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Assessment of the last-mile distribution performance in urban areas fragmented by transit infrastructure

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Abstract. Cities are dynamic systems that require continuous adaptation of sustainable mobility offers. Transitways, with dedicated infrastructure physically separated from other vehicle traffic, are considered solutions for increasing the attractiveness of public transport in high-density urban areas. However, the effects of the fragmentation caused in urban areas by transitways are insufficiently analysed. Mainly, the effects on the performance of freight vehicles in last-mile distribution are usually not assessed in the evaluation of the introduction of a new transitway. In this framework, the paper proposes a method for evaluating the influence of introducing a transitway on freight vehicle performance in last-mile distribution. An efficient algorithm to search for optimal distribution itineraries is presented. The method is exemplified for urban distribution in a fragmented area of Bucharest by introducing a transitway. For the new setting in which road traffic is channelised due to the fragmentation of the urban area by the transitway, the road traffic network is formalised and the itineraries for goods distribution to a set of six convenience stores are deter-mined. The presented method argues the necessity of an integrative analysis of all the consequences of introducing dedicated transitways. In addition, the method is useful in evaluating the effects of introducing one-way traffic on road networks in congested urban areas on city logistic performance.

Keywords: urban sustainable mobility; urban fragmentation; city logistics; last-mile distribution; vehicle routing problem.

1. Introduction

The city is a complex system characterised by defining economic, social and environmental features in a specific dynamic [1]. In this dynamic, the research goals mainly focus on spatial mobility policies reflected in the recorded level of the

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accessibility of points of interest in the urban area. The direct connections with the activities and life of the city motivate the research.

Urban settlements can be analysed, in a traditional Cartesian manner, as a structure of three different components: the location, social relations, and mobility/transport subsystem [2–4]. Two tendencies appear within these subsystems, as individual parts and a whole: one integrative tendency of functioning as a component of a more extensive structure and another tendency of self-constraining, of preserving in-dividual autonomy. The tendency of self-constraining (to preserve individuality) is necessary to maintain the hierarchical structure of the urban system, as the tendency of integration is emphasised by the need to achieve the requirements of a whole sustainable system [3,5-7]. The two tendencies are opposite but complementary. There is a trade-off between integration and self-constraining. This trade-off is not static. The interactions between the two complementary tendencies lead to a flexible urban system and openness to change [6,8].

At the synthesis level, the functioning of high-density cities and their centres depends on the effectiveness recorded on multiple levels of social life (often contradictory) [4,8,9].

On the one hand, high-density urban areas must represent attractive and functional spaces for living, professional activities, shopping, free time, tourists, and pendulum movements stimulated by the essential places of interest. The analysis mainly refers to the social relations and location subsystems. Nevertheless, the subsystem of mobility/transport cannot be omitted from the evaluation.

On the other hand, almost all urban socio-economic activities involve the movements of people and goods. The mobility of passengers and freight distribution movements are responsible for the quality of the living environment in cities [10]. In the analysis, the subsystem of mobility/transport is involved. Nevertheless, the connections with the other two subsystems (location and social relations) cannot be disregarded [11].

The paper aims to assess last-mile distribution performance in urban areas fragmented by transit infrastructures. The case study considers an urban area of Bucharest fragmented by a light rail infrastructure. It examines a last-mile distribution network based on a selection of streets without restrictions for freight vehicles (traffic and parking). The consequences of introducing the transitway on last-mile distribution performance are assessed. Seemingly, only one of the three urban subsystems is im-plied, namely the mobility/transport one. However, the intercorrelations with the other two subsystems (location and social relations) are apparent. Introducing dedicated ways for urban transit increases the attractiveness of collective public transport. It negatively affects the supply of small independent retailers. It has direct consequences in the subsystem of social relations (by reducing the accessibility of proximity convenience stores and increasing the length of trips for inhabitants of the area). Additionally, in the long term, it affects the location subsystem (by reconsidering the location of convenience stores).

The paper is organised as follows. The next section clarifies specific characteristics of last-mile deliveries to convenience stores. In the case of a fragmented area by a

transitway, due to the median physical separation of road vehicle traffic, the freight vehicle trips are channelised on one-way lanes and the accessibility to the convenience stores is diminished. In order to optimise the distribution itineraries, the particular requirements in the formalisation of the road traffic network are described. Then, the proposed algorithm for the optimal distribution itinerary search is presented.
The results section exemplifies the algorithm application for a set of six convenience stores in the area fragmented by the transitway. The effects of the structural changes generated by the building of the transitway on the goods distribution performance are discussed. Future options for using the proposed method to assess distribution solutions in a fragmented urban area are indicated. The paper concludes by emphasising the necessity of a holistic evaluation of the effects of the fragmentation caused by transitways.

