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A hybrid approach integrating Affinity Diagram, AHP and fuzzy TOPSIS for sustainable city logistics planning

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ABSTRACT

City logistics initiatives are steps taken by municipal administrations to ameliorate the condition of goods transport in cities and reduce their negative impacts on city residents and their environment. Examples of city logistics initiatives are urban distribution centers, congestion pricing, delivery timing and access restrictions. In this paper, we present a hybrid approach based on Affinity Diagram, AHP and fuzzy TOPSIS for evaluating city logistics initiatives. Four initiatives namely vehicle sizing restrictions, congestion charging schemes, urban distribution center and access timing restrictions are considered.

The proposed approach consists of four steps. The first step involves identification of criteria for assessing performance of city logistics initiatives using Affinity Diagram. The results are four categories of criteria namely technical, social, economical and environmental. In step 2, a decision making committee comprising of representatives of city logistics stakeholders is formed. These stakeholders are shippers, receivers, transport operators, end consumers and public administrators. The committee members weight the selected criteria using AHP. In step 3, the decision makers provide linguistic ratings to the alternatives (city logistics initiatives) to assess their performance against the selected criteria. These linguistic ratings are then aggregated using fuzzy TOPSIS to generate an overall performance score for each alternative. The alternative with the highest score is finally chosen as most suitable city logistics initiative for improving city sustainability. In the fourth step, we perform sensitivity analysis to evaluate the influence of criteria weights on the selection of the best alternative.

The proposed approach is novel and can be practically applied for selecting sustainable city logistics initiatives for cities. Another advantage is its ability to generate solutions under limited quantitative information. An empirical application of the proposed approach is provided.

1. Introduction

Modern cities are facing congestion, lack of public space, huge waiting times, air pollution, and noise arising air from goods movement in cities. To maintain the economic growth of cities and meet customer demands, organizations are continually involved in production and distribution of goods; however, this has come at an unexpected cost of degradation of quality of life in modern cities [1]. To cope up with this growing crisis, municipal administrations are investing in

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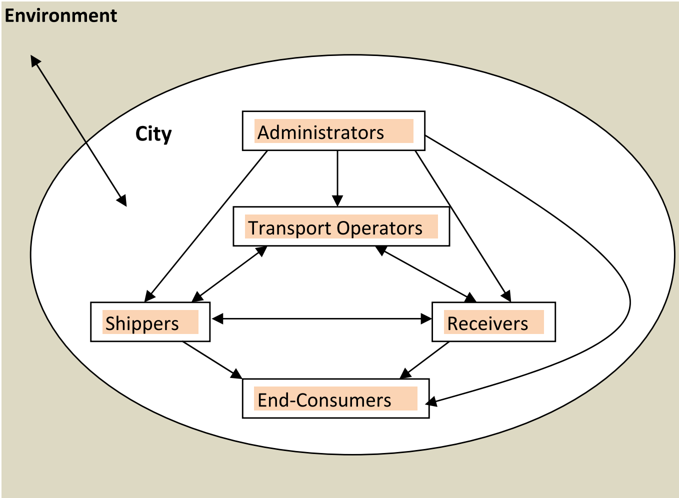

Fig. 1. City logistics stakeholders.

sustainable city logistics initiatives to ameliorate the condition of goods transport in cities and reduce their negative impacts on city residents and their environment. Examples of these initiatives are urban distribution centers, congestion pricing, delivery timing and access restrictions.

According to the Council of Logistics Management, [2], "Logistics is that part of the supply chain process that plans, implements, and controls the flow and storage of goods, services, and related information from the point of origin to the point of consumption in order to meet customer's requirements". The logistics associated with consolidation, transportation, and distribution of goods in cities is called city logistics. From a systems point of view, city logistics consists of many subsystems involving different stakeholders namely shippers, receivers, end consumers, transport operators and public administrators (see Fig. 1). The end-consumers are residents or the people that live and work in the metropolitan areas. Shippers (wholesalers) supply good to the receivers (retailers, shopkeepers) through transport operators (or carriers). Administrators represent the government or transport authorities whose objective is to resolve conflict between city logistics actors, while facilitating sustainable development of urban areas.

In recent years, several studies have been conducted by researchers on city logistics planning and evaluation. Munuzuri et al. [3] presents a compilation of solutions that can be implemented by local administrations in order to improve freight deliveries in urban environments. Visser et al. [4] present a classification of public, private and public-private measures related to urban freight. The COST 321 Action [5] report categorizes urban freight transport measures as promising and less promising measures based on experts survey. Dablanc [6] brings forth difficulties in implementing logistical measures in European cities and proposes consideration of stakeholder involvement and interests in devising new policies and regulations. A detailed study of modeling approaches for evaluating and planning city logistics measures can be found in Taniguchi et al. [7] and Crainic et al. [8].

The existing studies on city logistics planning can be mainly classified into (a) survey based approaches, (b) simulation based approaches, (c) multicriteria decision making based approaches, (d) heuristics based approaches and (e) cost-benefit analysis based approaches. Allen et al. [9] conducted group discussions with companies to analyze the potential impacts of sustainable distribution measures in UK urban areas. Esser and Kurte [10] use empirical data from customer survey to analyze the impact of B2C e-commerce on transport in urban areas in Germany. Anderson et al. [11] conduct a survey study to investigate the operational, financial and environmental effects of city logistics policy measures. Thompson and Hassall [12] use ratings scores for evaluating urban freight projects. Patier and Alligier [13] use Delphi study and Structural Equation Modeling to assess the current and future effects of online retailing on city logistics in France. Quak et al. [14] use case studies of 14 Dutch organizations to investigate the impact of governmental time-window pressure on retailers' logistical concepts and the consequential financial and environmental distribution performance.

