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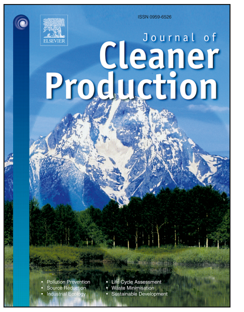

Remanufacturing facility location for automotive Lithium-ion batteries: An integrated neutrosophic decision-making model

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PII: S0959-6526(21)02650-0

DOI: https://doi.org/10.1016/j.jclepro.2021.128438

Reference: JCLP 128438

To appear in: *Journal of Cleaner Production*

Received Date: 12 March 2021

Revised Date: 30 June 2021

Accepted Date: 24 July 2021

Please cite this article as: Deveci M, Simic V, Torkayesh AE, Remanufacturing facility location for automotive Lithium-ion batteries: An integrated neutrosophic decision-making model, *Journal of Cleaner Production* (2021), doi: https://doi.org/10.1016/j.jclepro.2021.128438.

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Ali Ebadi Torkayesh: Conceptualization, Data acquisition, Methodology, Visualization, Writing - Original Draft, Review & Editing

Title Page

Remanufacturing Facility Location for Automotive Lithium-ion Batteries: An Integrated Neutrosophic Decision-Making Model

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Abstract

Automobile Lithium-ion battery (ALiB) is a fast-evolving technology that found widespread utilization in electric vehicles (EVs). Management of used ALiBs has become a crucial topic in the automotive industry and academic researches. ALiB remanufacturing is significant leverage to accomplish the circular economy paradigm, but many open questions still exist. This study addresses the following main research questions: (*i*) Which evaluation criteria influence the strategic decisions on locating ALiB remanufacturing facilities? (*ii*) How to determine the best location under uncertainty? To answer these questions and promote sustainable development of the EV industry, this study introduces a three-stage integrated neutrosophic decision-making model for the location selection of an ALiB remanufacturing facility. Key evaluation criteria are identified to offer a decision-making framework for practitioners. This study employs advanced type-2 neutrosophic numbers (T2NNs) to reduce the vagueness in experts' decision-making preferences and avoid erroneous facility location decisions. The innovative usage of the hierarchical best-worst method (BWM) is presented to select optimal evaluation criteria weights with the lowest subjectivity and biasedness. The combinative distance based assessment (CODAS) method is extended under the T2NN environment to rank location alternatives. A case study provides decision-making guidelines on how to identify the best location for an ALiB remanufacturing facility in the real-world context. Our findings indicate that "Gemlik/Bursa" is the best location in Turkey. The high reliability and robustness of the integrated neutrosophic decision-making model are demonstrated with the comparison and sensitivity analyses. The proposed model could solve other circular economy-related location problems.

Keywords: Automobile Lithium-ion Battery, Remanufacturing, Type-2 Neutrosophic Number, CODAS, BWM, Facility Location.

1. Introduction

Electric vehicles (EVs) have been increasingly used due to significant energy and environmental benefits (Alamerew and Brissaud, 2020; Loganathan et al., 2021). By 2040, EVs will account for approximately 20 % of the global road transport fleet (Kapustin and Grushevenko, 2020). Automobile Lithium-ion battery (ALiB) is a fast-evolving technology that found widespread utilization in these "green" vehicles. ALiB is a low environmental impact energy storage technology (Liu et al., 2016). Its advantages over other portable energy storage systems are higher energy and power density, and cycling property (Zhang et al., 2014; Liu et al., 2016). However, when an ALiB capacity depreciates to 70-80 % of its initial capacity, it cannot power a vehicle anymore and should be replaced (Alamerew and Brissaud, 2020).

Management of used ALiBs has become a crucial topic in the automotive industry and academic researches (Liu et al., 2016; Garg et al., 2020). Remanufacturing, repurposing (for secondary usage in less-stressful applications), and recycling are three prevalent management schemes for used ALiBs. Remanufacturing is the most environmentally friendly since it preserves the identity of ALiBs by replacing defective or outdated cells/modules (Standridge and Hasan, 2015). It is one of the key strategies for the sustainable development of the EV industry, improving business competitiveness, and reducing environmental burdens (Zhu et al., 2014; Standridge and Hasan, 2015; Hua et al., 2020). Besides, remanufacturing has positive impacts on the economic, environmental, and societal pillars of sustainability (Alfaro-Algaba and Ramirez, 2020; Zhang et al., 2020b). As a result, remanufacturing of ALiBs can mitigate the raw material problem for the EV industry, decline import dependency, counteract price volatility, reduce the carbon footprint, and ensure sustainable e-mobility.

By 2030, approximately 25 % of new ALiB production could be substituted by remanufacturing (Standridge and Hasan, 2015). ALiB remanufacturing is an industrial value-added process of transforming a used battery to at least its original performance by replacing defective or outdated cells/modules. It includes assessment, partial disassembly, screening, surface cleaning, repairing, reversible joining, and testing of ALiBs in a quasi-new condition to satisfy all standards imposed by original equipment manufacturers.

It is clear that ALiB remanufacturing is significant leverage to accomplish the circular economy paradigm, but many open questions still exist that hinder large-scale remanufacturing applications in industrial practice. As a result, this study addresses the following main research questions: (*i*) Which evaluation criteria influence the strategic decisions on locating ALiB remanufacturing facilities? (*ii*) How to determine the best ALiB remanufacturing facility location under uncertainty?

To answer these questions, this study introduces an integrated neutrosophic decision-making model for location selection of an ALiB remanufacturing facility with a real-life case study to promote sustainable development of the EV industry. The formulated three-stage integrated neutrosophic decision-making model hybridizes best-worst method (BWM) and type-2 neutrosophic number (T2NN) combinative distance based assessment (CODAS) method into a unique methodological framework. The study aims to boost ALiB remanufacturing adoption by revealing evaluation criteria for locating remanufacturing facilities and providing a straightforward decision-making framework for practitioners.

The additional motivations for this study are as follows: *a*) Despite a rich literature on remanufacturing, key strategic evaluation criteria that influence selecting ALiB remanufacturing facilities, are still missing; *b*) Determining the best ALiB remanufacturing facility location under uncertainty has not been addressed before in the literature; *c*) Although numerous multi-criteria decision-making (MCDM) approaches for remanufacturing have been introduced recently, no previous research employed this MCDM method in the remanufacturing research area considering high levels of vague, unreliable, and inexact information uncertainties; *d*) The CODAS method is a very popular and influential MCDM tool introduced by Keshavarz-Ghorabaee et al. (2016) which uses the overall score of an alternative by Euclidean and Hamming distances from a negative-ideal solution. Unfortunately, the CODAS method has not been extended before under the T2NN environment; *e*) The most critical step in locating an ALiB remanufacturing facility is to determine relative criteria weights. The BWM is an optimization-based weight determination tool introduced by Rezaei (2015) which has attracted remarkable attention from researchers in different fields due to its high reliability and preciseness. However, no previous research has utilized the BWM in the remanufacturing research area.

The contributions of this study to the present body of knowledge are as follows: *i*) For the first time, the ALiB remanufacturing facility location selection problem is comprehensively investigated and solved; *ii*) Key evaluation criteria that influence the strategic decisions on locating ALiB remanufacturing facilities are identified and briefly defined to offer a decision-making framework for practitioners; *iii*) Unlike other MCDM approaches for remanufacturing, this study uses advanced T2NNs to reduce the vagueness in experts' decision-making preferences, improve the recognition of information uncertainties in the remanufacturing environment, and avoid erroneous facility location decisions; *iv*) The integrated neutrosophic decision-making model is introduced to solve the ALiB remanufacturing facility location selection problem. The innovative usage of the hierarchical BWM is presented to select optimal criteria weights with the lowest subjectivity and biasedness, while the CODAS method is extended under the T2NN environment and applied in the remanufacturing research area for the first time; *v*) A case study of Turkey provides guidelines on how to identify the best location for an ALiB remanufacturing facility in the real-world context; *vi*) Although this research is devoted to ALiB remanufacturing, the presented integrated neutrosophic decision-making model could solve other circular economy-related location problems.

This research is structured as follows: Section 2 provides evaluation criteria for locating ALiB remanufacturing facilities and offers a comprehensive review of the related state-of-the-art research. Section 3 gives the problem definition and describes a real-life case study. Section 4 presents the integrated neutrosophic decision-making model for ALiB remanufacturing facility location selection. Section 5 presents the case study results and discussion. Finally, conclusions and implications are provided in Section 6.

2. Literature Review

The literature review is organized into four sub-sections. The first sub-section identifies criteria for locating ALiB remanufacturing facilities from the literature. The second sub-section surveys available MCDM approaches for remanufacturing. The third sub-section reviews available neutrosophic number-based decision-making models. The last sub-section presents identified research gaps.

2.1. Evaluation Criteria

Two electronic databases, namely Scopus and Web of Science, were the main information sources to identify criteria for locating ALiB remanufacturing facilities. Twenty key criteria are identified and briefly defined (Table 1). They are grouped into four clusters based on their nature. As can be seen from Table 1, the comprehensive literature review revealed eight economic, four environmental, three social, and five technical location selection criteria.

Table 1.
Evaluation criteria for locating Lithium-ion battery remanufacturing facilities.

Criteria	Code	Type	Definition	Reference(s)
Economic	MC_1			
Distance from collection centers	C_1	Min	An average transportation distance from local ALiB collection centers, car dealerships, and scrap yards	Li et al. (2018), Chakraborty et al. (2019), Song and Chu (2019), Alamerew and Brissaud (2020), Das et al. (2020a,c), Wang et al. (2020), Scheller et al. (2021)
Distance to a secondary market	C_2	Min	Transportation distance to a local secondary market for selling remanufactured ALiBs	Li et al. (2018), Gu et al. (2018b), Tosarkani and Amin (2018), Song and Chu (2019), Tang et al. (2019), Wang et al. (2020), Zhu et al. (2020), Scheller et al. (2021)
Distance to original equipment manufacturers	C_3	Min	An average transportation distance to OEMs for the acquisition of new battery cells to satisfy standards	Su (2017), Tang et al. (2018, 2019), Ocampo et al. (2019), Su et al. (2019), Qiao and Su (2020), Rallo et al. (2020), Zhang et al. (2020a), Zhu et al. (2020), Scheller et al. (2021)
Distance to recycling centers	C_4	Min	An average transportation distance to recycling centers for processing defective or outdated ALiB cells/modules	Hendrickson et al. (2015), Li et al. (2018), Su et al. (2019), Hua et al. (2020), Scheller et al. (2021)
Financial benefit	C_5	Max	A selling price of a remanufactured ALiB and indirect financial benefits	Li et al. (2018), Gu et al. (2018a,b), Tang et al. (2018, 2019), Ansari et al. (2020), Çolak and Kaya (2020), Hua et al. (2020), Zhang et al. (2020b), Scheller et al. (2021)
Investment cost	C_6	Min	An initial setup costs for new facilities and land	Abdulrahman et al. (2015), Hendrickson et al. (2015), Li et al. (2018), Farahani et al. (2019), Ocampo et al. (2019), Tang et al. (2019), Wang et al. (2020), Zhu et al. (2020)
Operational costs	C_7	Min	An expense of an ALiB remanufacturing facility to maintain its production and fixed asset depreciation	Gu et al. (2018b), Tosarkani and Amin (2018), Ansari et al. (2019), Gong et al. (2019), Farahani et al. (2019), Ding et al. (2020), Rallo et al. (2020), Zhu et al. (2020)
Subsidy	C_8	Max	Local financial support and tax preferences for remanufacturing enterprises	Abdulrahman et al. (2015), Bhatia and Srivastava (2018), Song and Chu (2019), Tang et al. (2018, 2019), Çolak and Kaya (2020), Qiao and Su (2020), Zhu et al. (2020)
Environmental	MC_2			
Air pollution	C_9	Min	Emissions of CO_2, SO_2, and other air pollutants generated by ALiB remanufacturing and related processes	Jindal and Sangwan (2016), Tang et al. (2018, 2019), Su (2017), Das et al. (2019), Çolak and Kaya (2020), Rallo et al. (2020), Wang et al. (2020), Xiong et al. (2020), Das et al. (in press)
Eco-awareness	C_{10}	Max	An environmental awareness level of local consumers and willingness to buy remanufactured ALiBs	Wei et al. (2015), Gu et al. (2018b), Bhatia and Srivastava (2018), Chakraborty et al. (2019), Tang et al. (2019)
Eco-disturbance	C_{11}	Min	Physical, chemical, and biological changes in environmental cond. around a location	Hendrickson et al. (2015), Kafuku et al. (2016), Wang et al. (2019), Çolak and Kaya (2020), Scheller et al. (2021)
Legislation	C_{12}	Max	Rules for the second use, certification, and compatibility to legislation such as Directives 2006/66/EC and 2000/53/EC	Abdulrahman et al. (2015), Wei et al. (2015), Govindan et al. (2016), Ocampo et al. (2019), Alamerew and Brissaud (2020), Ansari et al. (2020), Scheller et al. (2021)

Table 1. *(continued)*

Criteria	Code	Type	Definition	Reference(s)
Social	MC_3			
Aesthetic nuisance	C_{13}	Min	Affected population around a location	Kafuku et al. (2016), Tang et al. (2018), Wang et al. (2019), Çolak and Kaya (2020)
Health & safety	C_{14}	Min	Local health and safety working condition requirements for remanufacturing	Hendrickson et al. (2015), Wang et al. (2019), Ansari et al. (2020), Hua et al. (2020), Rallo et al. (2020), Loganathan et al. (2021)
Skilled workforce	C_{15}	Max	Availability of industry professionals and technical personnel for ALiB disassembly, reassembly, and cell replacement	Abdulrahman et al. (2015), Xia et al. (2015), Ansari et al. (2020), Hua et al. (2020), Çolak and Kaya (2020), Xiong et al. (2020)
Technical	MC_4			
Aftermarket service	C_{16}	Max	Availability of after-sale services for remanufactured ALiBs	Wei et al. (2015), Liu et al. (2016), Alamerew and Brissaud (2020)
Information system	C_{17}	Max	Accessibility to the history of the first use (remaining useful life and state-of-health)	Xia et al. (2015), Tang et al. (2018), Chakraborty et al. (2019), Garg et al. (2020), Scheller et al. (2021)
Infrastructure development	C_{18}	Max	Routing and processing time uncertainty correlates with the development level of a local infrastructure	Hendrickson et al. (2015), Xia et al. (2015), Ansari et al. (2019)
Remanufacturing supply chain	C_{19}	Max	Availability of a robust remanufacturing supply chain to provide a timely inflow and facilitate remanufacturing	Govindan et al. (2016), Su (2017), Ansari et al. (2019), Chakraborty et al. (2019), Alamerew and Brissaud (2020), Wang et al. (2020)
Resource accessibility	C_{20}	Max	The generated quantity of used ALiBs in a service zone of a remanufacturing facility	Tian et al. (2017), Li et al. (2018), Chakraborty et al. (2019), Farahani et al. (2019), Ocampo et al. (2019), Tang et al. (2019), Zhang et al. (2020a), Scheller et al. (2021)

2.2. Multi-Criteria Decision-Making Approaches for Remanufacturing

Remanufacturing attracted a large interest in academic research in recent years. As a result, many MCDM approaches have been introduced for solving diverse remanufacturing problems. The state-of-the-art contributions are summarized in Table 2.