2. Problem definition

2.1. Specific characteristics of last-mile deliveries to convenience stores

The increase in the extent of urban settlements and road traffic generating external effects has motivated the intensification of the research on solutions to limit the negative consequences (economic, environmental, social) of the movement of freight vehicles on road urban networks [12-14].
Urban distribution logistics has significantly progressed and constantly concerns researchers [12,13,15] and decision-makers [14,16]. In this context, the attractiveness of convenience stores is noticed by the residents of the neighbourhood and it is reflected in the decrease in the frequency of individual motorised trips for purchases [17].
Traffic flows related to distributions to convenience stores in high-density urban areas are characterised by specificity [18]. They must ensure the distribution of consumer-packaged goods that are usual products, frequently replaced and with critical delivery time. The logistics characteristics of the goods and the limited storage capacities of the retailers determine high frequencies of deliveries of heterogeneous goods flows in relatively reduced volumes, correlated with the estimated sales for a short period. Additionally, due to the variety of transport conditions required for different categories of goods, the small size of the deliveries is evident, as well as the high frequencies in given short periods of time [17,19,20]. These characteristics motivate identifying delivery services that satisfy any retailer's market interests by conforming with traffic regulations on the urban street network with the lowest overall costs.
All components of the logistics chain management of the large distribution in urban agglomerations have evolved to reduce the logistic cost from the producer to the consumer and to fulfil the increasingly high requirements for environmental protection [12,15,21]. The successive consolidation of transport demand into goods flows, transport flows, and finally, traffic flows represent a central objective of the

design of the distribution system and logistics management, with extended effects on collaborative logistics [15,19,21]. The consolidation process is dynamic mainly due to the topological and structural changes of the linear and nodal infrastructure networks in-volved in supply and distribution logistics and their particular restrictions regarding traffic or access [22,23].

The paper aims to emphasise the consequences of the changes in the structural and functional design of the urban traffic network on the performance of "one-to-many" distribution logistics. The presented case study considers the increasing weight of one-way traffic on the urban road network and the building of a transitway. Figure 1 shows the selected study area.

Fig. 1. The fragmented delivery service area by a central transitway.

The transitway (the double red line in Figure 1) is median and physically separated from other vehicle traffic. It provides a high level of service for passenger transport. Nevertheless, due to the median separation, it imposes left turn restrictions. It channelises other vehicle traffic, reducing the accessibility of the points of interest with access on the opposite side of the traffic (Figure 2).

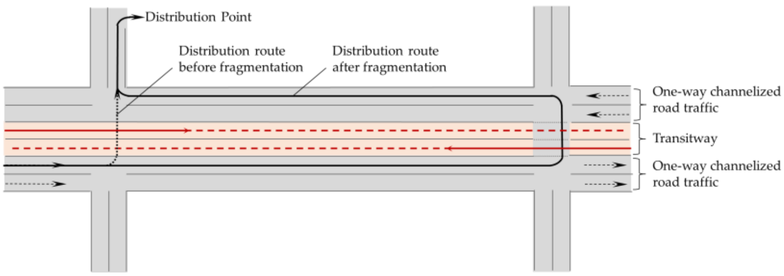


Fig. 2. Effects of the transitway on channelising other vehicle traffic.

In terms of the accessibility of the points of interest along the areas separated by the transitway, the situation is equivalent to the point location on two streets with different directions [24]. Therefore, for the routing problem, it is necessary to design a graph corresponding to the urban road network with roads that include transitways separating the traffic flow. The minimum routes between the nodes are identified on this graph, which is appropriately designed to access convenience stores by supplying freight vehicles. An effective algorithm is proposed to find the optimal routing solutions for satisfying the last-mile delivery tasks. The resulting solutions are compared with those obtained for the same set of distribution tasks on a graph corresponding to the street network before introducing a dedicated transitway (and fragmenting the last-mile distribution service area). Figure 3 shows the main steps applied to assess the transitway's effects on last-mile distribution performance.

The fragmentation effects on the performance of supply convenience stores are revealed by examining optimal last-mile distribution solutions in the presence and absence of roads with transitways. Solutions for reducing these effects can also aim strategies that need to re-examine the correlation between the distribution frequency and the storage capacities of convenience stores.

