УДК 656.025 DOI 10.33042/2522-1809-2020-6-159-153-160

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LOCAL DEPOT-BASED URBAN SUPPLY CHAIN FOR LIVEABLE CITIES

The paper presents the theoretical and experimental study results on construction sustainable urban supply chain, namely last mile delivery. Within the theoretical part we proposed to estimate the necessary number of local depots within the supply chain taking into account the direct and indirect impacts from a delivery system functioning. The indirect effect is presented with CO2 emissions. The conducted experiment has covered the pessimistic and optimistic scenarios for delivery system states. Within the experiment along with demand attributes we assessed the range of vehicle carrying capacity from 0.5 to 2 tons. The obtained experimental results revealed the shift in necessary local depots number to guarantee the sustainable effect for delivery system and promote liveable state for the urban area.

Keywords: *local depot, urban supply chain, environment, sustainability, tour*.

Problem statement

The transportation process implemented by motorized vehicles remains to be the urgent element of the supply chain [1–4]. Within the urban area, where the delivery system can form the strong negative environmental impact, the unsustainable problems attracted the great attention of the researchers around the globe for years [1, 5–9]. A list of measures has been proposed in this case giving the technical [5, 7, 10] and technological [1, 6, 9, 11–13] ways for leveling negative impact of the vehicle and truck-based urban logistic. Both of them are efficient and appropriate for the urban supply chain (USC) environmentally friendly state to be achieved.

In frame of this study we would like to focus on technological measures connected with construction of sustainable option for urban delivery system. A two echelon USC (2E-USC) will be considered as the frame structure for delivery system. In this case the number of LD plays an important role in deconsolidation, storage and transportation processes within 2E-USC. According to this we would like to assess the impact of LD number on 2E-USC total cost allowing us to define the conditions of the sustainable option for goods delivery system.

Literature analysis

The local depot-based supply chain has been considered as the key element promoting sustainable urban delivery system within a list of studies [11–18]. The number of LD in the supply channel can be considered as one of the major factors influencing on 2E-USC efficiency. It gives the possibility to achieve the sustainable option of the urban delivery system leveling the negative impact caused by the freight vehicles. According to this statement, for instance, the study made by Crainic et al. [11] proposed to formalize the relationship among LD number, their accessibility and transportation cost. The authors utilized Hansen’s model [19] to identify the accessibility index for every possible location of the satellite (can be referred to LD according to its functional purpose). Along with that the authors used the mean of normalized transportation cost as criterion to implement the complex assess the satellite location. In fact, the Crainic et al. identified the necessary number of LD for urban delivery system as the complementary issue in case of study’s [11], as the major aim was the LD location solving. The authors have used the limited interval to LD variation from two until five and considered the variable-density density of customers’ distribution. In turn the end-consumers’ number was variable from 50 till 250. The satellites have the random location not the centered one that gave, in some instances, the extra values for VMT and transportation cost. As this study has the exploratory features it became the base for further research in field of 2E-USC.

Thus, J. Gonzalez-Feliu within his study [12] proposed alternative to classic 2E-USC system based on cross docking strategy. It means the absence of stocking process in the LD but with the freight deconsolidation fulfillment. Under such conditions the vehicle routing problem (VRP) solving, and LD number estimation are the basic steps that have to be done. The study [12] are focused on VRP revealing most common used algorithms with description of their features and advantages.

Following up upon 2E-USC problem and contributing to [12] S. Manchini in work [14] has covered the wide range of questions in field of multi-echelon urban delivery, namely, the two echelon location routing problem, the two echelon VRP (2E-

VRP) and truck and trailer routing problem. Every of these issues is a part of general problem on sustainable development of the urban area. For instance, 2E-LRP deals with land use and facility location efficiency that are highly important for 2E-USC. As the density of end-consumers can vary within urban area and some restrictions on inner area entering by the truck can be deployed 2E-LRP can help in providing the appropriate location definition for LD. The number of LD is significant attribute in frame of 2E-VRP and should be formalized according to demand parameters. Besides that, 2E-VRP is strongly connected with vehicle load-carrying capacity estimation problem [20] and vehicle loading capacity usage rate [21]. Taking into account all these features of 2E-USC the 2E-VRP allows us to minimize the total VMT within both echelons and contribute into sustainable development of the urban area.