Studies on simulation based approaches involve simulation of urban freight over the road networks to assess their impacts. Barceló and Grzybowska [15] combine vehicle routing models and microscopic traffic simulation to model and evaluate city logistics applications. Taniguchi and Tamagawa [16] proposed a simulation based approach for evaluating city logistics measures considering the behavior of several stakeholders. Yamada and Taniguchi [17] use bilevel optimization model for representing the behavior of stakeholders associated with urban goods delivery. Taniguchi and Van Der Heijden [18] present a methodology for evaluating city logistics initiatives using a dynamic traffic simulation with optimal routing and scheduling. Awasthi and Proth [19] propose a system dynamics based approach for city logistics decision making. Segalou et al. [20] propose a traffic simulation model for environmental impact assessment of urban goods movement. Marquez and Salim [21] use scenario analysis to investigate the sensitivity of urban freight patterns to various greenhouse gas abatement policy measures.

In multicriteria decision making based approaches, alternatives (city logistics initiatives) are evaluated against several weighted criteria and the alternative with the highest performance score considering all criteria is finally chosen. Examples of few multicriteria decision making techniques are AHP (Analytical Hierarchy Process), TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) etc. Kapros et al. [22] present a multicriteria approach for evaluating intermodal freight villages. Kunadhamraks and Hanaoka [23] use fuzzy AHP for evaluation of logistics performance for freight mode choice at an intermodal terminal.

Application of metaheuristics for city logistics planning has been investigated by Rooijen et al. [24] who use VRPTW (Vehicle Routing Problem Under Time Windows) and genetic algorithm to model the impact of community level regulation on city logistics.

Cost-benefit analysis approaches involve evaluation of alternatives for benefits (the higher the better) vs costs (the lower the better). Van Duin et al. [25] use cost benefit analysis for evaluating city distribution centre.

The problem treated in this paper is practical in nature and inspired by growing congestion and space limitation problems arising in urban areas due to poorly managed goods distribution. We present a hybrid approach based on Affinity Diagram, AHP and fuzzy TOPSIS for evaluating city logistics initiatives. Affinity Diagram is used to generate criteria for selecting sustainable city logistics initiatives. AHP is used to generate criteria weights since they are known with precision by the city experts. Fuzzy TOPSIS is used for evaluating alternatives of city logistics planning since many of them are not known with certainty to the decision makers due to specific context of each city, no prior experience with alternatives, and lack of numeric data, thereby justifying the use of linguistic ratings and fuzzy theory in rating them. Besides it is much easier to represent performance of city logistics initiatives in linguistic terms such as good, very good, poor, very poor etc. than in numbers, therefore, linguistic assessments [26] are used in rating the performance of city logistics initiatives. Fuzzy set theory is used to model vagueness and uncertainty in decision making processes arising due to lack of complete information [27].

The rest of the paper is organized as follows. In Section 2, we present preliminaries of AHP, fuzzy set theory and fuzzy TOPSIS. In Section 3, we present our hybrid approach for evaluating city logistics initiatives. Section 4 presents an empirical application of the proposed approach. In the fifth and the last section, we present the conclusions and future work.

2. Methods

2.1. Affinity Diagram

An Affinity Diagram (or KJ method after its author, Kawakita Jiro) [28] is a tool to generate groupings of data based on their natural relationship through brainstorming or by analyzing verbal data gathered through survey, interviews or feedback results. Originally developed as a quality management tool, it is now applied in different domains for generating ideas for decision making. Ishikawa recommends using the Affinity Diagram when facts or thoughts are uncertain and need to be organized. The various steps of Affinity Diagram adapted from [28] are described as follows:

- Identify the problem and state it in a clear, concise and easily understandable way to the team members.
- Give the team members a supply of note cards and a pen and ask them to write down issues related to the problem. One idea should be written per card. Allow 10 min for the writing activity.
- Place the written cards on a flat surface. Lay out the finished cards so that all members can see and have access to all cards.
- Let everyone on the team move the cards into groups with a similar theme without discussing. If you disagree with someone's placement of a card, say nothing but move it silently.
- A consensus is reached when all cards are in groups and team members have stopped moving the cards. When team members agree on the placement of the cards, create header cards.
- Draw a finished Affinity Diagram and provide a working copy to all participants.

In this paper, we have used Affinity Diagram to generate criteria for evaluating city logistics initiatives. The team members participating in this exercise are representatives of city logistics stakeholders that is, Shippers (Wholesalers), Receivers (Shop Owners), End Consumers, Transport Operators (Carriers) and Public Administrators. These representatives should be chosen from different levels of hierarchy across all departments from these five categories to ensure uniform representation. There is no hard and fast rule on the minimum or maximum number of participants. Ideally, the number should be good enough to represent all decision makers involved in urban goods transport and urban logistics activities.

2.2. AHP

AHP is a multicriteria decision making technique developed by Saaty [29] for evaluating and selecting alternatives against a set of selected criteria. The strength of AHP is that it organizes tangible and intangible factors in a systematic way, and provides a structured yet relatively simple solution to the decision-making problems In addition, by breaking a problem down in a logical fashion from the large, descending in gradual steps, to the smaller and smaller, one is able to connect, through simple paired comparison judgments, the small to the large. AHP has been applied in several decision making situations. The different steps of AHP are explained as follows:

1. Define the problem and determine its goal.
2. Structure the hierarchy from the top (the objectives) through the intermediate levels (criteria) to the lowest level (alternatives).
3. Construct a set of pair-wise comparison matrices (size $n \times n$) for each of the lower levels with one matrix for each element in the level immediately above by using the relative scale measurement shown in Table 1. The pair-wise comparisons are done in terms of which element dominates the other.
4. There are $n(n-1)/2$ judgments required per matrix to develop the set of matrices in step 3. Reciprocals are automatically assigned in each pair-wise comparison.
5. Having made all the pair-wise comparisons, the consistency is determined by using the eigenvalue $\lambda_{\max}$ to calculate the consistency index CI where CI = $(\lambda_{\max} - n)/(n-1)$ where n is the matrix size. Judgment consistency can be checked by seeing the value of consistency ratio CR for the appropriate matrix value in Table 2. If CR $\leqslant 0.1$, the judgement matrix is acceptable otherwise it is considered inconsistent. To obtain a consistent matrix, judgments should be reviewed and improved.
6. Hierarchical synthesis is now used to weight the eigenvectors by the weights of the criteria and the sum is taken over all weighted eigenvector entries corresponding to those in the next lower level of the hierarchy.