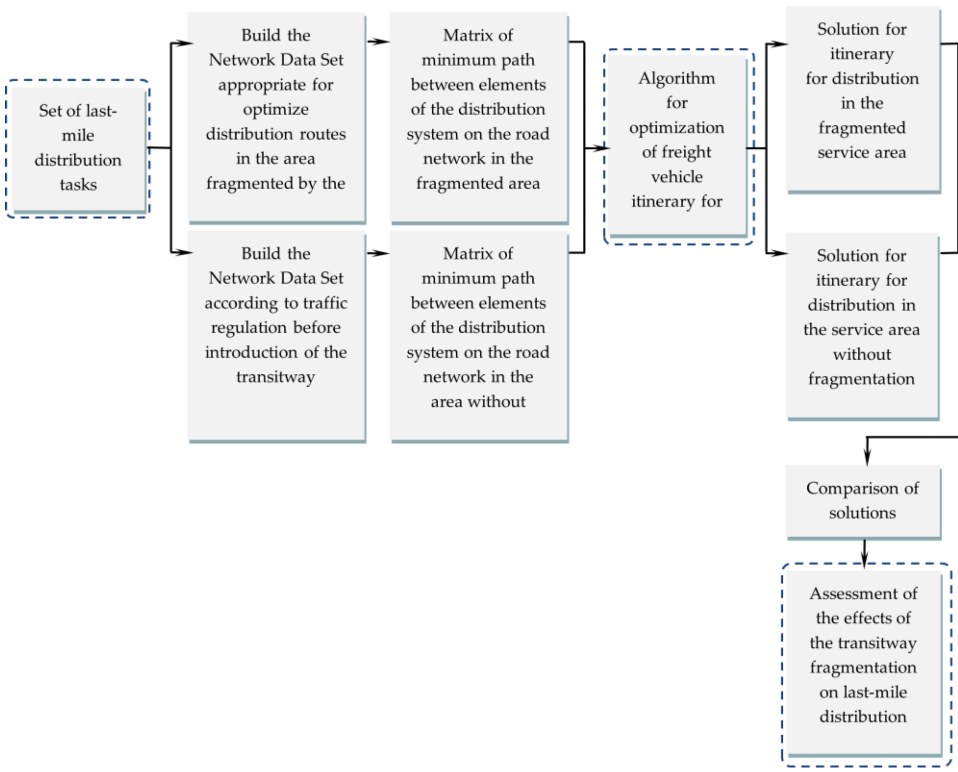


Fig. 3. Main blocks in assessing the effects of the service area fragmentation on last-mile delivery performance.

2.2. Modifications to access to convenience stores

The presented case study examines the consequences of introducing a transitway on the distribution route for convenience stores in the study area. The problem considers a set of six convenience stores (S_1, ..., S_6) supplied by a local warehouse (Figure 4). The network model is built based on the selection of the streets on which freight vehicle traffic is allowed.
After introducing the transitway that physically separates the road vehicle traffic, each link on which a convenience store is located is replaced by directed edges in the network graph.

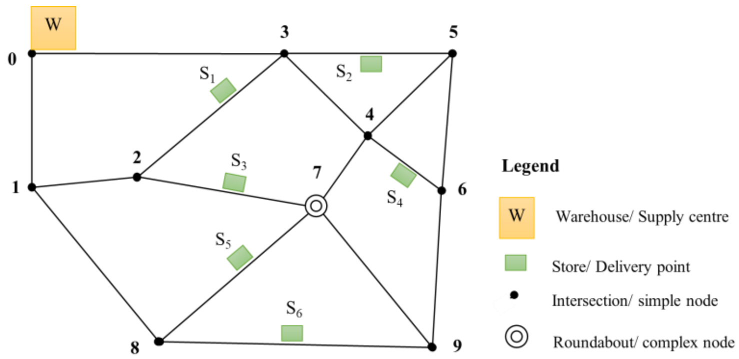


Fig. 4. Network model with the location of the warehouse and the convenience stores (settings before the building of the transitway).

The graph associated with the network in Figure 4 becomes a graph with directed edges depicted in Figure 5. The bidirectional edges are not affected by the new transitway or the modification of the traffic regulations. All convenience stores S_i (i = 1, ..., 6) selected in the study correspond to nodes of directed edges. The new graph with the set of vertices, including transport origins and destinations (Figure 5), is adapted to transport demand [18].