Another issue that should be revealed within liveable cities paradigm is the definition of LD number. To solve this problem some of the studies used analytical modeling [15, 16] revealing the environmental positive impact provided by 2E-USC. In such a way, the study [15] gave the insights into the environmental efficiency evaluation under LD-based delivery system usage versus private cars. As the criterion for extreme bounds definition, when the LD-based USC is efficient to be used, the authors have been considered the total vehicle mileage travelled (VMT). The analytical model has been developed based on Daganzo's approximation for the traveling salesman problem [22]. As the result of the study [15] the authors have estimated the hyperbolic tendency of emission coefficient ratio change that should be used as the guideline on promoting environmentally friendly LD-based supplies.

The new vison on LD number estimation has been proposed in [16]. Thus, the authors proposed to take into account the monetarized impact of the environment pollution caused by the freight vehicles. Under such conditions the LD number shifts into the bigger values than it could be without taken into account monetized environment impact. This effect has been revealed for suburban area under service of consumers from 30 till 45 units. The shift in LD rational number has been observed for all cases of vehicles usage (considered from 0.6 till 2 tons). Based on that the proposed methodology to LD number assessment gave the positive results and needs the deeper study in case of the city area with higher density of end-consumers location.

To promote the sustainable city development the local authorities may restrict or prohibit the inner area access by the vehicles with combustion engine [23]. Such measures are important for touristic cities, for instance Rome [13] or Cracow [17], to provide environmentally friendly inner area for residents and visitors [24]. Under such conditions the delivery of the goods to the end-consumers within inner area should be executed via 2E-SC construction. This type of the 2E-USC is known as nearby delivery area (NDA) system. As there is the restriction for the access the inner area by the vans the cargo bikes or electric cycles are appropriate to use within the second echelon. The static location of the LD becomes the key factor to fulfil the efficient and effectiveness delivery process to the end-consumers when the NDA system is used.

The usage of NDA with LD-based option may be considered as the multi commodities supply chain [13]. Furthermore, the end-consumer can be provided with alternative channels of the delivery implementation or purchase channels choice within one NDA system. According to these, in [13] authors have developed the scenarios for e-commerce and in-store purchase channels service based on 2E-USC with NDA option. The restoking trips of the vehicles within the second echelon is proposed to implement by trolleys making zero CO2 emissions. This guarantees the possibility to make the last mile delivery within the area having the access restriction for vans and cars with combustion engine. The e-commerce deliveries within the second echelon are executed by the end-consumers via parcel lockers system. The simulated data for NDA and alternative delivery bays-based system has revealed higher efficiency of NDA system with the reduction in 59 percent of the total delivery time for the studied area (Campo Marzio, inner area of Rome, Italy). Thus, as it is defined in [13] the NDA system may act as more flexible and time efficient SC option if to compare with regular deliveries within the inner area. Taking into account the environment effect under NDA system usage we may conclude about high efficiency of green 2E-SC and necessity to deeper evaluate the conditions for LD-based urban deliveries.

Naumov and Starczewski [17] have proposed to determine the rational location of the LD according to minimization of cargo bicycles freight turnover within the second echelon. The estimation of the rational location only of one satellite for the NDA system was the key feature of this research, as the bigger number of the LD would be excessive because of the low freight flow. Under such conditions the variance in order sizes and density of the end-consumers forms the basic characteristics of the demand for the service. The authors proposed to use Monte-Carlo method to assess the distribution of the freight turnover values. The study did not face with assessment of the monetary cost of the delivery process as the non-motorized vehicles have been used for the second echelon. The simulation data has shown that for the small delivery weight the mean of the freight turnover varies from 1.7 till 2.5 tons-kilometers for the alternative scenarios of LD location. The variance of total freight turnover was determined with the significant law values, less than 0.03 tkm2, making possible to assess the rational location of the LD with small number of the draws during the simulation.

