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Where to change from public transportation to car-sharing? Developing a transfer point optimization method

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ABSTRACT: The combined use of public transportation and car-sharing in the urban environment can provide a competitive alternative to private transportation. Public transportation, particularly the rapid rail network, provides quick access to the downtown while car-sharing services offer flexibility and convenience in the outer districts. Combined journeys can combine the benefits of both transportation modes, especially if transfers between them can be managed smoothly. We defined the Travel Chain Indicator to evaluate travel chains in terms of travel time and cost. To select the optimal transfer point, we used the TOPSIS method, which allows for ranking the evaluated indicators and choosing the best alternative. The method developed was tested in a case study in Budapest, considering a metro line and seven destination points in an outer district further from the metro line that can be reached by car-sharing use. The results showed that combined modes offer the best solution when time and cost criteria are defined with similar weights. The method developed can be used for route optimization and service area development for car-sharing operators, identifying the areas where multimodal travel is a competitive alternative.

KEYWORDS: multimodal transportation model; car-sharing; public transportation; transfer points; TOPSIS method

1. INTRODUCTION

Combining car-sharing (CS) services and public transportation (PT) in urban transportation systems can offer a competitive and substitutive alternative to private car use. This multimodal travel form merges the benefits and thus improves the efficiency and sustainability of the transportation system (Anis 2023): it reduces individual car use by combining the efficiency of public transportation with the flexibility of car use (Ogata et al. 2022). PT networks provide high-capacity and environmentally friendly mobility, while CS offers flexible and door-to-door transportation, complementing the coverage gaps of PT (Kłos and Sierpiński 2021).

Abbreviation	Description
PT	public transportation
CS	car-sharing
MM	multimodal transportation combining PT+CS modes
TCI	Travel Chain Indicator
OP	Origin Point
DP	Destination Point
TP	Transfer Point between PT and CS service
i	number of origin points
j	number of destination points
k	number of transfer points
c_{time}	total travel time (criteria)
c_{cost}	total travel cost (criteria)
t_{PT}	travel time by PT (parameter)
t_{TF}	travel time of transfer (parameter)
t_{CS}	travel time by CS (parameter)
c_{PT}	travel cost by PT (parameter)
c_{CS}	travel cost by CS (parameter)

Table 1. List of abbreviations

In the case of city center-suburb relations, fixed-route high-capacity rail transportation or dedicated bus lanes offer a faster and more reliable option for road congestion (Ceccato and Diana 2021). In addition, there is no loss of time in finding a parking space. At the same time, access to suburban residential areas and commuting needs (e.g., shopping) often require car use, for which car-sharing services can provide a solution (Ceccato and Diana 2021). Facilitating the willingness of private car users to shift mode is essential by providing a cost and time-competitive alternative. However, the key to the efficiency and success of the combined system is the availability and quality of transfer points (Digmayer, Vogelsang, and Jakobs 2015). Transfer options must be simple, quick, and convenient regarding space and time because they determine users' willingness to choose this multimodal transportation mode (Sun, Liu, and Tan 2018).

The integration process requires the development of data exchange standards and user interfaces for multimodal applications and dynamic vehicle assignment algorithms. Current practices focus on service integration, where CS vehicles are deployed at key PT nodes, and data sharing between service providers to optimize real-time vehicle availability and scheduling (Kłos and Sierpiński 2021). Transfer point optimization techniques use network analysis, GIS tools, and modal choice modeling to improve service coordination and user experience (Madhu et al. 2024). However, real-time coordination and user acceptance remain a challenge (Kramer et al. 2014).

The identified research gap is as follows: spatio-temporal optimization of transfer points between public transportation and car-sharing services. The study aims to develop a multimodal transportation model that provides a demand-centric framework between car-sharing and public transportation using TOPSIS multicriteria analysis. The model offers an optimization environment for transfer points by determining the Travel Chain Indicator (TCI). The user-centric optimization aims to minimize travel time and cost.

The structure of the paper is as follows. In section 2, the literature review focuses on existing analyses of travel chains and transfer points. The transfer point optimization method for combining the two transportation modes is presented in Section 3. In Section 4, the case study location is introduced. The results of the application case are discussed in Section 5. The paper is completed with concluding remarks.