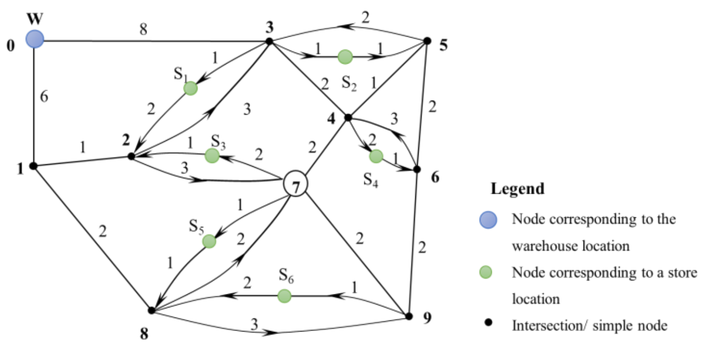


Fig. 5. The graph adapted to transport demand (with directed edges between nodes where stores are located).

On the weighted network adapted to transport demand (Figure 5), the matrix of minimal paths between warehouse W and stores Si and between stores S_i ($i = 1, ..., 6$) is obtained based on access directions to the convenience stores (Table 1). The lack of symmetry of the matrix of minimal paths relative to the main diagonal can be noticed.

Table 1. The minimum paths* between nodes of the network adapted to transport demand

To From	W	S_1	S_2	S_3	S_4	S_5	S_6
W	-	9/ (3)	9/ (3)	12/ (3, 2, 7)	12/ (3, 4)	11/ (1, 2, 7)	11/ (1, 8, 9)
S_1	9/ (2, 1)	-	6/ (2, 3)	7/ (2, 7)	9/ (2, 7, 4)	6/ (2, 7)	8/ (2, 7, 9)
S_2	11/ (5, 3)	4/ (5, 3)	-	8/ (5, 4, 7)	4/ (5, 4)	7/ (5, 4, 7)	7/ (5, 6, 9)
S_3	8/ (2, 1)	5/ (2, 3)	5/ (2, 3)	-	8/ (2, 3, 4)	5/ (2, 7)	7/ (2, 7, 9)
S_4	13/ (6, 5, 3)	6/ (6, 5, 3)	6/ (6, 5, 3)	8/ (6, 9, 7)	-	7/ (6, 9, 7)	6/ (6, 9)
S_5	9/ (6, 1)	8/ (8,7,4,3)	8/ (8, 7,4,3)	5/ (8, 7)	7/ (8, 7, 4)	-	5/ (8, 9)
S_6	10/ (8, 1)	9/ (8,7,4,3)	9/ (8, 7)	6/ (8, 7, 4)	8/ (8, 7, 4)	5/ (8, 7)	-

* For each origin-destination pair, the first term represents the characteristic size of the minimum path (operating cost, in this case), and the second term represents the sequence of nodes included in the minimum path.

2.3. The itinerary for distribution to convenience stores

Determining the itinerary for goods distribution to convenience stores convenience stores is included in the class of vehicle routing problems (VRP) from a single warehouse to several customers ("one-to-many"), initially defined by Danzig & Ramser [25]. VRP represents a combinatorial problem developed and particularised for different constraints related to city distribution schemes [26-28]. A wide range of studies covers various adjustments to the definition and solving of VRP in cities: approaches with constraints related to vehicle capacity [20,28,29], delivery schedule [30], structure of the street network [31], or problems defined for multilevel distribution schemes [26,32,33]. Nevertheless, VRP remains a challenging topic due to the dynamics of the cities and logistic systems mainly caused by new technologies and, implicitly, customer behaviour [26].

This study refers to a single distribution level corresponding to the last-mile distribution from the local warehouse to the selected convenience stores. The structure of the street network was considered in the design of the weighted network adapted to transport demand (by selecting streets allowing freight vehicle traffic and short-term parking for goods unloading).

Neighborhood search algorithms are applied to solve this type of VRP [20,34,35]. In this case, we propose a method which reduces the computation volume. The path of the minimum value (regarding the proposed criterion - distance, time, operating cost) must be found between the initial element, x_0, and the final element. x_{n+1}, serving in a specific succession, in n stages, the n intermediate elements, x_1, x_2, ..., x_n. If $x_0 \equiv x_{n+1}$, the search determines a Hamiltonian cycle [36].

The number of stages in determining the path is equal to the number n of the elements that must be included in the path (or cycle). In each stage, for an origin x_i there are n-1 options for the next element x_j ($j \neq i$) in which the transition must be made in the next stage to achieve the proposed optimum. The sequential process with options to select in each stage is included in dynamic programming. According to Bellman's optimality principle [36], potentially optimal solutions are identified going through the process in the reverse direction of its evolution (from x_{n+1} to x_0). I.e., from stage k to the previous one, k-1, for each of the elements x_1, x_2, ..., x_n. The search starts with stage $k = n$, from element x_{n+1} to each of the elements x_1, x_2, ..., x_n. Successively, in the reverse direction, the search is performed from stage $k = n$ to stage $k = 0$ so that the initial element x_0 is reached (Figure 6).