Subramoniam et al. (2013) prioritized automotive components remanufacturing (ACR) strategic factors based on an industry survey. Tian et al. (2014) identified the main key technology factors influencing the ACR industry. Zhu et al. (2014) examined the cause-effect relationships among implementation barriers for truck engine remanufacturing. Abdulrahman et al. (2015) investigated critical factors affecting remanufacturing practices in the Chinese auto-parts industry. Xia et al. (2015) analyzed and evaluated internal barriers in the implementation of remanufacturing in the automotive industry. Govindan et al. (2016) focused on evaluating critical barriers of the ACR industry in India. Ilgin (2017) studied the used product selection problem faced by third-party reverse logistics providers. Tian et al. (2017) investigated the main operation patterns of the ACR industry in China. Bhatia and Srivastava (2018) explored external barriers to remanufacturing electronic waste. Ansari et al. (2019) identified critical success factors for remanufacturing adoption in manufacturing organizations and prioritized related performance outcomes.

Recently, Ansari et al. (2020) presented a structural solution model to mitigate supply chain-related risks in organizations involved in manufacturing/remanufacturing activities. Ding et al. (2020) solved the part selection problem to improve the re-manufacturability of machine tools. Du et al. (2020) provided a simple quantitative method to determine remanufacturing values of heavy-duty machine tools. Zhang et al. (2020a) investigated the re-manufacturability of a used boom cylinder of a concrete pump truck.

Table 2
Summary of the available multi-criteria decision-making approaches for remanufacturing.

Author(s) and year	**Research focus**	**GDM**	**Parameter type**	**SA**	**CA**	**Method(s)**	**Application**		**MC**	**SC**	**Alt.**
							Country	**Type**			
Subramoniam et al. (2013)	ACR success factor evaluation	Yes	Deterministic	No	No	AHP	The U.S.	Real-life	9	-	-
Tian et al. (2014)	ACR technology indicator evaluation	No	Deterministic	No	No	DEMATEL, AHP	China	Real-life	3	15	-
Zhu et al. (2014)	Truck RSC barrier evaluation	Yes	Grey	Yes	No	DEMATEL	China	Real-life	2	19	-
Abdulrahman et al. (2015)	ACR practice selection	Yes	Deterministic	No	No	AHP	China	Real-life	5	16	3
Xia et al. (2015)	Automotive remanufacturing internal barriers	Yes	Grey	Yes	No	DEMATEL	China	Real-life	3	15	-
Govindan et al. (2016)	ACR barrier evaluation	Yes	Fuzzy	No	No	ISM, ANP	India	Real-life	4	20	-
Ilgin (2017)	Used product selection	No	Fuzzy	Yes	No	AHP, DES, TOPSIS	-	IE	5	-	3
Tian et al. (2017)	ACR provider selection	Yes	Fuzzy	Yes	No	AHP, GRA, TOPSIS	China	Real-life	3	9	3
Bhatia and Srivastava (2018)	Electronic remanufacturing barrier evaluation	Yes	Grey	Yes	No	DEMATEL	India	Real-life	10	-	-
Ansari et al. (2019)	Automotive RSC performance outcome selection	Yes	Fuzzy	Yes	No	AHP, TOPSIS	India	Real-life	6	32	16
Ansari et al. (2020)	Automotive RSC risk mitigation strategy selection	Yes	Fuzzy	Yes	No	SWARA, COPRAS	India	Real-life	3	24	12
Ding et al. (2020)	Machine tool guideway selection	Yes	Deterministic	Yes	Yes	AHP, TOPSIS	-	IE	3	20	8
Du et al. (2020)	Machine tool selection	No	Interval	No	No	AHP, SE	-	IE	7	-	3
Zhang et al. (2020a)	Machinery part remanufacturability evaluation	Yes	Interval, fuzzy	No	No	LCA, AHP	-	IE	3	8	-
Our study	*ALiB remanufacturing facility location selection*	*Yes*	*T2NN*	*Yes*	*Yes*	*BWM, CODAS*	*Turkey*	*Real-life*	*4*	*20*	*6*

Analytic Network Process: ANP; Analytical Hierarchy Process: AHP; Automobile Lithium-ion Battery: ALiB; Automotive Components Remanufacturing: ACR; Best-Worst Method: BWM; COmbinative Distance-based ASsessment: CODAS; Comparative Analysis: CA; COmplex PRoportional ASsessment: COPRAS; DEcision MAking Trial and Evaluation Laboratory: DEMATEL; Discrete Event Simulation: DES; Evaluation based on Distance from Average Solution: EDAS; Grey Relational Analysis: GRA; Group Decision-Making: GDM; Illustrative Example: IE; Interpretative Structural Modeling: ISM; Life Cycle Assessment: LCA; Main Criteria: MC; Remanufacturing Supply Chain: RSC; Sensitivity Analysis: SA; Shannon Entropy: SE; Stepwise Weight Assessment Ratio Analysis: SWARA; Sub-Criteria: SC; Technique for the Order Preference by Similarity to Ideal Solution: TOPSIS; Type-2 Neutrosophic Number: T2NN.

2.3. Neutrosophic Number-Based Decision-Making Models

The available triangular, trapezoidal, bipolar, and T2NN-based decision-making models are comprehensively surveyed in Table 3.

Liang et al. (2017) analyzed indicators of business-to-consumer e-commerce websites to increase customer satisfaction. Abdel-Basset et al. (2018a) evaluated factors influencing the selection of supply chain management (SCM) suppliers. Abdel-Basset et al. (2018b) investigated the security estimation problem for SCM systems based on Internet of Things (IoT) technologies and assessed relevant criteria. Abdel-Basset et al. (2018c) solved the performance estimation problem to improve the quality of cloud services. Abdel-Basset et al. (2018d) considered factors that affect organizational performances to compare strategic plans. Abdel-Basset et al. (2018e) provided a multi-dimensional strategy to evaluate government websites.

Abdel-Basset et al. (2019a) focused on the project selection phase to determine the best fighter aircraft alternative. Abdel-Basset et al. (2019b) proposed T2NNs and applied this advanced type of neutrosophic technique to select the best supplier for importing cars. Nabeeh et al. (2019a) evaluated IoT influential factors in enterprise alternatives for using big data tools. Nabeeh et al. (2019b) investigated the personnel selection problem to enhance resource management in enterprises. Zaied et al. (2019) compared vertical machining centers to identify a suitable tool model.

Abdel-Basset et al. (2020a) solved the chief executive officer selection problem under a bipolar neutrosophic environment. Abdel-Basset et al. (2020b) analyzed which management properties should be developed to reinforce sustainable supply chain finance in the gas industry. Abdel-Basset et al. (2020c) focused on the transition difficulties of emerging enterprises with IoT technologies. Baušys et al. (2020) compared plots for residential construction under a neutrosophic environment. Liou et al. (2020) evaluated possible failure modes of new products in the electronics industry to help power supply manufacturers. Rahim et al. (2020) applied bipolar neutrosophic sets to solve the sustainable energy management problem. Yörükoğlu and Aydın (2020) evaluated smart containers to determine the most reliable and traceable solution for Industry 4.0 applications.

Recently, Abdel-Basset et al. (2021a) assessed sustainable bioenergy production technologies from the viewpoint of energy policymakers by using trapezoidal neutrosophic numbers. Abdel-Basset et al. (2021b) explored appropriate locations for offshore wind power stations under the neutrosophic environment to accommodate the lack of decision information and achieve benefits in coastal management. Abdel-Basset et al. (2021c) explored suitable sources of renewable energy by using triangular neutrosophic numbers to support energy investors. Abdel-Basset et al. (2021d) evaluated sustainable hydrogen production options under the neutrosophic theory. Hezam et al. (2021) prioritized groups for allocating coronavirus vaccines to obtain a timetable and guidelines. Nabeeh et al. (2021) evaluated the effectiveness of the green credit policy on the SCM in manufacturing companies.

2.4. Research Gaps

According to the literature review, the research gaps are as follows: *a*) This is the first work to determine the best ALiB remanufacturing facility location through the neutrosophic number-based decision-making model; *b*) The ALiB remanufacturing facility location selection problem is not addressed in the previous studies; *c*) No earlier work has determined criteria for locating ALiB remanufacturing facilities; *d*) The available deterministic, grey, and/or fuzzy MCDM approaches for remanufacturing could generate wrong facility location decisions since they are unable to account for high levels of vague, unreliable, and inexact remanufacturing-related information uncertainties; *e*) No previous research has utilized the BWM in the remanufacturing research area; *f*) The CODAS method has neither been extended under the T2NN environment nor been applied in the remanufacturing research area.

Table 3
Summary of the available neutrosophic number-based models.

Author(s) and year	Research focus	GDM	Parameter type	SA	CA	Method(s)	Application		MC	SC	Alt.
							Country	Type			
Liang et al. (2017)	Website quality indicator evaluation	Yes	TrNN	Yes	Yes	DEMATEL	-	IE	4	22	-
Abdel-Basset et al. (2018a)	Supplier selection indicator evaluation	Yes	TrNN	No	No	DEMATEL	NP	Real-life	7	-	-
Abdel-Basset et al. (2018b)	SCM security indicator evaluation	Yes	TNN	No	No	DEMATEL, AHP	-	IE	4	19	-
Abdel-Basset et al. (2018c)	Cloud computing service evaluation	Yes	TNN	No	No	AHP	Egypt	Real-life	3	-	5
Abdel-Basset et al. (2018d)	Strategy selection	Yes	TNN	No	No	AHP, SWOT	NP	Real-life	4	13	4
Abdel-Basset et al. (2018e)	Website evaluation	Yes	TNN	No	Yes	VIKOR	-	IE	6	-	5
Abdel-Basset et al. (2019a)	Project selection	Yes	TrNN	No	No	DEMATEL, TOPSIS	-	IE	6	-	4
Abdel-Basset et al. (2019b)	Supplier selection	Yes	T2NN	No	No	TOPSIS	Egypt	Real-life	8	-	5
Nabeeh et al. (2019a)	IoT indicator evaluation	No	TNN	No	Yes	AHP	Egypt	Real-life	5	-	3
Nabeeh et al. (2019b)	Personnel selection	Yes	TNN	No	No	AHP, TOPSIS	Egypt	Real-life	3	-	5
Zaied et al. (2019)	Machine tool selection	Yes	TrNN	No	No	MOORA	Egypt	Real-life	4	-	4
Abdel-Basset et al. (2020a)	Personnel selection	Yes	BNN	Yes	Yes	ANP, TOPSIS	Egypt	Real-life	3	10	4
Abdel-Basset et al. (2020b)	Supply chain finance aspect evaluation	Yes	TNN	Yes	No	BWM, TOPSIS, TODIM	Egypt	Real-life	5	21	-
Abdel-Basset et al. (2020c)	IoT transition barrier evaluation	Yes	TNN	No	No	AHP	Egypt	Real-life	6	-	4
Baušys et al. (2020)	Family house plot selection	Yes	TNN	No	No	SWARA, WASPAS	Lithuania	Real-life	6	-	9
Liou et al. (2020)	Failure mode evaluation	Yes	TrNN	Yes	Yes	FMEA, BWM, WASPAS	Taiwan	Real-life	15	-	20
Rahim et al. (2020)	Sustainable energy selection	Yes	BNN	No	Yes	MABAC	Malaysia	Real-life	14	-	7
Yörükoğlu and Aydın (2020)	Smart container selection	Yes	TNN	Yes	No	TOPSIS	-	IE	7	-	3
Abdel-Basset et al. (2021a)	Production technology selection	Yes	TrNN	Yes	Yes	DEMATEL, EDAS	Egypt	Real-life	4	14	7
Abdel-Basset et al. (2021b)	Power station location selection	Yes	TrNN	Yes	Yes	AHP, PROMETHEE II	Egypt	Real-life	7	19	5
Abdel-Basset et al. (2021c)	Renewable energy system selection	Yes	TNN	Yes	Yes	AHP, VIKOR, TOPSIS	Egypt	Real-life	5	18	4
Abdel-Basset et al. (2021d)	Hydrogen production option selection	Yes	TNN	No	Yes	AHP, COPRAS, EDAS	NP	Real-life	5	17	7
Hezam et al. (2021)	COVID-19 vaccine allocation	Yes	TNN	No	No	AHP, TOPSIS	NP	Real-life	4	15	6
Nabeeh et al. (2021)	Green credit rating evaluation	Yes	TNN	No	Yes	GRA, ANP, DEMATEL, TOPSIS	China	Real-life	5	-	9
Our study	*ALiB remanufacturing facility location selection*	*Yes*	*T2NN*	*Yes*	*Yes*	*BWM, CODAS*	*Turkey*	*Real-life*	*4*	*20*	*6*

Analytic Network Process: ANP; Analytical Hierarchy Process: AHP; Automobile Lithium-ion Battery: ALiB; Best-Worst Method: BWM; Bipolar Neutrosophic Number: BNN; COmbinative Distance-based ASsessment: CODAS; Comparative Analysis: CA; COmplex PRoportional ASsessment: COPRAS; COronaVIirus Disease-2019: COVID-19; DEcision MAking Trial and Evaluation Laboratory: DEMATEL; Evaluation based on Distance from Average Solution: EDAS; Failure Mode and Effects Analysis: FMEA; Grey Relational Analysis: GRA; Group Decision-Making: GDM; Illustrative Example: IE; Internet of Things: IoT; Main Criteria: MC; Multi-Attributive Border Approximation area Comparison: MABAC; Multi-Objective Optimization by Ratio Analysis: MOORA; Not Provided: NP; Preference Ranking Organization METHod for Enrichment Evaluations: PROMETHEE; Sensitivity Analysis: SA; Step-wise Weight Assessment Ratio Analysis: SWARA; Strengths, Weaknesses, Opportunities, and Threats: SWOT; Sub-Criteria: SC; Supply Chain Management: SCM; Technique for the Order Preference by Similarity to Ideal Solution: TOPSIS; TOmada de Decisao Interativa Multicriterio: TODIM; Trapezoidal Neutrosophic Number: TrNN; Triangular Neutrosophic Number: TNN; Type-2 Neutrosophic Number: T2NN; VIšeKriterijumska Optimizacija i kompromisno Rešenje: VIKOR.

