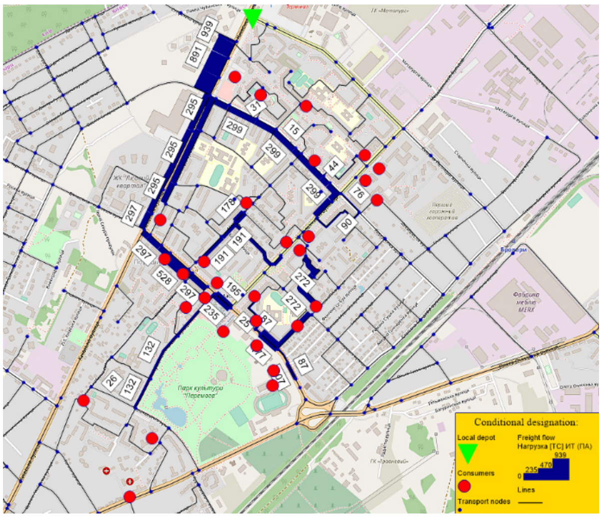

Fig. 4. The second echelon *GSC* freight flow chart, 2nd option

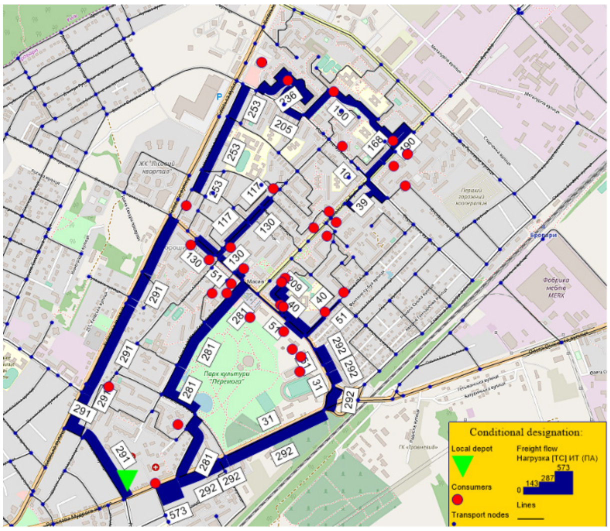

Fig. 5. The second echelon *GSC* freight flow chart, 3rd option

In the first delivery model, when using cargo bikes the maximum network load was 692 kg, in the second model – 939 kg, in the third model – 573 kg. It should be noted that an increase in the concentration of freight traffic on the road network does not lead to an increase in the negative effect of the transport use. This is due to the cargo bikes operation in the second echelon.

A graphical interpretation of the network load according to the three alternative *GSCs* made it possible to conclude that the *GSC* No 2 is preliminary effective, since for this system option the density and compactness of the cargo flow distribution over the network is the highest.

It has been suggested that this state of the object under research should guarantee the minimum freight turnover of cargo bikes. To test this hypothesis, the system performance indicators have been calculated using the models (13), (14), followed by consolidation into general system indicators according to (2)–(4). From the obtained values, an assessment of the rational local depot placement has been made by function (1).

The assessment results the under models (2)–(4) are presented in Fig. 6–8. On the data obtained, a matrix of rational options of local depot placement has been generated and its most effective location has been determined (Fig. 9).

Thus, according to the results presented, it is possible to make a conclusion that the most effective local depot placement is the GSC option No 2.

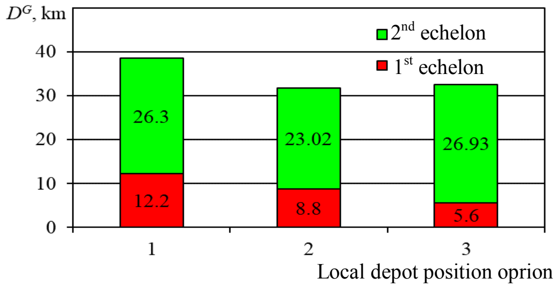

Fig. 6. Alternative *GSC* total mileage

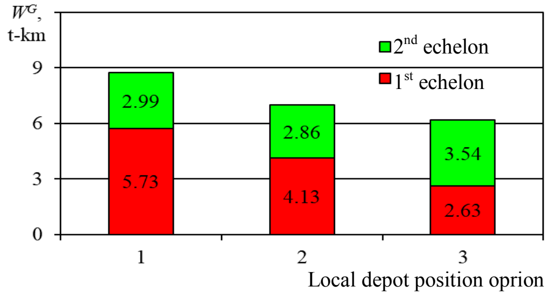

Fig. 7. Alternative *GSC* total freight turnover

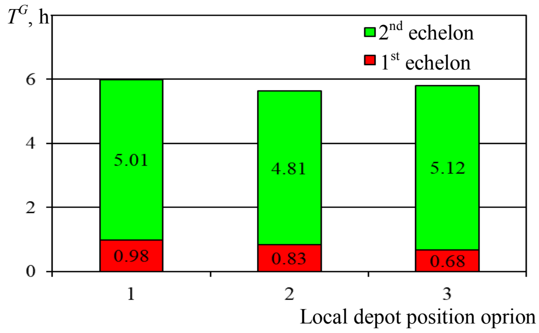

Fig. 8. Alternative *GSC* total delivery time

Criterion	*GSC* options		
	1	2	3
	Rational local depot position		
D^G		Rational	
W^G			Rational
T^G		Rational	
RP		Opt	