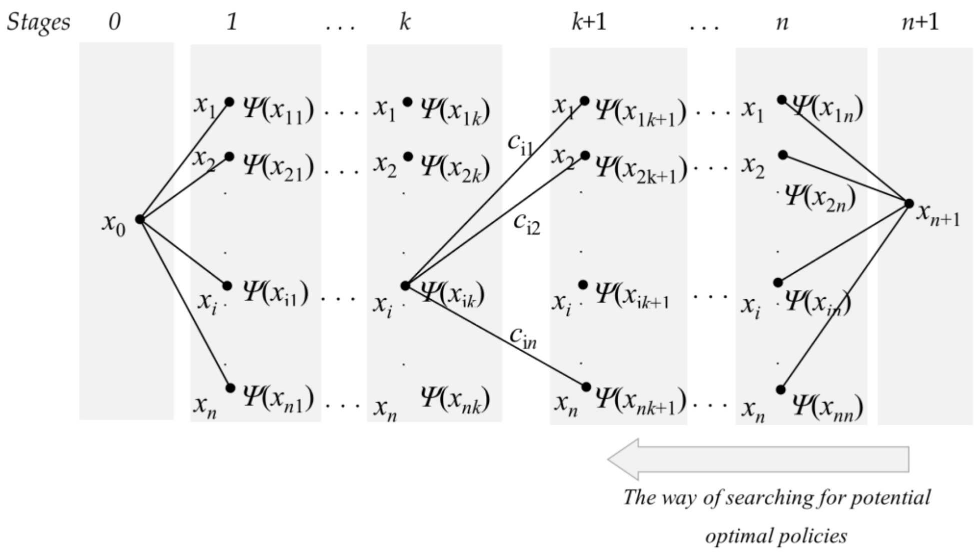


Fig. 6. Method for obtaining the values of the state functions Ψ and potentially optimal solutions.

The set of potentially optimal solutions, concatenated in the direction of the process evolution (from x_0 to x_{n+1}), designates the wanted optimal variant.

The potential optimal solutions are established based on a state function, Ψ. Denote

- $\Psi(x_{i,k})$ the state function assigned in each stage k to each element x_i of the set

$X = \{x_0, x_2, ..., x_n, x_{n+1}\}$ (Figure 6).

- c_{ij} the transfer value between the elements x_i and x_j (for i =1, ..., n; j =1, ..., n); for $i = j$, $\forall$ i, j = 1, ..., n, it is considered $c_{ii} = \infty$.

In stage $k = n$, for each element x_i, the state function is initialised with the value of the transfer between the final element, x_{n+1} and x_i, i.e., $\Psi(x_{i,n}) = c_{i,n+1}$.

In each stage, k, for decreasing $k = n$-1, n-2, …, 1, the value $\Psi(x_{i,k})$ is computed for each element, x_i, as a function of values of state function in stage k+1, $\Psi(x_{j,k+1})$, and values of the transfer function, c_{ij}, thus

$$\Psi(x_{i,k}) = \min_{j \neq i} \sum_{j=1}^{n} \left[\Psi(x_{j,k+1}) + c_{ij}\right], i = 1, \dots, n. \tag{1}$$

The elements x_{j_s} which minimize the state function $\Psi(x_{i,k})$ are determined. Accordingly, the optimal policy from stage k+1 to stage k is identified (i.e., the links $x_{j_s} - x_i$). In stage $k = 0$, the state function is computed based on eq. (1) only for the initial element, x_0 (i.e., i = 0).

3. Results

The presented method was applied to the studied problem (Figure 5) to identify the itinerary for distribution to the set of the six convenience stores S_i (i = 1, ..., 6) from warehouse W (corresponding to the initial, respective final element, $x_0 \equiv x_7$). The values in Table 1 (corresponding to transfer values between elements, c_{ij}) were used to compute the values of the state function, Ψ (Table 2).