2. LITERATURE REVIEW

Promoting multimodal transportation can reduce private car dependency (Heinen and Mattioli 2019), which is a key problem in urban environment, causing congestion, air and noise pollution, and increasing traffic safety risks. A shift towards multimodality is crucial for enhancing sustainability (Spickermann, Grienitz, and von der Gracht 2014). Accordingly, strengthening the connectivity between the two travel modes may encourage people to change their modes of transportation (Tarnovetckaia and Mostofi 2022).

When integrating different transportation systems – in this case, CS and PT – a critical element for the users is the link quality between the two systems, i.e., the transfer issue. The smoothness of the transfer considerably determines the parameters of the journey: the choice of location significantly impacts travel time and cost.

Time-saving and convenience influence traveler-choice regarding CS services (Kim, Rasouli, and Timmermans 2017). Travel-chain complexity also affects intentions to use public transportation; simpler, quicker travel chains are more likely to encourage public transportation use (Yuan et al. n.d.). There are several complementary advantages of combined usage, such as cost-effectiveness for short trips (Hu et al. 2024), contribution to low-carbon mobility (Silvestri et al. 2021), and significant cost savings compared to private car ownership (Dong et al. 2020).

The review examined the relationship between PT and CS from 4 categories: integration, multimodality, user preferences, and route and network optimization. Table II summarizes the literature reviewed. The review was assessed using the following aspects: travel chain analysis, GIS analysis, and transfer point analysis, which are related to the analytical techniques used in our methodology.

Regarding integration, the modeling and comparison methods developed focus on integrating PT and CS systems to facilitate multimodal mobility. A methodology based on the MILP model is proposed to improve the availability of PT systems (Anis 2023); its aim is to optimize the placement and distribution of CS depots and to concentrate CS resources in low-availability zones. The multimodality focuses on the interconnection of different transportation modes, such as how to support intermodal travel chains while considering user needs (e.g., through mobility applications or integrated services). In the user preferences, patterns of substitution and complementation between modes are analyzed (Digmayer et al. 2015), and the indicators needed to measure PT connectivity and performance within multimodal networks (Fahnenschreiber et al. 2016) are examined from the user perspective. Route and network optimization aims to support smooth transitions between different transportation modes through optimized distribution and routing approaches considering costs and network performance.

We can conclude that there is a substantial body of research available about the relationship between PT and CS services, both from the operational and the user side. However, the issue of optimizing transfer processes, which is key to efficient integration, is an unresearched area in the academic literature.

3. METHODOLOGY

Travel chains can be characterized by an origin point (OP), a destination point (DP), and intermediate transfer points (TP). The developed method examines travel alternatives between two points (OP, DP) to select the best-combined alternative. As a limitation, the method developed considers the direction from PT to CS service; OP is a PT stop, and DP is an optional point within the CS service area further from the PT service. Traveling with PT, namely, the route choice is assumed to be given; the route choice is not part of the optimization process.

The TP has a significant impact on the time and cost of the travel chain, so the choice of the TP location is crucial as the method aims at minimizing travel time and cost together. To evaluate travel chains, we have defined the Travel Chain Indicator (TCI), a combined indicator of the travel time and cost for travel chains. Three TCI indices were considered: PT only (TCIPT), CS only (TCICS), and a multimodal travel chain (TCIMM) combining the two transportation modes (Fig. 1).

This study aims to identify the optimal TP that corresponds to the selection of the most preferred travel chain that minimizes travel time and cost. The TOPSIS (The Technique for Order of Preference by Similarity to Ideal Solution) method was employed to address this selection process. The TOPSIS method offers a suitable solution for evaluating travel chains

	Paper	PT	CS	Method	Travel chain analysis	GIS analysis	Transfer analysis
Integration	(Anis 2023)	x	x	Simulation-based modeling	x	x	x
	(Kłos and Sierpiński 2021)	x	x	Framework development	x		
	(Horjus et al. 2022)	x	x	Mode choice modeling		x	x
	(Ogata et al. 2022)	x	x	Market potential analysis	x		x
	(Huwer 2004)	x	x	Comparative analysis			x
Multimodality	(Digmayer et al. 2015)	x		App design	x		x
	(Mishra, Welch, and Jha 2012)	x	x	Indicator-based analysis		x	
User preferences	(Ceccato and Diana 2021)	x	x	Behavioral analysis			
	(Feng et al. 2020)	x	x	Usage pattern analysis	x		x
Route and network optimization	(Fahnenschreiber et al. 2016)	x		Optimization algorithm	x		x
	(Nguyen, Hoang, and Vu 2022)	x	x	Activity-based modelling	x	x	
	(Madhu et al. 2024)	x		Fuzzy-TOPSIS analysis		x	x
	(Friedrich and Noekel 2017)	x	x	Network modeling		x	x
	(Kumar, Parida, and Swami 2013)	x		Performance evaluation		x	