Fig. 9. Rational local depot placement matrix

Evaluation of the research results

The purpose of the *GSC* is to ensure the viability of urban centers in the context of sustainable urban development. Achieving this goal is possible by the mileage reducing and, as a result, the amount of harmful emissions through rational placement of local depot in the first echelon as well as their complete elimination by using the green mode of transportation in the second echelon. In order to evaluate the presented GSC from the environmental efficiency viewpoint, a comparison should be made with the previous supply model, when the distribution of goods is performed only by trucks.

The technique [27] was used to calculate the reduced value of emissions of harmful substances released during the internal combustion engine operation. Reducing the mass of emissions is used to reflect the danger of atmospheric pollution in a comparable way with the weight coefficients

$$M = \sum_{i=1}^{n} A_i m_i, \qquad (15)$$

where M – reduced mass of the annual emission by motor vehicles, conv. t/year; n – total amount of impurities that are released into the atmosphere per year; A_i – indicator of the relative impurity aggressiveness of the i^{th} type (Tab. 2); m_i – annual emission mass of the i^{th} impurity into the atmosphere, t/year.

Table 2

Values of A_i for substances released into the atmosphere by trucks with a carrying capacity of 2 t

Substance	Index of relative impurity aggressiveness
Carbon monoxide – CO	1
Nitrogen oxides (by weight) – NO_x	42.1
Hydrocarbon gas vapours (by carbon) – CH	1.5

These substances are known to be dangerous for humans – carbon monoxide prevents the blood oxygen transfer, nitrogen oxides lead to irritation and damage to the mucous membranes, and hydrocarbon gasoline vapors are of a significant narcotic effect. In addition, they negatively contribute to an increase in atmospheric temperature and water and soil pollution.

The mass of the annual emission of the i^{th} impurity into the atmosphere is calculated by the dependence

$$m_i = m_{i*} D K_1 K_2 K_3 \cdot 10^{-6}, \qquad (16)$$

where m_{i*} – specific emission of i^{th} impurity per 1 km, g/km (Tab. 3); D – vehicle annual mileage, km; K_1, K_2, K_3 – influence coefficients of the rolling stock average age, technical state, environmental and climatic conditions, respectively (Tab. 3).

For the existing consumers and suppliers' network the goods distribution is along the route: Supplier–1–27–29–15–31–35–34–33–17–18–19–21–20–10–22–23–16–32–30–7–6–28–5–12–11–4–9–8–14–24–3–2–13–25–26–Supplier, in this case D =19.127 km/day. The dairy products are assumed to be delivered every day, then D = 6981.36 km/year. Thus, the calculated value of the reduced mass of emissions of harmful substances into the atmosphere will be equal 2.42 conv. t/year (Fig. 10).

Table 3

Values of m_{i*}, K_1, K_2, K_3 for internal combustion engine trucks

Substance	m_{i*}	K_1	K_2	K_3
CO	26.80	1.33	1.80	1.20
NO_x	5.10	1.00	1.00	1.20
CH	2.70	1.20	2.00	1.20

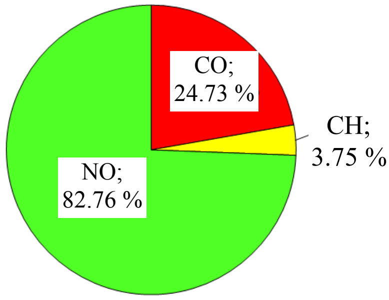

Fig. 10. Reduced mass of truck annual emission

With the selected rational local depot placement for the *GSC* No 2 option, the value of the reduced mass of pollutants will make 1.11 conv. t/year.

CONCLUSIONS

1. According to the research, it possible to make a conclusion that a two-echelon system of urban material supply should be created from the viewpoint of the sustainable urban development.

2. As a criterion for determining the local depot rational placement, it is advisable to use a comprehensive indicator to provide a simultaneous assessment of the freight turnover, delivery time and the vehicles' total mileage within two echelons. The three alternative systems of the urban supply chain have revealed a trend in the freight turnover when providing services with cargo bikes to end customers in the second echelon. From the distribution of freight flows over the network (within the second echelon), it has been established that the minimum freight turnover of cargo bicycles corresponds to the greatest load on the road network. At the same time, the use of freight bikes eliminates the congestion and guarantees the delivery of goods to end consumers with a minimal time window.

3. The study has also substantiated that the two-echelon green supply chain provides a significant reduction in the road transport negative environmental impact. It has been determined that even for an area of 3.88 km^2, the replacement of the in-

ternal combustion engine trucks with the cargo bikes can lead to an annual decrease in harmful emissions of 2.42 conventional tons (reduced CO, CH and NO_x units).

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