Rossolov et al. in [18] made the estimation of LD rational location for 2E-USC using multi criterion which covered the parameters for both echelons. It reflected the total vehicle mileage travelled, freight turnover and goods delivery time within the first and the second echelons. As the additional component of the NDA system usage the reduction in CO, NO and CH has been evaluated. The modeled data shown about significant contribution in sustainable city development under NDA system implementation. The complex assessment of the 2E-USC functioning results allowed to define the rational location of LD with consideration of consolidation center location and density of the end-consumers within the service area.

Methodology

To promote the sustainable option for USC we propose to take into account direct and indirect impact of the urban delivery system. The graphical interpretation of the proposed approach is presented in Fig. 1 and more detailed description of this approach can be found in [16].

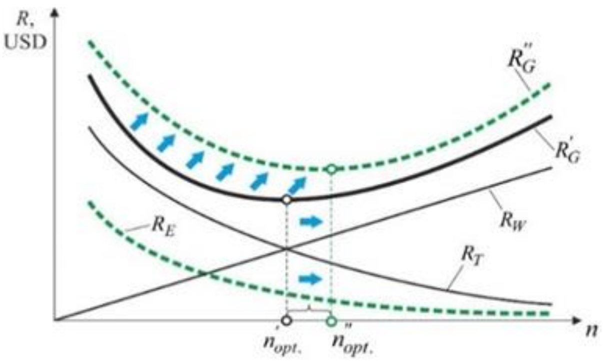

Fig. 1. Sustainable approach to determine the optimal number of local depots in the supply chain [16]

According to Fig. 1 the total impact of USC provided for the urban area can be calculated as follows:

$$R_G^{//} = R_T + R_W + R_E \,, \tag{1}$$

where $R_G^{//}$ is the total impact of the USC, USD;

R_T is the total transportation cost, USD;

R_W is the total storage cost, USD;

R_E is the negative environmental impact from the supply chain, USD.

The presented in Fig. 1 value $R_G^{/}$ reflects the common approach to LD number estimation based on direct effect. Under this statement the LD number do not provide the sustainable option as the indirect impact from USC is not taken into account. According to this we have:

$$R_G^{//} = R_G^{/} + R_E \,, \tag{2}$$

Following (1) the rational number of LD can be formalized as:

$$R_G^{//} = f\left(n_{LD}^{//}\right) \to \min \,, \tag{3}$$

where $n_{LD}^{//}$ is the number of LD under sustainable conditions for USC, units.

The transportation cost is calculated according to the number of the tours made by the vehicles:

$$R_T = C_{VMT} \cdot \sum_{j \in n_{LD}} \sum_{i \in \Psi} d_{ji} + C_{1hour} \cdot \sum_{j \in n_{LD}} \sum_{i \in \Psi} t_{ji} \,, \tag{4}$$

$$j, i, n_{LD}, \Psi, > 0 \tag{5}$$

where C_{VMT} is the transportation cost element depending on the mileage, USD/km;

C_{1hour} is the transportation cost element depending on the time, USD/hours;

d_i is the length of i tour, km;

t_i is the duration of i tour, hours;

n_{LD} is the total number of LD that is used within USC, units;

Ψ is the total number of tours, units.

K is the total number of the tours that should be made to service all clients of value N_{cl} located within the area S, units.

The tour length without vehicle capacity constraints is proposed to define based on Daganzo's approximation [22]:

$$D = k \cdot \sqrt{N_{cl} \cdot S} \,, \tag{6}$$

where D is the tour lengths without vehicle capacity constraints, km;

k is the coefficient, k = 0.75;

N_{cl} is the number of the clients that should be serviced within the area, units;

S is the square of the service area, km^2.