In Table 2, the first line (corresponding to step 6 in Figure 7) shows the values of the state functions $\Psi(S_i)$ given by the transfer values from stores S_i to warehouse W (c_{S_iW}). The values in the second line (corresponding to step 5 in Figure 7) are obtained for each S_i based on eq. (1), using the values from line 1 and the transfer values from S_i to the other stores S_j (j = 1, ..., 6). The values in the last line (corresponding to step 0 in Figure 7) are obtained based on the values from the previous line and the transfer values from warehouse W to the other stores S_i (c_{WS_i}). The second term in each cell of Table 2 shows the set of elements S_j, which minimises the state function for element S_i. Based on these sets of elements, the potential optimal solutions are depicted in Figure 7 (with thin lines). The minimum path can be identified by passing through the route from the warehouse to each store in the sequence given by the links that indicate the potentially optimal strategies.

Table 2. The defining elements* for potential optimal solutions

State function, Ψ, in stage k (k = 6, ..., 0)	**Element S_i**					
	S_1	**S_2**	**S_3**	**S_4**	**S_5**	**S_6**
$\Psi_6(S_i)$	9/W	11/W	8/W	13/W	9/W	10/W
$\Psi_5(S_i)$	15/(S_3, S_5)	15/(S_1)	14/(S_1, S_5)	15/(S_1, S_6)	15/(S_3)	14/(S_3, S_5)
$\Psi_4(S_i)$	19/(S_2, S_5)	19/(S_1, S_4)	18/(S_2)	19/(S_2, S_6)	19/(S_2, S_6)	18/(S_5)
$\Psi_3(S_i)$	25/(S_2, S_5)	23/(S_1, S_4)	24/(S_1,S_2,S_5)	23/(S_6)	23/(S_3, S_6)	24/(S_3, S_6)
$\Psi_2(S_i)$	29/(S_2, S_5)	27/(S_4)	28/(S_2, S_5)	29/(S_2, S_6)	29/(S_3, S_6)	28/(S_5)
$\Psi_1(S_i)$	33/(S_2)	33/(S_1)	32/(S_2)	33/(S_2, S_6)	33/(S_3, S_6)	34/(S_3, S_6)
$\Psi_0(S_i)$	42/(W)	42/(W)	44/(W)	44/(W)	44/(W)	46/(W)

* The first term in cells represents the minimum values of the state functions for the element Si in stage k; the second term defines the destinations for the origin Si that minimises the transfer function.

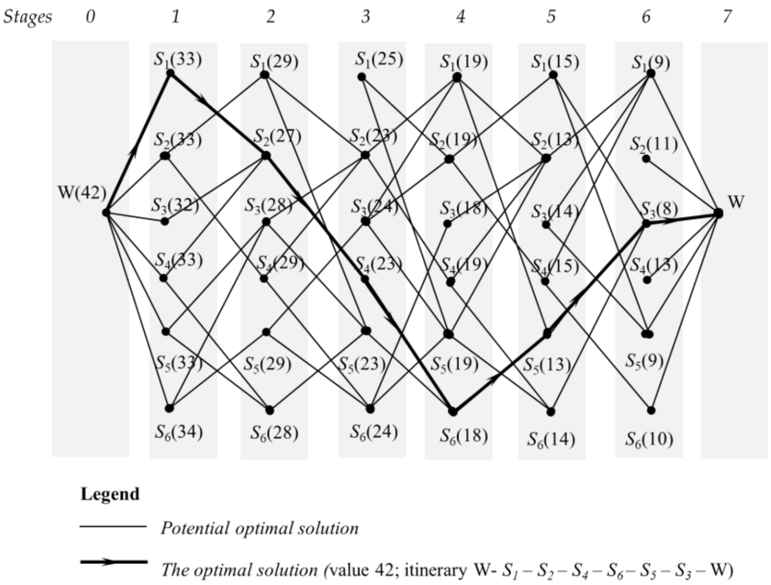


Fig. 7. Potential optimal solutions and the optimal solution for distribution itinerary

The value for the minimum path is 42, corresponding to the Hamiltonian cycle W - S_1 – S_2 – S_4 – S_6 –S_4 – S_5- S_3 - W (marked with thick lines in Figure 7).

Denote C = [c_{ij}] the matrix of the transfer value between the elements x_i and x_j (i =1, ..., n; j =1, ..., n). The travelling salesman problem determines the shortest cycle passing through each of n elements only once [37]. It is demonstrated that the value of any path l of the travelling salesman cycle cannot be less than the sum of constants (or amount of reduction) of the lines ($\sum_{i=1}^{n} h_i$) and the columns ($\sum_{j=1}^{n} H_j$) of the reduced matrix [38], respectively:

$$l \geq \sum_{i=1}^{n} h_i + \sum_{j=1}^{n} H_j, \tag{2}$$

where h_i represents the minimum element on each line *i* of matrix C of values c_{ij}:

