

A TWO-LEVEL, AHP-BASED RANKING MODEL FOR THE CITY LOGISTICS ANALYSIS OF URBAN AREAS AND ITS APPLICATION FOR THE CONCENTRATED SETS OF DELIVERY LOCATIONS IN BUDAPEST

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Highlights:

- a novel 2-level AHP ranking model was developed to simultaneously evaluate the current state of city logistics and the future development potential of urban zones;
- the methodology addresses the critical gap in urban planning by supporting data-driven selection of optimal zones for city logistics developments and pilot projects;
- the ranking model incorporates 56 subcriteria to assess the current state and 69 to evaluate future development potential, organized into multilevel hierarchies;
- case study results for Budapest's zones demonstrate a strong relationship between the degree of spatial concentration and city logistics development potentials;
- comprehensive sensitivity analyses identified parcel pick-up infrastructure, expected emission reductions, and consolidation degrees as the key impact factors.

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Abstract. Urban freight transport is a significant challenge nowadays because of its high impact on the sustainability of cities, and the pandemic has further increased the importance of these challenges in the last one and a half year, which has generated new challenges for urban logistics by changing the customer demands. Based on previous research results, it became clear that a ranking methodology would be very useful for city logistics projects, which makes it possible to evaluate the current city logistics state and future city logistics development potentials of urban zones to select the best zones for developments, which would be significant for the city logistics aspects of urban planning and logistics system planning as it could help to avoid selecting development and pilot areas based on limited information only. Previously, we developed a complex ranking system to handle this need. This article presents an improved version of this ranking model, which handles the criteria under consideration in a two-level system by using the Analytic Hierarchy Process (AHP). In our article, we are presenting the results of the literature review and the novelty of our research, then we will describe our previous results regarding the model development, our actual objectives, the two-level multi-criteria ranking model itself, its structure, the ranking criteria, the application of the ranking model in the city logistics system of the concentrated sets of delivery locations in Budapest (Hungary), and the results of a complex sensitivity analysis. The main result of our article is a complex city logistics ranking methodology, which can help future city logistics projects and developments to define those urban areas where the city logistics system should be developed and is possible to implement developments.

Keywords: logistics, city logistics, Budapest, AHP, ranking model, concentrated sets of delivery locations.

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Notations

AHP – analytic hierarchy process;	EDAS – evaluation based on distance from average solution;
BUTE – Budapest University of Technology and Economics;	ELECTRE – elimination and choice translating reality (in French: <i>élimination et choix traduisant la réalité</i>);
CSDL – concentrated set of delivery locations;	ERP – enterprise resource planning;
DC – degree of consolidation;	GIS – geographic information system;
DEA – data envelopment analysis;	IT – information technology;
DEMATEL – decision-making trial and evaluation laboratory;	MA – market hall;
DoC – degree of concentration;	

- MCA – multi-criteria analysis;
- MCDA – multiple-criteria decision analysis;
- MCE – multi-criteria evaluation;
- OT – other CSDL;
- PCA – principal component analysis;
- PROMETHEE – preference ranking organization method for enrichment of evaluation;
- SA – shopping area;
- SM – shopping mall;
- SKU – stock-keeping unit;
- TOPSIS – technique for order of preference by similarity to ideal solution;
- UN – university campus;
- VIKOR – multi-criteria optimization and compromise solution (in Serbian: *višekriterijumska optimizacija i kompromisno rešenje*).

1. Introduction

Since 2015, the BUTE City Logistics Research Group (BME ALRT 2026) of our university has been focusing on the urban concentrated sets of delivery locations. For this research, urban delivery locations can be classified into two groups: there are single delivery locations (which can be commercial, industrial, and service delivery locations) and concentrated sets of delivery locations that include several single delivery locations according to some aspect (Sárdi, Bóna 2021c). These CSDLs have two main types: CSDLs with closed infrastructure (like SMs) and CSDLs with open infrastructure (like SAs/streets). In our research, we focus mainly on the CSDLs; based on the concentration, significant city logistics development potentials can be assumed, and based on our results so far, we believe that it would be important to apply such a classification when developing city logistics systems. In previous city logistics research, researchers focused more on customer flows than city logistics aspects (Sárdi, Bóna 2021c). Our City Logistics Research Group, considering the shortcomings of previous research, has aimed to investigate these CSDLs in recent years by collecting data about their city logistics characteristics (Mészáros *et al.* 2017), developing mathematical, topological, and simulation models, and several new concepts (Sárdi, Bóna 2021c).

Based on the results of our research, we concluded that there is a need to develop a multi-criteria ranking model that would allow us to assess not only the CSDLs, but also larger urban zones containing single delivery locations (even smaller CSDLs), and to quantify the city logistics state and city logistics development potentials of each zone (Sárdi, Bóna 2021b). Such a ranking model is needed because in city logistics projects it is important to identify the zones to get developed as mostly it is not possible to develop a whole district or the whole city because of budget limitations, or 1st a pilot project should be carried out.

In our article, 1st, we are going to present the results of the literature review, in which we examined similar city logistics projects and the possible multi-criteria ranking models. After this, we are going to present the novelty of our research based on a theoretical example from Buda-

pest. Based on the literature review, we started to work with the AHP method, so next, we are going to present the previous steps of our related research. After this, we are going to write about the development of the two-stage ranking model, which is the focus of our actual article. In this section, the criteria and the model operation will be presented. Next, we are going to present the application of the model for CSDLs in Budapest, the results of the ranking and the related sensitivity analysis. At the end, we are going to present the main conclusions of our research.

2. Literature review

When we started this research project, it was very important to examine the available literature to see if such ranking methodologies are already available or not. To identify the published ranking methodologies applied in city logistics research and projects, a detailed literature search was performed as the 1st stage of our project (Sárdi, Bóna 2021b). In this phase, we used 3 scientific databases: *ScienceDirect*, *ResearchGate*, and *Google Scholar*. To identify the relevant articles, several keywords were used for the search, e.g., “city logistics MCDA”, “city logistics multiple-criteria analysis”, “city logistics MCDA”, “city logistics ranking model”, “city logistics ranking methodology”.

Based on the literature review, we would like to highlight 3 complex ranking models. The primary purpose of the 1st of them was to rank logistics centers with different functions (Antún, Alarcón 2014); a similar model could be implemented for the city logistics junctions and even for the zones of a city logistics network, similarly to our project purposes. Another published ranking model ranks city logistics projects (Patier, Browne 2010), and the 3rd one examines the operation suitability of electromobility concepts for last-mile delivery tasks (Teoh *et al.* 2016), so they have similar aspects as we needed for the evaluation of the city logistics development potentials. In the case of the other related publications, different ranking models were used for the evaluation of city logistics developments and pilot projects (Awasthi, Chauhan 2012; Tadić *et al.* 2017; Verlinde *et al.* 2014; Verlinde, Macharis 2016; Deveci *et al.* 2022) and the selection of the best city logistics concepts (Tadić *et al.* 2014).