The tour duration is the function of vehicle route speed and length:

$$t = f\left(d, V\right), \tag{7}$$

where V is the vehicle route speed, km/h.

It should be noticed that within this study we are considering the impact within the second echelon where the delivery process is implemented under the last mile conditions. In this case the end-consumers' number acts as the key attribute for the LD amount estimation. Within the urban scale this value is bigger than for suburban area that has been assessed by the authors in [16].

To assess the tour length, we have to make the estimation of the clients' number, that should be serviced within every tour. For that reason, at the first stage we have to evaluate the needed number of tours that should be implemented for all number of clients within the area covered by one LD:

$$\Psi = \frac{N_{cl} \cdot \phi}{1000 \cdot q_v \cdot n_{LD}}, \quad (8)$$

where ϕ is the average amount of goods that is delivered to one consumer, kg;

q_v is the vehicle loading capacity, tons.

Based on (8) the number of clients within one tour is the following:

$$n_{cl} = \frac{N_{cl}}{\Psi \cdot n_{LD}}, \quad (9)$$

where n_{cl} is the number of clients within one tour, units.

Given (8) and (9) we can estimate the actual tour length:

$$d_i = k \cdot \sqrt{n_{cl} \cdot \frac{S}{n_{LD}}} = k \cdot \sqrt{n_{cl} \cdot S^{/}}, \quad (10)$$

where $S^{/}$ is the service area covered by one LD, km^2.

In frame of this study we would like to test the Daganzo's approximation usage for predicting the tour length within the second echelon instead of used in [16] Pravdin et al. model [25]. Besides that, the tour length is constructed in the study according to the following assumption:

$$d_{LD-c} = d_{c-(c+1)}, \quad (11)$$

where d_{LD-c} is the mileage covered by the vehicle from LD to the first client within the tour, km;

$d_{c-(c+1)}$ is the mileage between two consecutive clients within the tour, km.

So, based on (11) we are considering that the location of LD in relation to consumers N_{cl} within the study area S forms the relevant densities. This allows us to implement the analytical modeling of the USC within the second echelon based on Daganzo's approximation. Having the modeled results on USC states under variable number of LD we will be able to evaluate the achieved sustainable effect making city liveable for the inhabitances.

The description for R_W and R_E modeling can be found in [16].

Results

The experimental part will be implemented following to experimental plan developed in [16]. We will consider the orthogonal plan of 2^n type (where n is the number of factors in the experimental plan). As the input variable attributes n we propose to use the following: x_1 – the average consignment delivered to every consumer; x_2 – the number of consumers within the study area. The square of city area is fixed at 350 km^2 reflecting the case study Kharkiv city. The extreme values for x_1 and x_2 are defined according to the considered last mile delivery system. So, within Kharkiv city case study we use parcel delivery company "Nova Poshta". This company has one central terminal within urban area and about 100 post offices that service the unattended deliveries for city's inhabitants. According to this $x_1^{min} = 50$ kg, $x_1^{max} = 100$ kg. In turn for x_2^{min} and x_2^{max} we used, accordingly, 50 and 150 post offices reflecting the pessimistic and optimistic scenarios.

The experiment plan has been carried out for a list of vehicle types as 0.5, 1.0, 1.5 and 2.0 tons. Given that we could assess the wide range of possible situations that can occur within USC. Also, it should be noticed that during the experiments implementation we detected both variants of the LD number estimation: under non sustainable (*eq. 1* without R_E) and sustainable (*eq. 1* taking the full range of components) conditions. That is why every experiment is presented by two values of LD number, as $n_{LD}^{/}$ and $n_{LD}^{//}$.

The obtained results of the conducted experiments are presented in Tables 1–4 and Fig. 2–5.