2.3. Fuzzy TOPSIS

Definition 1. A triangular fuzzy number is represented as a triplet $\tilde{a} = (a_1, a_2, a_3)$. Due to their conceptual and computational simplicity, triangular fuzzy numbers are very commonly used in practical applications [30,31]. The membership function $\mu_{\tilde{a}}(x)$ of triangular fuzzy number $\tilde{a}$ is given by:

$$\mu_{\tilde{a}}(x) = \begin{cases} 0, & x \leqslant a_1, \\ \frac{x-a_1}{a_2-a_1}, & a_1 \leqslant x \leqslant a_2, \\ \frac{a_3-x}{a_3-a_2}, & a_2 \leqslant x \leqslant a_3, \\ 0, & x > a_3, \end{cases} \tag{1}$$

where a_1, a_2, a_3 are real numbers and $a_1 < a_2 < a_3$. The value of x at a_2 gives the maximal grade of $\mu_{\tilde{a}}(x)$ i.e., $\mu_{\tilde{a}}(x) = 1$; it is the most probable value of the evaluation data. The value of x at a_1 gives the minimal grade of $\mu_{\tilde{a}}(x)$ i.e., $\mu_{\tilde{a}}(x) = 0$; it is the least probable value of the evaluation data. The narrower the interval $[a_1, a_3]$, the lower is the fuzziness of the evaluation data.

Definition 2. In fuzzy set theory, conversion scales are applied to transform the linguistic terms into fuzzy numbers. In this paper, we will use a scale of 1–9 to rate the criteria and the alternatives. Table 3 presents the linguistic variables and fuzzy ratings used for the alternatives.

The fuzzy TOPSIS approach involves fuzzy assessments of criteria and alternatives in TOPSIS [32]. The TOPSIS approach chooses alternative that is closest to the fuzzy positive ideal solution (FPIS) and farthest from the fuzzy negative ideal solution (FNIS). A positive ideal solution is composed of the best performance values for each criterion whereas the negative ideal solution consists of the worst performance values. If the objective is to maximize criteria then closeness to FPIS and far distance from FNIS is preferable. If the objective is to minimize criteria, then closeness to FNIS and distance from FPIS is preferable). Fig. 2 presents a graphical illustration of the FPIS and FNIS respectively. Two alternatives A1 and A2 are being

Table 1
Pairwise comparison scale for AHP preferences [33].

Numerical rating	Verbal judgement of preferences
1	Equally preferred
3	Moderately preferred
5	Strongly preferred
7	Very strongly preferred
9	Extremely preferred
2, 4, 6, 8	Intermediate values between the two adjacent judgements
Reciprocals	When activity *i* compared toy is assigned one of the above numbers, then activity *j* compared to *i* is assigned its reciprocal

Table 2
Average random consistency ratio (CR) [33].

Size of matrix	1	2	3	4	5	6	7	8	9	10
Random consistency	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 3
Linguistic terms for alternatives ratings.

Linguistic term	Membership function
Very poor (VP)	(1, 1, 3)
Poor(P)	(1, 3, 5)
Fair (F)	(3, 5, 7)
Good(G)	(5, 7, 9)
Very Good (VG)	(7, 9, 9)

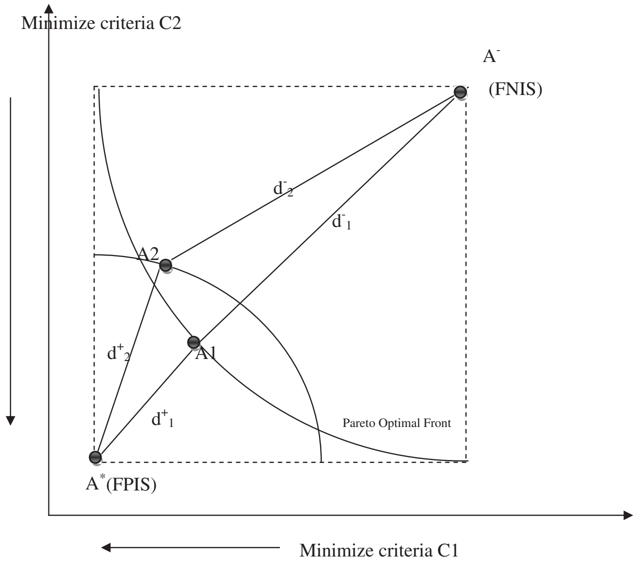

Fig. 2. Illustrations of notion of the ideal (FPIS) and anti ideal solutions (FNIS).

evaluated with respect to their distances from FPIS and FNIS, respectively. The goal is to minimize criteria C1 and C2. Since the alternative A2 is closer to FNIS (d_2^-) and farther from FPIS (d_2^+) than A1 (d_1^-, d_1^+), A2 is considered to be a better alternative over A1.

The various steps of Fuzzy TOPSIS [32,34] are presented as follows:

Step 1: Assignment of ratings to the criteria and the alternatives.
Let us assume there are m possible candidates called $A = \{A_1, A_2, \ldots, A_m\}$ which are to evaluated against n criteria, $C = \{C_1, C_2, \ldots, C_n\}$. The criteria weights are denoted by w_j ($j = 1, 2, \ldots, n$). In our study, we are using AHP to obtain criteria ratings. The performance ratings of each decision maker D_k ($k = 1, 2, \ldots, K$) for each alternative A_i ($i = 1, 2, \ldots, m$) with respect to criteria C_j ($j = 1, 2, \ldots, n$) are denoted by $\tilde{R}_k = \tilde{x}_{ijk}$ ($i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$; $k = 1, 2, \ldots, K$) with membership function $\mu_{\tilde{R}_k}(x)$.
Step 2: Compute aggregate fuzzy ratings for the criteria and the alternatives.
If the fuzzy ratings of all decision makers is described as triangular fuzzy number $\tilde{R}_k = (a_k, b_k, c_k)$, $k = 1, 2, \ldots, K$, then the aggregated fuzzy rating is given by $\tilde{R} = (a, b, c)$, $k = 1, 2, \ldots, K$ where;

$$a = \min_k\{a_k\}, \quad b = \frac{1}{K}\sum_{k=1}^{K} b_k, \quad c = \max_k\{c_k\}.$$