3. Problem Definition

Turkey heavily relies on imported fossil fuels from other countries for its automobile industry. There is a great motivation for Turkish authorities to replace fossil fuel vehicles with EVs.

ALiB is a major component of an EV, which provides the required energy storage due to the superiority of high energy density, high output voltage, low self-discharge rate, and long cycling life. ALiB remanufacturing can be seen as a critical issue due to the large number of EVs that can be sold in Turkey. With the initial usage of EVs in Turkey, there is a definite need to open an ALiB remanufacturing facility.

Four experts from Turkish industries dealing with both energy storage and EVs are invited to propose suitable locations for the construction of an ALiB remanufacturing facility as well as make realistic and logical evaluations of these alternatives and the evaluation criteria. Expert 1, a female with more than seven years of experience, is one of the directors of a private energy company which deals with fast-charging stations for EVs in Turkey. Expert 2, a male with almost 11 years of experience, and Expert 3, a male with five years of experience, are professionals in the relevant field and work in an ALiB production facility in Turkey. Expert 4, a male with three years of experience, is an energy management director from an energy storage facility in Ankara.

Six potential locations are identified as follows (Fig. 1): Gemlik/Bursa (A_1), Yunusemre/Manisa (A_2), Tuzla/Istanbul (A_3), Sincan/Ankara (A_4), Melikgazi/Kayseri (A_5), and Seyitgazi/Eskisehir (A_6). These are the major potential locations that can be considered suitable for the construction of an ALiB remanufacturing facility in Turkey.

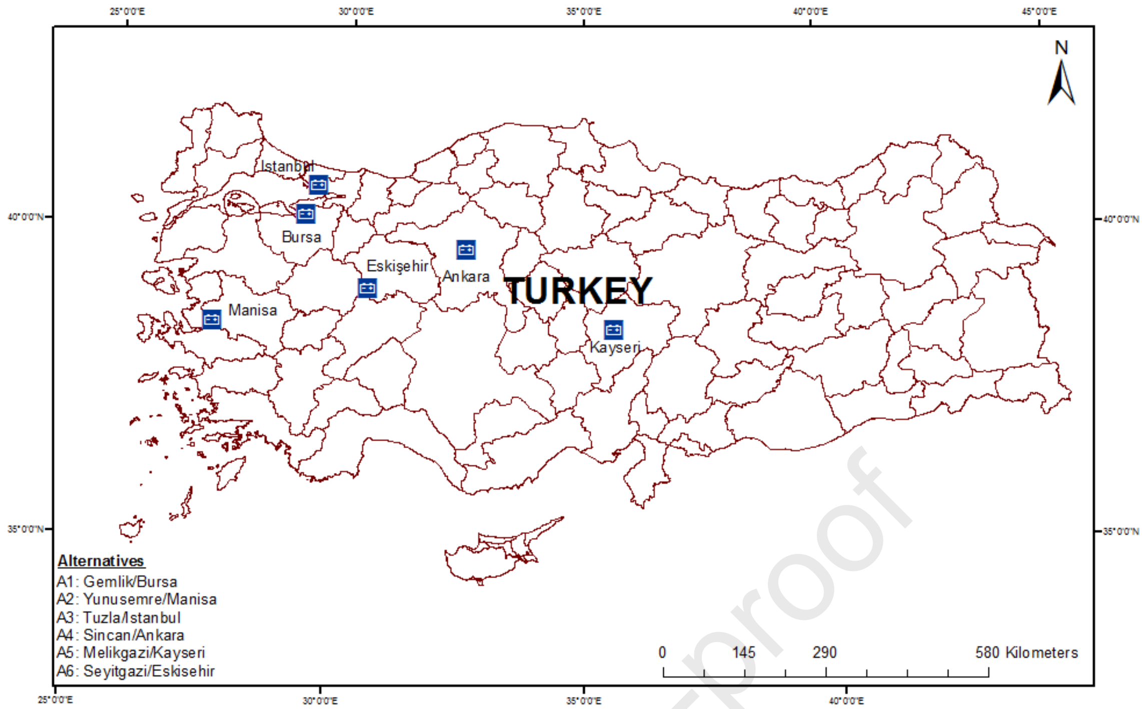

Fig. 1. The alternative locations for an ALiB remanufacturing facility in Turkey.

4. Methods

This section provides some preliminaries and introduces the integrated neutrosophic decision-making model for ALiB remanufacturing facility location selection.

4.1. Preliminaries

Definition 1 (Karnik et al., 1999; Mendel and John, 2002; Das et al., 2020b). A type-2 fuzzy set (T2FS), denoted $\tilde{E}$, in the universe X is characterized by a type-2 membership function $\mu_{\tilde{E}}(x,u)$, where $x \in X$ and $u \in J_x \subseteq [0,1]$:

$$\tilde{E} = \left\{ \left((x,u), \mu_{\tilde{E}}(x,u) \right) | \, x \in X, u \in J_x \subseteq [0,1] \right\}, \tag{1}$$

in which $0 \leq \mu_{\tilde{E}}(x,u) \leq 1$. T2FS $\tilde{E}$ can also be expressed as:

$$\tilde{E} = \int_{x \in X} \int_{u \in J_x} \mu_{\tilde{E}}(x,u) / (x,u), \tag{2}$$

where $J_x \subseteq [0,1]$, and $\iint$ denotes union over all admissible x and u.

Definition 2 (Ali and Smarandache, 2017; Smarandache, 2019). Let X be a space of points and let $x \in X$. A neutrosophic set A in X is characterized by a truth membership function T_A, an indeterminacy membership function I_A, and a falsity membership function F_A. $T_A(x)$, $I_A(x)$, and $F_A(x)$ are real standard or non-standard subsets of $]0^-, 1^+[$, and T_A, I_A, F_A: $X \rightarrow]0^-, 1^+[$.

The neutrosophic set can be represented as:

$$A=\left\{\left\langle x, T_A(x), I_A(x), F_A(x)\right\rangle \mid x \in X\right\}. \tag{3}$$

There is no restriction on the sum of $T_A(x), I_A(x),$ and $F_A(x),$ so:

$$0^{-} \le T_A(x)+I_A(x)+F_A(x) \le 3^{+}, \quad \forall x \in X. \tag{4}$$

Definition 3 (Abdel-Basset et al., 2019b). Consider Y as the limited universe of discourse and $D[0, 1]$ as the set of all triangular neutrosophic sets on $D[0, 1]$. A type-2 neutrosophic number set (T2NNS) represented by $\tilde{M}$ can be defined in Y as an object having the form:

$$\tilde{M}=\left\{\left\langle y, \tilde{T}_{\tilde{M}}(y), \tilde{I}_{\tilde{M}}(y), \tilde{F}_{\tilde{M}}(y) \mid y \in Y\right\rangle\right\}, \tag{5}$$

where $\tilde{T}_{\tilde{M}}(y): Y \to D[0,1],$ $\tilde{I}_{\tilde{M}}(y): Y \to D[0,1],$ and $\tilde{F}_{\tilde{M}}(y): Y \to D[0,1].$ A T2NNS $\tilde{T}_{\tilde{M}}(y)=\left(T_{T_{\tilde{M}}}(y), T_{I_{\tilde{M}}}(y), T_{F_{\tilde{M}}}(y)\right),$ $\tilde{I}_{\tilde{M}}(y)=\left(I_{T_{\tilde{M}}}(y), I_{I_{\tilde{M}}}(y), I_{F_{\tilde{M}}}(y)\right),$ and $\tilde{F}_{\tilde{M}}(y)=\left(F_{T_{\tilde{M}}}(y), F_{I_{\tilde{M}}}(y), F_{F_{\tilde{M}}}(y)\right),$ denote the truth, indeterminacy, and falsity memberships of y in $\tilde{M},$ respectively. The membership parameters satisfy the condition:

$$0 \le \tilde{T}_{\tilde{M}}(y)^3+\tilde{I}_{\tilde{M}}(y)^3+\tilde{F}_{\tilde{M}}(y)^3 \le 3, \quad \forall y \in Y. \tag{6}$$

For ease of simplicity, we consider $\tilde{M}=\left\langle\left(T_{T_{\tilde{M}}}(y), T_{I_{\tilde{M}}}(y), T_{F_{\tilde{M}}}(y)\right),\left(I_{T_{\tilde{M}}}(y), I_{I_{\tilde{M}}}(y), I_{F_{\tilde{M}}}(y)\right),\left(F_{T_{\tilde{M}}}(y), F_{I_{\tilde{M}}}(y), F_{F_{\tilde{M}}}(y)\right)\right\rangle,$ as a T2NN.

Definition 4 (Abdel-Basset et al., 2019b). Let $\tilde{M}=\left\langle\left(T_{T_{\tilde{M}}}(y), T_{I_{\tilde{M}}}(y), T_{F_{\tilde{M}}}(y)\right),\left(I_{T_{\tilde{M}}}(y), I_{I_{\tilde{M}}}(y), I_{F_{\tilde{M}}}(y)\right),\left(F_{T_{\tilde{M}}}(y), F_{I_{\tilde{M}}}(y), F_{F_{\tilde{M}}}(y)\right)\right\rangle,$ $\tilde{M}_1=\left\langle\left(T_{T_{\tilde{M}_1}}(y), T_{I_{\tilde{M}_1}}(y), T_{F_{\tilde{M}_1}}(y)\right),\left(I_{T_{\tilde{M}_1}}(y), I_{I_{\tilde{M}_1}}(y), I_{F_{\tilde{M}_1}}(y)\right),\left(F_{T_{\tilde{M}_1}}(y), F_{I_{\tilde{M}_1}}(y), F_{F_{\tilde{M}_1}}(y)\right)\right\rangle,$ and $\tilde{M}_2=\left\langle\left(T_{T_{\tilde{M}_2}}(y), T_{I_{\tilde{M}_2}}(y), T_{F_{\tilde{M}_2}}(y)\right),\left(I_{T_{\tilde{M}_2}}(y), I_{I_{\tilde{M}_2}}(y), I_{F_{\tilde{M}_2}}(y)\right),\left(F_{T_{\tilde{M}_2}}(y), F_{I_{\tilde{M}_2}}(y), F_{F_{\tilde{M}_2}}(y)\right)\right\rangle$ be three T2NNs and $\lambda>0$. Their operations are defined as follows:

(a) Addition "⊕"

$$\tilde{M}_1 \oplus \tilde{M}_2 = \Big\langle \Big(T_{T_{\tilde{M}_1}}(y) + T_{T_{\tilde{M}_2}}(y) - T_{T_{\tilde{M}_1}}(y) \times T_{T_{\tilde{M}_2}}(y),\ T_{I_{\tilde{M}_1}}(y) + T_{I_{\tilde{M}_2}}(y) - T_{I_{\tilde{M}_1}}(y) \times T_{I_{\tilde{M}_2}}(y),\ T_{F_{\tilde{M}_1}}(y) + T_{F_{\tilde{M}_2}}(y) - T_{F_{\tilde{M}_1}}(y) \times T_{F_{\tilde{M}_2}}(y) \Big), \Big(I_{T_{\tilde{M}_1}}(y) \times I_{T_{\tilde{M}_2}}(y),\ I_{I_{\tilde{M}_1}}(y) \times I_{I_{\tilde{M}_2}}(y),\ I_{F_{\tilde{M}_1}}(y) \times I_{F_{\tilde{M}_2}}(y) \Big), \Big(F_{T_{\tilde{M}_1}}(y) \times F_{T_{\tilde{M}_2}}(y),\ F_{I_{\tilde{M}_1}}(y) \times F_{I_{\tilde{M}_2}}(y),\ F_{F_{\tilde{M}_1}}(y) \times F_{F_{\tilde{M}_2}}(y) \Big) \Big\rangle, \quad (7)$$