Table 1

Results on USC impact under 1st experiment

Vehicle carrying capacity, tons	Impact (cost), USD	Number of LD, units			
		1	2	3	4
0.5	R_T	131.8	70.8	50.3	41.7
	R_W	26.1	37.5	56.4	83
	R_E	56	28	20	16
	$R_G^{/}$	158	108	107	125
	$R_G^{//}$	214	136	127	141

Vehicle carrying capacity, tons	Impact (cost), USD	Number of LD, units			
		1	2	3	4
1.0	R_T	102.2	58.8	41.3	35.1
	R_W	26.1	37.6	56.6	83.3
	R_E	48	24	16	12
	$R_G^{/}$	128	96	98	118
	$R_G^{//}$	176	120	114	130
1.5	R_T	91	51.8	36	36.4
	R_W	26.2	37.7	56.8	83.5
	R_E	44	24	16	12
	$R_G^{/}$	117	89	93	120
	$R_G^{//}$	161	113	109	132
2.0	R_T	88.8	51.9	42.9	33.4
	R_W	26.2	37.8	56.9	83.9
	R_E	44	24	16	12
	$R_G^{/}$	115	90	100	117
	$R_G^{//}$	159	114	116	129

Table 2

Results on USC impact under 2nd experiment

Vehicle carrying capacity, tons	Impact (cost), USD	Number of LD, units			
		1	2	3	4
0.5	R_T	91.2	49.8	33.6	27.4
	R_W	15	26.4	45.5	72.2
	R_E	40	20	12.8	8
	$R_G^{/}$	106	76	79	100
	$R_G^{//}$	146	96	91.8	108
1.0	R_T	72.6	39.2	30.1	22.5
	R_W	15	26.6	45.8	72.7
	R_E	36	16	12	8
	$R_G^{/}$	88	66	76	95
	$R_G^{//}$	124	82	88	103
1.5	R_T	61.8	37.9	27.7	17.4
	R_W	15.1	26.7	46	73.3
	R_E	32	16	12	8
	$R_G^{/}$	77	65	74	91
	$R_G^{//}$	109	81	86	99
2.0	R_T	59.7	33.6	20.7	20.5
	R_W	15.1	26.8	46.4	73.3
	R_E	32	16	9.2	8
	$R_G^{/}$	75	60	67	94
	$R_G^{//}$	107	76	76.2	102

Table 3

Results on USC impact under 3rd experiment

Vehicle carrying capacity, tons	Impact (cost), USD	Number of LD, units			
		1	2	3	4
0.5	R_T	43.9	23.6	15.7	14.9
	R_W	11.2	22.6	41.5	68.1
	R_E	20	8	5.6	4
	$R_G^{/}$	55	46	57	83
	$R_G^{//}$	75	54	62.6	87
1.0	R_T	34.1	21.1	15.5	9.7
	R_W	11.3	22.7	41.7	68.4
	R_E	16	8	6	4
	$R_G^{/}$	45	44	57	78
	$R_G^{//}$	61	52	63	82
1.5	R_T	28.6	19.3	12	12.1
	R_W	11.3	22.7	41.9	68.4
	R_E	16	8	4.8	4
	$R_G^{/}$	40	42	54	81
	$R_G^{//}$	56	50	58.8	85
2.0	R_T	31.7	14.4	14.3	15
	R_W	11.3	22.9	41.9	69.1
	R_E	16	8	5.2	4
	$R_G^{/}$	43	37	56	84
	$R_G^{//}$	59	45	61.2	88

Table 4

Results on USC impact under 4th experiment

Vehicle carrying capacity, tons	Impact (cost), USD	Number of LD, units			
		1	2	3	4
0.5	R_T	30.4	17.7	12.4	11.7
	R_W	7.5	19	38	64.7
	R_E	12	8	4.8	4
	$R_G^{/}$	38	37	50	76
	$R_G^{//}$	50	45	55	80
1.0	R_T	25.8	16.5	10	9.7
	R_W	7.6	19.1	38.1	65.3
	R_E	12	8	4	3.6
	$R_G^{/}$	33	36	48	75
	$R_G^{//}$	45	44	52	79
1.5	R_T	22.8	12.6	12	12.1
	R_W	7.6	19.1	38.6	65.3
	R_E	12	6	4.8	4
	$R_G^{/}$	30	32	51	77
	$R_G^{//}$	42	38	56	81
2.0	R_T	16.9	14.4	14.3	15
	R_W	7.7	19.5	38.6	65.4
	R_E	8	6.4	5.2	4.8
	$R_G^{/}$	25	34	53	80
	$R_G^{//}$	33	40	58	85

