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Picture Fuzzy Decision-Making Approach for Sustainable Last-Mile Delivery

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ABSTRACT In light of the increasing importance of last-mile delivery (LMD) and the associated high costs, air pollution, and logistical challenges, research on sustainable LMD is highly trending and dynamic. The selection of sustainable LMD mode is an emerging problem for decision-makers in the logistics industry. The key question is how to determine the best LMD mode from a set of alternatives under numerous criteria with ambiguous, vague, and uncertain sustainability-related information. This paper aims to provide an advanced decision-making approach for sustainable LMD. Firstly, 20 sustainable LMD mode evaluation criteria are identified. Secondly, picture fuzzy sets (PFSs) are exploited to help decision-makers to more naturally express their preferences by voting. Thirdly, a hybrid picture fuzzy criteria weighting method based on the Direct rating and R-norm entropy is developed to compute the importance of evaluation criteria. Fourthly, a novel picture fuzzy Combined Compromise Solution method is formulated to rank alternative LMD modes. Fifthly, the presented picture fuzzy approach for sustainable LMD is implemented in the real-life decision-making context. The results show that ''e-cargo bike'' is the best alternative in the Pardubice context. The comparative analysis with three state-of-the-art PFS-based MCDM methods approved the high reliability of the provided approach. The sensitivity analyses of the trade-off parameter and balancing factor confirmed the high robustness of the presented approach. The introduced approach can help decision-makers in the logistics industry to elucidate sustainable LMD mode. It can solve not only the highlighted problem but also other MCDM problems under the picture fuzzy environment.

INDEX TERMS CoCoSo, last-mile delivery, multi-criteria decision-making, picture fuzzy set, sustainability, uncertainty.

I. INTRODUCTION

Policy-makers strive to design as good as possible sustainable urban mobility plans. A significant part of these plans refers to last-mile delivery (LMD). The average number of delivered items in developed countries is around 310 per inhabitant annually [1]; e.g., in a city with 100,000 residents, there are 120,000 LMDs each working day. In light of the increasing importance of LMD and the associated high costs, air pollution, and logistical challenges, research on sustainable LMD is highly trending and dynamic. Numerous LMD modes have emerged such as autonomous delivery robot [2], [3], cargo bicycle [4], [5], drone [6], [7], e-cargo bike [8], [9], mobile parcel locker [10], [11], mobile post office [12], postomates (i.e., stationary parcel lockers) [13], [14], traditional approach (i.e., courier performs LMD using a traditional road vehicle) [15], [16], tube transport [17], etc. Introducing sustainable LMD mode in the system is of the highest interest, not just for the logistics industry, but also for authorities, citizens, and inter-related business entities.

The selection of sustainable LMD mode is an emerging problem for decision-makers in the logistics industry. It is a complex multi-criteria decision-making (MCDM) problem with a plethora of ambiguous, uncertain, and vague sustainability-related information. This problem is of critical importance for sustainable development worldwide. The key question is how to determine the best LMD mode. However: (*i*) No earlier work has identified criteria for sustainable

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LMD mode evaluation; (*ii*) Deterministic numbers or classical fuzzy sets have been dominantly exploited in the available decision-making approaches for LMD; (*iii*) There is no decision-making framework to elucidate sustainable LMD mode that can handle ambiguous, uncertain and vague sustainability-related information. As a result, this paper aims to provide an advanced decision-making approach for sustainable LMD.

Picture fuzzy sets (PFSs) [18], [19] are direct extensions of fuzzy sets introduced by Zadeh [20] and intuitionistic fuzzy sets (IFSs) proposed by Atanassov [21]. PFSs are considerably more close to human nature. These advanced fuzzy sets can reflect the ambiguous nature of subjective sustainability-related judgments [22] and mitigate information loss. Objects, notions, and ideas can be better measured in PFS than in other types of fuzzy sets [23]. They are adequate in situations when preferences of decision-makers in the logistics industry involve more answers of types: yes, abstain, no, refusal. To handle the uncertainty of information in the sustainable LMD mode evaluation problem, a PFS is a good choice, which is characterized by degrees of positive, neutral, negative, and refusal membership. As a result, using PFSs for describing uncertainty in the investigated MCDM problem is more realistic and accurate than fuzzy sets and IFSs. However, none of the available studies applied a PFS based decision-making approach for sustainable LMD.

The Combined Compromise Solution (CoCoSo) method is one of the newest MCDM approaches developed by Yazdani *et al.* [24], [25]. It unites compromise decision-making algorithms and aggregation strategies [26]. The CoCoSo method uses an aggregated multiplication rule to release the ranking of alternatives. Aggregation is carried out using three pooling strategies applied to each investigated alternative [27]. Its features are [26], [28]: no suffering from the counterintuitive phenomena, without division or antilogarithm by zero problem, strong ability to distinguish alternatives, and no rank reversals or ranking irregularities. However, the CoCoSo method has not been extended before using PFSs so it is unable to account for neutral/refusal information of managers who are in charge of LMD.

To achieve the highlighted main objective and fill the research gaps, this paper will: (1) Identify sustainable LMD mode evaluation criteria by reviewing the published literature; (2) Exploit PFSs to help managers who are in charge of LMD to more naturally express their preferences by voting. PFSs are superior in handling uncertain, imprecise, and vague sustainability-related information; (3) Compute the importance of each sustainable LMD mode evaluation criteria by using the new hybrid picture fuzzy criteria weighting method. This method is developed by coupling the Direct rating and R-norm entropy methods under the picture fuzzy environment; (4) Rank alternative LMD modes by employing the novel picture fuzzy CoCoSo method. For the first time, one of the newest MCDM methods is extended by using PFSs; and (5) Implement the presented picture fuzzy approach for sustainable LMD in the real-life decision-making context.

The rest of the paper is organized as follows: Section 2 provides criteria for sustainable LMD mode evaluation identified from the literature and overviews related state-of-the-art research. Section 3 reviews some definitions of picture fuzzy sets. Section 4 presents the introduced picture fuzzy decision-making approach for sustainable LMD. A real-life case study is described in Section 5. Section 6 presents the case study results and discussions. Section 7 gives the conclusions of the work and indicates possible extension areas.

II. LITERATURE REVIEW

The literature review is organized into four sub-sections to provide better insights into the concepts under this research and more clearly address the contributions of this paper. The first sub-section identifies criteria for sustainable LMD mode evaluation from the relevant literature. The second sub-section overviews existing decision-making approaches for LMD. The third sub-section overviews applications and extensions of the CoCoSo method. The last sub-section surveys available extensions of R-norm information measure and its applications in MCDM.

A. EVALUATION CRITERIA

A systematic approach is carried out to identify relevant criteria for sustainable LMD mode evaluation from the published literature. Only peer-reviewed journal papers were taken into consideration. Table 1 presents 20 identified sustainable LMD mode evaluation criteria. Each identified criterion is defined in this table.

B. DECISION-MAKING APPROACHES FOR LAST-MILE DELIVERY

Numerous studies provided decision-making approaches for the logistics industry. For this research, it is important to review those whose focus is on LMD. The structured survey of the relevant literature is shown in Table 2.

LMD is one of the most sensitive phases of shipment transfer in terms of sustainability. For that reason, there are numerous efforts to improve the efficiency of the realization of delivery activities, by applying modern systems based on the use of drones and autonomous robots. However, it is possible to identify some critical success factors and barriers that arise during their implementation [6], [7]. Additionally, depending on the territory where the implementation of these systems is planned, it is necessary to analyze and select its appropriate technical characteristics, primarily the type of drone and autonomous robots [34]. In addition to these delivery methods, research was conducted in which walking, bike-sharing, community bus, and on-demand ride-sharing services were singled out as modes of transport within LMD [52]. To improve the environmental dimension of sustainable development, delivery approaches, which are based on the use of electric vehicles, have been proposed and implemented in reality [53].

E-commerce generates the biggest share of delivery items, so this service is particularly analyzed [45], [54], [55].

TABLE 1. Sustainable last-mile delivery mode evaluation criteria identified from the relevant literature.

Criteria	Type	Definition	Author(s) and Reference
Economic			
Education cost	Min	Costs of employee education and training for a new technology	Aljohani and Thompson [29], Awasthi *et al.* [30]
Fleet acquisition cost	Min	Costs of purchasing a new vehicle fleet and equipment	de Mello Bandeira *et al.* [31]
Insurance and taxes	Min	Administrative costs of the delivery system	Seghezzi *et al.* [32]
Operational cost	Min	Operating cost of the delivery service	Aljohani and Thompson [29], Nguyen *et al.* [33], Nur *et al.* [34], Peng [35], Staricco and Brovarone [36]
Road network cost	Min	Costs of the necessary road infrastructure and technology	de Mello Bandeira *et al.* [31], Tadić *et al.* [37]
Environmental			
Air pollution	Min	Air pollution generated from last-mile delivery activities	Awasthi and Chauhan [38], Resat [39], Tadić *et al.* [37]
Congestion	Min	Traffic congestion generated by the last-mile delivery system	Carbone *et al.* [40], Carbone *et al.* [41], Frehe *et al.* [42]
Noise pollution	Min	Noise impact on urban population	Awasthi and Chauhan [38], Frehe *et al.* [42], Mladenow *et al.* [43], Resat [39]
Waste generation	Min	Average volume of solid wastes and harmful material releases during operation and after the life cycle (e.g., tires and batteries)	Buldeo Rai *et al.* [44]
Weather adaptability	Max	Ability of the system to operate successfully in normal and extreme (e.g., icing, wind, rain, hail, and fog) weather conditions	Nur *et al.* [34]
Social			
Accessibility	Max	Ease of accessing delivery systems and customer locations as well as simple delivery and receipt of packages for employees and customers	Awasthi and Chauhan [38], Buldeo Rai *et al.* [44], Frehe *et al.* [42], Resat [39]
Delivery time availability	Max	Availability of the system at the daily and weekly level	Madleňák and Madleňáková [45]
Land use	Min	Land and other public space use indicators	Aljohani and Thompson [29], Awasthi and Chauhan [38]
Mobility	Max	Facilitation of goods movement conditions inside cities	Awasthi and Chauhan [38]
Occupational safety	Max	Health and safety practices	Carbone *et al.* [40], Falsini et al. [46], Resat [39]
Technical			
Connectivity	Max	Ability of the system to combine with other delivery modes	Awasthi et al. [47]
Flexibility	Max	Flexibility of the system in exploitation	Buldeo Rai *et al.* [44], Falsini *et al.* [46], Staricco and Brovarone [36]
Loading factor	Max	Capacity of delivery vehicles	Frehe et al. [42], Nur *et al.* [34]
Reliability	Max	Reliability of the system in terms of failures and time constraints	Jovčić *et al.* [49], Kunadhamraks and Hanaoka [48], Madleňák and Madleňáková [45], Perçin [50]
Security	Max	Security of the goods being transported	Kunadhamraks and Hanaoka [48], Lazarević *et al.* [51]

The global development of e-commerce has forced the emergence of the association of companies in a common system of distribution of goods or the introduction of external collaborators to improve the sustainability of each system individually. An additional task within this approach is related to the selection of optimal partners [56]. One of the significant market advantages of e-commerce companies is the possession of their own, well-organized, and flexible delivery system. To improve their efficiency, various solutions are applied within the systems of LMD, such as the use of parcel-pickup points, which further requires solving location problems [57]. When it comes to location problems, the choice of locations of LMD centers is often analyzed, where the routing activities and storage of shipments are performed [58]. Aljohani and Thompson [29] provided an integrated spatial multi-criteria framework for an inner-city consolidation facility. Previously, the same authors applied a multi-stakeholder decision support approach to evaluate the suitability and potential of various delivery fleet configurations [59].

The sustainability of LMD is particularly endangered in rural areas, so it is necessary to develop strategies for its improvement. Improving the service quality of LMD is an important measure to promote the sustainable development of rural e-commerce logistics [60]. Besides, to improve the sustainability of the postal delivery systems, several types of research have been conducted, which include the analysis of services and performances of business processes. The results of these analyzes are mainly the selection of segments that need to be improved, as well as appropriate guidelines and distribution strategies for that purpose [38], [61], [62].

C. APPLICATIONS AND EXTENSIONS OF THE COCOSO METHOD

The CoCoSo method is one of the most recent MCDM approaches. Its usage increases the accuracy of the decision-making system and delivers beneficial consequences to management control. As a result, this method has attracted significant interest of researchers (Table 3).

Yazdani and Chatterjee [24] presented an AHP-CoCoSo approach to choose the best packaging technology for a dairy company.

Barua *et al.* [63] applied the AHP-CoCoSo approach to determine the most influencing parameter for the hybrid natural fiber-reinforced composite fabrication. Biswas *et al.* [64] introduced a CRITIC-CoCoSo approach to evaluate battery-operated electric vehicles. Ecer *et al.* [27] employed the CoCoSo method to evaluate sustainable development performances of OPEC countries.

TABLE 2. Summary of the available decision-making approaches for LMD.