$$h_i = \min_{j=\overline{1,n}} c_{ij}, i = \overline{1,n}, \tag{3}$$

and H_j represents the minimum element on each column *j* of matrix C' of reduced values $c'_{ij} = c_{ij} - h_i$:

$$H_j = \min_{i=\overline{1,n}} c'_{ij}, j = \overline{1,n}. \tag{4}$$

For matrix C corresponding to values in Table 1, the amounts are $\sum_{i=1}^{n} h_i = 39$ (Table 3) and $\sum_{j=1}^{n} H_j = 3$ (Table 4). Consequently, the minimum value of the Hamiltonian cycle starting from W or any S_1, S_2, ..., S_6 (Figure 5) is 42. Thus, the value 42 shown in Figure 7 (as the result of the algorithm applied for the Hamiltonian cycle starting from W) is confirmed.

Table 3. Values h_i for matrix C

j / i	W	S_1	S_2	S_3	S_4	S_5	S_6	h_i
W	∞	9	9	12	12	11	12	9
S_1	9	∞	6	7	9	6	8	6
S_2	11	4	∞	8	4	7	7	4
S_3	8	5	5	∞	8	5	7	5
S_4	13	6	6	8	∞	7	5	5
S_5	9	8	8	5	7	∞	5	5
S_6	10	9	9	6	8	5	∞	5

Table 4. Values *Hi* for matrix C'

j / i	W	S_1	S_2	S_3	S_4	S_5	S_6
W	∞	0	0	3	3	2	3
S_1	3	∞	0	1	3	0	2
S_2	7	0	∞	4	0	3	3
S_3	3	0	0	∞	3	0	2
S_4	8	1	1	3	∞	2	0
S_5	4	3	3	0	2	∞	0
S_6	5	4	4	1	3	0	∞
H_j	3	0	0	0	0	0	0

4. Discussion

In order to analyse the effects of the structural changes generated by the introduction of the transitway (Figure 1), the presented method was applied to the same set of six convenience stores for the initial urban road network. The values assigned to edges according to traffic regulation before the transitway's introduction define the transfer values matrix (Table 5). Due to bidirectional traffic, the matrix is symmetrical.

By applying the steps of the presented method, the optimal itinerary for distribution was determined. The value 34 was obtained for the itinerary W-S_3-S_5-S_6-S_4-S_2-S_1-W. Figure 8 highlights the differences induced by the building of the transitway on the distribution itinerary.

The solution of the routing problem after introducing the transitway (shown in Figure 7) allows the analysis of other distribution options. E.g., suppose the supply demand for the six stores exceeds the vehicle capacity for the considered delivery frequency. In that case, the distribution can be served in two cycles or by two vehicles. Assuming that one vehicle serves three of the six stores on each cycle, the selection must be made to minimise the total path.

Table 5. Transfer values between elements on the initial network

To / From	W	S_1	S_2	S_3	S_4	S_5	S_6
W	-	9	9	8	12	9	10
S_1	9	1	2	3	5	6	7
S_2	9	2	-	5	4	6	7
S_3	8	3	5	-	6	3	5
S_4	12	5	4	6	-	5	5
S_5	9	6	6	3	5	-	3
S_6	10	7	7	5	5	3	-