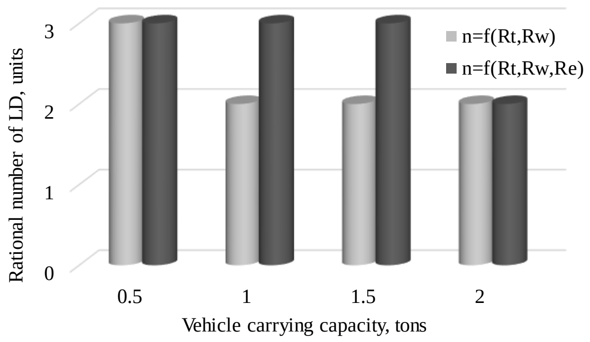

Fig. 2. The 1st experiment results on rational number of LD for non-sustainable and sustainable states of USC

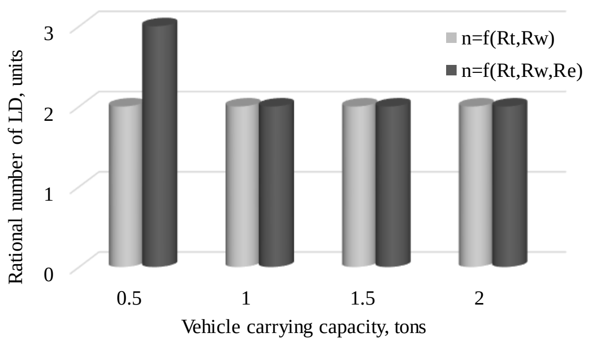

Fig. 3. The 2nd experiment results on rational number of LD for non-sustainable and sustainable states of USC

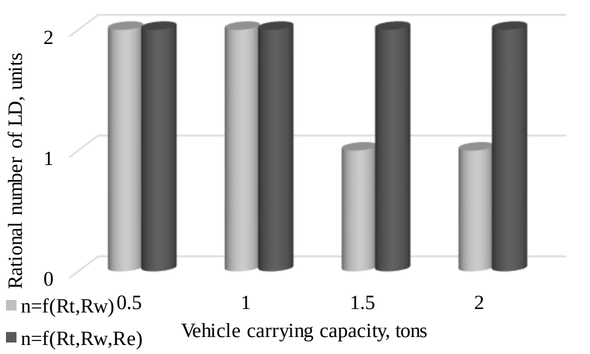

Fig. 4. The 3rd experiment results on rational number of LD for non-sustainable and sustainable states of USC

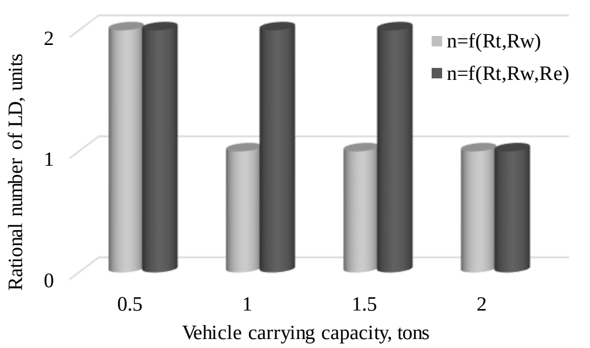

Fig. 5. The 4th experiment results on rational number of LD for non-sustainable and sustainable states of USC

Based on obtained results on the conducted experiments we can state that the shift in LD number to promote the sustainable option of the 2E-USC has been detected for all experiments. Moreover, within the first, third and fourth experiments this effect is observed for a list of vehicle carrying capacity values.