If the fuzzy rating of the kth decision maker are $\tilde{x}_{ijk} = (a_{ijk},\ b_{ijk},\ c_{ijk})$ $i = 1, 2, \ldots, m$, $j = 1, 2, \ldots, n$, then the aggregated fuzzy ratings ($\tilde{x}_{ij}$) of alternatives with respect to each criteria are given by $\tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij})$ where

$$a_{ij} = \min_k\{a_{ijk}\}, \quad b_{ij} = \frac{1}{K}\sum_{k=1}^{K} b_{ijk}, \quad c_{ij} = \max_k\{c_{ijk}\}. \tag{2}$$

The weights w_j of criterion $j = 1, 2, \ldots, n$ are obtained by averaging the weights obtained from the k decision makers that is

$$w_j = \frac{w_{j1} + w_{j2} + \cdots + w_{jk}}{k}. \tag{3}$$

Step 3: Compute the fuzzy decision matrix.
The fuzzy decision matrix for the alternatives ($\tilde{D}$) is constructed as follows:

$$\tilde{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ \\ A_m \end{array} \begin{array}{c} \begin{array}{cccc} C_1 & C_2 & \quad & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{ln} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \end{array} i = 1,2,\ldots,m;\ j = 1,2,\ldots,n. \tag{4}$$

Step 4: Normalize the fuzzy decision matrix.
The raw data are normalized using linear scale transformation to bring the various criteria scales into a comparable scale. The normalized fuzzy decision matrix $\tilde{R}$ is given by:

$$\tilde{R} = [\tilde{r}_{ij}]_{mxn}, \quad i = 1,2,\ldots,m;\ j = 1,2,\ldots,n, \tag{5}$$

where

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \text{ and } c_j^* = \max_i c_{ij} \quad \text{(benefit criteria)}. \tag{6}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) \text{ and } a_j^- = \min_i a_{ij} \quad \text{(cost criteria)}. \tag{7}$$

Step 5: Compute the weighted normalized matrix.
The weighted normalized matrix $\tilde{V}$ for criteria is computed by multiplying the weights (w_j) of evaluation criteria with the normalized fuzzy decision matrix $\tilde{r}_{ij}$.

$$\tilde{V} = [\tilde{v}_{ij}]_{mxn}, \quad i = 1,2,\ldots,m;\ j = 1,2,\ldots,n \text{ where } \tilde{v}_{ij} = \tilde{r}_{ij}(\cdot)w_j. \tag{8}$$

Note that $\tilde{v}_{ij}$ is a fuzzy triangular number represented by $(\tilde{a}_{ij}, \tilde{b}_{ij}, \tilde{c}_{ij})$.
Step 6: Compute the fuzzy ideal solution (FPIS) and fuzzy negative ideal solution (FNIS).
The FPIS and FNIS of the alternatives is computed as follows:

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_n^*) \text{ where } \tilde{v}_j^* = (\tilde{c}_j^*, \tilde{c}_j^*, \tilde{c}_j^*) \text{ and } \tilde{c}_j^* = \max_i\{\tilde{c}_{ij}\}, \tag{9}$$

$$\begin{aligned} &A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-) \text{ where } \tilde{v}_j^- = (\tilde{a}_j^-, \tilde{a}_j^-, \tilde{a}_j^-) \text{ and } \tilde{a}_j^- = \min_i\{\tilde{a}_{ij}\}, \\ &\forall i = 1,2\ldots,m; \quad j = 1,2,\ldots,n. \end{aligned} \tag{10}$$

Step 7: Compute the distance of each alternative from FPIS and FNIS:
The distance (d_i^+, d_i^-) of each weighted alternative $i = 1,2,\ldots,m$ from the FPIS and the FNIS is computed as follows:

$$d_i^+ = \sum_{j=1}^{n} d_v(\tilde{v}_{ij}, \tilde{v}_j^*), \quad i = 1,2,\ldots,m, \tag{11}$$

$$d_i^- = \sum_{j=1}^{n} d_v(\tilde{v}_{ij}, \tilde{v}_j^-), \quad i = 1,2,\ldots,m, \tag{12}$$

where $d_v(\tilde{a}, \tilde{b})$ is the distance measurement between two fuzzy numbers $\tilde{a}$ and $\tilde{b}$ and is equal to

$$d_v(\tilde{a}, \tilde{b}) = \sqrt{\frac{1}{3}\left[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2\right]}.$$

Step 8: Compute the closeness coefficient (CC_i) of each alternative.
The closeness coefficient CC_i represents the distances to the fuzzy positive ideal solution (A^*) and the fuzzy negative ideal solution (A^-) simultaneously. The closeness coefficient of each alternative is calculated as:

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+}, \quad i = 1,2,\ldots,m. \tag{13}$$

Step 9: Rank the alternatives.
In step 9, the different alternatives are ranked according to the closeness coefficient (CC_i) in decreasing order. The best alternative is closest to the FPIS and farthest from the FNIS.

3. Solution approach for selecting sustainable city logistics initiative

The proposed approach for selecting sustainable city logistics initiative consists of four steps:

1. Selection of evaluation criteria using Affinity Diagram.
2. Allocation of criteria weights using AHP.
3. Selection of best alternative (city logistics initiatives) using fuzzy TOPSIS.
4. Conducting sensitivity analysis to determine the influence of criteria weights on decision making.

These steps are presented in detail as follows:

3.1. Selection of evaluation criteria

The first step involves selection of criteria for evaluating city logistics initiatives. A committee comprising of representatives of city logistics stakeholders (end users, shippers, receivers, transport operators, public administrators) is formed to generate criteria for evaluating city logistics using Affinity Diagram (Section 2). The final list contains 4 criteria and 16 sub-criteria. The four criteria can be categorized into technical, economic, environmental and social respectively. The sub-criteria are Logistical Efficiency (C1), Mobility (C2), Accessibility (C3), Service quality (C4), Loading factor of vehicles (C5), Customer coverage (C6), Freeing of public space (C7), Energy conservation (C8), Trip effectiveness (C9), Revenues (C10), Volume of freight handled (C11), Accidents (C12), Costs (C13), Congestion (C14), Air pollution (C15), and Noise (C16). Fig. 3 presents the results of the Affinity Diagram.

Table 4 presents the detailed definitions of the 16 criteria.

It can be seen in Table 4 that among the 16 criteria, the first eleven criteria are the Benefit (B) category criteria that is the higher the value, the preferable the alternative is. For example, the higher the Logistical Efficiency (Criteria C1), the better the city logistics measure is. The last five criteria have the cost (C) category that is, the lower the value the preferable the alternative is. For example, the lower the congestion (criteria C14), the better is the city logistics measure.

3.2. Criteria weight generation using AHP

The second step involves allocation of preference ratings to the criteria by the decision making committee. AHP is used to generate the criteria weights from the ratings obtained. Table 5 presents the weights of the 16 criteria used for sustainability evaluation of city logistics. It can be seen in Table 5, that the environmental category has been given highest priority followed by the technical, economic and social category.

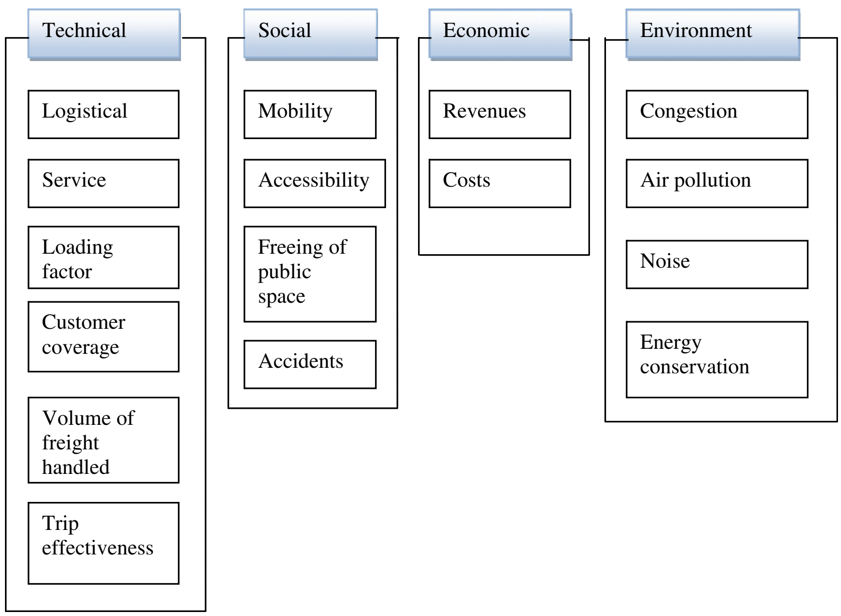

Fig. 3. Results of Affinity Diagram (criteria for evaluating city logistics initiatives).

Table 4
Selected criteria for evaluating city logistics initiatives.

Id	Category/ criteria	Sub-criteria	Definition	Category
C1	Technical	Logistical efficiency	Delivery targets successfully met by the logistical organizations	B(↑)
C2	Social	Mobility	Facilitation of passenger travel and goods movement conditions inside cities	B(↑)
C3	Social	Accessibility	Ease of accessing delivery depots and customer locations	B(↑)
C4	Technical	Service quality	Measured in terms of customer satisfaction with the delivery service performed	B(↑)
C5	Technical	Loading factor	Capacity utilization of delivery vehicles	B(↑)
C6	Technical	Customer coverage	Number of customers served by the delivery service within given geographical region	B(↑)
C7	Social	Freeing of public space	Number of parking spaces freed from the delivery service	B(↑)
C8	Environmental	Energy conservation	Reduction in consumption of fossil fuel by transportation resources	B(↑)
C9	Technical	Trip effectiveness	Measured by reduction in number of trips, distance between trips, trip travel time, reliability of trips, etc.	B(↑)
C10	Economic	Revenues	Revenues generated from the delivery service	B(↑)
C11	Technical	Volume of freight handled	Amount of freight handled by the delivery service	B(↑)
C12	Social	Accidents	Accidents caused due to the delivery service	C(↓)
C14	Economic	Costs	Costs involved in delivery of goods to customers	C(↓)
C14	Environmental	Congestion	Traffic congestion generated due to freight/goods delivery vehicles and material handling activities	C(↓)
C15	Environmental	Air pollution	Air pollution (CO_2, NO_x, particulates) generated from delivery activities	C(↓)
C16	Environmental	Noise	Noise generated from urban goods vehicle movement	C(↓)

*Benefit (The higher the better).
Cost (The lower the better).

Table 5
Weights of the 4 criteria and 14 sub-criteria.

Criteria	Sub-criteria	Overall weights
Technical (0.299)	Logistical efficiency (0.095)	0.0286
	Trip effectiveness (0.245)	0.021
	Volume of freight handled (0.083)	0.0108
	Service quality (0.179)	0.053
	Loading factor (0.326)	0.097
	Customer coverage (0.068)	0.0203
Economic (0.105)	Costs (0.75)	0.0585
	Revenues (0.249)	0.137
Environmental (0.499)	Energy conservation (0.274)	0.073
	Congestion(0.113)	0.026
	Air pollution (0.567)	0.025
	Noise (0.044)	0.0046
Social (0.095)	Mobility (0.221)	0.0791
	Accessibility (0.114)	0.0566
	Freeing of public space (0.615)	0.283
	Accidents (0.048)	0.022

3.3. Alternatives evaluation and selection using fuzzy TOPSIS

The third step involves allocation of linguistic ratings to potential alternatives for the selected criteria using scales given in Table 3. Four alternatives are considered in this study. They are Vehicle weight restrictions, Congestion charging schemes, Urban distribution center, and Access Timing Restrictions. These alternatives were considered based on our experience with a European project called CIVITAS-SUCCESS in the city of La Rochelle, France. The linguistics terms are then combined with criteria weights and subject to fuzzy TOPSIS (Section 2) to generate an overall performance score for the alternatives (city logistics initiatives). The alternative with the highest score is finally chosen.

3.4. Sensitivity analysis

The fourth step involves conducting the sensitivity analysis. Sensitivity analysis addresses the question, "How sensitive is the overall decision to small changes in the individual weights assigned during the pair-wise comparison process?". This is achieved by varying slightly the values of the weights and observing the effects on the decision. In our case, we will vary the criteria weights to assess their influence on selection of city logistics initiatives.

4. Application

Four alternatives (city logistics initiatives) were considered in our study based on our experience with them during the project CIVITAS-SUCCESS [35] in minimizing environmental impact and feasibility of implementation inside cities. These initiatives are Vehicle sizing restrictions (A1), Congestion charging schemes (A2), Urban distribution center (A3), and Access Timing Restrictions (A4). Under vehicle weight restrictions (A1), only limited size delivery vehicles are allowed to enter the city for distribution of goods for example, 3.5 tons or less. Such restrictions have been tested in Riga, Latvia [36].

Under congestion charging schemes (A2), users have to pay additional charges on usage of roads which are susceptible to congestion. The aim of such a scheme is to reduce road traffic levels in the urban area and traffic pollutant emissions. Such schemes are very popular in UK [2,37].

Under urban distribution center schemes, goods from large vehicles are consolidated into smaller size clean delivery vehicles for delivery inside city centers. The location of urban distribution centers is very important in managing congestion arising from large size delivery vehicles inside cities. Examples of successful implementation of urban distribution centers are ELCIDIS (France), Logistics platform (Monaco) and Broadmead freight consolidation scheme (UK) [35].

Under access timing restrictions (A4), delivery vehicles are allowed inside city only during restricted hours for example, between 5–7 am and 9–11 pm to avoid peak hour traffic and congestion. If deliveries are done during these restricted timings, additional charges are involved.

A committee of five decision makers was formed to evaluate the four city logistics initiatives. The decision makers are shippers (wholesalers), transport companies (carriers), receivers (shop owners), end-consumers (city residents, tourists) and public administrators. The linguistic ratings of the four alternatives against the 16 sub-criteria are presented in Table 6.

The aggregate fuzzy weights of the alternatives are computed using Eq. (2). For example, the aggregate rating for city logistics measure A1 for criteria C1 using the ratings given by the five stakeholders is computed as follows:

$$a_{ij} = \min_k(7,7,1,1,1), \quad b_{ij} = \frac{1}{5}\sum_{k=1}^{5}(9+9+3+1+1), \quad c_{ij} = \max_k(9,9,5,3,3) = (1,4.6,9).$$

Likewise, the aggregate ratings for all the four alternatives (A1, A2, A3, A4) with respect to the 16 criteria are computed. The aggregate fuzzy decision matrix for the alternatives is presented in Table 7.

After obtaining the fuzzy scores, we perform normalization of the alternatives using Eqs. (5)–(7). Then, the fuzzy weighted decision matrix for the four alternatives is constructed using Eq. (8) followed by the fuzzy positive ideal solution (A^*) and the fuzzy negative ideal solutions (A^-) using Eqs. (9) and (10). We then compute the distance $d_v(\cdot)$ of each alternative from the fuzzy positive ideal matrix (A^*) and the fuzzy negative ideal matrix (A^-) using Eqs. (11) and (12) and the distances d_i^+ and d_i^-. Using the distances d_i^+ and d_i^- (Eq. (13)), we compute the closeness coefficient (CC_i) of the four alternatives. For example, for alternative A1, the closeness coefficient is given by:

$$CC_i = d_i^-/(d_i^- + d_i^+) = 0.494/(0.494 + 0.596) = 0.453.$$

Likewise, CC_i for the other three alternatives are computed. The final results are presented in Table 8.

Table 6
Linguistic assessments for the four alternatives.

Criteria	Alternatives																			
	A1					A2					A3					A4				
	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5
C1	VG	VG	P	VP	VP	G	VP	M	VG	G	M	G	M	VG	VG	P	P	P	G	VG
C2	VP	P	P	VG	VP	M	M	P	G	M	G	VG	VG	P	VG	M	P	G	P	G
C3	G	M	P	P	M	VG	M	G	VP	VP	G	VG	P	M	VG	VG	P	VG	P	P
C4	G	VP	VG	VP	P	VG	G	VP	G	VG	P	G	M	P	VG	VP	M	G	P	G
C5	G	M	M	P	VP	G	VP	G	M	P	M	G	G	VP	VP	VG	VG	VG	G	P
C6	P	VP	M	G	VP	G	P	VP	G	P	M	P	M	P	G	P	G	P	P	M
C7	VG	P	M	VP	G	M	VP	G	VG	M	M	VG	M	M	M	G	G	VP	P	M
C8	VG	M	P	G	VP	VP	P	G	VG	G	P	M	VG	VP	G	G	G	P	M	VG
C9	VP	VG	VP	VP	M	P	VP	VG	P	G	VG	VG	VP	G	P	M	VP	M	G	VG
C10	M	P	G	G	P	M	VG	M	P	VG	VG	VG	P	G	G	P	VP	G	P	P
C11	VG	M	P	M	VG	P	G	P	VP	P	VP	M	VG	VG	G	G	G	VG	VP	VP
C12	VP	VG	VG	VP	P	M	M	VP	M	P	P	VP	M	G	P	G	P	VG	G	VG
C13	VP	P	P	P	P	G	VP	VP	VP	G	M	G	G	P	M	G	VP	VP	G	M
C14	VG	VG	VG	G	M	M	G	G	P	M	VG	VG	G	G	VG	VP	VP	M	G	G
C15	VG	VP	P	VP	M	M	M	VG	G	P	M	P	G	G	P	M	G	VP	P	P
C16	M	G	VP	P	VP	M	G	G	G	G	M	M	VG	G	VG	VP	P	G	VG	G

D1, Administrators; D2, Shippers; D3, Transport Operators; D4, Receivers; D5, End Consumers.

Table 7
Aggregate fuzzy decision matrix.

Criteria	Alternatives			
	A1	A2	A3	A4
C1	(1, 4.6, 9)	(1, 5.8, 9)	(3, 7, 9)	(1, 5, 9)
C2	(1, 3.4, 9)	(1, 5, 9)	(1, 7.4, 9)	(1, 5, 9)
C3	(1, 4.6, 9)	(1, 4.6, 9)	(1, 6.6, 9)	(1, 5.4, 9)
C4	(1, 4.2, 9)	(1, 6.6, 9)	(1, 5.4, 9)	(1, 4.6, 9)
C5	(1, 4.2, 9)	(1, 4.6, 9)	(1, 4.2, 9)	(1, 7.4, 9)
C6	(1, 3.4, 9)	(1, 4.2, 9)	(1, 4.6, 9)	(1, 4.2, 9)
C7	(1, 5, 9)	(1, 5.4, 9)	(3, 5.8, 9)	(1, 4.6, 9)
C8	(1, 5, 9)	(1, 5.4, 9)	(1, 5, 9)	(1, 6.2, 9)
C9	(1, 3.4, 9)	(1, 4.6, 9)	(1, 5.8, 9)	(1, 5.4, 9)
C10	(1, 5, 9)	(1, 6.2, 9)	(1, 7, 9)	(1, 3.4, 9)
C11	(1, 6.2, 9)	(1, 3.4, 9)	(1, 6.2, 9)	(1, 5, 9)
C12	(1, 4.6, 9)	(1, 3.8, 7)	(1, 3.8, 9)	(1, 7, 9)
C13	(1, 2.6, 5)	(1, 3.4, 9)	(1, 5.4, 9)	(1, 4.2, 9)
C14	(3, 7.8, 9)	(1, 5.4, 9)	(5, 8.2, 9)	(1, 4.2, 9)
C15	(1, 3.8, 9)	(1, 5.8, 9)	(1, 5, 9)	(1, 3.8, 9)
C16	(1, 3.4, 9)	(3, 6.6, 9)	(3, 7, 9)	(1, 5.4, 9)

Table 8
Closeness coefficient (CC_i) for the four alternatives.

	Alternatives			
	A1	A2	A3	A4
d_i^-	0.494	0.513	0.489	0.532
d_i^+	0.596	0.599	0.599	0.581
CC_i	0.453	0.461	0.449	0.477

By comparing the CC_i values of the four alternatives, we find that A4 > A2 > A1 > A3. Therefore, alternative A4 (Timing Restrictions) is chosen as the sustainable city logistics initiative and recommended for implementation.

Please note that if the difference between the closeness coefficients is very small, then all the solutions are equally likely to be selected. In that case, a second level feasibility analysis in terms of ease of implementation, budget and resource constraints etc. can be done to select the best alternative.

4.1. Sensitivity analysis

To investigate the impact of criteria weights (denoted by W_{Ci} for criteria C_i where $i = 1, 2, \ldots, n$) on the selection of city logistics measure with best performance, we conducted the sensitivity analysis. Nineteen experiments were conducted. Table 9 presents the details of these experiments.

Table 9
Experiments for sensitivity analysis.

Expt No.	Definition	Performance scores (CC_i)			
		A1	A2	A3	A4
1	$W_{C1} = 0.625$, $W_{C2-C16} = 0.025$	0.456	0.459	0.451	0.476
2	$W_{C2} = 0.625$, $W_{C1,C3-C16} = 0.025$	0.483	0.491	0.482	0.509
3	$W_{C3} = 0.625$, $W_{C1-C2,C4-C16} = 0.025$	0.477	0.478	0.507	0.497
4	$W_{C4} = 0.625$, $W_{C1-C3,C5-C16} = 0.025$	0.471	0.509	0.488	0.484
5	$W_{C5} = 0.625$, $W_{C1-C4,C6-C16} = 0.025$	0.471	0.478	0.469	0.527
6	$W_{C6} = 0.625$, $W_{C1-C5,C7-C16} = 0.025$	0.459	0.472	0.475	0.478
7	$W_{C7} = 0.625$, $W_{C1-C6,C8-C16} = 0.025$	0.483	0.491	0.532	0.484
8	$W_{C8} = 0.625$, $W_{C1-C7,C9-C16} = 0.025$	0.456	0.459	0.451	0.476
9	$W_{C9} = 0.625$, $W_{C1-C8,C10-16} = 0.025$	0.459	0.478	0.494	0.497
10	$W_{C10} = 0.625$, $W_{C1-C9,\ C11-16} = 0.025$	0.483	0.503	0.513	0.466
11	$W_{C11} = 0.625$, $W_{C1-C10,\ C12-16} = 0.025$	0.502	0.460	0.501	0.491
12	$W_{C12} = 0.625$, $W_{C1-C11,C14-16} = 0.025$	0.439	0.449	0.442	0.439
13	$W_{C13} = 0.625$, $W_{C1-C12,C14-16} = 0.025$	0.471	0.449	0.434	0.449
14	$W_{C14} = 0.625$, $W_{C1-C13,15-16} = 0.025$	0.268	0.437	0.222	0.449
15	$W_{C15} = 0.625$, $W_{C1-14,16} = 0.025$	0.444	0.436	0.435	0.452
16	$W_{C16} = 0.625$, $W_{C1-15} = 0.025$	0.448	0.272	0.266	0.443
17	$W_{C1-C16} = 0.0625$	0.456	0.459	0.451	0.476
18	$W_{C1-11} = 0.0909$, $W_{C12-C16} = 0$	0.489	0.499	0.521	0.503
19	$W_{C1-11} = 0$, $W_{C12-C16} = 0.2$	0.395	0.385	0.317	0.430