Above these, the multi-criteria methods can be used for several different purposes in city logistics and in logistics. They can be used the evaluation of the performance of city logistics terminals (Gogas *et al.* 2017), for urban sustainability (Kara 2019; Nathanail *et al.* 2017; Youssef *et al.* 2011; Silva *et al.* 2023) and smart city planning aspects (Milošević *et al.* 2017). In some research, they are used for the evaluation of regulations and policy measures (Janjevic *et al.* 2019; Morfoulaki *et al.* 2016), for vehicle selection (Wątróbski *et al.* 2017), for the examination of urban electrification (Lebeau 2016), for supplier and partner selection (Hruška *et al.* 2014; Awasthi *et al.* 2015), for investigating the use of urban public transport for city logistics purposes (Galkin *et al.* 2019), for the examination of collaboration possibilities (Lindawati *et al.* 2014), for software and GIS system selection (Smirlis *et al.* 2012; Sgura Viana, Delgado 2019), and for the planning of oversized

deliveries in the city (Wolnowska, Konicki 2019). Another popular application is to use them for solving urban facility location problems (Zhao *et al.* 2018, 2024; Awasthi *et al.* 2010; Uysal, Yavuz 2014; Bu *et al.* 2012; Rao *et al.* 2015; Önden, Eldemir 2022). Considering these, it can be stated that our two purposes (to examine the current city logistics state and the city logistics development potential at the same time) were not examined together in any of the published research (Sárdi, Bóna 2021b).

Based on the detailed literature review, we found that although the documented ranking models and methodologies used in city logistics and other logistics fields are very diverse, none of them match the objectives we have set.

In the literature review phase of our project, we were also looking for multi-criteria models that could be used for the examined city logistics purposes. For this, a sum of more than 50 articles, books, and other documentation were examined (the reviewed city logistics projects are referred to in the previous paragraphs, and additionally, we examine research from other logistics fields as well). Based on these, we can conclude that the AHP (Saaty 1987) was used in more than 50% of all the cases (Sárdi, Bóna 2021b). The use of AHP in sustainable development-related research is highlighted in an examined review article as well, which underpins the experiences of our literature review (Dos Santos *et al.* 2019). Next to AHP, TOPSIS, VIKOR, PROMETHEE, and PROMETHEE II. were used in 3 or 4 research. In the case of some other research, own methodologies were used, and several other models (like DEA, EDAS, ELECTRE, MCE, PCA, MCA, neural network-based solutions, etc.) were each used in one published research (Sárdi, Bóna 2021b). It is important to highlight here that there are already several new multi-criteria ranking methodologies (Zlaugotne *et al.* 2020), e.g., DEMATEL (Si *et al.* 2018) or the previously mentioned neural network-based models. In our research, we aimed to develop such a methodology, which is widely used and well-proven in the field of city logistics, so the resulting methodology will be easy to understand and apply for any stakeholders (for example, for a municipality or a logistics provider).

As a result of the literature review, we concluded that the multi-criteria model for assessing the current city logistics state and the future development potential is a completely new application. Moreover, we found that there are significantly more documented logistics applications of the AHP (Saaty 1987), which is associated with Saaty's name, so we used this method in our research (Sárdi, Bóna 2021b).

In the next section, we present the AHP-based ranking model developed in the 1st phase of our research, which examined criteria in a one-level structure, and then we present the further development of this model, with the results of the 2nd phase of our research.

3. Previous related research results

In the 1st phase of our research project, we developed an AHP-based multi-criteria ranking model that can be used to evaluate the current city logistics state of urban zones

and the future city logistics development potentials at the same time (Sárdi, Bóna 2021b). The model's primary purpose was to examine arbitrary urban zones and identify which zones should be developed (those with low current city logistics state) and which zones can be developed (those with high city logistics development potential). The two-level model presented later in this article will have the same objective.

3.1. Research contribution and novelty

Based on the literature review, it became clear that there are no such ranking models in the logistics (and within that, in the city logistics) literature, where the current city logistics state and the future city logistics development potentials are ranked at the same time, to identify which urban zones should be developed and which of them can be developed at all. To better illustrate the purposes of the ranking model and the research contribution of our project, consider the example in Figure 1.

In this entirely theoretical example, we would like to develop a new city logistics system in a selected part of Budapest's 11th district (Újbuda) and to do this, we need to choose the urban zones, which need to be developed and determine which zones are most suitable for developments. This can be very important, for example, when the budget for city logistics development is limited or if a pilot area should be selected to demonstrate the positive effects of new organizational solutions (e.g., to implement mini hubs), new regulations (e.g., a new entry system), or new city logistics technologies (e.g., to implement drones or high-capacity cargo bikes).

The left side of Figure 1 shows that the examined urban area can be divided into 7 zones (ZONE01...ZONE07), but the right side of Figure 1 shows that there are 7 more CSDLs in the area, which should be included as separate zones: SM001, SM002, and SM003 are 3 SMs in the area, MA001 is the only examined market, UN001 and UN002 are 2 UNs in the area, and OT001 is a service-type special CSDL next to UN002. This gives us a total of 14 zones to examine, and by using the ranking model developed in our research project, we will be able to identify which of these zones are most in need of development and which zones are most worth developing.

From an urban development perspective, it could be important to apply such a ranking model in practice, as it could identify the most important areas for development and where the most visible impact could be achieved. Currently, such a city logistics ranking model is not available, so the zone selection can be carried out only based on limited information or in an intuitive way, which will not give the appropriate solution. This can lead to a situation where a pilot is developed in a zone that is obviously in a bad city logistics state, and its problems can easily be identified, but its development potential is very low, so the pilot will not have a spectacular effect. In such a case, it is possible to give up the development project because of the bad experiences and reject the tested organization so-

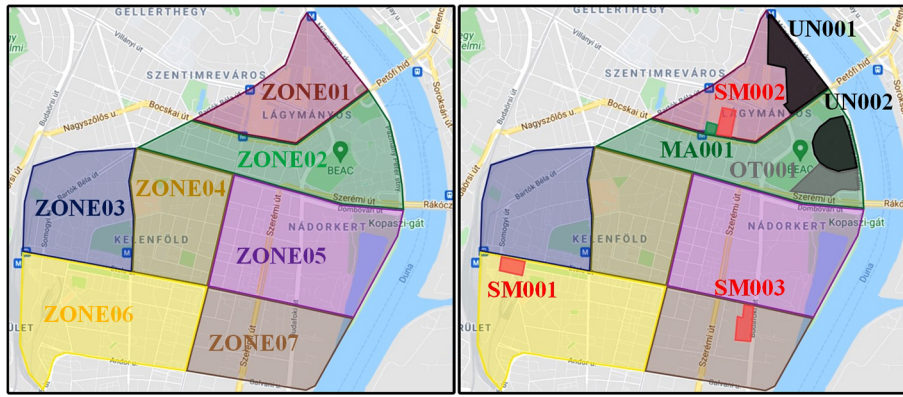


Figure 1. Example of zoning – target area in Google Maps

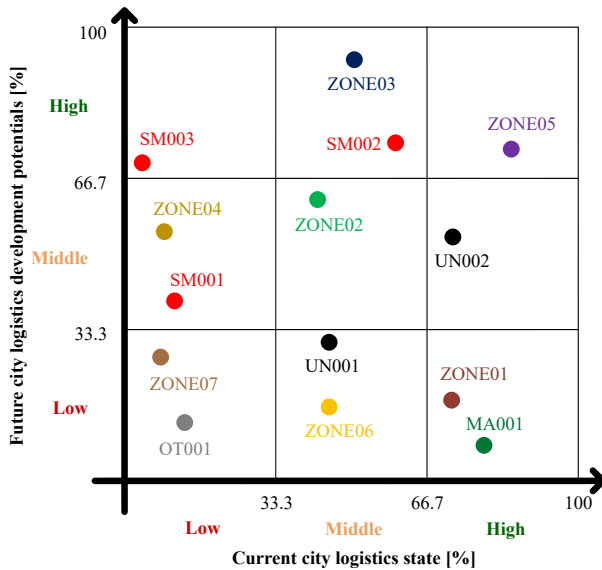


Figure 2. Example of zoning – expected results

lutions, regulations, or technologies, while in another urban zone, they would be more useful. For such cases, this new city logistics ranking model could provide useful help for the researchers and for other stakeholders as well; this is the main novelty of our research project.