(b) Multiplication "⊗"

$$\tilde{M}_1 \otimes \tilde{M}_2 = \Big\langle \Big(T_{T_{\tilde{M}_1}}(y) \times T_{T_{\tilde{M}_2}}(y),\ T_{I_{\tilde{M}_1}}(y) \times T_{I_{\tilde{M}_2}}(y),\ T_{F_{\tilde{M}_1}}(y) \times T_{F_{\tilde{M}_2}}(y) \Big), \Big(T_{T_{\tilde{M}_1}}(y) + T_{T_{\tilde{M}_2}}(y) - T_{T_{\tilde{M}_1}}(y) \times T_{T_{\tilde{M}_2}}(y),\ T_{I_{\tilde{M}_1}}(y) + T_{I_{\tilde{M}_2}}(y) - T_{I_{\tilde{M}_1}}(y) \times T_{I_{\tilde{M}_2}}(y),\ T_{F_{\tilde{M}_1}}(y) + T_{F_{\tilde{M}_2}}(y) - T_{F_{\tilde{M}_1}}(y) \times T_{F_{\tilde{M}_2}}(y) \Big), \Big(T_{T_{\tilde{M}_1}}(y) + T_{T_{\tilde{M}_2}}(y) - T_{T_{\tilde{M}_1}}(y) \times T_{T_{\tilde{M}_2}}(y),\ T_{I_{\tilde{M}_1}}(y) + T_{I_{\tilde{M}_2}}(y) - T_{I_{\tilde{M}_1}}(y) \times T_{I_{\tilde{M}_2}}(y),\ T_{F_{\tilde{M}_1}}(y) + T_{F_{\tilde{M}_2}}(y) - T_{F_{\tilde{M}_1}}(y) \times T_{F_{\tilde{M}_2}}(y) \Big) \Big\rangle, \quad (8)$$

(c) Scalar multiplication

$$\lambda \tilde{M} = \Big\langle \Big(1 - \big(1 - T_{T_{\tilde{M}}}(y)\big)^{\lambda}, 1 - \big(1 - T_{I_{\tilde{M}}}(y)\big)^{\lambda}, 1 - \big(1 - T_{F_{\tilde{M}}}(y)\big)^{\lambda} \Big), \Big(\big(I_{T_{\tilde{M}}}(y)\big)^{\lambda}, \big(I_{I_{\tilde{M}}}(y)\big)^{\lambda}, \big(I_{F_{\tilde{M}}}(y)\big)^{\lambda} \Big), \Big(\big(F_{T_{\tilde{M}}}(y)\big)^{\lambda}, \big(F_{I_{\tilde{M}}}(y)\big)^{\lambda}, \big(F_{F_{\tilde{M}}}(y)\big)^{\lambda} \Big) \Big\rangle, \quad (9)$$

(d) Power

$$\tilde{M}^{\lambda} = \Big\langle \Big(\big(T_{T_{\tilde{M}}}(y)\big)^{\lambda}, \big(T_{I_{\tilde{M}}}(y)\big)^{\lambda}, \big(T_{F_{\tilde{M}}}(y)\big)^{\lambda} \Big), \Big(1 - \big(1 - I_{T_{\tilde{M}}}(y)\big)^{\lambda}, 1 - \big(1 - I_{I_{\tilde{M}}}(y)\big)^{\lambda}, 1 - \big(1 - I_{F_{\tilde{M}}}(y)\big)^{\lambda} \Big), \Big(1 - \big(1 - F_{T_{\tilde{M}}}(y)\big)^{\lambda}, 1 - \big(1 - F_{I_{\tilde{M}}}(y)\big)^{\lambda}, 1 - \big(1 - F_{F_{\tilde{M}}}(y)\big)^{\lambda} \Big) \Big\rangle. \quad (10)$$

Definition 5 (Abdel-Basset et al., 2019b). Suppose that $\tilde{M}_l = \left\langle \left(T_{T_{\tilde{M}_l}}(y), T_{I_{\tilde{M}_l}}(y), T_{F_{\tilde{M}_l}}(y) \right), \left(I_{T_{\tilde{M}_l}}(y), I_{I_{\tilde{M}_l}}(y), I_{F_{\tilde{M}_l}}(y) \right), \left(F_{T_{\tilde{M}_l}}(y), F_{I_{\tilde{M}_l}}(y), F_{F_{\tilde{M}_l}}(y) \right) \right\rangle$ (l=1, …, p) is a collection of T2NNs, and $\gamma=(\gamma_1, ..., \gamma_p)^T$ be the weight vector of them, with $\gamma_l \in [0, 1]$ and $\sum_{l=1}^{p} \gamma_l = 1$. A type-2 neutrosophic number weighted averaging (T2NNWA) operator is defined as follows:

$$\begin{aligned} T2NNWA_{\gamma}(\tilde{M}_1, ..., \tilde{M}_l, ..., \tilde{M}_p) &= \gamma_1 \tilde{M}_1 \oplus \cdots \oplus \gamma_l \tilde{M}_l \oplus \cdots \oplus \gamma_p \tilde{M}_p = \bigoplus_{l=1}^{p} \gamma_l \tilde{M}_l \\ &= \Bigg\langle \left(1 - \prod_{l=1}^{p} \left(1 - T_{T_{\tilde{M}_l}}(y)\right)^{\gamma_l}, 1 - \prod_{l=1}^{p} \left(1 - T_{I_{\tilde{M}_l}}(y)\right)^{\gamma_l}, 1 - \prod_{l=1}^{p} \left(1 - T_{F_{\tilde{M}_l}}(y)\right)^{\gamma_l} \right), \\ &\quad \left(\prod_{l=1}^{p} \left(I_{T_{\tilde{M}_l}}(y) \right)^{\gamma_l}, \prod_{l=1}^{p} \left(I_{I_{\tilde{M}_l}}(y) \right)^{\gamma_l}, \prod_{l=1}^{p} \left(I_{F_{\tilde{M}_l}}(y) \right)^{\gamma_l} \right), \\ &\quad \left(\prod_{l=1}^{p} \left(F_{T_{\tilde{M}_l}}(y) \right)^{\gamma_l}, \prod_{l=1}^{p} \left(F_{I_{\tilde{M}_l}}(y) \right)^{\gamma_l}, \prod_{l=1}^{p} \left(F_{F_{\tilde{M}_l}}(y) \right)^{\gamma_l} \right) \Bigg\rangle. \end{aligned} \tag{11}$$

Definition 6 (Abdel-Basset et al., 2019b). Let $\tilde{M} = \left\langle \left(T_{T_{\tilde{M}}}(y), T_{I_{\tilde{M}}}(y), T_{F_{\tilde{M}}}(y) \right), \left(I_{T_{\tilde{M}}}(y), I_{I_{\tilde{M}}}(y), I_{F_{\tilde{M}}}(y) \right), \left(F_{T_{\tilde{M}}}(y), F_{I_{\tilde{M}}}(y), F_{F_{\tilde{M}}}(y) \right) \right\rangle$ be a T2NN. The score function of $\tilde{M}$ is defined as follows:

$$\begin{aligned} S(\tilde{M}) = \frac{1}{12} \Big\langle 8 &+ \left(T_{T_{\tilde{M}}}(y) + 2\left(T_{I_{\tilde{M}}}(y) \right) + T_{F_{\tilde{M}}}(y) \right) - \left(I_{T_{\tilde{M}}}(y) + 2\left(I_{I_{\tilde{M}}}(y) \right) + I_{F_{\tilde{M}}}(y) \right) \\ &- \left(F_{T_{\tilde{M}}}(y) + 2\left(F_{I_{\tilde{M}}}(y) \right) + F_{F_{\tilde{M}}}(y) \right) \Big\rangle. \end{aligned} \tag{12}$$

4.2. The Integrated Neutrosophic Decision-Making Model for ALiB Remanufacturing Facility Location Selection

The flowchart of the integrated neutrosophic decision-making model is presented in Fig. 2. The introduced methodological framework for an ALiB remanufacturing facility location selection involves three stages. In the first stage, the systematic literature review identifies evaluation criteria and relevant experts propose suitable locations for the construction of an ALiB remanufacturing facility. In the second stage, the hierarchical BWM determines optimal criteria weights. In the last stage, the T2NN-based CODAS method orders ALiB remanufacturing facility locations.

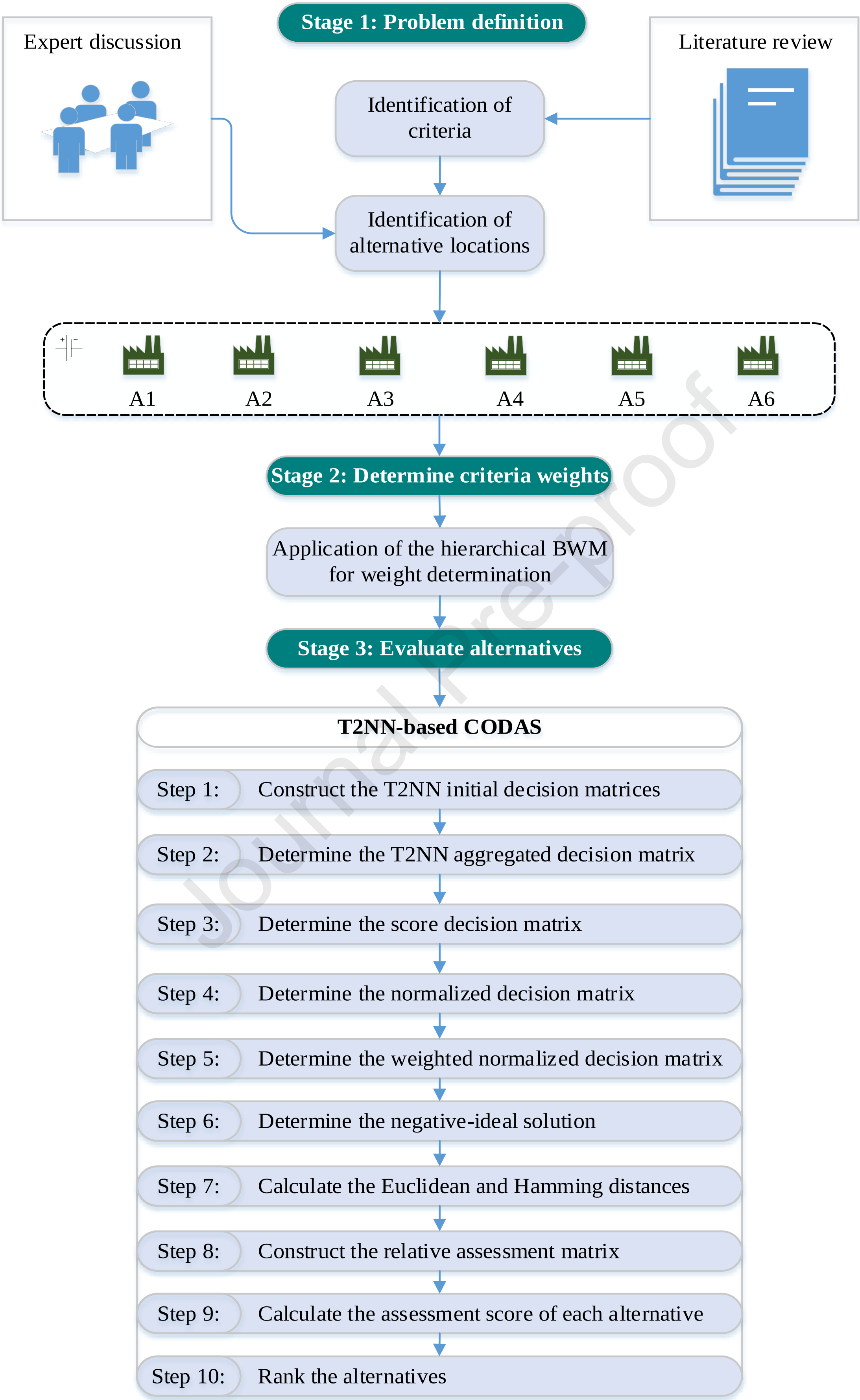

Fig. 2. The flowchart of the proposed integrated neutrosophic decision-making model for ALiB remanufacturing facility location selection.

4.2.1. Hierarchical Best-Worst Method

Rezaei (2015) developed the BWM as an optimization-based weight determination tool for complicated decision-making problems. Since its development, the BWM has attracted many researchers from different fields due to its high reliability and preciseness to determine optimal weight coefficient values. Previously, the BWM has been used for criteria weight determination in construction management (Maghsoodi et al., 2020), energy management (van de Kaa et al., 2019; Mousavi-Nasab and Sotoudeh-Anvari, 2020), environmental engineering (Torkayesh et al., 2021a), healthcare management (Yazdani et al., 2020), logistics (Gupta and Barua, 2017; Ecer and Pamucar, 2020), and urban planning (Torkayesh et al., 2021b). Two main reasons that BWM is selected to determine the optimal weight coefficient values of the locating criteria are related to the high reliability of the BWM in comparison to other methods such as AHP or SWARA, and also the fact that no study in the remanufacturing field has used it before. Due to the hierarchical nature of the criteria in this research, we adopted the hierarchical form of the BWM, which enabled us to determine local weights of the sub-criteria and finally calculate global weight coefficient values by using weights of the main criteria.

The systematic literature review identifies a finite set of location selection criteria as C={C_1, …, C_j, …, C_n} (n≥2). The hierarchical BWM has the following steps:

Step 1: Experts identify the best and the worst location selection criteria.

Step 2: All criteria are evaluated through a pairwise evaluation. The experts select the preference of the best criterion over others using a nine-point scale, where nine represents the highest preference and one represents the lowest preference. The comparison outcome is a vector $\Pi_B = (\pi_{B1}, ..., \pi_{Bj}, ..., \pi_{Bn}),$ called the Best-to-others vector, where π_{Bj} represents the preference of the best criterion C_B over the criterion C_j, and $\pi_{BB} = 1.$

Step 3: The experts continue the same process for the worst criterion. Each expert does a pairwise comparison between the other criteria and the worst criterion. Final results are shown as a vector $\Pi_W = (\pi_{1W}, ..., \pi_{jW}, ..., \pi_{nW})^T,$ labeled as the Others-to-worst vector, where π_{jW} represents the preference of the criterion C_j over the worst criterion C_W, and $\pi_{WW} = 1.$

Step 4: Optimal weights of the criteria for locating ALiB remanufacturing facilities are calculated as $(\omega_1^*, ..., \omega_j^*, ..., \omega_n^*).$ For each pair of ω_B/ω_j and ω_j/ω_W an optimal weight has to meet the requirement of $\omega_B/\omega_j = \pi_{Bj}$ and $\omega_j/\omega_W = \pi_{jW},$ respectively. To satisfy these equations, the maximum absolute differences $|\omega_B/\omega_j - \pi_{Bj}|$ and $|\omega_j/\omega_W - \pi_{jW}|$ need to be minimized for all criteria. The BWM model can be formulated considering the non-negativity features and sum condition of the criteria weights as follows:

$$\min \max_{1\le j\le n} \left\{ \left| \frac{\omega_B}{\omega_j} - \pi_{Bj} \right|, \left| \frac{\omega_j}{\omega_W} - \pi_{jW} \right| \right\}$$
$$s.t. \begin{cases} \sum_{j=1}^{n} \omega_j = 1 \\ \omega_j \ge 0, \ \ \forall j = 1, \ldots, n. \end{cases} \tag{13}$$

This model can be reformulated as:

$$\min \xi$$
$$s.t. \begin{cases} \left| \frac{\omega_B}{\omega_j} - \pi_{Bj} \right| \le \xi, \ \ \forall j = 1, \ldots, n \\ \left| \frac{\omega_j}{\omega_W} - \pi_{jW} \right| \le \xi, \ \ \forall j = 1, \ldots, n \\ \sum_{j=1}^{n} \omega_j = 1 \\ \omega_j \ge 0, \ \ \forall j = 1, \ldots, n. \end{cases} \tag{14}$$

Results obtained from model (14) have to be checked as defined by Rezaei (2015). The consistency ratio (*CR*) can be calculated by using ξ^* and the corresponding consistency index (*CI*) from Table 4 as follows:

$$CR = \frac{\xi^*}{CI}. \tag{15}$$

Table 4
BWM consistency index.