Author(s) and Reference	Research focus	Parameter type	SA (Yes/No)	CA (Yes/No)	Method(s)	Application type
Awasthi and Chauhan [38]	Distribution strategy evaluation	Det., fuzzy	Yes	No	AD, AHP, TOPSIS	Ill. example
Chiu *et al.* [54]	E-store business strategy evaluation	Deterministic	No	No	DEMATEL, ANP, VIKOR	Real-life
He *et al.* [56]	Distribution partner evaluation	Fuzzy	Yes	No	SE, AHP, TOPSIS	Real-life
Wątróbski *et al.* [53]	Electric freight vehicle evaluation	Det., fuzzy	Yes	Yes	PROMETHEE II, TOPSIS	Real-life
Amchang and Song [58]	Consolidation facility location selection	Deterministic	No	No	AHP	Real-life
Aljohani and Thompson [59]	Fleet configuration evaluation	Fuzzy	Yes	No	AHP, PROMETHEE	Ill. example
Jiang *et al.* [60]	Rural LMD indicator evaluation	Fuzzy	No	No	AHP, ISM, MICMAC	Real-life
Raj and Sah [6]	Drone implementation indicator evaluation	Grey	Yes	No	DEMATEL	Real-life
Titiyal *et al.* [55]	E-tailer performance indicator evaluation	Deterministic	No	No	DEMATEL, ANP	Ill. example
Zhao *et al.* [52]	Travel mode evaluation	Deterministic	No	No	Data mining	Real-life
Aljohani and Thompson [29]	Consolidation facility location selection	Fuzzy, det.	Yes	No	GIS, TOPSIS	Real-life
Jiang *et al.* [61]	Rural LMD indicator evaluation	Fuzzy	No	No	RA, ISM	Real-life
Madleňák and Madleňáková [45]	Delivery mode evaluation	Deterministic	No	No	TOPSIS	Real-life
Melkonyan *et al.* [62]	Sustainable distribution strategy evaluation	Deterministic	No	No	SDS, PROMETHEE	Ill. example
Nur *et al.* [34]	Drone evaluation	IVIF	Yes	No	TOPSIS	Real-life
Zheng *et al.* [57]	Parcel-pickup point location selection	Deterministic	Yes	No	GIS, AHP	Real-life
Sah *et al.* [7]	Drone implementation barrier evaluation	Fuzzy, det.	No	No	Delphi, AHP	Real-life
Our study	*Sustainable LMD mode evaluation*	*Picture fuzzy*	*Yes*	*Yes*	*R-norm entropy, DR, CoCoSo*	*Real-life*

Affinity Diagram: AD; Combined Compromise Solution: CoCoSo; Comparative analysis: CA; Cross-impact matrix multiplication applied to classification: MICMAC; Direct rating: DR; Interpretative structural modeling: ISM; Interval-valued intuitionistic fuzzy: IVIF; Regression analysis: RA; Sensitivity analysis: SA; Shannon entropy: SE; System dynamics simulation: SDS.

Erceg *et al.* [65] coupled the ABC analysis, FUCOM criteria weighting method, and an interval rough CoCoSo method to rank suppliers for three inventory classes. Hashemkhani Zolfani *et al.* [66] developed a BWC-CoCoSo approach to solve the sustainable supplier selection problem for a steel company. Karaşan and Bolturk [67] proposed an interval neutrosophic CoCoSo method to rank solid waste disposal sites. Wen *et al.* [68] introduced a probabilistic linguistic SWARA-CoCoSo approach to compare drug cold chain logistics suppliers in the pharmaceutical manufacturing industry. Besides, the authors revised the function of aggregating the appraisal score strategies in the CoCoSo method. Wen *et al.* [69] proposed a target-based hesitant fuzzy linguistic CoCoSo method to assess third-party logistics providers for financial institutions. They aggregated the appraisal score strategies based on the ORESTE method. Yazdani *et al.* [70] formulated a grey CoCoSo method to evaluate suppliers of a construction-based company. They integrated the DEMATEL and BWM methods to determine subjective criteria weights. Yazdani *et al.* [25] developed the CoCoSo method and applied it to solve the logistics provider selection problem.

Recently, Biswas *et al.* [71] applied the CRITIC-CoCoSo approach to rank passenger vehicles. Ecer and Pamucar [72] integrated the fuzzy BWM and CoCoSo methods with Bonferroni functions to assess sustainable suppliers for the home appliance industry. Hashemkhani Zolfani *et al.* [73] applied the grey CoCoSo method to evaluate locations for a temporary hospital for infected patients with COVID-19. They used the CRITIC method to determine objective criteria weights. Maghsoodi *et al.* [74] coupled target-based CoCoSo and MULTIMOORA methods under the interval-valued environment to select phase change materials for interior building surface applications. The authors utilized the BWM method to determine subjective criteria weights. Peng and Huang [28] developed a q-rung orthopair fuzzy CRITIC-CoCoSo approach to evaluate enterprise financial risk. Peng *et al.* [75] presented a Pythagorean fuzzy CRITIC-CoCoSo approach to assess communication products of 5th generation enterprises. Ulutaş *et al.* [76] proposed a GIS-based fuzzy SWARA-CoCoSo approach to rank suitable locations for a logistics center. Yazdani *et al.* [77] presented a rough FUCOM-CoCoSo approach to evaluate geographical areas for a logistics center. The DEA method was used to identify inappropriate alternatives. Zhang *et al.* [78] formulated a probabilistic linguistic BWM-CoCoSo approach to select the most suitable construction component supplier for property developers. Wen *et al.* [79] applied the target-based hesitant fuzzy linguistic CoCoSo method to solve the personnel selection problem. The logarithmic least-square method and cross-entropy were used to determine subjective and objective criteria weights, respectively.

D. R-NORM INFORMATION MEASURE

Criteria weight determination using entropy methods is one of the most trusted approaches [80]. A well-known information measure is R-norm [81], which is known as R-norm entropy. The usage of the R-norm information measure is suitable for real-world applications since this non-extensive entropy has pseudo-additive property. The R-norm information measure involves parameter that provides choice and flexibility. Its strength lies in properties and applications [82].

TABLE 3. Summary of the available applications of the CoCoSo method.

Author(s) and Reference	Research focus	GDM (Yes/No)	Parameter type	SA (Yes/No)	CA (Yes/No)	Criteria weighting method(s) Subjective	Objective	Hybrid (Yes/No)	Application type
Yazdani and Chatterjee [24]	Technology evaluation	Yes	Deterministic	Yes	No	AHP	–	No	Ill. example
Barua *et al.* [63]	Manufacturing environment	No	Deterministic	No	No	AHP	–	No	Real-life
Biswas *et al.* [64]	Electric vehicle evaluation	No	Deterministic	Yes	Yes	–	CRITIC	No	Real-life
Ecer *et al.* [27]	Performance evaluation	Yes	Deterministic	Yes	Yes	–	Equal weight	No	Real-life
Erceg *et al.* [65]	Supplier selection	No	Det., IR	Yes	Yes	FUCOM	–	No	Real-life
Hashemkhani Zolfani *et al.* [66]	Supplier selection	No	Deterministic	Yes	No	BWM	–	No	Real-life
Karaşan and Bolturk [67]	Landfill LS	Yes	IN	No	Yes	Direct rating	–	No	From lit.
Wen *et al.* [68]	Supplier selection	Yes	PLT	No	Yes	SWARA	–	No	From lit.
Wen *et al.* [69]	3PL provider selection	Yes	HFLT	Yes	Yes	Direct rating	Cross-entropy	Yes	Real-life
Yazdani *et al.* [70]	Supplier selection	Yes	Det., grey	No	Yes	DEMATEL, BWM	–	No	Real-life
Yazdani *et al.* [25]	Logistics provider selection	No	Deterministic	Yes	Yes	Not specified			Real-life
Biswas *et al.* [71]	Passenger vehicle evaluation	No	Deterministic	Yes	No	–	CRITIC	No	Real-life
Ecer and Pamucar [72]	Supplier selection	Yes	Fuzzy	Yes	Yes	BWM	–	No	Real-life
Hashemkhani Zolfani *et al.* [73]	Hospital LS	Yes	Det., grey	No	No	–	CRITIC	No	Real-life
Maghsoodi *et al.* [74]	Material selection	Yes	Det., interval	Yes	Yes	BWM	–	No	Real-life
Peng and Huang [28]	Financial risk evaluation	Yes	qROF	Yes	Yes	Direct rating	CRITIC	Yes	Ill. example
Peng *et al.* [75]	5G industry evaluation	Yes	PyF	Yes	Yes	Direct rating	CRITIC	Yes	Ill. example
Ulutaş *et al.* [76]	Logistics center LS	Yes	Fuzzy	Yes	Yes	SWARA	–	No	Real-life
Yazdani *et al.* [77]	Logistics center LS	Yes	Rough	Yes	Yes	FUCOM	–	No	Real-life
Zhang *et al.* [78]	Supplier selection	Yes	PLT	No	Yes	BWM	–	No	Real-life
Wen *et al.* [79]	Personnel selection	Yes	HFLT	No	No	LLS	Cross-entropy	Yes	Ill. example
Our study	*Sust. LMD mode evaluation*	*Yes*	*Picture fuzzy*	*Yes*	*Yes*	*Direct rating*	*R-norm entropy*	*Yes*	*Real-life*

5th Generation: 5G; Comparative analysis: CA; Group decision-making: GDM; Hesitant fuzzy linguistic term: HFLT; Interval neutrosophic: IN; Interval rough: IR; Last-mile delivery mode: LMD; Location selection: LS; Logarithmic least-square: LLS; Probabilistic linguistic term: PLT; Pythagorean fuzzy: PyF; q-rung orthopair fuzzy: qROF; Sensitivity analysis: SA; Third-party logistics: 3PL.

Several extensions of the R-norm fuzzy information measure were proposed. Hooda [83] formulated R-norm fuzzy information measure. Bajaj *et al.* [84] introduced R-norm intuitionistic fuzzy entropy and a weighted R-norm intuitionistic fuzzy directed divergence measure. Joshi and Kumar [85] presented an interval-valued intuitionistic fuzzy (IVIF) R-norm entropy. Finally, Joshi *et al.* [86] developed R-norm picture fuzzy information measure.

Besides, the application of the R-norm entropy in MCDM attracted researchers in recent years. Joshi *et al.* [82] proposed a dissimilarity measure based on Jensen inequality and R-norm divergence measure. They solve the supplier selection problem by ranking alternative suppliers based on the values of the dissimilarity measure. Joshi and Kumar [85] employed the IVIF R-norm entropy to study real-life MCDM examples. Joshi *et al.* [86] integrated the R-norm entropy and VIKOR method under the picture fuzzy environment. The provided approach is employed to solve the election forecast and investment problems. Joshi and Kumar [87] used the intuitionistic fuzzy R-norm entropy to solve MCDM problems in which criteria weights were expressed with intuitionistic fuzzy values.

According to the literature review, the research gaps are as follows: (*i*) No earlier work has identified criteria for sustainable LMD mode evaluation; (*ii*) There is no decision-making framework to elucidate sustainable LMD mode that can handle ambiguous, uncertain, and vague sustainability-related information; (*iii*) No previous research has applied a PFS-based decision-making approach for LMD; (*iv*) The Direct rating and R-norm entropy methods have not been coupled under the picture fuzzy environment to determine the importance of sustainable LMD mode evaluation criteria; and (*v*) The CoCoSo method has not been extended before using picture fuzzy sets.

III. PRELIMINARIES

This section primarily reviews some definitions of picture fuzzy sets.

Definition 1 [18], [19]: Let PFS A on a universe X is an object in the form of:

$$A = \{< x,\ \mu_A(x),\ \eta_A(x),\ \upsilon_A(x) > | x \in X\}, \tag{1}$$

where $\mu_A(x) \in [0, 1]$ is called the degree of positive membership of x in A; $\eta_A(x) \in [0, 1]$ is the degree of neutral membership of x in A; $\upsilon_A(x) \in [0, 1]$ is the degree of negative membership of x in A; and $\mu_A(x)$, $\eta_A(x)$, and $\upsilon_A(x)$ satisfy the following condition:

$$0 \leq \mu_A(x) + \eta_A(x) + \upsilon_A(x) \leq 1, \quad \forall x \in X. \tag{2}$$

The word "picture" in PFS refers to generality, as this set is the direct extension of fuzzy sets and IFSs. In the case when $\eta_A(x) = 0$, the PFS returns to the IFS set. When both $\eta_A(x) = \upsilon_A(x) = 0$, the PFS returns to the fuzzy set. The integration of the degree of neutral membership $\eta_A(x)$ measures the information of objects more accurately and increase the quality and accuracy of achieved results [23]. In PFS theory, decision-makers are divided into four groups: vote for (its ratio is denoted as μ), abstain (its ratio is denoted as η), vote against (its ratio is denoted as υ), refusal (its ratio is denoted as ξ) [88].

The degree of refusal membership of x in the PFS A can be calculated as follows:

$$\xi_A(x) = 1 - (\mu_A(x) + \eta_A(x) + \upsilon_A(x)), \quad \forall x \in X. \tag{3}$$

If the value of $\xi_A(x)$ is small, then the knowledge about x is more certain. On the other hand, if the value of $\xi_A(x)$ is great, then the value of x is more uncertain.

In particular, if X has only one element, then $A = \{< x, \mu_A(x), \eta_A(x), \upsilon_A(x) > | x \in X\}$ is called a picture fuzzy number (PFN) in which $\mu_A \in [0, 1]$, $\eta_A \in [0, 1]$, $\upsilon_A \in [0, 1]$, and $0 \leq \mu_A + \eta_A + \upsilon_A \leq 1$. For convenience, a PFN is denoted by $A =< \mu_A, \eta_A, \upsilon_A >$.

Definition 2 [18], [19]: The complement of a PFS $A = \{< x, \mu_A(x), \eta_A(x), \upsilon_A(x) > |x \in X\}$ on a universe X is represented as:

$$A^c = \{< x, \upsilon_A(x), \eta_A(x), \mu_A(x) > |x \in X\}. \tag{4}$$

Definition 3 [89]: Let $A =< \mu_A, \eta_A, \upsilon_A >$, $A_1 =< \mu_{A_1}, \eta_{A_1}, \upsilon_{A_1} >$, and $A_2 =< \mu_{A_2}, \eta_{A_2}, \upsilon_{A_2} >$ be three PFNs, the operational parameter $\Re > 0$, and $\lambda > 0$. The Dombi T-norm and T-conorm operations of PFNs are defined as follows:

(1) Addition "$\oplus$"

$$A_1 \oplus A_2 = < 1 - \frac{1}{1 + \{(\frac{\mu_{A_1}}{1-\mu_{A_1}})^{\Re} + (\frac{\mu_{A_2}}{1-\mu_{A_2}})^{\Re}\}^{1/\Re}}, \frac{1}{1 + \{(\frac{1-\eta_{A_1}}{\eta_{A_1}})^{\Re} + (\frac{1-\eta_{A_2}}{\eta_{A_2}})^{\Re}\}^{1/\Re}}, \frac{1}{1 + \{(\frac{1-\upsilon_{A_1}}{\upsilon_{A_1}})^{\Re} + (\frac{1-\upsilon_{A_2}}{\upsilon_{A_2}})^{\Re}\}^{1/\Re}} >, \tag{5}$$

(2) Multiplication "$\otimes$"

$$A_1 \otimes A_2 = < \frac{1}{1 + \{(\frac{1-\mu_{A_1}}{\mu_{A_1}})^{\Re} + (\frac{1-\mu_{A_2}}{\mu_{A_2}})^{\Re}\}^{1/\Re}}, 1 - \frac{1}{1 + \{(\frac{\eta_{A_1}}{1-\eta_{A_1}})^{\Re} + (\frac{\eta_{A_2}}{1-\eta_{A_2}})^{\Re}\}^{1/\Re}}, 1 - \frac{1}{1 + \{(\frac{\upsilon_{A_1}}{1-\upsilon_{A_1}})^{\Re} + (\frac{\upsilon_{A_2}}{1-\upsilon_{A_2}})^{\Re}\}^{1/\Re}} >, \tag{6}$$

(3) Scalar multiplication

$$\lambda \cdot A =< 1 - \frac{1}{1 + \{\lambda(\frac{\mu_A}{1-\mu_A})^{\Re}\}^{1/\Re}}, \frac{1}{1 + \{\lambda(\frac{1-\eta_A}{\eta_A})^{\Re}\}^{1/\Re}}, \frac{1}{1 + \{\lambda(\frac{1-\upsilon_A}{\upsilon_A})^{\Re}\}^{1/\Re}} >, \tag{7}$$

(4) Power

$$A^{\lambda} =< \frac{1}{1 + \{\lambda(\frac{1-\mu_A}{\mu_A})^{\Re}\}^{1/\Re}}, 1 - \frac{1}{1 + \{\lambda(\frac{\eta_A}{1-\eta_A})^{\Re}\}^{1/\Re}}, 1 - \frac{1}{1 + \{\lambda(\frac{\upsilon_A}{1-\upsilon_A})^{\Re}\}^{1/\Re}} >. \tag{8}$$

Definition 4 [86], [90], [91]: Let $A = \{A_1, \ldots, A_f\}$ and $B = \{B_1, \ldots, B_f\}$ be two PFSs in X. A function *En*: *PFSs*$(X) \rightarrow [0, 1]$ is an entropy on PFS, if *En* satisfies the following axiomatic requirements:

(1) Sharpness: $En(A) = 0$, if and only if A is a crisp set.

(2) Maximality: $En(A) = 1$, if $\mu_{A_t} = \eta_{A_t} = \upsilon_{A_t} = \xi_{A_t} = 0.25$ for all $t = 1, \ldots, f$.

(3) Resolution: $En(A) \leq En(B)$, if $A, B \in PFS(X)$ satisfy either $\mu_{A_t} \leq \mu_{B_t}, \eta_{A_t} \leq \eta_{B_t}, \upsilon_{A_t} \leq \upsilon_{B_t}$ when $\max\{\mu_{A_t}, \eta_{A_t}, \upsilon_{A_t}\} \leq 0.25$ or $\mu_{A_t} \geq \mu_{B_t}, \eta_{A_t} \geq \eta_{B_t}, \upsilon_{A_t} \geq \upsilon_{B_t}$ when $\min\{\mu_{B_t}, \eta_{B_t}, \upsilon_{B_t}\} \geq 0.25$ for all $t = 1, \ldots, f$.

(4) Symmetry: $En(A) = En(A^c)$, where A^c denotes the complement of A.

Definition 5 [86]: Let $A = \{A_1, \ldots, A_f\}$ be a PFS in X and $R > 0\ (\neq 1)$ be the information measure parameter. Based on Definition 4 the picture fuzzy R-norm entropy measure of the PFS A is defined as follows:

$$En(A) = \frac{R}{f(R-1)} \sum_{t=1}^{f} \{1 - (\mu_{A_t}^R + \eta_{A_t}^R + \upsilon_{A_t}^R + \xi_{A_t}^R)^{1/R}\}, \quad R > 0\ (\neq 1). \tag{9}$$

Definition 6 [89]: Let $A_l =< \mu_{A_l}, \eta_{A_l}, \upsilon_{A_l} > (l = 1, \ldots, s)$ be a collection of PFNs, the operational parameter $\Re > 0$, and $\varphi = (\varphi_1, \ldots, \varphi_s)^T$ be the weight vector of the collection of PFNs with $\varphi_i > 0$ and $\sum_{l=1}^{s} \varphi_l = 1$. The picture fuzzy Dombi weighted average (PFDWA) operator is defined as follows:

$$PFDWA_{\varphi}(A_1, \ldots, A_s) = \overset{s}{\underset{l=1}{\oplus}} (\varphi_l A_l) = < 1 - \frac{1}{1 + \{\sum_{l=1}^{s} \varphi_l (\frac{\mu_{A_l}}{1-\mu_{A_l}})^{\Re}\}^{1/\Re}}, \frac{1}{1 + \{\sum_{l=1}^{s} \varphi_l (\frac{1-\eta_{A_l}}{\eta_{A_l}})^{\Re}\}^{1/\Re}}, \frac{1}{1 + \{\sum_{l=1}^{s} \varphi_l (\frac{1-\upsilon_{A_l}}{\upsilon_{A_l}})^{\Re}\}^{1/\Re}} >, \tag{10}$$

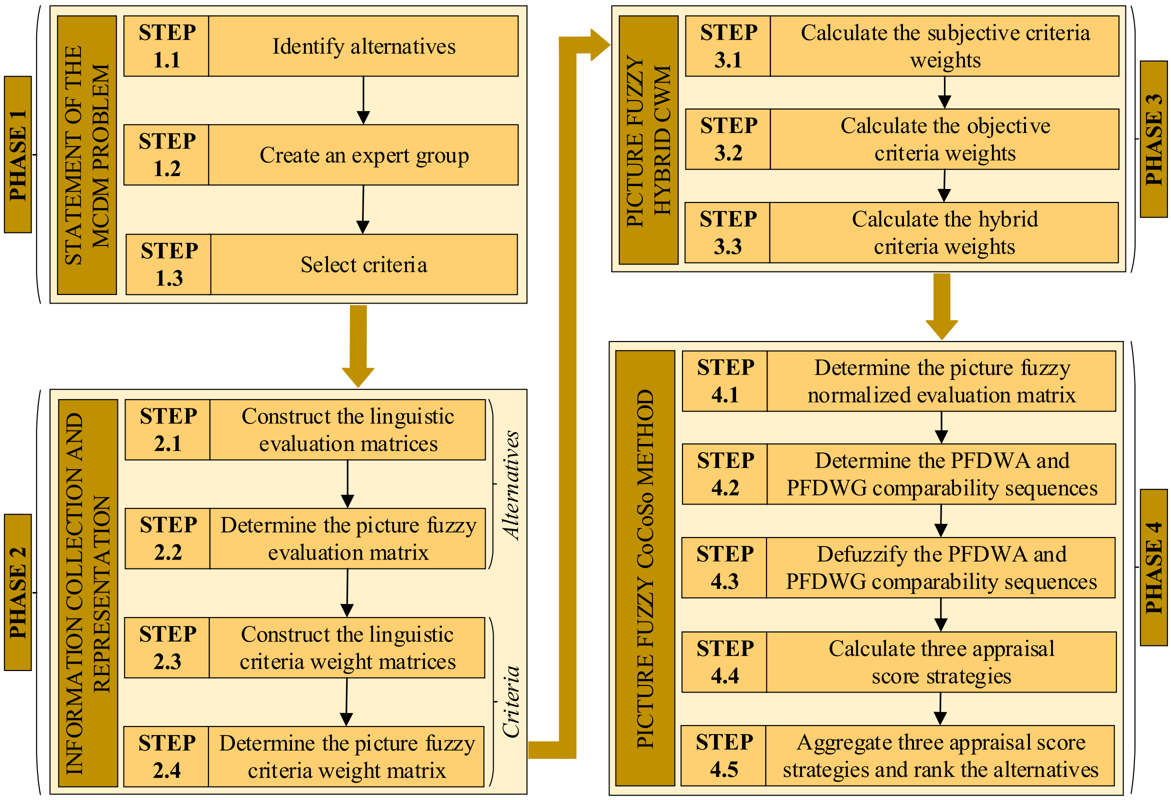

FIGURE 1. The flowchart of the developed picture fuzzy decision-making approach.

and the picture fuzzy Dombi weighted geometric (PFDWG) operator is defined as follows:

$$\begin{aligned} PFDWG(A_1, \ldots, A_s) &= \underset{l=1}{\overset{s}{\otimes}} (A_l)^{\varphi_l} \\ &= < \frac{1}{1+\{\sum_{l=1}^{s} \varphi_l (\frac{1-\mu_{A_l}}{\mu_{A_l}})^{\Re}\}^{1/\Re}}, \\ &\quad 1-\frac{1}{1+\{\sum_{l=1}^{s} \varphi_l (\frac{\eta_{A_l}}{1-\eta_{A_l}})^{\Re}\}^{1/\Re}}, \\ &\quad 1-\frac{1}{1+\{\sum_{l=1}^{s} \varphi_l (\frac{\upsilon_{A_l}}{1-\upsilon_{A_l}})^{\Re}\}^{1/\Re}} > . \end{aligned} \tag{11}$$

Definition 7 [92], [93]: Let $A =< \mu_A, \eta_A, \upsilon_A >$ be a PFN. A two-step defuzzification method to obtain a crisp value of the PFN A is:

Step 1. Distribute the neutral degree to the positive and negative degrees as follows:

$$\mu'_A = \mu_A + \frac{\eta_A}{2}, \tag{12}$$

$$\upsilon'_A = \upsilon_A + \frac{\eta_A}{2}. \tag{13}$$

Step 2. Calculate the defuzzification value y by:

$$y = \mu'_A + \frac{1+\mu'_A - \upsilon'_A}{2}\xi. \tag{14}$$

IV. PICTURE FUZZY DECISION-MAKING APPROACH

This section presents the developed picture fuzzy decision-making approach for sustainable LMD. The flowchart of the approach is presented in Fig. 1. It involves four phases. In phase 1, alternatives, experts, and criteria are chosen. In phase 2, linguistic importance evaluations towards alternatives and criteria are collected and expressed as PFNs. In phase 3, subjective, objective, and hybrid weights of criteria are determined. In phase 4, the ranking results of the alternatives are obtained.

The details of the phases are given in the following:

Phase 1: Statement of the MCDM problem.

Step 1.1. *Identify alternatives.* Let $A = \{A_1, \ldots, A_m\}$ $(m \geq 2)$ be a finite set of alternatives which experts have to choose from. ***Step 1.2.*** *Create an expert group.* Let $D = \{D_1, \ldots, D_k\}$ $(k \geq 2)$ be a set of invited experts.

Step 1.3. *Select criteria.* Let $C = \{C_1, \ldots, C_n\}$ $(n \geq 2)$ be a finite set of criteria selected from the relevant literature.

Phase 2: Information collection and representation.

Step 2.1. *Construct the linguistic evaluation matrices* $\Gamma_i = [\gamma^i_{ej}]_{k\times n}$:

$$\Gamma_i = \begin{matrix} & \begin{matrix} C_1 & \cdots & C_n \end{matrix} \\ \begin{matrix} D_1 \\ \vdots \\ D_k \end{matrix} & \begin{bmatrix} \gamma^i_{11} & \cdots & \gamma^i_{1n} \\ \vdots & \ddots & \vdots \\ \gamma^i_{k1} & \cdots & \gamma^i_{kn} \end{bmatrix} \end{matrix}, \quad i = 1, \ldots, m, \tag{15}$$

where γ_{ej}^{i} is the linguistic evaluation given by the expert D_e towards the alternative A_i ($i = 1,\ldots, m$) with respect to the criterion C_j. Importance evaluations can be yes, abstain, no, and refusal. Group abstain means that the voting paper is a white paper rejecting both "yes" and "no" but still takes the vote. Group refusal of voting either is invalid voting papers or does not take the vote.

Step 2.2. *Determine the picture fuzzy evaluation matrix* $Z = [z_{ij}]_{m\times n}$:

$$Z = \begin{array}{c} \\ A_1 \\ \vdots \\ A_m \end{array}\overset{\begin{array}{ccc} C_1 & \cdots & C_n \end{array}}{\begin{bmatrix} z_{11} & \cdots & z_{1n} \\ \vdots & \ddots & \vdots \\ z_{m1} & \cdots & z_{mn} \end{bmatrix}}, \tag{16}$$

where $z_{ij} =< \mu_{z_{ij}}, \eta_{z_{ij}}, \upsilon_{z_{ij}} >$ is a PFN which represents an evaluation of the alternative A_i with respect to the criterion C_j given by the experts. The four types of voting results are fully in accordance with the four components of a PFN. Importance evaluations given by the experts can be expressed as PFNs by calculating the proportion of each item in the voting results.

Step 2.3. *Construct the linguistic criteria weight matrices* $\Psi^e = [\psi_j^e]_{n\times 1}$:

$$\Psi^e = \begin{array}{c} C_1 \\ \vdots \\ C_n \end{array}\begin{bmatrix} \psi_1^e \\ \vdots \\ \psi_n^e \end{bmatrix}, \quad e = 1, \ldots, k, \tag{17}$$

where ψ_j^e is the linguistic importance evaluation given by the expert D_e ($e = 1, \ldots, k$) towards the criterion C_j ($j = 1, \ldots, n$). Importance evaluations towards criteria can be yes, abstain, no, and refusal.

Step 2.4. *Determine the picture fuzzy criteria weight matrix* $V = [v_j]_{n\times 1}$:

$$V = \begin{array}{c} C_1 \\ \vdots \\ C_n \end{array}\begin{bmatrix} v_1 \\ \vdots \\ v_n \end{bmatrix}, \tag{18}$$

where $v_j =< \mu_{v_j}, \eta_{v_j}, \upsilon_{v_j} >$ is a PFN which represents importance evaluation of the criterion C_j given by the experts. It is calculated as the proportion of each item in the voting results.

Phase 3: Hybrid picture fuzzy criteria weighting method.

Step 3.1. *Calculate the subjective criteria weights:*

$$w_j^S = \frac{\mu_{v_j} + \frac{\eta_{v_j}}{2} + \frac{\xi_{v_j}}{2}(1+\mu_{v_j} - \upsilon_{v_j})}{\sum_{t=1}^{n} [\mu_{v_t} + \frac{\eta_{v_t}}{2} + \frac{\xi_{v_t}}{2}(1 + \mu_{v_t} - \upsilon_{v_t})]}, \quad j = 1, \ldots, n, \tag{19}$$

where $v_j =< \mu_{v_j}, \eta_{v_j}, \upsilon_{v_j} >$ is a PFN which represents importance evaluation of the criterion C_j given by the experts; and $w^S = (w_1^S, \ldots, w_n^S)^T$ represents the subjective weight vector of the criteria, with $w_j^S \in [0, 1]$ and $\sum_{j=1}^{n} w_j^S = 1$. The subjective criteria weights are based on experts' voting on the criteria. They are calculated by using a picture fuzzy Direct rating method. More detailed, white papers are divided into half; i.e., one half for the experts who vote for and one half for the experts who vote against; and $\xi_{v_j} = 1 - \mu_{v_j} - \eta_{v_j} - \upsilon_{v_j}$ ($j = 1, \ldots, n$) is the ratio of experts which refuse to provide importance evaluation towards the criterion C_j.

Step 3.2. *Calculate the objective criteria weights*:

$$w_j^O = \frac{1 - \frac{R}{m(R-1)} \sum_{i=1}^{m} [1 - (\mu_{z_{ij}}^R + \eta_{z_{ij}}^R + \upsilon_{z_{ij}}^R + \xi_{z_{ij}}^R)^{1/R}]}{\sum_{t=1}^{n} \{1 - \frac{R}{m(R-1)} \sum_{l=1}^{m} [1 - (\mu_{z_{lt}}^R + \eta_{z_{lt}}^R + \upsilon_{z_{lt}}^R + \xi_{z_{lt}}^R)^{1/R}]\}}, \quad R > 0\ (\neq 1);\ j = 1, \ldots, n \tag{20}$$

where $z_{ij} =< \mu_{z_{ij}}, \eta_{z_{ij}}, \upsilon_{z_{ij}} >$ is a PFN which represents an evaluation of the alternative A_i with respect to the criterion C_j given by the experts; R is the information measure parameter; and $w^O = (w_1^O, \ldots, w_n^O)^T$ represents the objective weight vector of the criteria, with $w_j^O \in [0, 1]$ and $\sum_{j=1}^{n} w_j^O = 1$. The objective criteria weights are based on experts' voting on the alternatives. They are calculated by using a picture fuzzy R-norm entropy method.

Step 3.3. *Calculate the hybrid criteria weights*:

$$w_j = \gamma w_j^S + (1 - \gamma) w_j^O, \quad j = 1, \ldots, n, \tag{21}$$

where $w = (w_1, \ldots, w_n)^T$ represents the hybrid weight vector of the criteria, with $w_j \in [0, 1]$ and $\sum_{j=1}^{n} w_j = 1$; and $\gamma \in [0, 1]$ is the trade-off parameter. The criteria have subjective weights when γ is equal to 1. The criteria have objective weights when $\gamma = 0$. If $\gamma \in (0, 1)$ the criteria weights are hybridized.

Phase 4: Picture fuzzy CoCoSo method.

Step 4.1. *Determine the picture fuzzy normalized evaluation matrix* $R = [r_{ij}]_{m\times n}$:

$$r_{ij} = \begin{cases} z_{ij} =< \mu_{z_{ij}}, \eta_{z_{ij}}, \upsilon_{z_{ij}} > & \text{if } C_j \text{ is a benefit criterion} \\ (z_{ij})^c =< \upsilon_{z_{ij}}, \eta_{z_{ij}}, \mu_{z_{ij}} > & \text{if } C_j \text{ is a cost criterion,} \end{cases} \quad i = 1, \ldots, m; j = 1, \ldots, n, \tag{22}$$

where r_{ij} denotes the normalized evaluation of the alternative A_i with respect to the criterion C_j given by the experts. Only experts' evaluations with respect to cost criteria are transformed by utilizing the complement operation.

Step 4.2. *Determine the picture fuzzy weighted average and geometric comparability sequences of each alternative.*

(1) Picture fuzzy Dombi weighted average comparability sequences:

$$\Theta_i = < \mu_{\Theta_i}, \eta_{\Theta_i}, \upsilon_{\Theta_i} >= PFDWA(r_{i1}, \ldots, r_{in}) = \bigoplus_{j=1}^{n} (w_j r_{ij})$$
$$= < 1 - \frac{1}{1 + \{\sum_{j=1}^{n} w_j (\frac{\mu_{r_{ij}}}{1-\mu_{r_{ij}}})^{\Re}\}^{1/\Re}},$$

$$\frac{1}{1+\{\sum_{j=1}^{n} w_j(\frac{1-\eta_{r_{ij}}}{\eta_{r_{ij}}})^{\Re}\}^{1/\Re}}, \frac{1}{1+\{\sum_{j=1}^{n} w_j(\frac{1-\upsilon_{r_{ij}}}{\upsilon_{r_{ij}}})^{\Re}\}^{1/\Re}} >, \Re > 0;\ i = 1, \ldots, m, \tag{23}$$

(2) Picture fuzzy Dombi weighted geometric comparability sequences:

$$\begin{aligned}\Phi_i &= <\mu_{\Phi_i}, \eta_{\Phi_i}, \upsilon_{\Phi_i}> = PFDWG_w(r_{i1}, \ldots, r_{in}) \\ &= \bigotimes_{j=1}^{n}(r_{ij})^{w_j} \\ &= < \frac{1}{1+\{\sum_{j=1}^{n} w_j(\frac{1-\mu_{r_{ij}}}{\mu_{r_{ij}}})^{\Re}\}^{1/\Re}}, \\ &\quad 1-\frac{1}{1+\{\sum_{j=1}^{n} w_j(\frac{\eta_{r_{ij}}}{1-\eta_{r_{ij}}})^{\Re}\}^{1/\Re}}, \\ &\quad 1-\frac{1}{1+\{\sum_{j=1}^{n} w_j(\frac{\upsilon_{r_{ij}}}{1-\upsilon_{r_{ij}}})^{\Re}\}^{1/\Re}} >, \quad \Re > 0; \\ &\quad i = 1, \ldots, m, \end{aligned} \tag{24}$$

where $\Re$ is the operational parameter.

Step 4.3. *Defuzzify the picture fuzzy weighted average and geometric comparability sequences of each alternative.*

(1) Crisp Dombi weighted average comparability sequences:

$$S_i = \mu_{\Theta_i} + \frac{\eta_{\Theta_i}}{2} + \frac{\xi_{\Theta_i}}{2}(1+\mu_{\Theta_i}-\upsilon_{\Theta_i}), \quad i = 1, \ldots, m, \tag{25}$$

(2) Crisp Dombi weighted geometric comparability sequences:

$$P_i = \mu_{\Phi_i} + \frac{\eta_{\Phi_i}}{2} + \frac{\xi_{\Phi_i}}{2}(1+\mu_{\Phi_i}-\upsilon_{\Phi_i}), \ i = 1, \ldots, m, \tag{26}$$

Step 4.4. *Calculate three appraisal score strategies for each alternative.*

(1) Arithmetic mean:

$$K_i^{(1)} = \frac{S_i + P_i}{\sum_{l=1}^{m}(S_l + P_l)}, \quad i = 1, \ldots, m, \tag{27}$$

(2) Relative score (to the worst value):

$$K_i^{(2)} = \frac{S_i}{\min\limits_{l=1,\ldots,m} S_l} + \frac{P_i}{\min\limits_{l=1,\ldots,m} P_l}, \quad i = 1, \ldots, m, \tag{28}$$

(3) Balanced compromise:

$$K_i^{(3)} = \frac{\lambda S_i + (1-\lambda)P_i}{\lambda \max\limits_{l=1,\ldots,m} S_l + (1-\lambda)\max\limits_{l=1,\ldots,m} P_l}, \quad i = 1, \ldots, m, \tag{29}$$

where $\lambda \in [0, 1]$ is the balancing factor. A decision-maker provides the value of the balancing factor.

Step 4.5. *Aggregate three appraisal score strategies and rank the alternatives*:

$$K_i = \sum_{s=1}^{3}\{0.5[\frac{K_i^{(s)}}{\max\limits_{l=1,\ldots,m} K_l^{(s)}} + (\frac{m - r_i^{(s)}}{m})^2]\}^{1/2}, \quad i = 1, \ldots, m, \tag{30}$$

where the highest value is the most desirable alternative; and $r_i^{(s)}$ is the rank of the alternative A_i with respect to a value of the appraisal score strategy $K_i^{(s)}$ $(s = 1, 2, 3)$.

V. CASE STUDY

In this section, a real-life case study of sustainable LMD mode evaluation in the Pardubice context is presented. The introduced picture fuzzy decision-making approach is implemented to determine the best LMD mode from the set of six alternative LMD modes under the identified sustainable evaluation criteria.

Pardubice is an administrative center of the Pardubice region, one of 14 regions in the Czech Republic (Figure 2). With its 91.727 inhabitants and area of 78 km^2, it is the tenth biggest city in the country. It is very well developed and often called the city of industry. There are several leading factories at the state level; e.g., FOXCONN CZ producing consumer electronics is the second-largest exporter in the Czech Republic, right after ŠKODA AUTO. High economic achievements are followed by appropriate transport infrastructure. Railway station Pardubice is very busy providing links with the biggest cities in the country and international connections. There is also Pardubice Airport. The city is very attractive for providing LMD, which can be noticed by the presence of 29 registered providers.

All providers perform LMD mainly in the traditional way, as does the Czech Post. The designated postal operator has the most developed infrastructure and resources to perform LMD. Figure 3 shows the locations of the postal network units of the Czech Post, together with the layers that indicate the altitude of the observed territory. It can be seen that the city center (which is marked in Figure 3) is well covered by postal network units. It is located at the lowest altitude with negligible altitude variations.

Pardubice has a well-developed road network, both in the city and with other regions of the Czech Republic. This is due to its developed industry and the existence of the airport. It is a good basis for performing the traditional LMD mode. However, during peak hours there are congestions on its streets. This further undermines the traditional LMD mode in terms of sustainability, which already has high operating costs and emissions. On the other hand, Pardubice has developed bicycle traffic (Figure 4). Approximately 40% of the main streets of the inner city are covered with bicycle lanes. One part of the bicycle lanes is located within the road, while the rest are physically independent and mostly extend parallel to streets.

FIGURE 2. The regions in the Czech Republic.

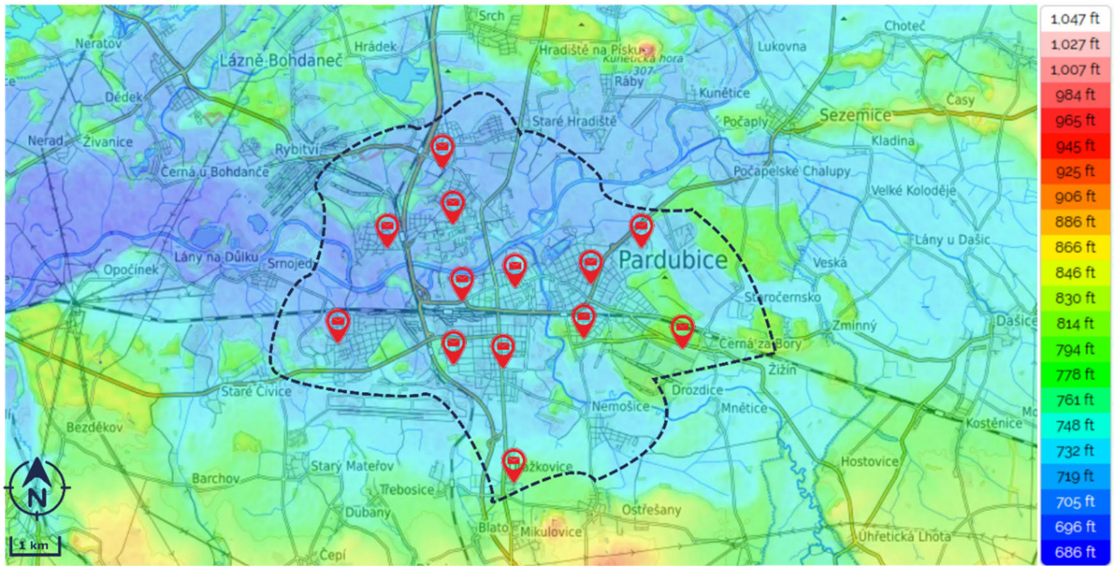

FIGURE 3. Locations of the postal units in Pardubice on the relief map.

The alternative LMD modes for Pardubice are as follows (Figure 5):

- (A_1) *Traditional.* LMD providers mainly use traditional mode. Courier performs LMD. This delivery process involves several activities, such as loading shipments into a traditional vehicle, going to the field, and visiting LMD locations.
- (A_2) *E-cargo bike*. It implies a delivery concept similar to the traditional. The difference is that a courier uses an e-cargo bike instead of a traditional vehicle. This LMD mode is especially suitable for lowland areas with a developed network of bicycle lanes. It has a significantly positive impact on the environment because it reduces air pollution.
- (A_3) *Mobile parcel locker*. It represents the improvement of a stationary parcel locker. It can change a location by requirements and get closer to customers. A zero location can be an existing network unit.
- (A_4) *Autonomous delivery robot*. A robot starts its route from a certain larger mean of transport where shipments are loaded. Then, it continues to predefined addresses. All these activities are performed autonomously, except loading, which is mostly realized traditionally.
- (A_5) *Drone*. The delivery process involves the usage of an unmanned aerial vehicle to deliver shipments to customer addresses. It implies the existence of a control panel, which can be a part of the existing infrastructure, in which loading is performed. Afterward, a drone flies

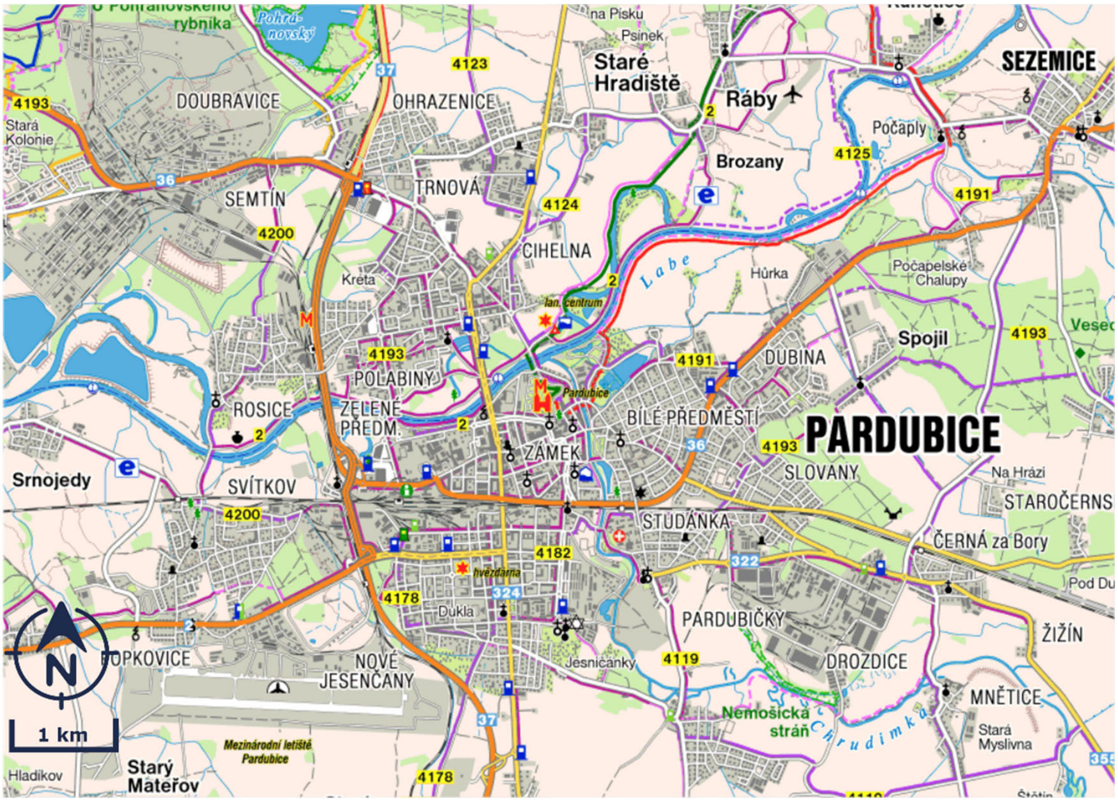

FIGURE 4. Street network with specially designated bicycle lanes in Pardubice (purple – lane within the road, pink – independent bicycle lane).

to users' addresses according to the given coordinates. This type of LMD can be very suitable for inaccessible terrain. The main disadvantages relate to small cargo space and underdeveloped legislation.

- (A_6) *Tube transport.* The forerunner of this alternative is the pneumatic transport at an internal level. The modern concept implies the transfer of packages in the appropriate capsules through tubes over longer distances to predetermined stations. It does not occupy public lands since most of the infrastructure is located underground. However, it is not flexible.

VI. RESULTS AND DISCUSSION

A. EXPERIMENTAL RESULTS

Phase 1: Statement of the sustainable LMD mode evaluation problem.

Step 1.1. As outlined in the previous section, six alternative LMD modes in the Pardubice context are as follows: "traditional" (A_1), "e-cargo bike" (A_2), "mobile parcel locker" (A_3), "autonomous delivery robot" (A_4), "drone" (A_5), and "tube transport" (A_6).

Step 1.2. Ten managers with a wide range of real-world expertise in LMD were invited to participate in the case study. Only online interviews with the selected experts were conducted due to the COVID-19 outbreak.

Step 1.3. Twenty criteria for sustainable LMD mode evaluation are identified from the relevant state-of-the-art literature. The evaluation criteria are defined in Table 1. As can be seen from this table, the comprehensive literature review revealed five economic, five environmental, five social, and five technical criteria.

Phase 2: Information collection and representation.

Step 2.1. Linguistic evaluations given by 10 invited experts towards six alternative LMD modes in the Pardubice context are showed in Table 4. The linguistic evaluation matrices are constructed by using Eq. (15).

Step 2.2. The picture fuzzy evaluation matrix is given in Table 5. It is determined based on six linguistic evaluation matrices (Table 4) with the help of Eq. (16). The picture fuzzy evaluations of investigated alternatives are computed as the proportion of each item in the voting results of 10 invited managers who are in charge of LMD. For instance, an evaluation of the "traditional" LMD mode (A_1) with respect to the education cost criterion (C_1) given by the experts is $z_{11} =< \mu_{z_{11}}, \eta_{z_{11}}, \upsilon_{z_{11}} >=< 0.3, 0.1, 0.5>$. More detailed, from Table 4 it can be seen that three experts have positive attitude and support (i.e., vote "yes") A_1 in terms of C_1, one expert has a neutral attitude (i.e., white paper rejecting both "yes" and "no" but still takes the vote) about A_1 in terms of C_1, five experts have a negative attitude and oppose (i.e., vote "no") A_1 in terms of C_1, and one expert refuses to provide an evaluation of A_1 in terms of C_1 (i.e., invalid voting paper or does not take the vote). As a result, the corresponding degree of positive membership $\mu_{z_{11}}$ is 3/10 = 0.3, the degree of neutral membership $\eta_{z_{11}}$ is 1/10 = 0.1, the degree of negative membership $\upsilon_{z_{11}}$ is 5/10 = 0.5, and the degree of

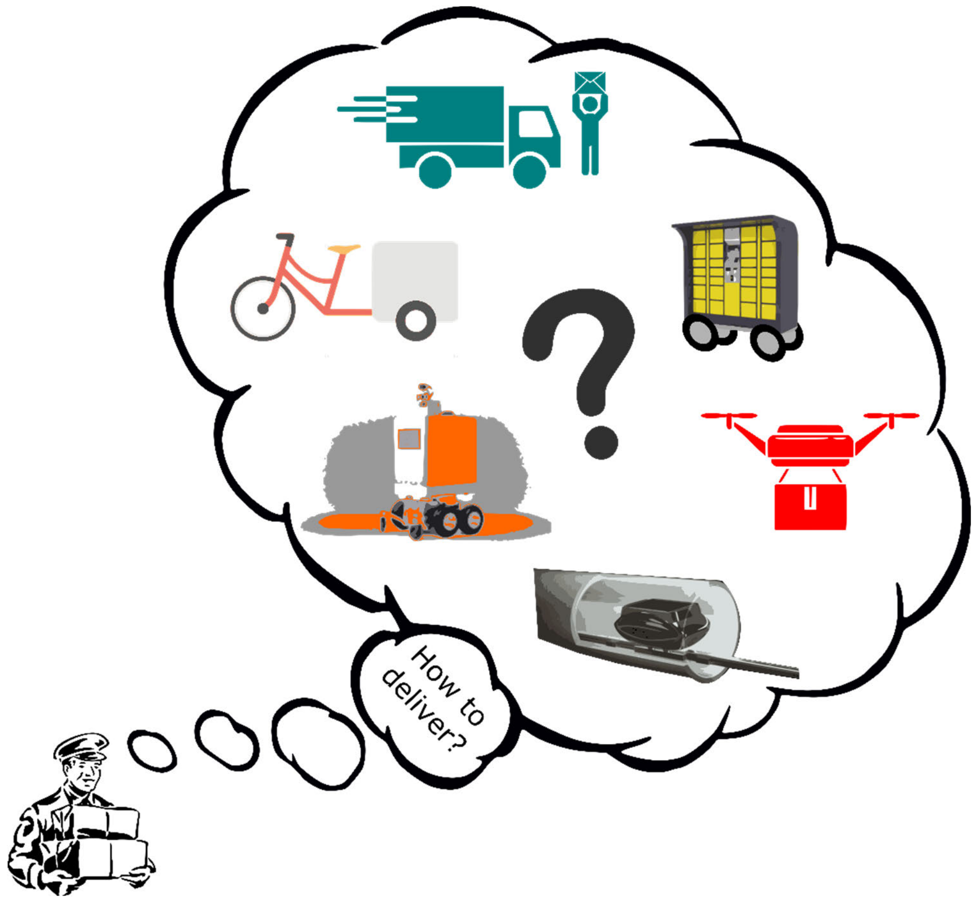

FIGURE 5. The alternative LMD modes in the Pardubice context.

refusal membership $\xi_{z_{11}}$ is 1/10 = 0.1 or 1−(0.3+0.1+0.5) = 0.1.

Step 2.3. Twenty criteria are evaluated by 10 managers who are in charge of LMD. Linguistic importance evaluations are presented in Table 6. Ten linguistic criteria weight matrices are constructed with the help of Eq. (17).

Step 2.4. Table 7 presents the picture fuzzy criteria weight matrix, which is determined with the help of Eq. (18). The linguistic importance evaluations of 20 criteria for sustainable LMD mode evaluation are expressed as PFNs by calculating the proportion of each item in the voting results of 10 selected experts (Table 6).

Phase 3: Hybrid picture fuzzy criteria weighting method.

Step 3.1. The subjective weights (Table 8) are based on experts' voting on the sustainable LMD evaluation criteria. The picture fuzzy Direct rating method is applied to obtain these values. The subjective weights are determined based on the picture fuzzy criteria weight matrix (Table 7) with the help of Eq. (19).

Step 3.2. The objective criteria weights are based on experts' voting on six alternative LMD modes in the Pardubice context. The picture fuzzy *R*-norm entropy method is used to obtain objective weights of the sustainable LMD evaluation criteria. The objective criteria weights are given in Table 8. They are determined based on the picture fuzzy evaluation matrix (Table 5) and Eq. (20). It is adopted that the information measure parameter *R* is 2.

Step 3.3. The hybrid weights of the sustainable LMD evaluation criteria are presented in Table 8. They are calculated by using Eq. (21). It is assumed that the value of the trade-off parameter γ is 0.5 to equally appraise the proposed subjective and objective criteria weighting methods.

Phase 4. Picture fuzzy CoCoSo method.

Step 4.1. According to Table 1, cost criteria are education cost (C_1), fleet acquisition cost (C_2), insurance and taxes (C_3), operational cost (C_4), road network cost (C_5), air pollution (C_6), congestion (C_7), noise pollution (C_8), waste generation (C_9), and land use (C_{13}). The other 10 sustainable LMD evaluation criteria are benefit. The picture fuzzy normalized evaluation matrix is provided in Table 9. It is determined based on the picture fuzzy evaluation matrix (Table 5) and criterion type by employing the complement operation defined in Eq. (22).

Step 4.2. Two picture fuzzy comparability sequences for each alternative LMD mode in the Pardubice context are determined based on the hybrid criteria weights (Table 8) and picture fuzzy normalized evaluation matrix (Table 9). The picture fuzzy Dombi aggregation operators are applied

TABLE 4. Linguistic evaluations of the alternatives.

Alternative	Expert	Criterion																			
		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{20}
A_1	D_1	N	R	N	Y	N	Y	Y	R	N	Y	Y	Y	N	Y	R	A	A	Y	Y	Y
	D_2	Y	A	A	A	A	Y	Y	Y	Y	N	Y	R	Y	Y	N	Y	R	R	N	N
	D_3	N	R	N	Y	Y	N	Y	Y	Y	Y	Y	R	Y	Y	Y	N	Y	Y	N	Y
	D_4	N	N	N	Y	N	Y	A	Y	R	N	Y	Y	R	R	A	A	Y	R	R	R
	D_5	Y	N	Y	Y	N	Y	N	R	A	Y	Y	A	A	A	Y	N	Y	R	Y	A
	D_6	N	A	Y	Y	R	Y	Y	Y	R	A	Y	N	N	A	Y	Y	A	N	N	Y
	D_7	A	Y	Y	N	N	A	A	N	Y	Y	N	Y	Y	N	R	N	Y	R	N	A
	D_8	Y	N	A	Y	N	Y	Y	A	R	A	A	N	R	Y	Y	Y	N	Y	A	A
	D_9	R	R	A	Y	N	Y	Y	Y	Y	Y	Y	N	A	R	A	N	Y	A	R	Y
	D_{10}	N	N	N	Y	N	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	R	Y	Y	Y	Y
A_2	D_1	N	N	N	R	N	N	Y	N	N	N	Y	Y	Y	A	A	Y	Y	N	Y	A
	D_2	Y	A	N	A	Y	N	N	N	N	A	Y	R	Y	N	Y	N	A	N	Y	Y
	D_3	A	N	A	N	R	N	Y	A	N	Y	Y	Y	A	Y	N	Y	Y	N	R	Y
	D_4	N	N	N	N	N	Y	N	A	Y	A	A	Y	A	R	A	N	Y	A	Y	A
	D_5	N	N	N	A	A	N	A	N	R	Y	N	A	R	Y	Y	Y	A	R	A	Y
	D_6	N	N	N	Y	N	N	N	N	N	A	A	N	Y	Y	A	A	A	Y	Y	Y
	D_7	Y	Y	R	A	A	A	N	N	A	N	Y	Y	N	Y	N	A	N	N	N	Y
	D_8	N	N	N	N	N	N	A	A	Y	Y	A	R	R	Y	Y	R	N	A	Y	A
	D_9	N	N	Y	N	Y	N	N	A	N	R	Y	Y	R	R	A	N	A	N	Y	Y
	D_{10}	N	N	N	A	N	N	N	Y	N	N	Y	Y	N	A	Y	N	Y	N	Y	N
A_3	D_1	N	A	N	N	N	N	N	N	A	A	R	Y	N	A	N	N	A	Y	Y	Y
	D_2	N	N	Y	N	N	N	N	N	N	Y	Y	Y	A	Y	N	R	Y	A	Y	Y
	D_3	Y	N	N	N	N	A	N	N	N	Y	A	Y	N	N	Y	N	N	R	Y	Y
	D_4	A	Y	N	Y	N	N	R	N	N	Y	N	Y	A	N	N	A	Y	A	Y	Y
	D_5	R	A	R	N	R	N	A	A	R	N	A	A	Y	N	A	N	N	Y	A	Y
	D_6	A	N	R	N	A	N	Y	N	Y	Y	Y	N	N	A	N	N	A	A	Y	A
	D_7	N	A	A	R	Y	Y	Y	Y	N	Y	Y	Y	N	R	N	Y	R	N	N	Y
	D_8	N	N	N	N	N	Y	N	Y	Y	N	A	Y	N	Y	N	N	N	R	Y	N
	D_9	R	A	N	A	N	N	N	N	N	Y	A	Y	N	Y	N	Y	N	N	Y	Y
	D_{10}	Y	Y	N	N	N	N	N	N	N	Y	N	Y	Y	Y	A	N	N	Y	Y	Y
A_4	D_1	Y	A	Y	N	Y	Y	R	R	N	N	N	N	A	N	R	N	N	A	N	N
	D_2	Y	Y	R	Y	R	N	A	Y	Y	Y	A	A	A	N	N	Y	A	N	N	R
	D_3	R	N	A	A	Y	A	Y	N	R	R	R	Y	R	N	N	N	N	R	N	A
	D_4	Y	A	R	A	R	R	A	A	A	N	Y	Y	A	A	Y	R	N	N	N	Y
	D_5	R	Y	Y	N	N	Y	N	R	Y	A	A	A	A	R	A	N	Y	R	R	R
	D_6	A	Y	N	N	Y	Y	N	N	Y	R	Y	Y	N	Y	N	A	N	N	R	Y
	D_7	A	Y	R	Y	N	N	Y	Y	Y	R	N	N	A	Y	A	N	N	Y	Y	N
	D_8	Y	Y	Y	Y	A	Y	Y	A	R	A	A	A	Y	Y	N	N	R	N	R	N
	D_9	N	R	Y	A	Y	N	Y	Y	N	N	R	R	N	A	A	N	A	R	A	R
	D_{10}	Y	Y	Y	N	Y	R	Y	N	Y	R	A	N	A	Y	A	A	N	N	R	N
A_5	D_1	Y	A	Y	A	A	A	N	R	A	N	Y	N	Y	N	A	N	Y	N	N	Y
	D_2	N	A	A	Y	N	N	Y	A	Y	N	A	A	N	A	Y	N	A	N	Y	N
	D_3	Y	N	N	N	Y	A	Y	Y	N	N	N	N	A	R	N	N	A	N	R	N
	D_4	R	A	Y	A	Y	R	N	A	Y	A	Y	N	A	Y	A	A	A	N	N	R
	D_5	Y	Y	A	N	N	A	N	R	N	N	Y	N	R	Y	A	Y	Y	N	N	N
	D_6	A	N	Y	N	Y	N	N	A	N	N	N	Y	N	Y	N	N	A	Y	Y	N
	D_7	R	A	R	A	Y	Y	A	Y	N	N	A	N	A	A	A	R	Y	N	N	R
	D_8	Y	A	N	N	R	N	N	A	N	Y	Y	A	N	Y	A	A	A	A	R	A
	D_9	Y	Y	N	Y	A	N	A	N	Y	N	Y	R	N	N	N	N	N	R	A	N
	D_{10}	Y	A	Y	A	N	Y	N	Y	Y	N	N	N	A	N	A	N	A	N	R	R
A_6	D_1	N	A	Y	A	Y	N	N	N	Y	Y	N	A	A	N	A	N	N	N	R	Y
	D_2	Y	Y	Y	R	A	N	N	N	R	A	N	Y	N	R	N	N	N	N	N	R
	D_3	Y	Y	A	N	Y	Y	N	R	N	Y	A	A	N	N	A	N	A	A	N	Y
	D_4	R	Y	R	N	Y	N	N	N	R	Y	R	R	N	A	N	N	N	N	N	R
	D_5	A	Y	N	A	N	A	Y	N	Y	Y	N	A	N	Y	N	N	N	Y	Y	Y
	D_6	A	Y	Y	N	Y	A	Y	A	A	Y	A	N	A	A	A	Y	N	N	N	N
	D_7	N	N	Y	A	Y	R	A	N	N	Y	N	Y	Y	Y	N	A	A	A	Y	N
	D_8	Y	Y	R	N	A	N	A	A	N	Y	N	A	N	N	A	N	N	R	A	Y
	D_9	Y	Y	R	Y	R	N	N	A	Y	N	R	A	N	Y	Y	A	N	Y	A	R
	D_{10}	Y	Y	Y	A	N	N	N	Y	N	Y	Y	Y	N	N	Y	N	Y	N	Y	A

Yes: Y; Abstain: A; No: N; Refusal: R.

to determine comparability sequences. More detailed, picture fuzzy Dombi weighted average comparability sequences are computed by using the PFDWA operator defined in Eq. (23), while Picture fuzzy Dombi weighted geometric comparability sequences are calculated by utilizing the PFDWG operator defined in Eq. (24). The values can be found in Table 10.

TABLE 5. The picture fuzzy evaluation matrix.

Criterion	Alternative					
	A_1	A_2	A_3	A_4	A_5	A_6
C_1	<0.3, 0.1, 0.5>	<0.2, 0.1, 0.7>	<0.2, 0.2, 0.4>	<0.5, 0.2, 0.1>	<0.6, 0.1, 0.1>	<0.5, 0.2, 0.2>
C_2	<0.1, 0.2, 0.4>	<0.1, 0.1, 0.8>	<0.2, 0.4, 0.4>	<0.6, 0.2, 0.1>	<0.2, 0.6, 0.2>	<0.8, 0.1, 0.1>
C_3	<0.3, 0.3, 0.4>	<0.1, 0.1, 0.7>	<0.1, 0.1, 0.6>	<0.5, 0.1, 0.1>	<0.4, 0.2, 0.3>	<0.5, 0.1, 0.1>
C_4	<0.8, 0.1, 0.1>	<0.1, 0.4, 0.4>	<0.1, 0.1, 0.7>	<0.3, 0.3, 0.4>	<0.2, 0.4, 0.4>	<0.1, 0.4, 0.4>
C_5	<0.1, 0.1, 0.7>	<0.2, 0.2, 0.5>	<0.1, 0.1, 0.7>	<0.5, 0.1, 0.2>	<0.4, 0.2, 0.3>	<0.5, 0.2, 0.2>
C_6	<0.8, 0.1, 0.1>	<0.1, 0.1, 0.8>	<0.2, 0.1, 0.7>	<0.4, 0.1, 0.3>	<0.2, 0.3, 0.4>	<0.1, 0.2, 0.6>
C_7	<0.7, 0.2, 0.1>	<0.2, 0.2, 0.6>	<0.2, 0.1, 0.6>	<0.5, 0.2, 0.2>	<0.2, 0.2, 0.6>	<0.2, 0.2, 0.6>
C_8	<0.6, 0.1, 0.1>	<0.1, 0.4, 0.5>	<0.2, 0.1, 0.7>	<0.3, 0.2, 0.3>	<0.3, 0.4, 0.1>	<0.1, 0.3, 0.5>
C_9	<0.5, 0.1, 0.1>	<0.2, 0.1, 0.6>	<0.2, 0.1, 0.6>	<0.5, 0.1, 0.2>	<0.4, 0.1, 0.5>	<0.3, 0.1, 0.4>
C_{10}	<0.5, 0.2, 0.3>	<0.3, 0.3, 0.3>	<0.7, 0.1, 0.2>	<0.1, 0.2, 0.3>	<0.1, 0.1, 0.8>	<0.8, 0.1, 0.1>
C_{11}	<0.8, 0.1, 0.1>	<0.6, 0.3, 0.1>	<0.3, 0.4, 0.2>	<0.2, 0.4, 0.2>	<0.5, 0.2, 0.3>	<0.1, 0.2, 0.5>
C_{12}	<0.4, 0.1, 0.3>	<0.6, 0.1, 0.1>	<0.8, 0.1, 0.1>	<0.3, 0.3, 0.3>	<0.1, 0.2, 0.6>	<0.3, 0.5, 0.1>
C_{13}	<0.4, 0.2, 0.2>	<0.3, 0.2, 0.2>	<0.2, 0.2, 0.6>	<0.1, 0.6, 0.2>	<0.1, 0.4, 0.4>	<0.1, 0.2, 0.7>
C_{14}	<0.5, 0.2, 0.1>	<0.5, 0.2, 0.1>	<0.4, 0.2, 0.3>	<0.4, 0.2, 0.3>	<0.4, 0.2, 0.3>	<0.3, 0.2, 0.4>
C_{15}	<0.5, 0.2, 0.1>	<0.4, 0.4, 0.2>	<0.1, 0.2, 0.7>	<0.1, 0.4, 0.4>	<0.1, 0.6, 0.3>	<0.2, 0.4, 0.4>
C_{16}	<0.3, 0.2, 0.4>	<0.3, 0.2, 0.4>	<0.2, 0.1, 0.6>	<0.1, 0.2, 0.6>	<0.1, 0.2, 0.6>	<0.1, 0.2, 0.7>
C_{17}	<0.6, 0.2, 0.1>	<0.4, 0.4, 0.2>	<0.2, 0.2, 0.5>	<0.1, 0.2, 0.6>	<0.3, 0.6, 0.1>	<0.1, 0.2, 0.7>
C_{18}	<0.4, 0.1, 0.1>	<0.1, 0.2, 0.6>	<0.3, 0.3, 0.2>	<0.1, 0.1, 0.5>	<0.1, 0.1, 0.7>	<0.2, 0.2, 0.5>
C_{19}	<0.3, 0.1, 0.4>	<0.7, 0.1, 0.1>	<0.8, 0.1, 0.1>	<0.1, 0.1, 0.4>	<0.2, 0.1, 0.4>	<0.3, 0.2, 0.4>
C_{20}	<0.5, 0.3, 0.1>	<0.6, 0.3, 0.1>	<0.8, 0.1, 0.1>	<0.2, 0.1, 0.4>	<0.1, 0.1, 0.5>	<0.4, 0.1, 0.2>

TABLE 6. Linguistic importance evaluations of the sustainable LMD mode criteria.

Criterion	Expert									
	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}
C_1	No	No	Yes	No	No	Abstain	No	No	No	No
C_2	Yes	Refusal	Yes	Yes	Abstain	No	Yes	Yes	Yes	Yes
C_3	Abstain	No	No	Yes	Abstain	No	No	Yes	Refusal	No
C_4	Abstain	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
C_5	No	Abstain	Yes	No	Yes	Abstain	Refusal	No	Yes	No
C_6	Yes	Abstain	Abstain	Yes	Yes	Yes	Abstain	Yes	Yes	No
C_7	Yes	Abstain	Refusal	Yes	Refusal	Yes	Abstain	Abstain	Yes	Yes
C_8	No	No	No	Abstain	Abstain	No	Yes	No	No	Abstain
C_9	No	Abstain	Yes	No	No	Yes	Abstain	Abstain	Refusal	Yes
C_{10}	Abstain	Yes	Abstain	Refusal	Yes	Yes	No	Yes	Yes	Refusal
C_{11}	Yes	Yes	No	Yes	Yes	Abstain	Refusal	No	No	Yes
C_{12}	No	Yes	Yes	Abstain	Abstain	No	Yes	Yes	Refusal	Yes
C_{13}	Yes	No	No	Yes	No	No	Abstain	Abstain	No	No
C_{14}	Yes	Abstain	No	No	Yes	No	No	No	Yes	Yes
C_{15}	Refusal	Abstain	Abstain	Abstain	Yes	No	Yes	Yes	No	Abstain
C_{16}	Abstain	No	No	No	Refusal	No	No	Yes	No	No
C_{17}	Refusal	No	Abstain	Refusal	No	Yes	Abstain	Abstain	Yes	Yes
C_{18}	Abstain	Yes	Yes	No	Refusal	No	Yes	Abstain	No	Abstain
C_{19}	Yes	Yes	Abstain	Yes	Yes	Refusal	Yes	Yes	No	Yes
C_{20}	Yes	Abstain	Refusal	Abstain	Yes	No	Yes	Refusal	Yes	Yes

It is adopted that the operational parameter $\Re$ of the PFDWA and PFDWG operators is 0.5.

Step 4.3. The crisp Dombi weighted average and geometric comparability sequences of six alternative LMD modes are calculated with the help of Eq. (25) and Eq. (26), respectively (Table 10).

Step 4.4. Table 11 presents the values of three appraisal score strategies for compared LMD modes. They are calculated by using Eqs. (27)-(29). The preferred value of the balancing factor λ is 0.5 since it gives equal relative importance to the crisp Dombi weighted average and geometric comparability sequences of the alternatives. This value is used for computing the third appraisal score strategy (i.e., balanced compromise).

Step 4.5. Three appraisal score strategies are aggregated with the help of Eq. (30). Six alternative LMD modes are ranked according to the decreasing values of their aggregated appraisal score strategies (Table 11). The ordering is $A_2 \succ A_3 \succ A_1 \succ A_6 \succ A_5 \succ A_4$. According to the proposed picture fuzzy decision-making approach for sustainable LMD, "e-cargo bike" (A_2) is the best LMD mode in the Pardubice context.

TABLE 7. The picture fuzzy criteria weight matrix.

Criterion	Degree of positive membership	Degree of neutral membership	Degree of negative membership	Degree of refusal membership
C_1	0.1	0.1	0.8	0
C_2	0.7	0.1	0.1	0.1
C_3	0.2	0.2	0.5	0.1
C_4	0.8	0.1	0.1	0
C_5	0.3	0.2	0.4	0.1
C_6	0.6	0.3	0.1	0
C_7	0.5	0.3	0	0.2
C_8	0.1	0.3	0.6	0
C_9	0.3	0.3	0.3	0.1
C_{10}	0.5	0.2	0.1	0.2
C_{11}	0.5	0.1	0.3	0.1
C_{12}	0.5	0.2	0.2	0.1
C_{13}	0.2	0.2	0.6	0
C_{14}	0.4	0.1	0.5	0
C_{15}	0.3	0.4	0.2	0.1
C_{16}	0.1	0.1	0.7	0.1
C_{17}	0.3	0.3	0.2	0.2
C_{18}	0.3	0.3	0.3	0.1
C_{19}	0.7	0.1	0.1	0.1
C_{20}	0.5	0.2	0.1	0.2

TABLE 8. Subjective, objective, and hybrid criteria weights.

Criterion	Subjective weight		Objective weight		Hybrid weight	
	Value	Rank	Value	Rank	Value	Rank
C_1	0.0136	20	0.0474	15	0.0305	19
C_2	0.0752	2	0.0550	4	0.0651	3
C_3	0.0304	16	0.0476	14	0.0390	15
C_4	0.0771	1	0.0562	2	0.0667	1
C_5	0.0403	15	0.050	11	0.0452	14
C_6	0.0680	5	0.0629	1	0.0655	2
C_7	0.0725	4	0.0559	3	0.0642	4
C_8	0.0227	18	0.0471	16	0.0349	17
C_9	0.0453	12	0.0487	13	0.0470	12
C_{10}	0.0671	6	0.0536	5	0.0604	6
C_{11}	0.0553	9	0.0512	9	0.0533	9
C_{12}	0.0603	8	0.0513	8	0.0558	8
C_{13}	0.0272	17	0.0404	19	0.0338	18
C_{14}	0.0408	14	0.0350	20	0.0379	16
C_{15}	0.0503	11	0.0510	10	0.0507	10
C_{16}	0.0154	19	0.0450	18	0.0302	20
C_{17}	0.0508	10	0.050	11	0.0504	11
C_{18}	0.0453	12	0.0459	17	0.0456	13
C_{19}	0.0752	2	0.0524	7	0.0638	5
C_{20}	0.0671	6	0.0535	6	0.0603	7

B. RANKING DISCUSSION

According to the proposed picture fuzzy decision-making approach for sustainable LMD, "e-cargo bike" (A_2) is the best alternative among six evaluated modes in the investigated real-world scenario. This result follows all three dimensions of sustainable development. The main reasons for positioning this alternative in the first place are favorable relief, the existence of an extensive network of bicycle lanes, and the rich tradition of using bicycles in Pardubice. The implementing cost is significantly lower comparing to other modes since it relates only to the purchasing of e-cargo bikes. This alternative contributes to the sustainability of LMD by significantly reducing air and noise pollution as well as waste generation. Besides, e-cargo bikes can easily avoid traffic jams, which greatly increases the reliability and flexibility of the system. One potential disadvantage of this sustainable LMD mode is the low adaptability to extreme weather conditions.

The second-best alternative is "mobile parcel locker" (A_3). It is highly welcomed to increase the delivery time availability and flexibility of LMD by introducing mobile parcel lockers in the system. The Czech Post has a well-developed network of its branches in Pardubice. The city residents can already use some stationary parcel lockers. As a result, it is expected that mobile parcel lockers, as an improved version of traditional parcel lockers, could be widely accepted by customers.

"Traditional" mode (A_1) is the third-best mode. It is in operation for many years in Pardubice. The most significant advantages of this LMD mode are the low fleet acquisition

TABLE 9. The picture fuzzy normalized evaluation matrix.

Criterion	Alternative					
	A_1	A_2	A_3	A_4	A_5	A_6
C_1	<0.5, 0.1, 0.3>	<0.7, 0.1, 0.2>	<0.4, 0.2, 0.2>	<0.1, 0.2, 0.5>	<0.1, 0.1, 0.6>	<0.2, 0.2, 0.5>
C_2	<0.4, 0.2, 0.1>	<0.8, 0.1, 0.1>	<0.4, 0.4, 0.2>	<0.1, 0.2, 0.6>	<0.2, 0.6, 0.2>	<0.1, 0.1, 0.8>
C_3	<0.4, 0.3, 0.3>	<0.7, 0.1, 0.1>	<0.6, 0.1, 0.1>	<0.1, 0.1, 0.5>	<0.3, 0.2, 0.4>	<0.1, 0.1, 0.5>
C_4	<0.1, 0.1, 0.8>	<0.4, 0.4, 0.1>	<0.7, 0.1, 0.1>	<0.4, 0.3, 0.3>	<0.4, 0.4, 0.2>	<0.4, 0.4, 0.1>
C_5	<0.7, 0.1, 0.1>	<0.5, 0.2, 0.2>	<0.7, 0.1, 0.1>	<0.2, 0.1, 0.5>	<0.3, 0.2, 0.4>	<0.2, 0.2, 0.5>
C_6	<0.1, 0.1, 0.8>	<0.8, 0.1, 0.1>	<0.7, 0.1, 0.2>	<0.3, 0.1, 0.4>	<0.4, 0.3, 0.2>	<0.6, 0.2, 0.1>
C_7	<0.1, 0.2, 0.7>	<0.6, 0.2, 0.2>	<0.6, 0.1, 0.2>	<0.2, 0.2, 0.5>	<0.6, 0.2, 0.2>	<0.6, 0.2, 0.2>
C_8	<0.1, 0.1, 0.6>	<0.5, 0.4, 0.1>	<0.7, 0.1, 0.2>	<0.3, 0.2, 0.3>	<0.1, 0.4, 0.3>	<0.5, 0.3, 0.1>
C_9	<0.1, 0.1, 0.5>	<0.6, 0.1, 0.2>	<0.6, 0.1, 0.2>	<0.2, 0.1, 0.5>	<0.5, 0.1, 0.4>	<0.4, 0.1, 0.3>
C_{10}	<0.5, 0.2, 0.3>	<0.3, 0.3, 0.3>	<0.7, 0.1, 0.2>	<0.1, 0.2, 0.3>	<0.1, 0.1, 0.8>	<0.8, 0.1, 0.1>
C_{11}	<0.8, 0.1, 0.1>	<0.6, 0.3, 0.1>	<0.3, 0.4, 0.2>	<0.2, 0.4, 0.2>	<0.5, 0.2, 0.3>	<0.1, 0.2, 0.5>
C_{12}	<0.4, 0.1, 0.3>	<0.6, 0.1, 0.1>	<0.8, 0.1, 0.1>	<0.3, 0.3, 0.3>	<0.1, 0.2, 0.6>	<0.3, 0.5, 0.1>
C_{13}	<0.2, 0.2, 0.4>	<0.2, 0.2, 0.3>	<0.6, 0.2, 0.2>	<0.2, 0.6, 0.1>	<0.4, 0.4, 0.1>	<0.7, 0.2, 0.1>
C_{14}	<0.5, 0.2, 0.1>	<0.5, 0.2, 0.1>	<0.4, 0.2, 0.3>	<0.4, 0.2, 0.3>	<0.4, 0.2, 0.3>	<0.3, 0.2, 0.4>
C_{15}	<0.5, 0.2, 0.1>	<0.4, 0.4, 0.2>	<0.1, 0.2, 0.7>	<0.1, 0.4, 0.4>	<0.1, 0.6, 0.3>	<0.2, 0.4, 0.4>
C_{16}	<0.3, 0.2, 0.4>	<0.3, 0.2, 0.4>	<0.2, 0.1, 0.6>	<0.1, 0.2, 0.6>	<0.1, 0.2, 0.6>	<0.1, 0.2, 0.7>
C_{17}	<0.6, 0.2, 0.1>	<0.4, 0.4, 0.2>	<0.2, 0.2, 0.5>	<0.1, 0.2, 0.6>	<0.3, 0.6, 0.1>	<0.1, 0.2, 0.7>
C_{18}	<0.4, 0.1, 0.1>	<0.1, 0.2, 0.6>	<0.3, 0.3, 0.2>	<0.1, 0.1, 0.5>	<0.1, 0.1, 0.7>	<0.2, 0.2, 0.5>
C_{19}	<0.3, 0.1, 0.4>	<0.7, 0.1, 0.1>	<0.8, 0.1, 0.1>	<0.1, 0.1, 0.4>	<0.2, 0.1, 0.4>	<0.3, 0.2, 0.4>
C_{20}	<0.5, 0.3, 0.1>	<0.6, 0.3, 0.1>	<0.8, 0.1, 0.1>	<0.2, 0.1, 0.4>	<0.1, 0.1, 0.5>	<0.4, 0.1, 0.2>

TABLE 10. The Dombi weighted average and geometric comparability sequences.

Alternative	DWA comparability sequence		DWG comparability sequence	
	Picture fuzzy	Crisp	Picture fuzzy	Crisp
A_1	<0.40, 0.142, 0.226>	0.607	<0.272, 0.157, 0.399>	0.426
A_2	<0.572, 0.181, 0.146>	0.735	<0.477, 0.219, 0.179>	0.668
A_3	<0.603, 0.136, 0.177>	0.731	<0.477, 0.162, 0.232>	0.638
A_4	<0.190, 0.173, 0.378>	0.382	<0.161, 0.210, 0.420>	0.343
A_5	<0.278, 0.204, 0.308>	0.482	<0.205, 0.279, 0.406>	0.388
A_6	<0.376, 0.184, 0.245>	0.578	<0.256, 0.216, 0.384>	0.427

Dombi weighted average: DWA; Dombi weighted geometric: DWG.

TABLE 11. Appraisal score strategies and alternative ranking.

Alternative	Arithmetic mean		Relative score		Balanced compromise		Aggregated value	Final rank
	Value	Rank	Value	Rank	Value	Rank		
A_1	0.161	3	2.831	3	0.736	3	1.884	3
A_2	0.219	1	3.872	1	1.0	1	2.761	1
A_3	0.214	2	3.774	2	0.976	2	2.507	2
A_4	0.113	6	2.0	6	0.517	6	1.096	6
A_5	0.136	5	2.393	5	0.620	5	1.361	5
A_6	0.157	4	2.758	4	0.716	4	1.674	4

and road network costs. However, it rates very low when the environmental dimension of sustainability is taken into account. Significant improvement of the traditional mode can be achieved by substituting traditional with electric and/or hybrid vehicles.

''Tube transport'' (A_6) ranks fourth. Its advantages are high security of the goods being transported and low land use since its infrastructure is mostly located underground. However, it cannot be considered as the most practical LMD mode in the Pardubice context. The reason relates primarily to the high cost of building the necessary infrastructure. Besides, this alternative characterizes the low flexibility for LMD.

The two worst-ranked alternatives are ''drone'' (A_5) and ''autonomous delivery robot'' (A_4). At first glance, these sustainable LMD modes seem very attractive. The main obstacles for their wider application in Pardubice are the high costs of purchasing a new vehicle fleet and equipment. Besides, legislation concerning these modes does not promptly follow the accelerated technological development. Certainly, by eliminating these problems in the future, these two alternatives could be very competitive as sustainable LMD concepts.

C. SENSITIVITY ANALYSES

The sensitivity analyses are performed to examine the robustness of the picture fuzzy decision-making approach for

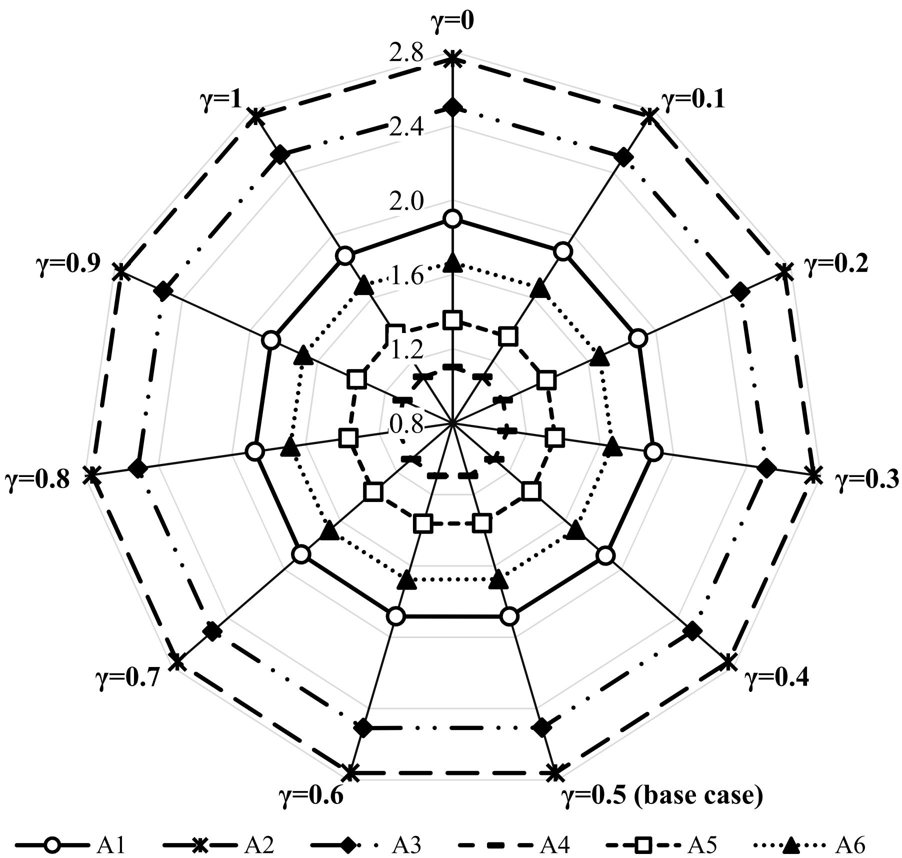

FIGURE 6. The sensitivity analysis to changes in the trade-off parameter γ.

TABLE 12. The comparison with state-of-the-art PFS-based MCDM methods.

Method	Ranking
Picture fuzzy decision-making approach for sustainable LMD (our study)	$A_2 \succ A_3 \succ A_1 \succ A_6 \succ A_5 \succ A_4$
Picture fuzzy TODIM [94], [95]	$A_2 \succ A_3 \succ A_1 \succ A_6 \succ A_5 \succ A_4$
Picture fuzzy TOPSIS [96], [97]	$A_2 \succ A_3 \succ A_1 \succ A_6 \succ A_5 \succ A_4$
Picture fuzzy VIKOR [98]	$A_2 \succ A_3 \succ A_1 \succ A_6 \succ A_5 \succ A_4$

sustainable LMD. Firstly, the influence of the trade-off parameter γ of the provided hybrid picture fuzzy criteria weighting method on the sustainable LMD mode evaluation is analyzed (Figure 6).

In the base case, the value of the trade-off parameter was 0.5 to equally appraise the Direct rating and R-norm entropy of the hybrid picture fuzzy criteria weighting method. In the first sensitivity analysis, the values of γ are varied in the interval [0, 1] (with an increment value of 0.1) since the criteria have subjective weights when $\gamma = 1$ and objective weights when $\gamma = 0$. According to Figure 6, the same ranking of LMD modes in the analyzed real-life decision-making context is generated in all created problem instances; i.e., the ordering is $A_2 \succ A_3 \succ A_1 \succ A_6 \succ A_5 \succ A_4$. The ranks of all six alternative LMD modes are stable to changes in the trade-off parameter.

Secondly, the effect of the balancing factor λ of the picture fuzzy CoCoSo method for ranking alternative LMD modes on the results is investigated (Figure 7). In the base case, λ was set to 0.5 to give equal relative importance to the crisp Dombi weighted average and geometric comparability sequences of the alternatives. In the second sensitivity analysis, the values of λ are varied in the interval [0, 1] with an increment value of 0.1. Figure 7 presents the aggregated values of three appraisal score strategies of alternative LMD modes in the Pardubice context under different settings of the balancing factor. As can be seen from this figure, "e-cargo bike" (A_2) is the best LMD mode in all test problems since it has the highest aggregated value. Besides, by varying the values of λ, the ranking order is unchanged. As a result, it can be concluded that the sensitivity analyses approved the high robustness of the developed approach.

D. COMPARATIVE ANALYSIS

The comparative analysis is performed to investigate the reliability of the introduced picture fuzzy decision-making approach. The highlighted sustainable LMD mode evaluation

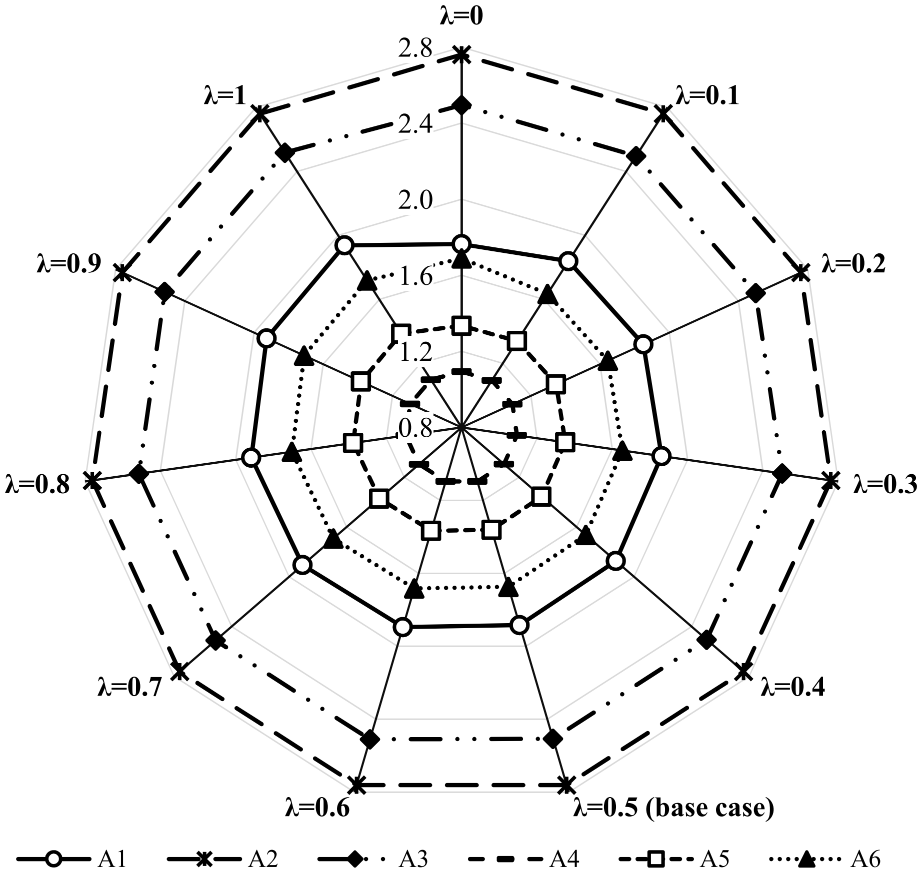

FIGURE 7. The sensitivity analysis to changes in the balancing factor λ.

problem is solved with the picture fuzzy TODIM [94], [95], TOPSIS [96], [97], and VIKOR [98] methods.

The comparison results are given in Table 12. As can be seen from this table, "e-cargo bike" is the best-ranked alternative in the analyzed real-life decision-making context by all four methods. The developed approach and these three state-of-the-art PFS-based MCDM methods have the ideal agreement between themselves since they generate the same ordering of the alternative LMD modes in the Pardubice context (Table 12); i.e., the perfect correlation of ranks exists between the generated results of the compared methods. Therefore, it can be concluded that the comparative analysis confirmed the high reliability of the formulated approach.

The presented picture fuzzy approach for sustainable LMD involves four operational parameters: (1) The trade-off parameter γ of the provided hybrid picture fuzzy criteria weighting method; (2) The balancing factor λ of the picture fuzzy CoCoSo method; (3) The information measure parameter R of the picture fuzzy R-norm entropy; and (4) The parameter $\Re$ of the picture fuzzy Dombi weighted average and the picture fuzzy Dombi weighted geometric operators. As a result, compared to the available PFS based MCDM methods, the introduced picture fuzzy approach has higher flexibility in evaluating sustainable LMD modes. Besides, this multi-parametric nature of the provided advanced decision-making framework, as its intrinsic feature, could motivate practitioners to apply it for solving other emerging MCDM problems.

VII. CONCLUSION

This paper provides the advanced decision-making framework for sustainable LMD. The major contributions are as follows: (1) Twenty sustainable LMD mode evaluation criteria are identified from the literature review; (2) Advanced PFSs are implemented in the introduced decision-making framework to catch ambiguous, uncertain, and vague sustainability-related information; (3) Hybrid picture fuzzy criteria weighting method based on the Direct rating and R-norm entropy is developed to determine the importance of sustainable LMD mode evaluation criteria; (4) Picture fuzzy CoCoSo method is formulated to rank alternative LMD modes; and (5) The presented picture fuzzy decision-making approach for sustainable LMD is implemented in the Pardubice context.

The provided real-life case study of evaluating a sustainable LMD mode illustrated the practicality and effectiveness of the introduced approach. It identified "e-cargo bike" as the best alternative between six potential LMD modes. "Mobile parcel locker" is the second-best LMD mode in the Pardubice context. The effect of the trade-off parameter of the formulated hybrid picture fuzzy criteria weighting method on the sustainable LMD mode evaluation is investigated.

Besides, the influence of the balancing factor of the developed picture fuzzy CoCoSo method for ranking alternative LMD modes on the results is analyzed. The ranks of all six alternative LMD modes in the Pardubice context are stable to changes in the trade-off parameter and balancing factor. Therefore, the sensitivity analyses confirmed the high robustness of the picture fuzzy decision-making approach for sustainable LMD. The comparative analysis with the picture fuzzy TODIM, TOPSIS, and VIKOR methods is performed. The proposed approach and these three state-of-the-art PFS-based MCDM methods have the ideal agreement between themselves since they generate the same ordering of the alternatives. Besides, the introduced picture fuzzy approach has four operational parameters. As a result, its solutions are far more flexible, compared to the available PFS based MCDM methods.

In real-life decision-making, managers are usually divided into four groups of those who vote for, abstain, vote against, and refuse to vote. The voting mechanism is efficiently implemented in the presented picture fuzzy decision-making approach for sustainable LMD. As a result, this approach can help decision-makers in the logistics industry to more naturally express their preferences by voting and elucidate sustainable LMD mode under a plethora of ambiguous, uncertain, and vague sustainability-related information. They can efficiently reveal the best LMD mode by applying the proposed picture fuzzy approach.

The presented picture fuzzy approach is highly scalable as the number of alternatives, sustainable LMD mode evaluation criteria, and decision-makers have a low impact on computational complexity. It can be used to solve not only the sustainable LMD mode evaluation problem but also any other MCDM problem under the picture fuzzy environment.

This paper also has some limitations, which can provide the scope for future research. The interrelationships among the sustainable LMD mode evaluation criteria are neglected. One of the succeeding studies may try to improve the formulated approach to handle this issue. Another limitation is the complex mathematical algorithm for calculation. The proposed approach may be developed in a decision support system as a web-based application to ease-up its widespread use in the logistics industry.

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