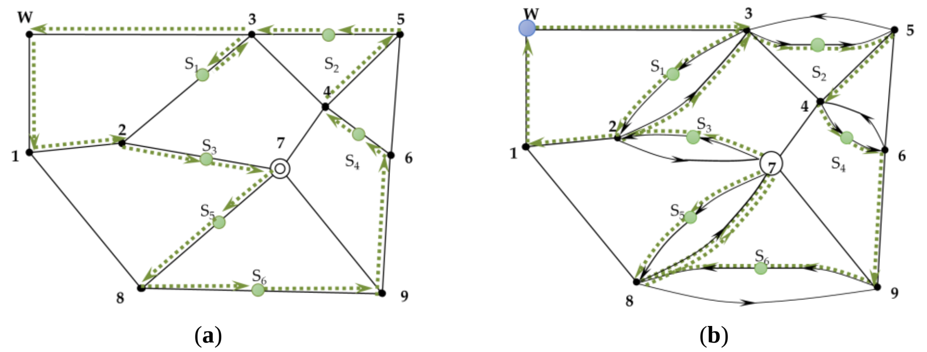
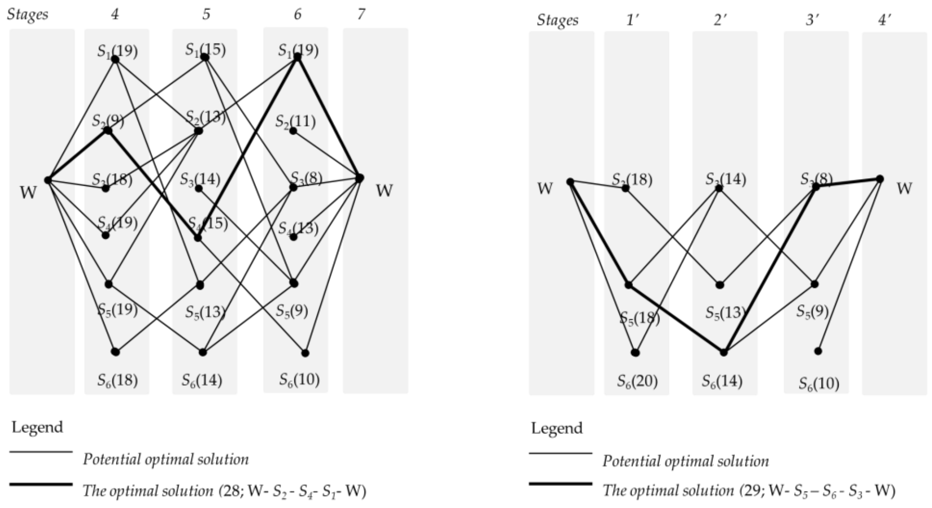


Fig. 8. Comparison of the distribution itineraries (**a**) initial network, without fragmentation caused by the transitway (**b**) network after transitway building; distribution itinerary W - S_1 – S_2 – S_4 – S_6 – S_5 – S_3 – W

For the first cycle, using the representations of potentially optimal solutions in Figure 7, stages 7 – 4 can be used. Next, the state functions in sequence 4 are updated for return to warehouse W (with the transfer values from S_1, S_2, ..., S_6 to W).

The results are shown in Figure 9.a. Then, the presented method is applied to the other three stores (S_1, S_5, S_6). The potential optimal solutions and then the optimal solution are obtained (Figure 9.b).



(**a**) (**b**)

Fig. 9. Distribution with two cycles (**a**) Selection of the elements on the first cycle (S_2, S_4, S_1); (**b**) Optimal solution for the second cycle (S_5, S_6, S_3).

Obviously, the trips related to additional departures and returning from and into the warehouse determine a higher value in the case of the two distribution cycles (57, compared to 42 in the case of one vehicle serving all six convenience stores in the same cycle). Suppose the distribution frequency is reduced to two days instead of daily deliveries (the quantities delivered are double). In that case, the solution with the circuit W - S_2 - S_4 - S_3 - W in one day and W - S_1 - S_6 - S_5 - W on the following day means a better solution (57, compared to 2 x 42 for two days with daily itinerary for serving all stores in the same cycle).

5. Conclusions

Cities are in constant transformation in time and space. The multiplication of urban activities requires adaptations of mobility/transport offers to the new urban structure. Through their topological, structural and operational characteristics, the traffic infrastructures have to ensure short transfer times for almost all travel relationships and, implicitly, a high level of accessibility for all urban area zones. The transitways (as the light rail exemplified in the paper), due to their dedicated ways for transit vehicles, provide a high level of service and increase the attractiveness of public transportation in congested urban areas. Nevertheless, the fragmentation caused by the transitways generates adverse effects for proximity trips. The urban goods distribution is also negatively affected (longer distances, increased time, additional energy consumption).

Usually, the current cost-benefit analyses (CBA) for new surface dedicated ways of transit almost entirely omit the negative effects on the performance of city logistics. The study aims to provide a quantitative evaluation of some of these consequences. In this stage, the research is limited to assessing the performance of last-mile distribution for convenience stores in an area fragmented by a transitway. For this goal, we propose a method suitable for programming to determine optimal routes for serving the convenience stores. The presented case study demonstrates the quantitative evaluation that could be included in socio-economic analyses.

CBA has to be enhanced with methods for quantifying the additional consequences of new dedicated transitways. Besides the effects of the urban space fragmentation experienced by the inhabitants in terms of spatial mobility, analysis is necessary to evaluate the decrease in the accessibility to convenience stores for the population in their vicinity (with impact on losses of the attractiveness of the convenience stores, and, consequently, possible decisions on relocation).

Consequently, the research emphasises the necessity of an integrative analysis of all the consequences of introducing dedicated transit ways, especially introducing one-way traffic on road networks. Solutions motivated by increasing the level of service on congested networks require more integrative, holistic assessments.

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