π_{BW}	1	2	3	4	5	6	7	8	9
Consistency index	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

4.2.2. Type-2 Neutrosophic Number-Based CODAS Method

The invited experts D={D_1, …, D_e, …, D_k} ($k \ge 2$) propose a finite set of suitable locations for the construction of an ALiB remanufacturing facility as A={A_1, …, A_i, …, A_m} ($m \ge 2$). In this study, the CODAS method is extended under the T2NN environment to order ALiB remanufacturing facility locations. The steps of the introduced T2NN-based CODAS method are given in the following:

Step 1: Construct the T2NN initial decision matrices $\tilde{\Psi}^e = [\tilde{\psi}^e_{ij}]_{m \times n}$:

$$\tilde{\Psi}^e = \begin{matrix} \\ A_1 \\ \vdots \\ A_m \end{matrix} \begin{bmatrix} C_1 & \cdots & C_n \\ \left\langle \begin{matrix} \left(T_{T_{\tilde{\psi}^e_{11}}}(y), T_{I_{\tilde{\psi}^e_{11}}}(y), T_{F_{\tilde{\psi}^e_{11}}}(y)\right), \\ \left(I_{T_{\tilde{\psi}^e_{11}}}(y), I_{I_{\tilde{\psi}^e_{11}}}(y), I_{F_{\tilde{\psi}^e_{11}}}(y)\right), \\ \left(F_{T_{\tilde{\psi}^e_{11}}}(y), F_{I_{\tilde{\psi}^e_{11}}}(y), F_{F_{\tilde{\psi}^e_{11}}}(y)\right) \end{matrix} \right\rangle & \cdots & \left\langle \begin{matrix} \left(T_{T_{\tilde{\psi}^e_{1n}}}(y), T_{I_{\tilde{\psi}^e_{1n}}}(y), T_{F_{\tilde{\psi}^e_{1n}}}(y)\right), \\ \left(I_{T_{\tilde{\psi}^e_{1n}}}(y), I_{I_{\tilde{\psi}^e_{1n}}}(y), I_{F_{\tilde{\psi}^e_{1n}}}(y)\right), \\ \left(F_{T_{\tilde{\psi}^e_{1n}}}(y), F_{I_{\tilde{\psi}^e_{1n}}}(y), F_{F_{\tilde{\psi}^e_{1n}}}(y)\right) \end{matrix} \right\rangle \\ \vdots & \ddots & \vdots \\ \left\langle \begin{matrix} \left(T_{T_{\tilde{\psi}^e_{m1}}}(y), T_{I_{\tilde{\psi}^e_{m1}}}(y), T_{F_{\tilde{\psi}^e_{m1}}}(y)\right), \\ \left(I_{T_{\tilde{\psi}^e_{m1}}}(y), I_{I_{\tilde{\psi}^e_{m1}}}(y), I_{F_{\tilde{\psi}^e_{m1}}}(y)\right), \\ \left(F_{T_{\tilde{\psi}^e_{m1}}}(y), F_{I_{\tilde{\psi}^e_{m1}}}(y), F_{F_{\tilde{\psi}^e_{m1}}}(y)\right) \end{matrix} \right\rangle & \cdots & \left\langle \begin{matrix} \left(T_{T_{\tilde{\psi}^e_{mn}}}(y), T_{I_{\tilde{\psi}^e_{mn}}}(y), T_{F_{\tilde{\psi}^e_{mn}}}(y)\right), \\ \left(I_{T_{\tilde{\psi}^e_{mn}}}(y), I_{I_{\tilde{\psi}^e_{mn}}}(y), I_{F_{\tilde{\psi}^e_{mn}}}(y)\right), \\ \left(F_{T_{\tilde{\psi}^e_{mn}}}(y), F_{I_{\tilde{\psi}^e_{mn}}}(y), F_{F_{\tilde{\psi}^e_{mn}}}(y)\right) \end{matrix} \right\rangle \end{bmatrix}, \quad (16)$$

$e = 1, \ldots, k,$

where $\tilde{\psi}^e_{ij} = \left\langle \left(T_{T_{\tilde{\psi}^e_{ij}}}(y), T_{I_{\tilde{\psi}^e_{ij}}}(y), T_{F_{\tilde{\psi}^e_{ij}}}(y)\right), \left(I_{T_{\tilde{\psi}^e_{ij}}}(y), I_{I_{\tilde{\psi}^e_{ij}}}(y), I_{F_{\tilde{\psi}^e_{ij}}}(y)\right), \left(F_{T_{\tilde{\psi}^e_{ij}}}(y), F_{I_{\tilde{\psi}^e_{ij}}}(y), F_{F_{\tilde{\psi}^e_{ij}}}(y)\right) \right\rangle$,

(i=1, ..., m; j=1, ..., n; e=1, ..., k) is a T2NN that represents the evaluation of the alternative A_i with respect to the location selection criterion C_j given by the invited expert D_e. The initial decision matrices are structured by using a T2NN linguistic scale. The seven-point T2NN linguistic scale presented in Table 5 can be used to present alternative evaluation preferences of the experts.

Table 5
T2NN linguistic variables for evaluating suitable locations for an ALiB remanufacturing facility.

Linguistic variable	Type-2 neutrosophic number
Very Bad (VB)	<(0.20, 0.20, 0.10), (0.65, 0.80, 0.85), (0.45, 0.80, 0.70)>
Bad (B)	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>
Medium Bad (MB)	<(0.50, 0.30, 0.50), (0.50, 0.35, 0.45), (0.45, 0.30, 0.60)>
Medium (M)	<(0.40, 0.45, 0.50), (0.40, 0.45, 0.50), (0.35, 0.40, 0.45)>
Medium Good (MG)	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>
Good (G)	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>
Very Good (VG)	<(0.95, 0.90, 0.95), (0.10, 0.10, 0.05), (0.05, 0.05, 0.05)>

Step 2: Determine the T2NN aggregated decision matrix $\tilde{Z} = [\tilde{z}_{ij}]_{m \times n}$:

$$\tilde{z}_{ij} = T2NNWA_{\delta}(\tilde{\psi}_{ij}^{1}, ..., \tilde{\psi}_{ij}^{e}, ..., \tilde{\psi}_{ij}^{k}) = \mathop{\oplus}_{e=1}^{k} \delta_e \tilde{\psi}_{ij}^{e}$$

$$= \left\langle \left(1 - \prod_{e=1}^{k} \left(1 - T_{T_{\tilde{\psi}_{ij}^{e}}}(y) \right)^{\delta_e}, 1 - \prod_{e=1}^{k} \left(1 - T_{I_{\tilde{\psi}_{ij}^{e}}}(y) \right)^{\delta_e}, 1 - \prod_{e=1}^{k} \left(1 - T_{F_{\tilde{\psi}_{ij}^{e}}}(y) \right)^{\delta_e} \right), \right.$$

$$\left(\prod_{e=1}^{k} \left(I_{T_{\tilde{\psi}_{ij}^{e}}}(y) \right)^{\delta_e}, \prod_{e=1}^{k} \left(I_{I_{\tilde{\psi}_{ij}^{e}}}(y) \right)^{\delta_e}, \prod_{e=1}^{k} \left(I_{F_{\tilde{\psi}_{ij}^{e}}}(y) \right)^{\delta_e} \right), \tag{17}$$

$$\left. \left(\prod_{e=1}^{k} \left(F_{T_{\tilde{\psi}_{ij}^{e}}}(y) \right)^{\delta_e}, \prod_{e=1}^{k} \left(F_{I_{\tilde{\psi}_{ij}^{e}}}(y) \right)^{\delta_e}, \prod_{e=1}^{k} \left(F_{F_{\tilde{\psi}_{ij}^{e}}}(y) \right)^{\delta_e} \right) \right\rangle, \; i = 1, \dots, m; \; j = 1, \dots, n,$$

where the aggregation is determined by applying the T2NNWA operator (Definition 5),

$$\tilde{z}_{ij} = \left\langle \left(T_{T_{\tilde{z}_{ij}}}(y), T_{I_{\tilde{z}_{ij}}}(y), T_{F_{\tilde{z}_{ij}}}(y) \right), \left(I_{T_{\tilde{z}_{ij}}}(y), I_{I_{\tilde{z}_{ij}}}(y), I_{F_{\tilde{z}_{ij}}}(y) \right), \left(F_{T_{\tilde{z}_{ij}}}(y), F_{I_{\tilde{z}_{ij}}}(y), F_{F_{\tilde{z}_{ij}}}(y) \right) \right\rangle$$

is the T2NN aggregated evaluation of the alternative A_i with respect to the location selection criterion C_j given by the experts, and $\delta = (\delta_1, \dots, \delta_e, \dots, \delta_k)^T$ is the importance vector of the invited experts, with $\delta_e \in [0,1]$ (e=1, …, k), and $\sum_{e=1}^{k} \delta_e = 1$.

Step 3: Determine the score decision matrix $\Theta = [S(\tilde{z}_{ij})]_{m \times n}$:

$$S(\tilde{z}_{ij}) = \frac{1}{12} \left\langle 8 + \left(T_{T_{\tilde{z}_{ij}}}(y) + 2\left(T_{I_{\tilde{z}_{ij}}}(y) \right) + T_{F_{\tilde{z}_{ij}}}(y) \right) - \left(I_{T_{\tilde{z}_{ij}}}(y) + 2\left(I_{I_{\tilde{z}_{ij}}}(y) \right) + I_{F_{\tilde{z}_{ij}}}(y) \right) \right.$$

$$\left. - \left(F_{T_{\tilde{z}_{ij}}}(y) + 2\left(F_{I_{\tilde{z}_{ij}}}(y) \right) + F_{F_{\tilde{z}_{ij}}}(y) \right) \right\rangle, \; i = 1, \dots, m; \; j = 1, \dots, n. \tag{18}$$

where $S(\tilde{z}_{ij})$ represents the score function of the T2NN aggregated evaluation of the alternative A_i with respect to the location selection criterion C_j given by the experts.

Step 4: Determine the normalized decision matrix $\mathrm{R} = [r_{ij}]_{m \times n}$:

$$r_{ij} = \begin{cases} \dfrac{S(\tilde{z}_{ij})}{\max\limits_{1 \le t \le m} S(\tilde{z}_{ij})} \mid C_j \in \mathrm{C}^{+} \\ \dfrac{\min\limits_{1 \le t \le m} S(\tilde{z}_{ij})}{S(\tilde{z}_{ij})} \mid C_j \in \mathrm{C}^{-} \end{cases}, \; i = 1, \dots, m; \; j = 1, \dots, n, \tag{19}$$

where r_{ij} denotes a normalized evaluation of the alternative A_i with respect to the location selection criterion C_j given by the experts, $\mathrm{C}^{+} \subseteq \mathrm{C}$ is the set of benefit evaluation criteria,

$C^{-} \subseteq C$ is the set of cost evaluation criteria, and $C^{+} \cup C^{-} = C$.

Step 5: Determine the weighted normalized decision matrix $G = [g_{ij}]_{m\times n}$:

$$g_{ij} = \omega_j^{*} r_{ij},\ i = 1, \ldots, m;\ j = 1, \ldots, n, \tag{20}$$

where g_{ij} denotes a weighted normalized evaluation of the alternative A_i with respect to the location selection criterion C_j given by the experts.

Step 6: Determine the negative-ideal solution $O = [o_j]_{1\times n}$:

$$o_j = \min_{1\le i\le m} p_{ij},\ j = 1, \ldots, n, \tag{21}$$

where o_j represents a minimum value of the alternatives with respect to the location selection criterion C_j given by the experts.

Step 7: Calculate the Euclidean and Hamming distances of alternatives from the negative-ideal solution.

(i) The Euclidean distance:

$$ED_i = \sqrt{\sum_{j=1}^{n} (g_{ij} - o_j)^2},\ i = 1, \ldots, m, \tag{22}$$

(ii) The Hamming distance:

$$HD_i = \sum_{j=1}^{n} | g_{ij} - o_j |,\ i = 1, \ldots, m. \tag{23}$$

Step 8: Construct the relative assessment matrix $V = [v_{it}]_{m\times m}$:

$$v_{it} = ED_i - ED_t + \Phi_{it}\left(ED_i - ED_t\right)\cdot(HD_i - HD_t),\ i, t = 1, \ldots, m, \tag{24}$$

where Φ is a threshold function to recognize the equality of Euclidean distance measures of two alternative locations for an ALiB remanufacturing facility. It is defined as follows:

$$\Phi_{it}\left(ED_i - ED_t\right) = \begin{cases} 1 \mid & \phi \le | ED_i - ED_t | \\ 0 \mid & \phi > | ED_i - ED_t | \end{cases},\ i, t = 1, \ldots, m; \phi \ge 0, \tag{25}$$

where ϕ is the threshold parameter.