Conclusions

Based on the conducted theoretical and experimental studies we can conclude the following. The literature analysis allowed us to assess the scope of LD usage in frame of 2E-USC. The wide range of problems can be solved based on LD-based supply system. Among them we would like to emphasize on deconsolidation features for LD positively influencing the VMT and transportation cost.

The developed analytical model for estimating the rational number of LD takes into account the direct and indirect impacts of USC. This gives us the possibility to define the sustainable states of the delivery system and promote the liveable cities development. In this frame the special attention should be given to VMT and number of tours prediction. To do this we used the Daganzo's approximation. In turn, the necessary number of tours has been estimated based on vehicle carrying capacity constraints.

The experiment results covered the pessimistic (low demand) and optimistic (demand possible growth) scenarios with range of vehicle carrying capacity from 0.5 to 2 tons. The modeled data has revealed the necessity of taking into account the indirect impact of USC. For all four experiments we observed the condition of $n_{LD}^{//} > n_{LD}^{/}$ where $n_{LD}^{/}$ is defined based only on direct impact from USC. This effect has a slight power within the pessimistic scenario (the 4th experiment) when the consignment and consumers' density within the service area decrease.

As the further research steps, we would like to implement the assessment of LD number under conditions of attended deliveries, such as home delivery. Besides that, the first echelon has to be included in the model allowing us to describe the whole chain of commodities' delivery within the urban area.

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МІСЬКИЙ ЛАНЦЮГ ПОСТАЧАНЬ НА ОСНОВІ ЛОКАЛЬНИХ ПЕРЕВАНТАЖУВАЛЬНИХ ПУНКТІВ ДЛЯ ЗАБЕЗПЕЧЕННЯ ВИСОКОЇ ЯКОСТІ ЖИТТЯ В СУЧАСНИХ МІСТАХ

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У статті представлені результати теоретичного та експериментального дослідження впровадження сталого ланцюгу постачань в рамках доставки останньої милі. Авторами запропоновано новий підхід до побудови міського ланцюгу постачань на основі локальних перевантажувальних пунктів. В контексті вирішення даної задачі представлено методику оцінки раціональної кількості локальних перевантажувальних пунктів для міської території. В теоретичній частини статті розкрито сутність нового підходу до визначення раціональної кількості локальних перевантажувальних пунктів, який передбачає врахування прямого та непрямого впливів від функціонування міської системи матеріальних постачань. Непрямий вплив формалізовано через обсяг викидів СО2 з подальшою монетарізацією цієї складової. На основі апроксимації Доганзо розроблено аналітичну модель оцінки середнього пробігу вантажного транспорту при доставці товарів споживачам в межах міста. Поряд з цим в аналітичній моделі враховано обмеження по вантажності транспортних засобів, що стало основою для визначення кількості транспортних циклів виконаних на транспортній мережі. Проведений експеримент охопив песимістичний та оптимістичний сценарії стану системи доставки. В якості факторних ознак для опису сценаріїв застосовано середній розмір постачання та загальну кількість пунктів видачі «Нової Пошти» в місті Харків. В експерименті разом із характеристиками попиту проведена оцінка вантажопідйомності транспортних засобів в діапазоні від 0,5 до 2 тон. Отримані експериментальні результати показали зміну в кількості необхідних місцевих складів в порівнянні з базовою оцінкою на основі лише прямих витрат. Зафіксовано наявність здвигу в сторону зростання потрібної кількості локальних перевантажувальних пунктів при побудові сталого варіанту міського ланцюгу постачань. В результаті застосування запропонованого підходу очікується досягнення сталого стану міської системи матеріальних постачань що повинно сприяти зростанню життєздатності міста.

Ключові слова: *локальний перевантажувальний пункт, міський ланцюг постачань, навколишнє середовище, сталість, маршрут.*