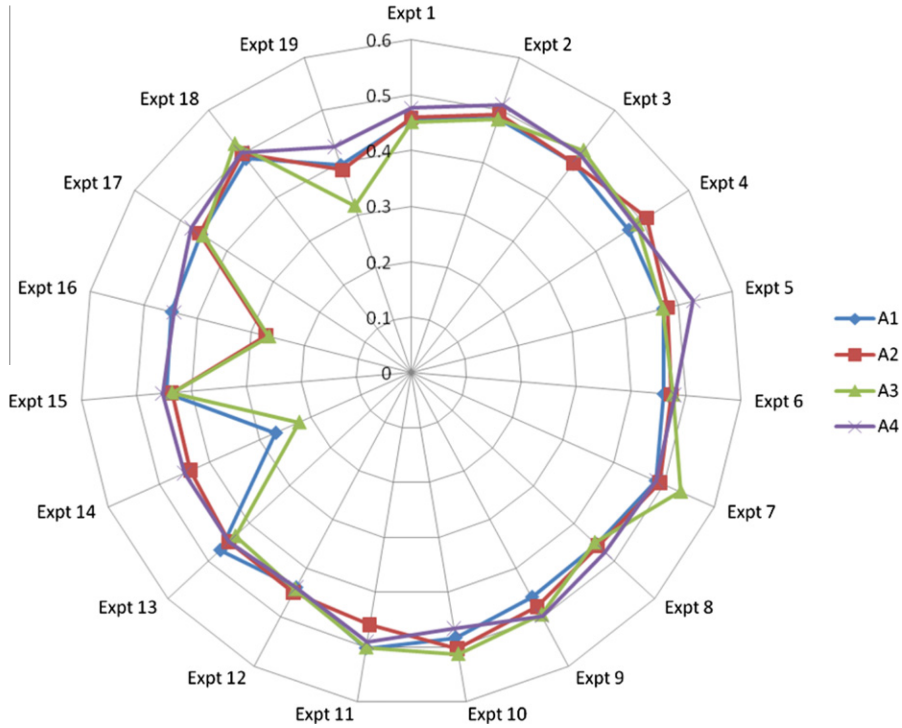

Fig. 4. Results of sensitivity analysis (CCi scores).

It can be seen in Table 9, that in the first sixteen experiment, weight of each criteria is set as highest one by one and others are set to low and equal values. For example, in experiment 1 weight of criteria C1 = 0.0625 and the weight of remaining criteria (C2–C16) = 0.025. The computation of highest weight = 0.625 is done as follows. Since there are 16 criteria in total, 15 of which (C2–C16) are assumed to be of equal importance, therefore they are allocated equal weight = 0.025. This leaves $1 - 0.025 * 15 = 0.625$ weight for criteria 1. This computation ensures that the sum of all criteria weights should be equal to 1. Likewise in the next 15 experiments, we have set each criteria as most important one by giving it a weight of 0.625 and leaving equal weight = 0.025 for the remaining criteria. In experiment 17, weights of all criteria are set equal to 0.0625. In experiment 18, weight of all cost criteria (C12–C16) = 0 and the other criteria have equal weight = 0.0909. In experiment 19, weight of all benefit criteria (C1–C11) = 0 and cost criteria weight = 0.2. Please note that it is possible to generate experiments in other ways by bringing a range of small estimation error $[-\langle \text{sigma} \rangle, +\langle \text{sigma} \rangle]$ to the criteria weights, denoted by weight $w + -\langle \text{sigma} \rangle$. Here, we have demonstrated those 19 experiments which are most useful for our study. More number of experiments can be performed depending on their utility in relation to the problem under treatment.

Fig. 4 presents the results of sensitivity analysis for the 19 experiments (CC_i scores can be found from Table 9).

It can be seen from Table 9 and Fig. 4, that out of 19 experiments, alternative A4 ((Timing Restrictions)) has the highest score in 10/19 experiments. Therefore, we can say that based on the evaluations obtained, our city logistics decision making process is relatively insensitive to the criteria weights with A4 emerging as the winner in majority of the cases (10/19). Please note that this result is based on evaluation of the alternatives from a technical–social–economic–environmental point (Table 5). Among these the environmental dimension is most important followed by technical, economic and social ones. The alternative A4 (timing restrictions) emerges as the winner considering the 4 criteria and 16 sub-criteria. If the decision makers provide different weights to these criteria, then the final results would change.

5. Conclusions and future works

In this paper, we present a multi-criteria multi-stakeholder approach for evaluating city logistics initiatives under fuzzy environment. Four initiatives namely vehicle sizing restrictions, congestion charging schemes, urban distribution center and access timing restrictions are considered. These initiatives are evaluated by a decision making team comprising of representatives of city logistics stakeholders namely Shippers (Wholesalers), Receivers (Retailers/Shop Owners), End Users (Consumers), Transport Operators (Carriers) and Public Administrators.

The evaluation process involves four steps. In step 1, the criteria for evaluating city logistics initiatives are identified using Affinity Diagram. These criteria are technical, economic, environmental and social. In the second step, the criteria and the sub-criteria are weighted by a committee of decision makers. AHP is used to rate the criteria. In the third step, the decision making committee provides linguistic ratings to the criteria, sub-criteria and the alternatives. Fuzzy TOPSIS is used to aggregate the ratings and generate an overall performance score for measuring the performance of each alternative (city logistics initiative). The alternative with the highest score is finally chosen. In the last step, we perform sensitivity analysis to determine the influence of criteria weights on the decision making process.

The advantage of the proposed approach is its practical applicability and the ability to generate solutions under limited quantitative information. It can be applied in new cities with no prior experience with city logistics initiatives. The limitation of the proposed approach is that it is sensitive to the number of decision makers involved and their experience with city logistics, hence, their selection should be carefully done.

Our future work involves validation of proposed model results by comparison with other techniques available for selection of sustainable city logistics planning alternatives in literature.

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