Step 9: Calculate the assessment score of each alternative:

$$\rho_i = \sum_{t=1}^{m} v_{it},\ i = 1, \ldots, m. \tag{26}$$

where ρ_i represents the assessment scores of the alternative A_i.

Step 10: Rank the alternative locations for an ALiB remanufacturing facility according to the decreasing values of assessment scores. The highest score is the best location.

5. Results and Discussion

In this section, the experimental results of proposed model, comparative analysis, and sensitivity analysis are presented.

5.1. Results of the Hierarchical BWM

Four experts from the EV and energy storage industries participated in the case study. This sub-section presents the results of the criteria weight determination process.

Firstly, the experts are asked to identify the best and worst main criteria. Weights of the main criteria are calculated based on the opinions of each expert. Then, an aggregated weight of each main criteria is calculated. Table 6 represents the details of this step. As shown in this table, three out of four experts consider the economic criterion (MC_1) as the most important and the social criterion (MC_3) as the worst. Results show the following order of importance $MC_1>MC_4>MC_2>MC_3$.

Table 6
Results of the hierarchical BWM for the main criteria.

Expert	Main criteria selection		Vector	Main criteria			
				MC_1	MC_2	MC_3	MC_4
Expert 1	Best	MC_1	Best-to-others	1	6	9	2
	Worst	MC_3	Others-to-worst	9	4	1	7
	Weight			0.5177	0.1064	0.0567	0.3191
	Ksi^*			0.1206			
Expert 2	Best	MC_1	Best-to-others	1	5	8	3
	Worst	MC_3	Others-to-worst	8	5	1	7
	Weight			0.5687	0.1416	0.0536	0.2361
	Ksi^*			0.1395			
Expert 3	Best	MC_4	Best-to-others	2	3	7	1
	Worst	MC_3	Others-to-worst	7	5	1	6
	Weight			0.2885	0.1923	0.0577	0.4615
	Ksi^*			0.1154			
Expert 4	Best	MC_1	Best-to-others	1	7	5	3
	Worst	MC_3	Others-to-worst	5	3	1	4
	Weight			0.5719	0.1031	0.0844	0.2406
	Ksi^*			0.1500			
Aggregated weight				**0.4867**	**0.1359**	**0.0631**	**0.3143**

Secondly, local weights of the criteria are calculated within each main criteria group and aggregated. Then, global aggregated weights are obtained by multiplying the aggregated weights of the main criteria (Table 6) with the aggregated local weights of the criteria. Tables A.1–A.4 (Appendix) presents the hierarchical BWM operations and results for the economic, environmental, social, and technical criteria.

5.2. Results of the T2NN-CODAS Method

Step 1: The six alternative locations with respect to twenty criteria are evaluated by four experts by using T2NN linguistic variables given in Table 5. The linguistic evaluations of the

ALiB remanufacturing facility locations are presented in Table 7. The T2NN initial decision matrices are constructed based on the experts' input and provided in Table A.5 (Appendix).

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Table 7
Experts' evaluations of the locations for an ALiB remanufacturing facility with respect to the criteria.

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: Gemlik/Bursa	E_1	VB	B	VB	VB	VG	B	VB	VG	VB	VG	VB	VG	VB	VB	VG	VG	G	VG	VG	VG
	E_2	VB	VB	B	VB	G	VB	VB	VG	VB	VG	VB	VG	VB	VB	VG	VG	VG	G	VG	VG
	E_3	VB	B	MB	B	VG	MB	VB	VG	VB	G	MB	VG	B	VB	VG	G	MG	VG	G	VG
	E_4	VB	B	B	VB	VG	B	MB	VG	MB	MG	VB	VG	B	VB	G	VG	MG	G	VG	G
A_2: Yunusemre/Manisa	E_1	M	MB	M	MG	MG	MG	MB	G	B	G	G	MG	MG	M	MG	MG	MG	MG	M	MB
	E_2	MG	M	MB	M	MG	M	MG	MG	M	G	MG	MG	M	MG	MG	G	G	G	MG	MG
	E_3	B	MB	M	MG	MG	MG	B	G	B	MG	MB	MG	MB	M	MG	M	M	B	MG	M
	E_4	B	MG	M	MG	MG	G	M	M	B	B	G	M	VB	B	MB	MG	M	MG	B	M
A_3: Tuzla/Istanbul	E_1	MB	MB	MB	B	G	M	MB	MG	MB	G	MG	G	M	MB	G	MG	G	M	G	MG
	E_2	B	MB	B	MB	VG	MB	MB	G	B	G	M	G	B	MB	MG	G	VG	VG	MG	G
	E_3	M	MG	MB	M	G	M	MB	VG	G	M	VG	G	MG	G	M	G	MB	MG	VG	G
	E_4	M	VG	VG	MB	G	M	MG	VG	M	MG	MG	M	VG	B	MG	G	M	G	G	MG
A_4: Sincan/Ankara	E_1	M	MG	MB	G	MG	G	G	B	B	M	M	M	G	G	MB	M	MB	MG	M	M
	E_2	MG	MG	VG	MG	M	G	MG	M	MG	M	G	B	MG	MG	M	MG	MG	MG	MG	MG
	E_3	MB	MG	M	MB	M	MG	M	M	M	MG	M	G	G	MB	VG	MB	B	M	M	MG
	E_4	G	M	MG	M	M	MG	G	G	G	M	G	MG	MG	M	M	B	MB	MB	MG	VB
A_5: Melikgazi/Kayseri	E_1	G	MG	M	G	MG	G	MG	B	G	M	G	M	VG	G	MB	B	B	B	VB	B
	E_2	G	VG	VG	G	M	VG	VG	MB	VG	MB	VG	B	G	VG	VB	MB	MB	VB	B	B
	E_3	MG	MB	MG	MB	B	G	MG	MB	MB	MB	G	M	MG	M	M	B	G	G	MB	B
	E_4	MB	MG	MB	M	MG	G	VG	G	MG	M	MB	B	M	MB	MG	B	B	MB	M	B
A_6: Seyitgazi/Eskişehir	E_1	VG	VG	G	VG	B	VG	VG	VB	G	VB	VG	VB	VG	VG	B	VB	B	B	B	VB
	E_2	G	VG	G	MG	M	VG	MG	MB	VG	VB	VG	B	VG	G	B	B	VB	B	B	MB
	E_3	G	VG	VG	VG	VB	G	G	VB	M	B	G	MB	G	VG	MB	B	MB	VB	B	MB
	E_4	MG	VG	G	G	B	VG	MG	B	MG	G	G	VB	VG	MG	B	MB	B	M	MB	B

Very Bad: VB; Bad: B; Medium Bad: MB; Medium: M; Medium Good: MG; Good: G; Very Good: VG.

Step 2: The same importance is assigned to four experts that participated in the case study; i.e., $\delta = (0.25, 0.25, 0.25, 0.25)^T$. Four T2NN initial decision matrices (Table A.5) are aggregated with the help of the T2NNWA operator defined in Eq. (17). The determined T2NN aggregated decision matrix can be found in Table A.6 (Appendix). For example, the T2NN evaluations of the alternative "Yunusemre/Manisa" (A_2) with respect to the criterion "distance from collection centers" (C_1) are (Table A.5):

- expert 1 – $\tilde{\psi}_{21}^{1} =$ <(0.40, 0.45, 0.50), (0.40, 0.45, 0.50), (0.35, 0.40, 0.45)>,
- expert 2 – $\tilde{\psi}_{21}^{2} =$ <(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>,
- expert 3 – $\tilde{\psi}_{21}^{3} =$ <(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>, and
- expert 4 – $\tilde{\psi}_{21}^{4} =$ <(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>.

After aggregation, it is determined that the T2NN aggregated evaluation of A_2 with respect to C_1 given by four experts is:

$$\tilde{z}_{21} = \left\langle \begin{pmatrix} 1-(1-0.40)^{0.25}\cdot(1-0.60)^{0.25}\cdot(1-0.35)^{0.25}\cdot(1-0.35)^{0.25}, \\ 1-(1-0.45)^{0.25}\cdot(1-0.45)^{0.25}\cdot(1-0.35)^{0.25}\cdot(1-0.35)^{0.25}, \\ 1-(1-0.50)^{0.25}\cdot(1-0.50)^{0.25}\cdot(1-0.10)^{0.25}\cdot(1-0.10)^{0.25} \end{pmatrix}, \right.$$

$$\left. \begin{pmatrix} 0.40^{0.25}\cdot 0.20^{0.25}\cdot 0.50^{0.25}\cdot 0.50^{0.25}, \\ 0.45^{0.25}\cdot 0.15^{0.25}\cdot 0.75^{0.25}\cdot 0.75^{0.25}, \\ 0.50^{0.25}\cdot 0.25^{0.25}\cdot 0.80^{0.25}\cdot 0.80^{0.25} \end{pmatrix}, \begin{pmatrix} 0.35^{0.25}\cdot 0.10^{0.25}\cdot 0.50^{0.25}\cdot 0.50^{0.25}, \\ 0.40^{0.25}\cdot 0.25^{0.25}\cdot 0.75^{0.25}\cdot 0.75^{0.25}, \\ 0.45^{0.25}\cdot 0.15^{0.25}\cdot 0.65^{0.25}\cdot 0.65^{0.25} \end{pmatrix} \right\rangle$$

=<(0.436, 0.402, 0.329), (0.376, 0.441, 0.532), (0.306, 0.487, 0.411)>.

Step 3: The score decision matrix is given in Table 8. It is determined based on the T2NN aggregated decision matrix (Table A.6) with the help of Eq. (18). For example, the score function of the T2NN aggregated evaluation of the alternative "Seyitgazi/Eskişehir" (A_6) with respect to the criterion "distance to original equipment manufacturers" (C_3) given by the experts is (Table 8):

$$S(\tilde{z}_{63}) = \frac{1}{12}\left\langle 8 + (0.808 + 2\cdot 0.801 + 0.859) - (0.136 + 2\cdot 0.168 + 0.167) - (0.084 + 2\cdot 0.114 + 0.141) \right\rangle = 0.848.$$

Step 4: The normalized decision matrix (Table A.7) is determined by using Eq. (19) with the help of Table 8.

Table 8
The score decision matrix.

Alternative	Criterion									
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
A_1: Gemlik/Bursa	0.238	0.292	0.363	0.256	0.910	0.363	0.329	0.929	0.329	0.874
A_2: Yunusemre/Manisa	0.507	0.590	0.534	0.678	0.708	0.708	0.553	0.733	0.375	0.708
A_3: Tuzla/Istanbul	0.488	0.747	0.683	0.487	0.848	0.534	0.588	0.874	0.587	0.733
A_4: Sincan/Ankara	0.670	0.678	0.748	0.670	0.592	0.764	0.733	0.586	0.638	0.592
A_5: Melikgazi/Kayseri	0.733	0.778	0.748	0.696	0.605	0.848	0.863	0.586	0.797	0.532
A_6: Seyitgazi/Eskişehir	0.836	0.929	0.848	0.874	0.360	0.910	0.821	0.347	0.797	0.470
Type	Min	Min	Min	Min	Max	Min	Min	Max	Min	Max
Best	*0.238*	*0.292*	*0.363*	*0.256*	*0.910*	*0.363*	*0.329*	*0.929*	*0.329*	*0.874*

Alternative	Criterion									
	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{20}
A_1: Gemlik/Bursa	0.329	0.929	0.275	0.238	0.910	0.910	0.821	0.883	0.910	0.910
A_2: Yunusemre/Manisa	0.733	0.678	0.540	0.552	0.676	0.708	0.670	0.680	0.605	0.592
A_3: Tuzla/Istanbul	0.778	0.753	0.724	0.586	0.708	0.784	0.768	0.797	0.836	0.764
A_4: Sincan/Ankara	0.695	0.638	0.764	0.670	0.712	0.553	0.552	0.639	0.640	0.593
A_5: Melikgazi/Kayseri	0.812	0.434	0.797	0.768	0.540	0.378	0.545	0.533	0.422	0.308
A_6: Seyitgazi/Eskişehir	0.883	0.347	0.910	0.874	0.378	0.363	0.363	0.360	0.378	0.422
Type	Min	Max	Min	Min	Max	Max	Max	Max	Max	Max
Best	*0.329*	*0.929*	*0.275*	*0.238*	*0.910*	*0.910*	*0.821*	*0.883*	*0.910*	*0.910*

Step 5-6: The corresponding normalized evaluations (Table A.7) and the optimal weights of the criteria for locating ALiB remanufacturing facilities are taken into account to determine the weighted normalized decision matrix by utilizing Eq. (20). This matrix is given in Table 9. Then, the negative-ideal solution (NIS) (Table 9) is determined with the help of Eq. (21).

Table 9
The weighted normalized decision matrix.

Alternative	Criterion									
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
A_1: Gemlik/Bursa	0.028	0.023	0.017	0.036	0.081	0.117	0.095	0.091	0.071	0.010
A_2: Yunusemre/Manisa	0.013	0.011	0.011	0.013	0.063	0.060	0.057	0.072	0.062	0.008
A_3: Tuzla/Istanbul	0.014	0.009	0.009	0.019	0.075	0.080	0.053	0.085	0.040	0.008
A_4: Sincan/Ankara	0.010	0.010	0.008	0.014	0.052	0.056	0.043	0.057	0.037	0.007
A_5: Melikgazi/Kayseri	0.009	0.009	0.008	0.013	0.054	0.050	0.036	0.057	0.029	0.006
A_6: Seyitgazi/Eskişehir	0.008	0.007	0.007	0.010	0.032	0.047	0.038	0.034	0.029	0.005
Negative-ideal solution	*0.008*	*0.007*	*0.007*	*0.010*	*0.032*	*0.047*	*0.036*	*0.034*	*0.029*	*0.005*

Alternative	Criterion									
	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{20}
A_1: Gemlik/Bursa	0.033	0.022	0.005	0.019	0.040	0.023	0.067	0.063	0.071	0.091
A_2: Yunusemre/Manisa	0.015	0.016	0.003	0.008	0.029	0.018	0.054	0.049	0.047	0.059
A_3: Tuzla/Istanbul	0.014	0.018	0.002	0.007	0.031	0.020	0.062	0.057	0.066	0.076
A_4: Sincan/Ankara	0.015	0.015	0.002	0.007	0.031	0.014	0.045	0.046	0.050	0.059
A_5: Melikgazi/Kayseri	0.013	0.010	0.002	0.006	0.023	0.009	0.044	0.038	0.033	0.031
A_6: Seyitgazi/Eskişehir	0.012	0.008	0.002	0.005	0.016	0.009	0.029	0.026	0.030	0.042
Negative-ideal solution	*0.012*	*0.008*	*0.002*	*0.005*	*0.016*	*0.009*	*0.029*	*0.026*	*0.030*	*0.031*

Step 7: Table 10 provides the Euclidean and Hamming distances of each ALiB remanufacturing facility location alternative from the NIS, which are calculated by using Eq. (22) and Eq. (23), respectively. The corresponding weighted normalized evaluations and the NIS (Table 9) are taken into account to compute these two distance measures.