The expected results of the example under consideration are illustrated in Figure 2 (the values in the figure are randomly selected to illustrate the results). It can be seen that in this case, MA001 and ZONE01 are currently highly developed, but they cannot be developed well anymore. ZONE05 is currently highly developed and can be even more developed; ZONE07 and OT001 are currently low developed but cannot be developed well at all, while SM003 is currently low developed but can be developed well in the future from a city logistics point of view. Based on the currently available toolkit (so when no such ranking model is available), it would be possible to select for a theoretical pilot ZONE07 or OT001 if they are obviously low developed, and the pilot could fail as they have low development potential as well. By using the ranking model presented in this article, selecting SM003, ZONE03, SM002, or ZONE05 could be a good decision, and a successful project would become possible.

3.2. Results of the previous research phases

In the ranking model to achieve these objectives, 43 criteria were included to examine the current city logistics state and 56 criteria to identify future city logistics development potentials (Sárdi, Bóna 2021b). The importance of the criteria was ranked by a total of 13 experts from our City Logistics Research Group, the BUTE Department of Transport Technology and Economics (BME KTKG 2026), the Centre for Budapest Transport (BKK 2026), and the Clean Air Action Group (LM 2026). During the testing of the ranking model, it was concluded that defining a so-called fictive zone was necessary since the AHP can only rank the zones to the best of the zones examined. The fictive zone was included to be able to compare the examined urban zones with a fully fictive zone with good characteristics (i.e., high development state and high development potential) (Sárdi, Bóna 2021b). This one-level ranking model was tested on 3 and then 4 shopping center zones in Budapest (Sárdi, Bóna 2021b), for which detailed data (Mészáros *et al.* 2017) and a previously developed simulation model (Sárdi, Bóna 2021c) were available. In the 1st phase of the research, we found that the model developed is suitable for identifying urban zones for future city logistics developments and for supporting the development of urban areas and cities. We also found that handling such a large number of criteria in a one-level hierarchy could be problematic. The model became too large, and we concluded that it is necessary to develop the model into a two-level structure.

4. Development of the two-level ranking model

The primary objective of developing the two-level version of the AHP-based multi-criteria ranking model was to ensure that it could handle a large number of criteria efficiently while still meeting the original objectives of evaluating the current city logistics state and the future city logistics development potential. In the following, we will 1st describe the two-level criteria, we will define the DoC and the DC, and then we will explain the model operation.

4.1. Criteria

The full criteria can be seen in the Appendix. 13 main criteria have been defined for analysing the current city logistics state, with a total of 56 subcriteria. To analyse the future city logistics development potentials, 16 main criteria have been identified, within which a total of 69 subcriteria have been defined. The set of criteria was extended by 13–13 aspects compared to the previous, one-level version (Sárdi, Bóna 2021b). The resulting two-level criteria system is summarized as a decision tree in Figure 3.

We consider it important that the two-level hierarchy has allowed us to extend the ranking criteria. In the previous, one-level version of the ranking model (Sárdi, Bóna 2021b), we did not consider the characteristics of logistics providers and their vehicle fleets, which gave 3 and 2 new criteria. In a research project on markets (Matiscsák 2020), the DC was defined; this added 7–7 new criteria. In addition, only a few aspects had previously examined the IT background, its current state, and the improvements needed, so 3 and 4 new criteria were added.

Among the criteria, we would like to describe two categories in more detail: the DoC (Sárdi & Bóna, 2021b) and the DC (Matiscsák 2020). The DoC examines the concentration of the delivery locations in a given zone, which seems to be related to the development potentials. 4 variants of the DoC have been defined:

- DoC₁: DoC of the examined zone [pcs of delivery locations / km² floor area];
- DoC₂: DoC of the examined zone, considering the multilevel concentrated sets of delivery locations [pcs of delivery locations / km² sum available area];
- DoC₃: area proportional DoC of the examined zone [m² floor area of the delivery locations / m² floor area];
- DoC₄: area proportional DoC of the examined zone, considering the multilevel concentrated sets of delivery locations [m² floor area of the delivery locations / m² sum available area].

Another important indicator is the DC, a ratio that aims to determine the proportion of goods handled in a consolidated way. It gives a good indicator of the development of the city logistics system. 7 variants of the DC have been defined (Matiscsák 2020):

- average mass-based DC (DC_Q): what share of the total mass of goods arrives on a consolidated basis;

- average volume-based DC (DC_V): what share of the total volume of goods arrives on a consolidated basis;
- goods value-based DC (DC_E): what share of the total value of goods arrives on a consolidated basis;
- delivery location-based DC (DC_{SH}): what share of delivery locations delivers on a consolidated basis;
- supplier-based DC (DC_{SUP}): what share of suppliers delivers on a consolidated basis;
- product group-based DC (DC_G): what share of all product groups are handled on a consolidated basis;
- transaction-based DC (DC_N): what share of all transactions that are consolidated.

In the next part of this article, we will describe how the two-level ranking model operates.

4.2. Operation of the two-level ranking model

The whole process of the ranking is described in Figure 4.

The ranking process is characterized by a peer review of the importance of the criteria. The peer review was carried out by the members of the BUTE City Logistics Research Group, experts from the BUTE Department of Material Handling and Logistics Systems and the BUTE Department of Transport Technology and Economics (BME KTKG 2026), and experts from the Clean Air Action Group (LM 2026), who provided a total of 18 answers, which were used to determine the final importance of each criterion. When choosing their importance, 4 categories were available: “less important”, “medium important”, “important” and “significantly important”.

The final importance of each criterion and subcriteria were determined based on the answers of the experts, considering the length of time the expert has been working in the field of city logistics and urban transport. The experts’ experience was rated on a scale of 4. Considering these scores, performance scores were determined for each criterion, comparing the actual scores with the maximum available score. Based on these scores, we ranked the criteria. Then, considering the shares of the 4 categories in the experts’ answers, we assigned the criteria to the final importance categories, 1st the main criteria and then the subcriteria. According to this method, for example, if category 1 were selected by the experts in 10% of the cases, then the 1st 10% of the ascending ranking would be placed in category 1. Then, if category 2 is selected 25%

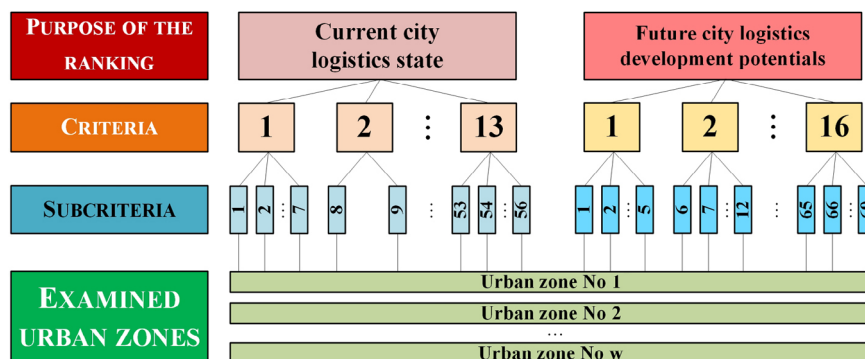


Figure 3. Decision tree of the two-level ranking model

of the time, the next 25% of the ranking will be placed in that category, so a total of 35% will be in categories 1 and 2, and so on.

Another essential part of the process is the AHP-based evaluation, i.e., the mathematical background of the model itself. The mathematical formulae were published in the 1st phase of our research (Sárdi, Bóna 2021b), based on Saaty's work (Saaty 1987). The ranking process is the same at analysing the current city logistics state and future city logistics development potentials. The 1st step of the process is to determine the importance vector based on the results of the experts' evaluation, which indicates the importance of each criterion. Then, based on the importance vector, the pairwise comparison matrix is generated, normalized, and then the model solves the system of linear equations using Faddeev's method (Helmberg *et al.* 1993), determines the final weights, and checks the consistency. Then, from the sources described in Figure 4, the actual values for each examined zone are defined, the preference ratios are calculated, and finally, the ranking values are determined: the highest value represents the highest current

state or the highest development potential, and the lowest value the lowest.

Next, we present the application of the ranking model for CSDLs in Budapest.

5. Results of the ranking

The application of the ranking model was tested on 7 zones in Budapest: 4 shopping centers (already included in the 1st phase of the model development), 1 market with closed infrastructure, and the zone defined by the northern and southern areas of the "Váci utca" SA were ranked to examine their current city logistics state and their future city logistics development potentials. The model of these Budapest zones under study (for anonymity reasons, the CSDLs are not placed in their actual locations) is presented in Figure 5. Thus, we examined which zones from these 7 we would like to, which zones are most in need of development, and which zones would be most worth developing.

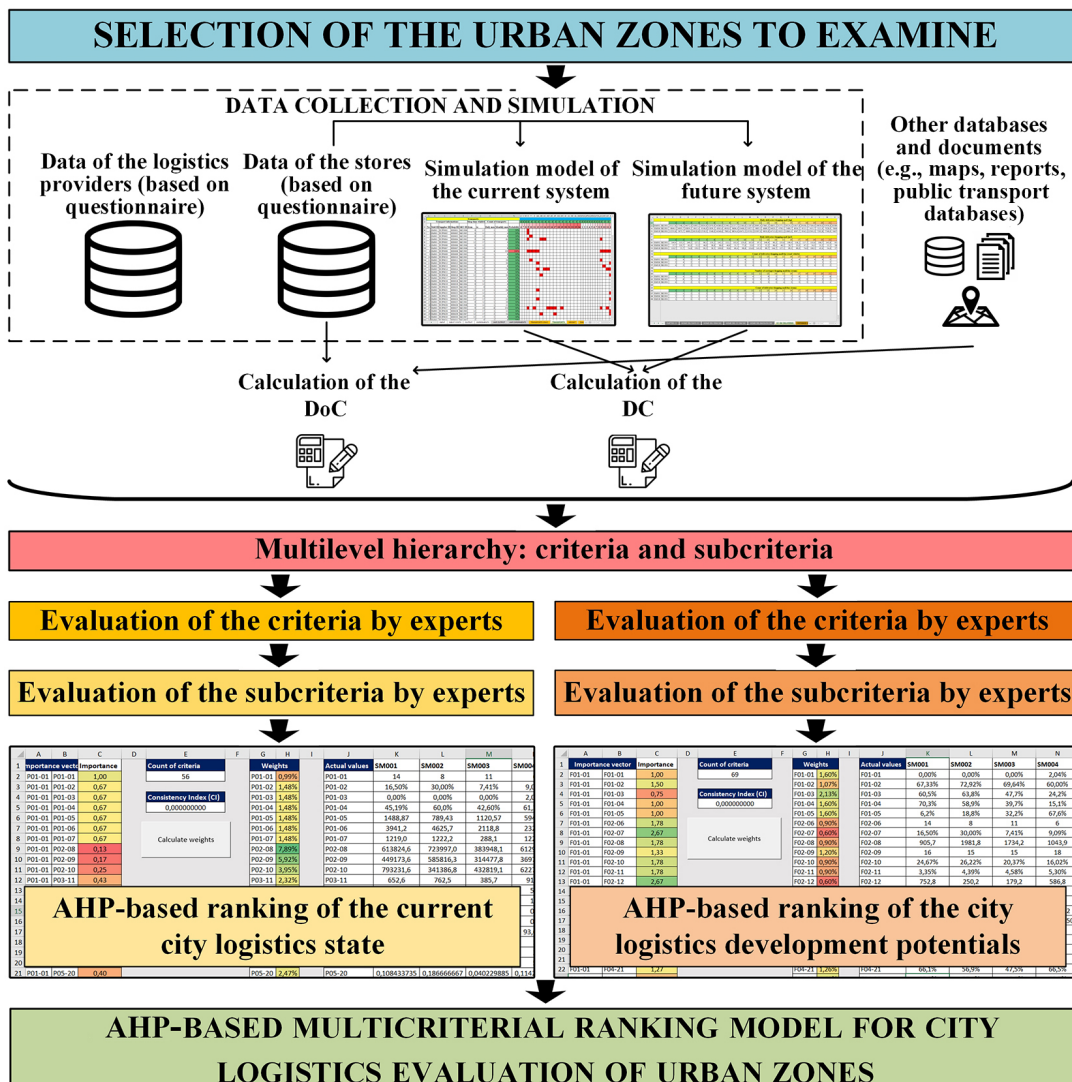


Figure 4. Steps to apply the two-level AHP-based multi-criteria ranking model

We chose these CSDLs because we had data about their delivery locations and the simulation model of the 4 shopping centers (Sárdi, Bóna 2021b), which allowed us to create a simulation model of the market and the SA. To examine the CSDLs in Budapest, we had to include their data using the sources described in Figure 4. Some own data sources were used: the database of questionnaire data collection on CSDLs (Mészáros *et al.* 2017; Sárdi, Bóna 2021b); *Microsoft Excel* based mesoscopic simulation models of the current and the consolidation-based future city logistics system (Sárdi, Bóna 2021c); calculated DC (Matiscsák 2020), the DoC values; the database on logistics service provider characteristics; and data from other research reports. Of course, in addition to our data, we also had to use other databases to know transport infrastructure characteristics, the location of parcel pick-up points and parcel machines, 5G coverage, and the availability of the cycle path network and the electric charging network.