Table 2. Literature overview

and selecting the optimal solution since it allows decision-making in a less subjective way based on predefined parameters; the selected alternative should be the shortest possible distance from the ideal solution and the furthest from the negative-ideal solution (Triantaphyllou 2000). The method developed ranks the alternatives by selecting the minimum value of the TCI. The steps of the TCI determination are depicted in Fig. 2.

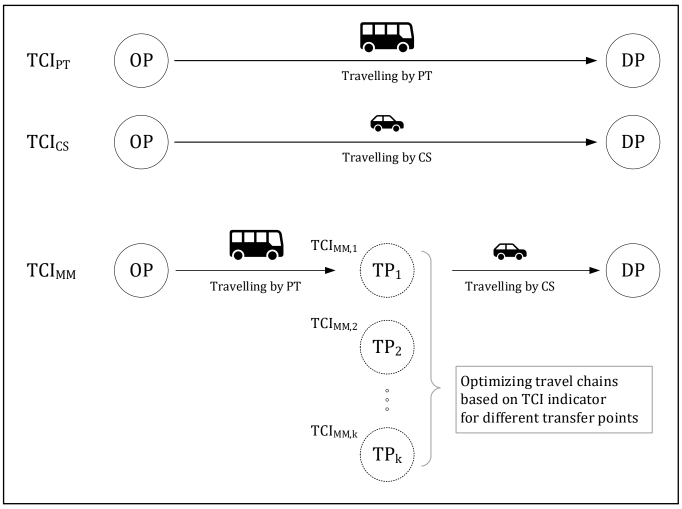

Fig. 1. Representation of Transfer Point and Travel Chain Indicator (source: authors' own work).

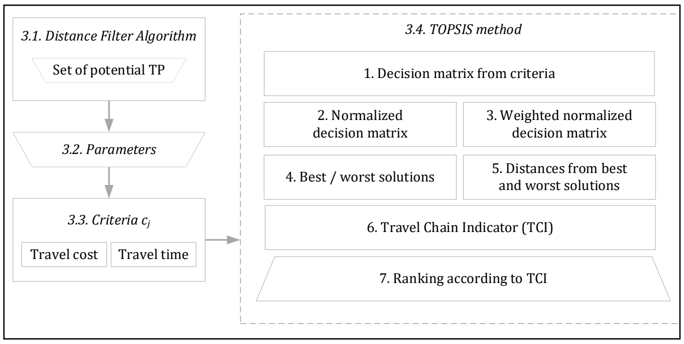

Fig. 2. Steps of the Travel Chain Indicator determination (source: authors' own work).

A. Distance filter algorithm

Distance filter algorithm

Input: PT = {pt_1, pt_2, ..., pt_i, ... pt_n} set of PT stops

CS = {cs_1, cs_2, ..., cs_j, ... cs_m} set of available vehicles in the CS service

d(pt_i, cs_j): distance between PT stop and available CS vehicle

r the maximum distance set between PT stop and available CS vehicle

tp_k = {pt_i, d_{min}, cs_j} transfer point

Output: TP = {tp_k}

```
TP = {0}
for i = 1 to n
    d_min(pt_i, cs_j) = r
    for j = 1 to m
        d_ij = distance(pt_i, cs_j)
        if d_ij < d_min
            d_min = d_ij
    if d_min < r
        TP = TP ∪ tp_k
return: TP
```

To determine the potential TP set, a *Distance filter algorithm* have been developed. The algorithm filters TPs with a transfer walking distance above a certain threshold. This algorithm identifies potential TP points, although it requires computing capacity.

A. Parameters

Time and cost parameters were considered to define the criteria for the method. The total travel time can be divided into main segments: travel time by PT (t_{PT}), travel time of transfer (t_{TF}), and travel time by CS (t_{CS}). Travel costs are divided according to the services used: PT cost (c_{PT}) and CS cost (c_{CS}). The parameters can be zero if only one mode is used.

The t_{PT}, t_{CS}, c_{PT}, c_{CS} parameters can be taken directly from the service parameters (timetable, tariff, fares) and the navigation systems. The value of t_{TF} can be approximated from the distance between the PT stop and the location of the CS vehicle.

B. Criteria

Two criteria were defined: total travel cost (c_{cost}) and total travel time (c_{time}). They are quantified by summarizing the following parameters (1), (2).

(1) $c_{cost} = c_{PT} + c_{CS}$

(2) $c_{time} = t_{PT} + t_{TF} + t_{CS}$

Although the criteria differ in unit, the TOPSIS method handles this in the normalization step, calculating unit-independent values.

A. TOPSIS method adaptation

The TOPSIS method was applied in two steps: in the first step, only multimodal travel chains were evaluated and selected as the optimal access, which in the second step was compared with unimodal PT and CS services to determine how competitive it is with them.

1. The decision matrix (3) is derived from the criteria and travel alternatives. The *mxn* matrix consists of m rows based on travel alternatives (O_i where i = 1 ... m) and n columns according to the criteria (c_j where j = 1 ... n, in this paper n = 2 as two criteria were analyzed). The c_{ij} cell of the matrix represents the value of the i-th alternative corresponding to the c_j criterion.

(3) $$M = \begin{bmatrix} O_1 \\ O_2 \\ \vdots \\ O_i \\ \vdots \\ O_m \end{bmatrix} = \begin{bmatrix} c_{11} & c_{1j} \\ c_{21} & c_{2j} \\ \vdots & \vdots \\ c_{i1} & c_{ij} \\ \vdots & \vdots \\ c_{m1} & c_{mj} \end{bmatrix}$$

2. Normalized decision matrix $R(= r_{ij})$ is determined by (4).

(4) $$r_{ij} = \frac{c_{ij}}{\sqrt{\sum_{i=1}^{m} c_{ij}^2}}$$

3. Weighted normalized decision matrix $V(= v_{ij})$ is determined by (5). Weighting the criteria allows their impact to be enforced. The w_j weight can be determined according to the different objective functions.

(5) $v_{ij} = r_{ij} \cdot w_j$

4. Best/worst solution: determining a positive v_{best} best travelling option (6), and a negative v_{worst} worst travelling option (7).

(6) $v_{best,j} = \min_i(v_{ij})$

(7) $v_{worst,j} = \max_i(v_{ij})$

5. Distance from best and worst solution are calculated based on (8) and (9).

(8) $d_{i,best} = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_{best,j})^2}$

(9) $d_{i,worst} = \sqrt{\sum_{j=1}^{n}(v_{ij} - v_{worst,j})^2}$

6. The Travel Chain Indicator is determined based on the distance from the best and worst solution (10).

(10) $TCI = \frac{d_{i,worst}}{d_{i,worst} + d_{i,best}}$

7. Ranking according to TCI indicator. TCI indicators are ranked in ascending order by score, and the alternative with the highest score is selected.

4. CASE STUDY

The method was applied in a case study in Budapest, Hungary, to demonstrate its usability and practical feasibility. The choice of location is justified for two reasons. On the one hand, the capital has competitive public transportation (metro network, suburban rapid rail lines, etc.), which provides passengers with fast and affordable transportation, and car-sharing services (GreenGo, MOL Limo, wigo) available in many districts. On the other hand, there is likely to be potential demand for multimodal travel, as the capital has a high proportion of commuters, who could emerge as a financially capable demand group.

The following delimitations were applied in the case study using the TOPSIS method. In total, *35 scenarios* were examined. Sample trips have been defined between the one predetermined origin point (OP) and the seven predefined destination points (DP), which results in *7 accessions*. Criteria weights are determined in *5 case groups* (0.3, 0.4, ... 0.7). Accordingly, 35 scenarios were formed: 7 accessions x 5 case groups. Only the M2 metro line was considered as a public transportation mode. The number and location of vehicles available in the CS service have been estimated according to the actual conditions in the service area.

In the case study, we addressed the question of which TP choice results in the optimal travel time and cost between OP and DP points when using a combination of PT and CS. The choice of TP, in this case, is equivalent to (1) which metro station to change at and then (2) which CS vehicle to continue the journey (Fig. 3).

The possible alternatives and their associated travel time and cost parameters were determined for each of the DP-OP trips; from the OP to all metro stops with PT and from the closest CS vehicle of the metro stops to all seven destination points with CS; travelling only by PT; and using only CS.

Parameters were quantified from Budapest municipal public transportation operator (BKK) – timetable data (t_{PT}) and tariff system (c_{PT}); and using QGIS QNEAT module (c_{CS}), (t_{TF}). Travel time by CS was estimated and calculated based on the tariff system of GreenGo (t_{CS}) car-sharing service operator. In Budapest, a single ticket currently costs ca. 1 euro, while the Greengo fare package consists of two components: a rental unlock fee of 0.75 euro and a minutes-based fee of 0.6 euro.

5. RESULTS AND DISCUSSION

According to the structure presented in the case study, TCI indicators were examined for 35 scenarios. The $TCI_{MM,opt}$ values are summarized in Table III. In all scenarios, changing the weights slightly changes the characteristics of the TPs: increasing the weight of the cost slightly reduces travel time and increases the cost. As the PT costs are low, higher cost weights increase the length of the journey on the metro.

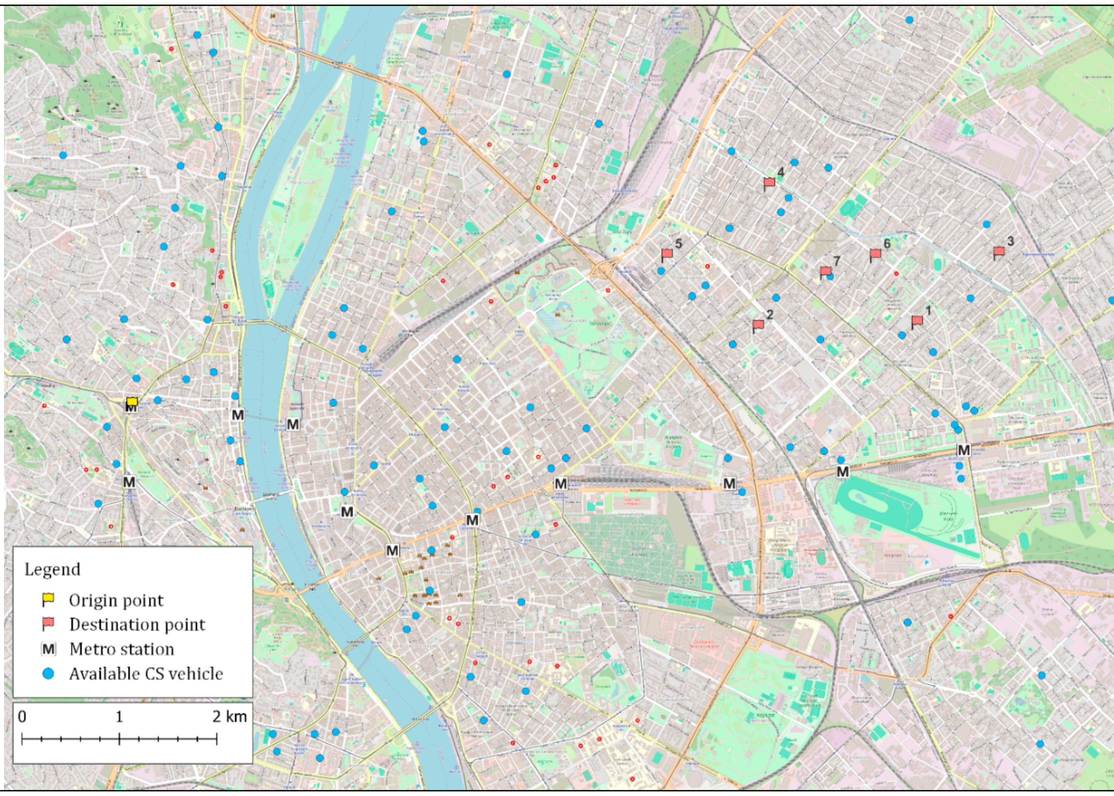

Fig. 3. Case study map (source: authors' own work).

	cost weight	cost [euro]	time [minutes]	TCI_{MM}
Access_1	0.3	2,70	32	0,9561
	0.4	2,70	32	0,9675
	0.5	2,70	32	0,9761
	0.6	2,70	32	0,9824
	0.7	2,70	32	0,9866
Access_2	0.3	3,62	28	0,9686
	0.4	3,28	29	0,9657
	0.5	3,28	29	0,9635
	0.6	3,28	29	0,9608
	0.7	3,06	31	0,9688
Access_3	0.3	3,24	34	0,9931
	0.4	3,24	34	0,9922
	0.5	3,24	34	0,9918
	0.6	3,19	35	0,9916
	0.7	3,19	35	0,9945
Access_4	0.3	4,35	31	0,9216
	0.4	4,35	31	0,9052
	0.5	4,35	31	0,8950
	0.6	4,26	33	0,9009
	0.7	4,26	33	0,9076
Access_5	0.3	3,68	28	0,9722
	0.4	3,68	28	0,9671
	0.5	3,68	28	0,9626
	0.6	3,68	28	0,9594
	0.7	3,68	28	0,9575
Access_6	0.3	3,20	34	0,8870
	0.4	3,20	34	0,9184
	0.5	3,20	34	0,9419
	0.6	3,20	34	0,9593
	0.7	3,20	34	0,9722
Access_7	0.3	3,71	32	0,8840
	0.4	3,71	32	0,8842
	0.5	3,49	33	0,8976
	0.6	3,49	33	0,9156
	0.7	3,27	34	0,9402

Table 3. Optimal multimodal accesses – 35 scenarios

For all the accesses, the results obtained were evaluated by comparing the $TCI_{MM,opt}$ values with the TCI_{PT} and TCI_{CS} values again using the TOPSIS method developed. The best alternatives in the 35 scenarios are shown in Fig. 4.

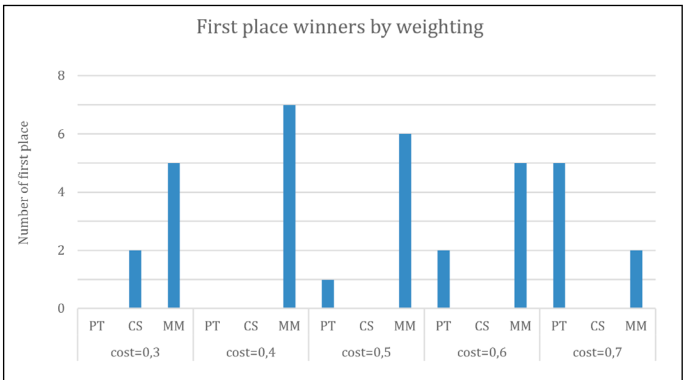

Fig. 4. First place winners by weighting (source: authors' own work).

The effectiveness of the combined solution is demonstrated by offering a more favorable access (in terms of time and cost) alternative than the exclusive use of PT and CS systems. By increasing the weight of the cost, it is natural to observe a disappearance of the CS service and an increase in the use of PT. In the present application environment, in terms of travel time and tariff, combined travel is most favorable when cost and time factors are weighted almost equally.

In addition, the results were aggregated in a win-matrix to verify the goodness of the method (Table IV). In columns are the standings and in rows are the access modes. The win matrix shows that in the 35 analyses examined, the combined use was the best alternative in more than 2/3 of the cases, and not even once was the worst choice. And if only the middle interval in terms of weights is considered (0.4-0.6), it offers the best alternative in most cases: 86%.

	All				Middle		
	1.	2.	3.		1.	2.	3.
MM	71%	29%	0%	MM	86%	14%	0%
PT	23%	43%	34%	PT	14%	57%	29%
CS	6%	29%	66%	CS	0%	29%	71%

Table 4. Win-matrix

6. CONCLUSION

This study presents the effectiveness of combining public transportation (PT) and car-sharing (CS) in urban mobility by evaluating transfer points (TP). We defined a Travel Chain Indicator (TCI) to identify optimal transfer points that rank TPs based on travel time and cost criteria.

The results show that combined travel chains consistently outperform PT or CS alone in more than two-thirds of the cases. In 86% of the cases, the combined solution is the best alternative when the time and cost weights are balanced between 0.4 and 0.6. The analysis also highlights that the preference for CS decreases with increasing cost weights, favoring PT in low-cost environments such as Budapest.

The proposed methodology offers a systematic approach to optimize TPs, ensuring a smoother transition between modes. Its adaptability to different weighting scenarios proves its robustness and applicability in various urban environments. Future studies could extend this approach to include additional factors, such as environmental impacts or user preferences, thus improving the transfer point assessment. Another improvement option is network optimization, which performs optimization at the entire PT network level.

Future developments will focus on dynamic routing algorithms for the entire mobility platform, enabling real-time optimization of travel time and costs. Integrating machine learning tools and intelligent mobility platforms is expected to increase the efficiency of these systems, solving scalability and operational coordination challenges.

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