Table 10

The distance measures of the ALiB remanufacturing facility location alternatives.

Distance measure	Alternative					
	A_1: Gemlik/ Bursa	A_2: Yunusemre/ Manisa	A_3: Tuzla/ Istanbul	A_4: Sincan/ Ankara	A_5: Melikgazi/ Kayseri	A_6: Seyitgazi/ Eskişehir
Euclidean	0.164	0.082	0.109	0.058	0.039	0.011
Hamming	0.616	0.284	0.360	0.192	0.098	0.013

Step 8: The relative assessment matrix is given in Table 11. It is constructed based on Table 10 with the help of Eqs. (24)–(25). In the base case scenario, ϕ is set to 0.05.

Steps 9-10: The assessment scores of the ALiB remanufacturing facility locations are calculated by employing Eq. (26) and presented in Table 11. Then, six alternative locations are ranked according to the decreasing values of the assessment scores. The ordering is $A_1 \succ A_3 \succ A_2 \succ A_4 \succ A_5 \succ A_6$ (Table 12). Finally, the best location for the construction of an ALiB remanufacturing facility in Turkey is "Gemlik/Bursa" (A_1).

Table 11

The relative assessment matrix, scores, and ranks of the ALiB remanufacturing facility locations.

Alternative	A_1: Gemlik/ Bursa	A_2: Yunusemre/ Manisa	A_3: Tuzla/ Istanbul	A_4: Sincan/ Ankara	A_5: Melikgazi/ Kayseri	A_6: Seyitgazi/ Eskişehir	Assessment score	Rank
A_1: Gemlik/Bursa	0	0.413	0.310	0.530	0.644	0.755	2.652	1
A_2: Yunusemre/Manisa	–0.413	0	–0.027	0.024	0.044	0.342	–0.030	3
A_3: Tuzla/Istanbul	–0.310	0.027	0	0.220	0.334	0.445	0.716	2
A_4: Sincan/Ankara	–0.530	–0.024	–0.220	0	0.019	0.046	–0.709	4
A_5: Melikgazi/Kayseri	–0.644	–0.044	–0.334	–0.019	0	0.027	–1.014	5
A_6: Seyitgazi/Eskişehir	–0.755	–0.342	–0.445	–0.046	–0.027	0	–1.615	6

5.3. Comparative Analysis

The method introduced by Abdel-Basset et al. (2019b) is the only available T2NN-based MCDM approach in the literature. The T2NN-based TOPSIS method assumes that criteria weights are known in advance. Different from this method, our integrated neutrosophic decision-making model determines optimal criteria weights with the hierarchical BWM and orders alternatives with the T2NN-based CODAS method. Also, our model has one build-in parameter that provides higher flexibility when selecting public transportation pricing systems while the T2NN-based TOPSIS method has no intrinsic parameters.

The comparative analysis with the T2NN-based TOPSIS method (Abdel-Basset et al., 2019b) is carried out to explore the reliability of the proposed integrated neutrosophic decision-making model for ALiB remanufacturing facility location selection. Table 12 presents the comparison results. As can be seen from this table, "Gemlik/Bursa" (A_1) is the best location for sitting an ALiB remanufacturing facility in Turkey by both T2NN-based approaches. In addition, two compared T2NN-based approaches give the same ordering of six ALiB remanufacturing facility locations. It can be concluded that the proposed integrated neutrosophic decision-making model is highly reliable.

Table 12
The comparison of different T2NN-based approaches.

Approach	Ranking	Best location
Integrated neutrosophic decision-making model *(our study)*	$A_1 \succ A_3 \succ A_2 \succ A_4 \succ A_5 \succ A_6$	A_1
T2NN-based TOPSIS method (Abdel-Basset et al., 2019b)	$A_1 \succ A_3 \succ A_2 \succ A_4 \succ A_5 \succ A_6$	A_1

5.4. Sensitivity Analysis

The sensitivity analysis is carried out to explore the robustness of the integrated neutrosophic decision-making model by changing the threshold parameter ϕ. The values of the threshold parameter are changed from ϕ=0 to ϕ=0.20 with an increment value of 0.01. The results of the sensitivity analysis are shown in Fig. 2. As can be seen from this figure, "Gemlik/Bursa" (A_1) is the best location, while "Seyitgazi/Eskişehir" (A_6) is the worst under all threshold parameter values. In all examined scenarios, the alternative ordering of the major potential locations for the construction of an ALiB remanufacturing facility in Turkey is $A_1 \succ A_3 \succ A_2 \succ A_4 \succ A_5 \succ A_6$. The same result is obtained in the base case scenario when the threshold parameter is set to 0.05. As a result, it can be outlined that the proposed integrated neutrosophic decision-making model is highly robust.

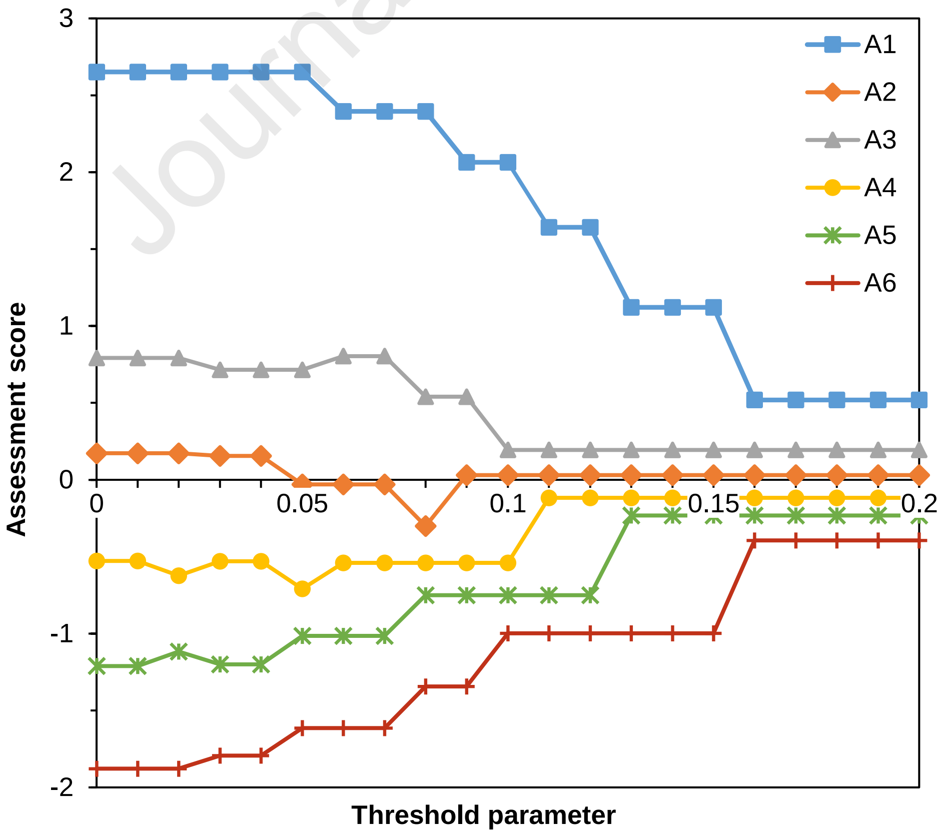

Fig. 3. The sensitivity analysis of the integrated neutrosophic decision-making model.

6. Conclusions and Implications

This study promotes the sustainable development of the EV industry and boosts large-scale ALiB remanufacturing applications in industrial practice. The presented decision-making framework, including four main criteria and twenty evaluation criteria, offers a primer for remanufacturing practitioners when making strategic facility location decisions. The developed three-stage integrated neutrosophic decision-making model provides a straightforward and flexible optimization tool for identifying the best ALiB remanufacturing facility location under uncertainty. The hierarchical BWM efficiently determines the optimal weights of economic, environmental, social, and technical clusters as well as the key evaluation criteria with the lowest subjectivity and biasedness. The innovative T2NN-based CODAS method ranks ALiB remanufacturing facility locations with high accuracy. Its findings indicate the effectiveness of the formulated methodological framework.

The case study provides valuable decision-making guidelines on how to identify the best location for an ALiB remanufacturing facility in the real-world context. Its findings indicate that "Gemlik/Bursa" is the best location for the construction of an ALiB remanufacturing facility in Turkey. The comparative analysis with the T2NN-based TOPSIS method, the only available T2NN-based MCDM approach in the literature, approved the high reliability of the proposed integrated neutrosophic decision-making model. Also, the extensive sensitivity analysis confirmed the high robustness of the newly-introduced methodological framework for ALiB remanufacturing facility location selection.

The proposed integrated neutrosophic decision-making model provides the following advantages over the available decision-making approaches for remanufacturing: (*i*) Advanced T2NNs reduce the vagueness in experts' preferences, improve the recognition of information uncertainties in the remanufacturing environment, and avoid erroneous facility location decisions; (*ii*) The mathematical framework does not change with the number of potential locations and their indicators. As such, the proposed model can be easily expanded to a larger number of alternatives and criteria; and (*iii*) Stable solutions can be generated irrespective of criteria measurement scales.

A transition period to more frequent use of Lithium-ion batteries is envisaged in many fields, including EVs, in the whole world. Therefore, this study could have high importance since the remanufacturing facility location selection problem is becoming increasingly important. It could guide pioneering projects in the transition to remanufacturing systems with the provided integrated neutrosophic decision-making model. On the other hand, the study can be extended in various directions. The primary direction is to use the developed model for solving MCDM problems under uncertainty in environmental engineering, economics, energy management, logistics, and manufacturing engineering research areas. Another important direction is to use the integrated neutrosophic decision-making model to tackle other related MCDM problems like the evaluation of ALiB repurposing alternatives, location selection of a recovery center for ALiBs, deciding the most viable management options to handle end-of-life ALiBs, etc. Besides, available resources such as the operational and financial are important criteria in deciding which circular economy principle to apply for sustainable environmentally-friendly facilities. The formulated model could also be used to determine the importance of these criteria and for the assessment of facility sites.

CRediT authorship contribution statement

Muhammet Deveci: Methodology, Software, Validation, Visualization, Data acquisition, Writing - original draft, review & editing, Supervision. **Vladimir Simic**: Conceptualization, Methodology, Validation, Writing - original draft, review & editing, Supervision. **Ali Ebadi Torkayesh**: Methodology, Data acquisition, Writing - original draft, review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A.1

Results of the hierarchical BWM for the economic criteria.

Expert	Criteria selection		Vector	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
Expert 1	Best	C_6	Best-to-others	7	8	8	5	3	1	2	3
	Worst	C_3	Others-to-worst	2	2	1	5	7	9	8	8
	Local weight			0.0576	0.0504	0.0280	0.0806	0.1343	0.3134	0.2015	0.1343
	Ksi^*			0.0895							
Expert 2	Best	C_7	Best-to-others	6	9	7	5	2	2	1	2
	Worst	C_2	Others-to-worst	3	1	3	4	8	9	9	7
	Local weight			0.0571	0.0254	0.0490	0.0686	0.1714	0.1714	0.2857	0.1714
	Ksi^*			0.0571							
Expert 3	Best	C_6	Best-to-others	8	7	8	5	2	1	2	2
	Worst	C_3	Others-to-worst	3	3	1	3	6	8	7	7
	Local weight			0.0429	0.0490	0.0306	0.0686	0.1716	0.2941	0.1716	0.1716
	Ksi^*			0.0490							
Expert 4	Best	C_8	Best-to-others	5	6	7	5	2	2	3	1
	Worst	C_3	Others-to-worst	2	2	1	3	7	9	8	6
	Local weight			0.0740	0.0617	0.0280	0.0740	0.1850	0.1850	0.1233	0.2691
	Ksi^*			0.1009							
Aggregated local weight				0.0579	0.0466	0.0339	0.0729	0.1656	0.2410	0.1955	0.1866
Global aggregated weight				**0.0282**	**0.0227**	**0.0165**	**0.0355**	**0.0806**	**0.1173**	**0.0952**	**0.0908**

Table A.2

Results of the hierarchical BWM for the environmental criteria.

Expert	Criteria selection		Vector	C_9	C_{10}	C_{11}	C_{12}
Expert 1	Best	C_9	Best-to-others	1	8	5	6
	Worst	C_{10}	Others-to-worst	8	1	3	4
	Local weight			0.5777	0.0709	0.1318	0.2196
	Ksi^*			0.0811			
Expert 2	Best	C_9	Best-to-others	1	7	4	5
	Worst	C_{10}	Others-to-worst	9	1	5	3
	Local weight			0.6004	0.0655	0.1856	0.1485
	Ksi^*			0.1419			
Expert 3	Best	C_{11}	Best-to-others	2	6	1	3
	Worst	C_{10}	Others-to-worst	9	1	6	4
	Local weight			0.3000	0.0500	0.4500	0.2000
	Ksi^*			0.1500			
Expert 4	Best	C_9	Best-to-others	1	9	5	4
	Worst	C_{12}	Others-to-worst	3	4	6	1
	Local weight			0.6128	0.1064	0.1915	0.0894
	Ksi^*			0.3447			
Aggregated local weight				0.5227	0.0732	0.2397	0.1644
Global aggregated weight				**0.0710**	**0.0099**	**0.0326**	**0.0223**

Table A.3
Results of the hierarchical BWM for the social criteria.