The data of the zones examined are presented in Table 1. The 4th column of the table shows the number and percentage of stores that answered the questionnaire, and the last column shows the number and percentage of these data series that could be included in the simulation model.

Next, we present the results of the analysis.

5.1. Results for the CSDLs of Budapest

The results for the 7 zones of the CSDLs in Budapest described above are shown in Figure 6, in which a circle indicates the shopping centers, a triangle shows the market,

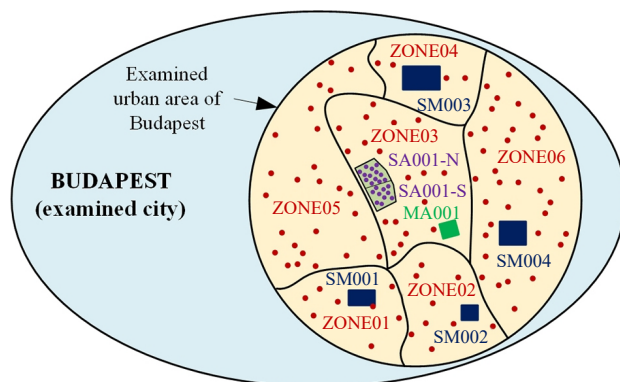


Figure 5. Model of the examined urban zones from Budapest

a rhombus the 2 zones of the “Váci utca” SA, and a square the fictive zone as a benchmark, whose current state and development potential are 100% (Sárdi, Bóna 2021b). The colours of the markers are the same as in Table 1.

It can be seen that all the zones examined are currently of medium development and have medium development potential, in line with our expectations. Currently, the large shopping center zone in the inner districts, the southern area of the “Váci utca” SA, and the market under study are the most developed, while the 3 shopping centers in the inner districts of Budapest have the highest city logistics development potentials.

As we focus on the CSDLs in our research, and this time we have also examined CSDLs using the ranking model we have developed, we found it important to investigate the relationship between the current development, the development potentials, and the DoC. The results are presented in Table 2.

Based on the results, it can be concluded that the higher the simple DoC is, the more developed the examined zone is. Besides that, the higher the area-proportional DoC is, the less developed the examined zone is expected to be. Additionally, the higher the simple DoC is, the less developable the examined zone is, and the higher the area proportional DoC is, the more developable the examined zone is. It is clear from the results that the DoC is related to the degree of development of each zone, and further studies in this direction will be worthwhile.

As these 7 zones showed a similar characteristic, we added 2 random zones to the analysis: one currently highly developed and well-developable zone and one currently undeveloped but not well-developable zone, with positive and negative random properties. These 2 random zones were tested together with the 7 Budapest zones in the next step of the testing, and the results are shown in Figure 7.

In Figure 7, the black square shows the positive random zone and the grey square the negative random zone. It can be seen that the positive one was ranked with high development and high development potentials, and the negative one with low development and low development potentials, as expected. Meanwhile, the ratings of the other examined zones did not change significantly. These results show that the ranking model not only works well for zones with medium but also for zones with positive and negative attributes, and it gives us the expected results.

Table 1. The examined CSDLs from Budapest in the testing phase

Zone	Description	Year	Responding	Modelled
SM001	medium, central SM	2015	105 (75.0%)	70 (66.7%)
SM002	small, central SM	2016	51 (68.0%)	32 (62.7%)
SM003	large, central SM	2016	171 (55.5%)	76 (47.2%)
SM004	medium, external SM	2019	50 (41.7%)	39 (78.0%)
SA001-N	northern area of “Váci utca”	2017–2018	92 (45.5%)	56 (60.9%)
SA001-S	southern area of “Váci utca”	2017–2018	71 (29.6%)	32 (45.1%)
MA001	central market (closed infrastructure)	2020	87 (56.1%)	39 (44.8%)

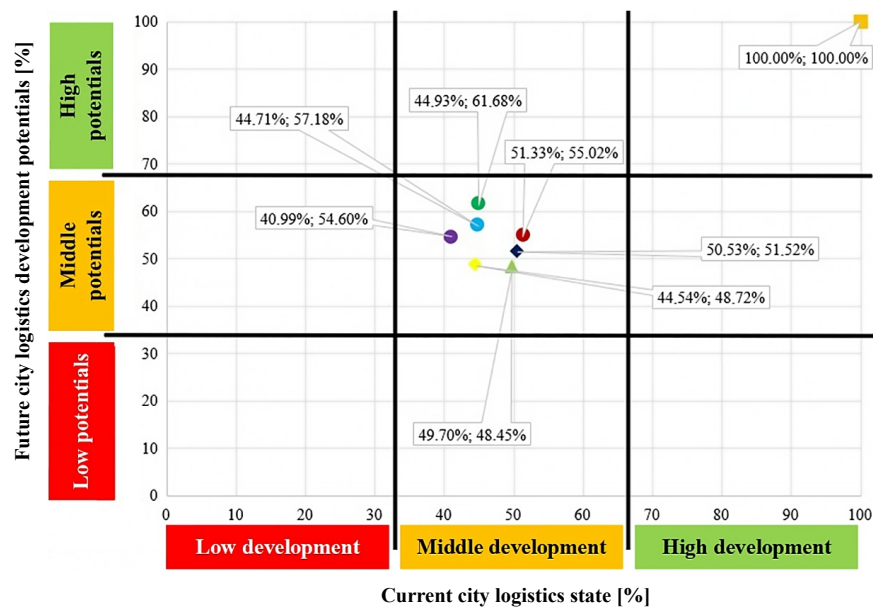


Figure 6. Results of the multi-criteria ranking for 7 zones from Budapest

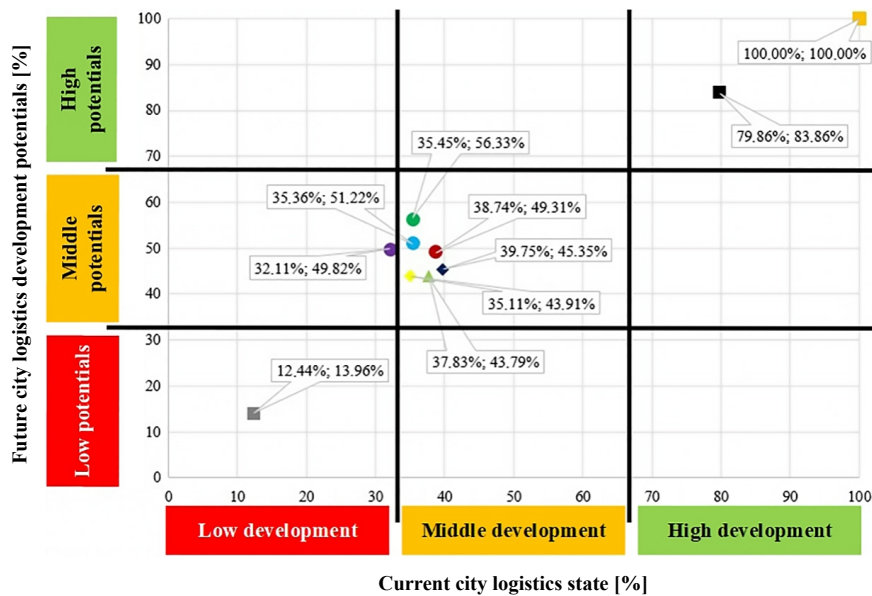


Figure 7. Results of the multi-criteria ranking for 7 zones from Budapest and for 2 random zones

Table 2. Correlation of the results and DoC (Pearson)

	Current city logistics state	Development potentials
DoC ₁	41.2%	-10.0%
DoC ₂	43.6%	-39.1%
DoC ₃	-36.0%	84.0%
DoC ₄	-54.0%	69.2%

Based on the presented results, we can conclude that the two-level ranking model will be able to provide even more support for future city logistics projects to identify the urban zones that need to be and can be developed.

5.2. Sensitivity analysis

In the next step, we performed sensitivity analyses to identify the criteria that have the greatest impact on the results, and thus the most appropriate directions for improvement. With this, it becomes possible to show which elements of the city logistics system should be improved. The analysis was 1st performed on the main criteria, changing the weight of the criteria currently being examined from minimum to maximum, and adjusting the weights of the other criteria to the values being tested. In a 2nd step, the sensitivity test was also performed on the subcriteria, analysing only within the current main criteria, adjusting the weight of the subcriteria from the minimum weight within the main item to the maximum weight, adjusting the weights of the other subcriteria within the main item

to the tested value. In evaluating the results, two aspects were examined: the extent to which changing the weight of a given criterion changed the final ranking values and how it changed the final sequence of the zones. Considering these, we ranked the criteria.

In each case, the criterion with the most sequence change is highlighted by bold, and italics highlight the criterion with the greatest average absolute change. In terms of the final sequence, only the change in the weights of the main criteria was significant, so the change in ranking caused by the subcriteria is not shown below. For the criteria of the current development, the impact of the following 4 criteria is the most significant:

- application of parcel pick-up points and pedestrian couriers;
- transportation infrastructure in the examined zone;
- actual IT background in the examined zone;
- DC.

The results show that the more parcel machines and pedestrian couriers are used, and the better the transport, the better the current city logistics system can be.

Figure 8 illustrates the impact of the main criterion, “Application of parcel pick-up points and pedestrian couriers”.

For the subcriteria of the current development, the impact of the following 4 criteria was the most significant:

- actual 5G network coverage in the examined zone;
- the sum operation cost of the logistics infrastructure in the zone;
- the extent of the available GIS support in the examined zone;
- the actual state of the transportation infrastructure in the examined zone.

For the main criteria of the analysis of the future development potentials, the impact of the following 4 criteria was the most significant:

- expected emission change;
- DC;
- the willingness of the delivery locations to participate in new city logistics systems;
- application of parcel pick-up points and pedestrian couriers.

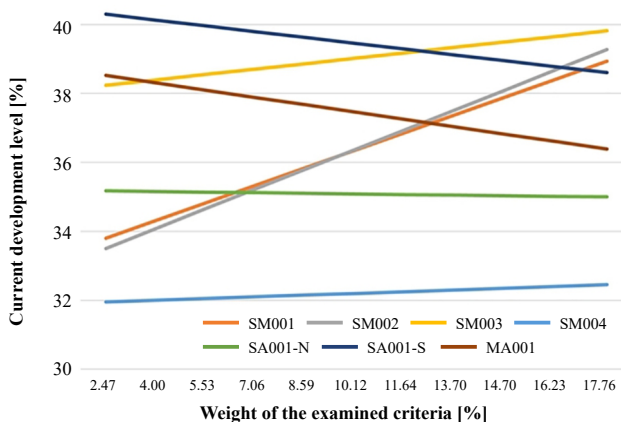


Figure 8. Results of the sensitivity analysis – current city logistics state, application of parcel pick-up points and pedestrian couriers

The results show that the more significant emission reduction can be expected, and the higher the expected DC will be, the more efficient a zone can be developed. These results give us an indication of which development should be performed.

For the subcriteria of the future development potentials, the following 4 criteria had the most significant impact:

- the average willingness of the delivery locations to participate in new city logistics systems;
- share of delivery locations with existing IT or ERP system [%];
- the expected reduction in the number of arrival delivery transactions to the zone;
- potential future 5G network coverage in the examined zone.

We also performed correlation analysis based on the results of the sensitivity analysis. These showed that for the criteria of the current city logistics state, the greater the relative standard deviation is, the greater the average absolute change, and the less the expected sequence change will be in the examined city logistics system. For the criteria of the future development potentials, the greater the calculated importance of an aspect is, the greater the average absolute change will be, and the more sequence change is expected. Also, the greater the relative standard deviation is, the smaller the average absolute change will be, and the less sequence change is expected.

Based on the results, it can be concluded that there are 3 main subcriteria groups in both cases, based on the relative standard deviation and the average absolute change, as illustrated in Figure 9 for the current city logistics state subcriteria. Basically, a hyperbolic relationship can be observed, and a similar relationship can be observed when examining the relative standard deviation and the fluctuations.

These results show that this ranking model can also be used to indicate which criteria are critical for the current state and for the development potentials, and thus to identify the appropriate directions for city logistics developments, which is significantly important for the city logistics aspects of urban developments.

6. Conclusions

In our article, we presented an AHP-based two-level ranking model for city logistics analysis of urban zones, which could be important for urban development. In our city logistics research, the need arose to develop a ranking model that can determine the current city logistics state of different urban zones and their potential for city logistics developments. Before the model development, we performed a complex literature review, and based on that, such a ranking methodology would be a completely new one as no such solutions were published in the literature. Additionally, based on the experiences, the AHP was selected as it is widely used and well-proven in the field of city logistics, and we aimed to develop such a model that could be useful even for other stakeholders of the city logistics developments as well.

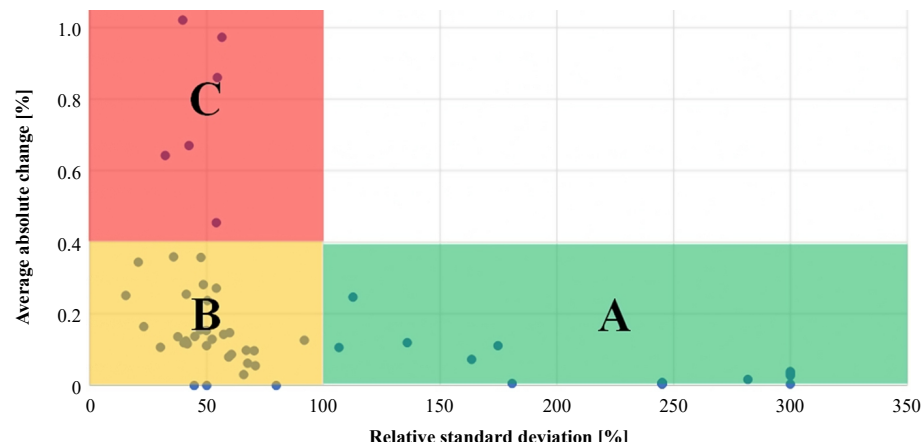


Figure 9. Correlation of the relative standard deviation of the actual values of the subcriteria and the average absolute change

In the 1st phase of our research, we developed this ranking tool as an AHP-based one-level model (Sárdi, Bóna 2021b). As a very complex set of criteria was developed, we decided to reorganize the model into a two-level hierarchy; this was the focus of our actual article. In the next part of our article, we described the criteria used for the evaluation of the current city logistics state (56 criteria) and the future city logistics development potentials (69 criteria). Next, we presented how the ranking model works and how the criteria are evaluated by experts. After these, we characterized the urban zones (concentrated sets of delivery locations, i.e., SMs, a SA, and a market from Budapest) to be tested by the two-level ranking model and described the results of the tests and the correlation analysis. In the testing phase, we found that the ranking model meets our objectives and is clearly suitable for supporting city logistics developments. Based on the correlation analysis, we concluded that the current state and development potentials of the examined zones are related to the DoC: the higher the simple DoC is, the more developed the examined zone is; the higher the area-proportional DoC is, the less developed the examined zone is expected to be; the higher the simple DoC is, the less developable the examined zone is, and the higher the area proportional DoC is, the more developable the examined zone is. These results are novel in the field of city logistics, as such connections between the city logistics developments and the concentration of the urban areas were not identified. As a final step of our article, we presented a sensitivity analysis, which allowed us to identify the critical criteria of the Budapest example with CSDLs. For the current city logistics state, the application of parcel pick-up points and pedestrian couriers and the transportation infrastructure seem to be the most crucial, while in the case of the future city logistics development potentials, the expected emission change and the DC have the most significant effect.

We already have identified several important tasks to continue our research. It will be important to test the model in such urban environments, where new city logistics

technologies, like drones (Sárdi, Bóna 2021a; Kikutis *et al.* 2019), autonomous road vehicles (Viktor, Szeghegyi 2022) and the 5G-network (Taboada, Shee 2021) will be used, as based on the experiences of these systems, the role of the related criteria in our model can be reconsidered. Additionally, the application of the model to other types of urban zones should be investigated; for example, in Budapest, open infrastructure markets, old town areas, hypermarkets, and simple urban zones will also be necessary. In addition, the model should be tested in other cities in Hungary (e.g., Győr or Szeged). It will also be worth looking at cities abroad, especially those with a high level of city logistics (e.g., Utrecht or Bristol). To make these possible, we are planning to use this ranking methodology in several research projects together with our national and international partners.

Based on the results of our research so far, it can be concluded that the two-level ranking model can be used for future city logistics developments and for the logistics aspects of urban developments, and it is fully capable of identifying the urban zones that need to be developed and selecting those that are worth developing. This can be very useful in the case of city logistics development, for example, when it is necessary to decide based on a limited budget or when a pilot area must be selected. Considering these, the tool developed in our research is useful not only for researchers but also for stakeholders of the examined city logistics systems (municipalities, urban infrastructure operators, logistics providers). At this point, it is necessary to highlight the managerial implications regarding the use of the ranking model presented in our article. As we mentioned, it will be useful not only for the researchers but for other stakeholders as well. When city logistics projects are prepared, all these stakeholders should be involved, as all of them are needed to evaluate the criteria and to define the parameters used for the ranking. This means that in city logistics projects, they are going to use this tool together: for example, the researchers will provide knowledge about the innovations, the municipality about the regulations, the operators about the actual infrastruc-

ture, and the logistics providers (together with the store operators) about the goods to be delivered. Nowadays, there are lots of city logistics projects where only one or two stakeholders are involved, and they are choosing the development areas based on limited data or even intuitively, without evaluating the actual situation and modelling the possible effects of the developments. Hopefully, by using our multi-criteria ranking methodology, in the future, these problems can be eliminated, and the data-based evaluation of the possibilities will help to have more efficient and successful city logistics developments.

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Author contributions

Dávid Lajos Sárdi and Krisztián Bóna were responsible for the model development, model testing and sensitivity analysis.

Dávid Lajos Sárdi was responsible for data collection, data analysis, literature review, figures, correlation analysis.

Dávid Lajos Sárdi wrote the 1st draft of the article, and Krisztián Bóna revised the article.

Disclosure statement

The authors report there are no competing interests to declare.

Declaration on the use of Artificial Intelligence (AI)

During the preparation of this manuscript, the authors did not use generative AI or AI-assisted technologies.

The authors take full responsibility for the content of this manuscript.

Appendix

In the following lists, *italics* indicate those criteria for which the lower value is better; for every other criterion, the higher value is better.

A.1. Criteria and subcriteria of the evaluation of the current city logistics state

Properties of the delivery transactions:

- *number of different logistics units used by the delivery locations of the zone*;
- share of the delivery locations, which use unit loads in the zone [%];
- the actual share of night deliveries in the zone [%];
- *the actual share of peak-time deliveries in the zone* [%];
- *number of arrival delivery transactions to the zone* [delivery / time period];
- *the average mileage of a delivery location in the zone* [km / location/time period];
- *the average delivery performance of a delivery location in the zone* [tkm / location / time period],

Current logistics costs:

- *average sum logistics cost an average delivery location in the zone* [monetary unit / location / time period];
- *average sum delivery cost of an average delivery location in the zone* [monetary unit / location / time period];
- *the sum operation cost of the logistics infrastructure in the zone* [monetary unit / time period].

Current emission:

- *average CO₂ emission of a delivery location in the zone* [kg / location / time period];
- *average CO emission of a delivery location in the zone* [kg / location / time period];
- *average NO_x emission of a delivery location in the zone* [kg / location / time period];
- *average HC emission of a delivery location in the zone* [kg / location / time period];
- *average PM emission of a delivery location in the zone* [kg / location / time period].

Entry regulations for delivery vehicles in the examined zone:

- the existence of the entry regulations in the examined zone;
- compliance with the actual entry regulations by the delivery locations of the zone [%];
- adequacy of the actual entry regulations in the examined zone;
- enforceability of the actual entry regulations in the examined zone.

Loading regulation and infrastructure in the examined zone:

- loading possibilities in the examined zone [pcs of loading areas / delivery location];
- *the average distance of the delivery locations from the loading areas in the zone* [m];
- verifiability of the actual loading regulation in the examined zone.

Current application and possibilities of alternative green delivery solutions:

- share of delivery location with cargo bike deliveries in the zone [%];

- possibilities of cargo bike deliveries (availability of proper bike path network);
- the actual share of railway deliveries in the examined zone [%];
- the actual share of waterway deliveries in the examined zone [%];
- the actual share of combined deliveries in the examined zone [%];
- share of autonomous delivery vehicles in the examined zone [%];
- possibilities of deliveries by autonomous delivery vehicles based on the actual infrastructure and regulations;
- share of delivery drones in the examined zone [%];
- possibilities of deliveries delivery drones, based on the actual infrastructure and regulations.

DC (actual share of consolidated deliveries):

- the actual average mass-based DC of the examined zone [%];
- the actual average volume-based DC of the examined zone [%];
- the actual average goods value-based DC of the examined zone [%];
- the actual delivery location-based DC of the examined zone [%];
- the actual supplier-based DC of the examined zone [%];
- the actual product group-based DC of the examined zone [%];
- the actual transaction-based DC of the examined zone [%].

Transportation infrastructure in the examined zone:

- the actual state of the transportation infrastructure in the examined zone;
- coverage provided by the electric charging network in the examined zone [pcs of chargers / km²].

Properties of the logistics providers in the examined zone:

- number of active logistics providers in the examined zone;
- *number of delivery vehicles of the active logistics providers in the examined zone [pcs vehicle / delivery location];*
- share of the green delivery vehicles of the active logistics providers in the examined zone [%].

Properties of inverse logistics and home deliveries:

- *Share of outbound deliveries in the zone (except the home deliveries) [%];*
- *Share of delivery locations with home deliveries in the examined zone [%];*
- *Share of home deliveries from the delivery locations in the examined zone [%].*

Storage possibilities and actual stocks:

- the average floor area of the warehouse areas in the examined zone [m² / delivery location];
- average time, which can be served from the full capacity of the delivery locations of the zone [day];
- *average sum stock (in the whole supply system) of an average delivery location in the zone [t / location / time period].*

Application of parcel pick-up points and pedestrian couriers:

- number of parcel pick-up points in the examined zone [pcs];
- the density of the parcel pick-up points in the examined zone [pcs/km²];
- application possibilities of pedestrian couriers.

Actual IT background in the examined zone:

- share of delivery locations with existing IT or ERP system [%];
- the extent of the available GIS support in the examined zone;
- availability of a city logistics topological model in the examined zone;
- actual 5G network coverage in the examined zone [%].

A.2. Criteria and subcriteria of the evaluation of the future city logistics development potentials

Properties of the delivery and inverse logistics transactions and their expected change:

- the actual share of night deliveries in the zone [%];
- *share of outbound deliveries in the zone (except the home deliveries) [%];*
- the expected reduction in the number of arrival delivery transactions to the zone [%];
- the expected reduction of the sum mileage in the examined zone [%];
- *expected growth of the sum delivery performance in the examined zone [%].*

Properties of the goods to be handled:

- *number of different logistics units used by the delivery locations of the zone [pcs];*
- share of the delivery locations, which use unit loads in the zone [%];
- *the average number of SKUs (goods) of a delivery location in the examined zone [pcs of SKUs];*
- *number of groups of SKUs that can be merged in the examined zone [pcs of SKU groups];*
- *share of special goods at an average delivery location in the zone [%];*
- *share of perishable/refrigerated goods at an average delivery location in the zone [%];*
- sum arrival amount of goods to the examined zone [t / time period].

Expected change of logistics costs:

- the expected reduction of the sum logistics costs in the examined zone [%];
- the expected reduction of the sum delivery cost in the examined zone [%];
- *the expected operation cost of the logistics infrastructure in the examined zone [monetary unit];*
- *expected investment cost of the cross docks of the examined zone [monetary unit];*
- *expected investment cost of the signed loading areas of the examined zone [monetary unit].*

Expected emission change:

- the expected reduction of the sum CO₂ emission in the zone [%];
- the expected reduction of the sum CO emission in the zone [%];
- the expected reduction of the sum NO_x emission in the zone [%];
- the expected reduction of the sum HC emission in the zone [%];
- the expected reduction of the sum PM emission in the zone [%].

Entry regulations for delivery vehicles in the examined zone:

- the existence of the entry regulations in the examined zone;
- adequacy of the actual entry regulations in the examined zone;
- enforceability of the actual entry regulations in the examined zone.

Loading regulation and infrastructure in the examined zone, expected transshipment points:

- loading possibilities in the examined zone [pcs of loading areas / delivery location];
- *the average distance of the delivery locations from the loading areas in the zone [m];*
- *the necessary number of transshipment points in the expected new city logistics system of the examined zone [pcs of transshipment points].*

Current application and possibilities of alternative green delivery solutions:

- share of delivery location with cargo bike deliveries in the zone [%];
- possibilities of cargo bike deliveries (availability of proper bike path network);
- availability of urban railway delivery solutions in the examined zone;
- availability of urban waterway delivery solutions in the examined zone;
- possibilities of combined delivery solutions in the examined zone;
- the average distance of the delivery locations from the railway network in the examined zone [km];
- the average distance of the delivery locations from the waterway network in the examined zone [km];
- possibilities of deliveries by autonomous delivery vehicles based on the actual infrastructure and regulations;
- possibilities of deliveries delivery drones, based on the actual infrastructure and regulations.

DC (potential future share of consolidated deliveries):

- the potential, average mass-based DC of the examined zone [%];
- the potential, average volume-based DC of the examined zone [%];
- the potential, average goods value-based DC of the examined zone [%];
- the potential, delivery location-based DC of the examined zone [%];

- the potential, supplier-based DC of the examined zone [%];
- the potential, product group-based DC of the examined zone [%];
- the potential, transaction-based DC of the examined zone [%].

Transportation infrastructure in the examined zone:

- the actual state of the transportation infrastructure in the examined zone;
- coverage provided by the electric charging network in the examined zone [pcs of chargers / km²].

DoC in the examined zone:

- DoC of the examined zone [pcs of delivery locations / km² floor area];
- DoC of the examined zone, considering the multilevel concentrated sets of delivery locations [pcs of delivery locations / km² sum available area];
- area proportional DoC of the examined zone [m² floor area of the delivery locations / m² floor area];
- area proportional DoC of the examined zone, considering the multilevel concentrated sets of delivery locations [m² floor area of the delivery locations / m² sum available area].

The willingness of the delivery locations to participate in new city logistics systems:

- the average willingness of the delivery locations to participate in new city logistics systems;
- average importance of green aspects for the delivery locations;
- average importance of urban transportation aspects for the delivery locations.

Available brownfield lands for new city logistics systems:

- number of possible brownfield lands for a cross-dock in the examined zone [pcs of possible brownfield lands];
- the sum floor area of possible brownfield lands for a cross-dock in the examined zone [m² floor area of possible brownfield lands];
- *the average distance of the loading areas from the possible brownfield lands [km].*

Properties of the logistics providers (to be included in the new system) in the examined zone:

- number of active logistics providers in the examined zone who are capable of operating a consolidation-based city logistics system;
- *number of green delivery vehicles of the active logistics providers to be used in consolidation-based city logistics system in the examined zone [pcs vehicle / delivery location].*

Storage possibilities and expected stocks:

- the average floor area of the warehouse areas in the examined zone [m² / delivery location];
- average time, which can be served from the full capacity of the delivery locations of the zone [day];
- *expected growth of the sum stock (in the whole supply system) of the examined zone [%].*

Application of parcel pick-up points and pedestrian couriers:

- number of parcel pick-up points in the examined zone [pcs];
- the density of the parcel pick-up points in the examined zone [pcs / km²];
- application possibilities of pedestrian couriers.

Actual IT background and necessary IT developments in the examined zone:

- share of delivery locations with existing IT or ERP system [%];
- *the extent of the need for IT development in the examined zone;*
- the extent of the available GIS support in the examined zone;
- availability of a city logistics topological model in the examined zone;
- potential future 5G network coverage in the examined zone [%].

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