Expert	Criteria selection		Vector	Criteria		
				C_{13}	C_{14}	C_{15}
Expert 1	Best	C_{15}	Best-to-others	8	4	1
	Worst	C_{13}	Others-to-worst	1	4	8
	Local weight			0.0769	0.2051	0.7179
	Ksi^*				0.1026	
Expert 2	Best	C_{14}	Best-to-others	6	1	2
	Worst	C_{13}	Others-to-worst	1	3	7
	Local weight			0.0909	0.5227	0.3864
	Ksi^*				0.2500	
Expert 3	Best	C_{15}	Best-to-others	7	3	1
	Worst	C_{13}	Others-to-worst	1	5	6
	Local weight			0.0833	0.2667	0.6500
	Ksi^*				0.1500	
Expert 4	Best	C_{15}	Best-to-others	8	5	1
	Worst	C_{13}	Others-to-worst	1	4	5
	Local weight			0.0769	0.1758	0.7473
	Ksi^*				0.1319	
Aggregated local weight				0.0820	0.2926	0.6254
Global aggregated weight				**0.0052**	**0.0185**	**0.0395**

Table A.4
Results of the hierarchical BWM for the technical criteria.

Expert	Criteria selection		Vector	Criteria				
				C_{16}	C_{17}	C_{18}	C_{19}	C_{20}
Expert 1	Best	C_{19}	Best-to-others	7	5	6	1	3
	Worst	C_{16}	Others-to-worst	1	2	4	3	5
	Local weight			0.0806	0.1331	0.1109	0.4536	0.2218
	Ksi^*					0.2117		
Expert 2	Best	C_{17}	Best-to-others	8	1	7	3	5
	Worst	C_{16}	Others-to-worst	1	3	3	5	7
	Local weight			0.0596	0.4512	0.1034	0.2412	0.1447
	Ksi^*					0.2724		
Expert 3	Best	C_{18}	Best-to-others	8	4	1	7	2
	Worst	C_{19}	Others-to-worst	6	2	5	1	4
	Local weight			0.0766	0.1532	0.4189	0.0450	0.3063
	Ksi^*					0.1937		
Expert 4	Best	C_{20}	Best-to-others	9	6	4	4	1
	Worst	C_{16}	Others-to-worst	1	3	3	5	4
	Local weight			0.0720	0.1120	0.1680	0.1680	0.4800
	Ksi^*					0.1920		
Aggregated local weight				0.0722	0.2123	0.2003	0.2270	0.2882
Global aggregated weight				**0.0227**	**0.0667**	**0.0630**	**0.0713**	**0.0906**

Table A.5
The T2NN initial decision matrices.

Alternative	Expert	Criterion		
		C_1	···	C_{20}
A_1: Gemlik/Bursa	E_1	<(0.20, 0.20, 0.10), (0.65, 0.80, 0.85), (0.45, 0.80, 0.70)>	···	<(0.95, 0.90, 0.95), (0.10, 0.10, 0.05), (0.05, 0.05, 0.05)>
	E_2	<(0.20, 0.20, 0.10), (0.65, 0.80, 0.85), (0.45, 0.80, 0.70)>	···	<(0.95, 0.90, 0.95), (0.10, 0.10, 0.05), (0.05, 0.05, 0.05)>
	E_3	<(0.20, 0.20, 0.10), (0.65, 0.80, 0.85), (0.45, 0.80, 0.70)>	···	<(0.95, 0.90, 0.95), (0.10, 0.10, 0.05), (0.05, 0.05, 0.05)>
	E_4	<(0.20, 0.20, 0.10), (0.65, 0.80, 0.85), (0.45, 0.80, 0.70)>	···	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>
A_2: Yunusemre/Manisa	E_1	<(0.40, 0.45, 0.50), (0.40, 0.45, 0.50), (0.35, 0.40, 0.45)>	···	<(0.50, 0.30, 0.50), (0.50, 0.35, 0.45), (0.45, 0.30, 0.60)>
	E_2	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>	···	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>
	E_3	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>	···	<(0.40, 0.45, 0.50), (0.40, 0.45, 0.50), (0.35, 0.40, 0.45)>
	E_4	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>	···	<(0.40, 0.45, 0.50), (0.40, 0.45, 0.50), (0.35, 0.40, 0.45)>
A_3: Tuzla/Istanbul	E_1	<(0.50, 0.30, 0.50), (0.50, 0.35, 0.45), (0.45, 0.30, 0.60)>	···	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>
	E_2	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>	···	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>
	E_3	<(0.40, 0.45, 0.50), (0.40, 0.45, 0.50), (0.35, 0.40, 0.45)>	···	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>
	E_4	<(0.40, 0.45, 0.50), (0.40, 0.45, 0.50), (0.35, 0.40, 0.45)>	···	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>
A_4: Sincan/Ankara	E_1	<(0.40, 0.45, 0.50), (0.40, 0.45, 0.50), (0.35, 0.40, 0.45)>	···	<(0.40, 0.45, 0.50), (0.40, 0.45, 0.50), (0.35, 0.40, 0.45)>
	E_2	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>	···	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>
	E_3	<(0.50, 0.30, 0.50), (0.50, 0.35, 0.45), (0.45, 0.30, 0.60)>	···	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>
	E_4	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>	···	<(0.20, 0.20, 0.10), (0.65, 0.80, 0.85), (0.45, 0.80, 0.70)>
A_5: Melikgazi/Kayseri	E_1	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>	···	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>
	E_2	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>	···	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>
	E_3	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>	···	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>
	E_4	<(0.50, 0.30, 0.50), (0.50, 0.35, 0.45), (0.45, 0.30, 0.60)>	···	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>
A_6: Seyitgazi/Eskişehir	E_1	<(0.95, 0.90, 0.95), (0.10, 0.10, 0.05), (0.05, 0.05, 0.05)>	···	<(0.20, 0.20, 0.10), (0.65, 0.80, 0.85), (0.45, 0.80, 0.70)>
	E_2	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>	···	<(0.50, 0.30, 0.50), (0.50, 0.35, 0.45), (0.45, 0.30, 0.60)>
	E_3	<(0.70, 0.75, 0.80), (0.15, 0.20, 0.25), (0.10, 0.15, 0.20)>	···	<(0.50, 0.30, 0.50), (0.50, 0.35, 0.45), (0.45, 0.30, 0.60)>
	E_4	<(0.60, 0.45, 0.50), (0.20, 0.15, 0.25), (0.10, 0.25, 0.15)>	···	<(0.35, 0.35, 0.10), (0.50, 0.75, 0.80), (0.50, 0.75, 0.65)>

Table A.6
The T2NN aggregated decision matrix.

Criterion	Alternative		
	A_1: Gemlik/Bursa	···	A_6: Seyitgazi/Eskişehir
C_1	<(0.200, 0.200, 0.100), (0.650, 0.800, 0.850), (0.450, 0.800, 0.700)>	···	<(0.794, 0.758, 0.822), (0.146, 0.157, 0.167), (0.084, 0.130, 0.132)>
C_2	<(0.315, 0.315, 0.100), (0.534, 0.762, 0.812), (0.487, 0.762, 0.662)>	···	<(0.950, 0.900, 0.950), (0.100, 0.100, 0.050), (0.050, 0.050, 0.050)>
C_3	<(0.359, 0.303, 0.223), (0.534, 0.630, 0.703), (0.474, 0.606, 0.649)>	···	<(0.808, 0.801, 0.859), (0.136, 0.168, 0.167), (0.084, 0.114, 0.141)>
C_4	<(0.240, 0.240, 0.100), (0.609, 0.787, 0.837), (0.462, 0.787, 0.687)>	···	<(0.868, 0.807, 0.874), (0.132, 0.132, 0.112), (0.071, 0.098, 0.093)>
C_5	<(0.922, 0.874, 0.929), (0.111, 0.119, 0.075), (0.059, 0.066, 0.071)>	···	<(0.329, 0.343, 0.223), (0.505, 0.671, 0.722), (0.445, 0.651, 0.604)>
C_6	<(0.359, 0.303, 0.223), (0.534, 0.630, 0.703), (0.474, 0.606, 0.649)>	···	<(0.922, 0.874, 0.929), (0.111, 0.119, 0.075), (0.059, 0.066, 0.071)>
C_7	<(0.289, 0.226, 0.223), (0.609, 0.651, 0.725), (0.450, 0.626, 0.674)>	···	<(0.779, 0.705, 0.776), (0.157, 0.146, 0.167), (0.084, 0.147, 0.122)>
C_8	<(0.950, 0.900, 0.950), (0.100, 0.100, 0.050), (0.050, 0.050, 0.050)>	···	<(0.325, 0.265, 0.223), (0.570, 0.640, 0.714), (0.462, 0.616, 0.661)>
C_9	<(0.289, 0.226, 0.223), (0.609, 0.651, 0.725), (0.450, 0.626, 0.674)>	···	<(0.755, 0.705, 0.776), (0.186, 0.192, 0.199), (0.115, 0.165, 0.161)>
C_{10}	<(0.868, 0.807, 0.874), (0.132, 0.132, 0.112), (0.071, 0.098, 0.093)>	···	<(0.406, 0.432, 0.382), (0.422, 0.557, 0.617), (0.317, 0.518, 0.502)>
C_{11}	<(0.289, 0.226, 0.223), (0.609, 0.651, 0.725), (0.450, 0.626, 0.674)>	···	<(0.878, 0.842, 0.900), (0.122, 0.141, 0.112), (0.071, 0.087, 0.100)>
C_{12}	<(0.950, 0.900, 0.950), (0.100, 0.100, 0.050), (0.050, 0.050, 0.050)>	···	<(0.325, 0.265, 0.223), (0.570, 0.640, 0.714), (0.462, 0.616, 0.661)>
C_{13}	<(0.279, 0.279, 0.100), (0.570, 0.775, 0.825), (0.474, 0.775, 0.675)>	···	<(0.922, 0.874, 0.929), (0.111, 0.119, 0.075), (0.059, 0.066, 0.071)>
C_{14}	<(0.200, 0.200, 0.100), (0.650, 0.800, 0.850), (0.450, 0.800, 0.700)>	···	<(0.868, 0.807, 0.874), (0.132, 0.132, 0.112), (0.071, 0.098, 0.093)>
C_{15}	<(0.922, 0.874, 0.929), (0.111, 0.119, 0.075), (0.059, 0.066, 0.071)>	···	<(0.391, 0.338, 0.223), (0.500, 0.620, 0.693), (0.487, 0.596, 0.637)>
C_{16}	<(0.922, 0.874, 0.929), (0.111, 0.119, 0.075), (0.059, 0.066, 0.071)>	···	<(0.359, 0.303, 0.223), (0.534, 0.630, 0.703), (0.474, 0.606, 0.649)>
C_{17}	<(0.779, 0.705, 0.776), (0.157, 0.146, 0.167), (0.084, 0.147, 0.122)>	···	<(0.359, 0.303, 0.223), (0.534, 0.630, 0.703), (0.474, 0.606, 0.649)>
C_{18}	<(0.878, 0.842, 0.900), (0.122, 0.141, 0.112), (0.071, 0.087, 0.100)>	···	<(0.329, 0.343, 0.223), (0.505, 0.671, 0.722), (0.445, 0.651, 0.604)>
C_{19}	<(0.922, 0.874, 0.929), (0.111, 0.119, 0.075), (0.059, 0.066, 0.071)>	···	<(0.391, 0.338, 0.223), (0.500, 0.620, 0.693), (0.487, 0.596, 0.637)>
C_{20}	<(0.922, 0.874, 0.929), (0.111, 0.119, 0.075), (0.059, 0.066, 0.071)>	···	<(0.400, 0.290, 0.329), (0.534, 0.521, 0.609), (0.462, 0.482, 0.636)>

Table A.7
The normalized decision matrix.

Alternative	Criterion									
	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}
A_1: Gemlik/Bursa	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
A_2: Yunusemre/Manisa	0.468	0.494	0.680	0.378	0.779	0.512	0.596	0.789	0.878	0.809
A_3: Tuzla/Istanbul	0.487	0.391	0.531	0.526	0.932	0.680	0.561	0.941	0.562	0.839
A_4: Sincan/Ankara	0.354	0.431	0.485	0.383	0.651	0.475	0.449	0.630	0.516	0.678
A_5: Melikgazi/Kayseri	0.324	0.375	0.485	0.369	0.665	0.428	0.382	0.631	0.413	0.609
A_6: Seyitgazi/Eskişehir	0.284	0.314	0.428	0.293	0.396	0.399	0.401	0.373	0.413	0.538

Alternative	Criterion									
	C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_{17}	C_{18}	C_{19}	C_{20}
A_1: Gemlik/Bursa	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
A_2: Yunusemre/Manisa	0.449	0.729	0.508	0.430	0.744	0.779	0.817	0.770	0.665	0.651
A_3: Tuzla/Istanbul	0.423	0.811	0.379	0.405	0.779	0.862	0.935	0.902	0.919	0.840
A_4: Sincan/Ankara	0.474	0.687	0.359	0.354	0.783	0.608	0.672	0.723	0.703	0.653
A_5: Melikgazi/Kayseri	0.406	0.468	0.344	0.309	0.594	0.416	0.665	0.604	0.464	0.339
A_6: Seyitgazi/Eskişehir	0.373	0.373	0.302	0.272	0.416	0.399	0.442	0.407	0.416	0.464

HIGHLIGHTS:

> The study aims to boost ALiB remanufacturing and promote sustainable development.

> The BWM-T2NN-CODAS model for locating ALiB remanufacturing facilities is introduced.

> Presented key evaluation criteria offer a decision-making framework for practitioners.

> The case study of Turkey provides decision-making guidelines in the real-world context.

> The introduced model can solve other circular economy-related location problems.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: