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Circular economy and circularity supplier selection: a fuzzy group decision approach

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ABSTRACT

The circular economy (CE) seeks to maintain products and materials at their highest utility and value. The organisational and governmental policy have seised onto the CE philosophy to advance socio-economic and environmental development. CE remains an essentially contested concept – making its utilisation as a foundation for managerial and policy decisions challenging. Circularity assessment has not been systematically adopted, especially within supply chain management. Using critical scholarly and practical evidential foundation, we proposed a comprehensive set of metrics that can be utilised in supplier selection, monitoring, and development for circularity. These metrics include the macro, meso, and micro levels. A group decision-making method integrating best-worst method (BWM), regret theory (RT), and dual hesitant fuzzy sets (DHFS) for circular economy and circularity (CEC) supplier evaluation and selection is introduced – providing instrumental value for the identified metrics typology. The proposed BWM-DHFE-RT integrative analytical method can accommodate decisionmaker psychological behaviour under uncertainty while simultaneously capturing divergent or conflicting opinions of different decision-makers. An illustrative business scenario is utilised to demonstrate the application of the proposed method. Though the proposed CE performance metrics and methodology are used for CEC supplier management reasons they have broader applicability. Future research and application directions are discussed.

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Circular economy; sustainability; supplier selection; supply chain management; best-worst method

1. Introduction

A circular economy represents a restorative and regenerative business model (Stahel 2016). Circular economy practices seek to maintain products, components, and materials at their highest utility and value. Although increasing in organisational and governmental policy, the circular economy philosophy is still an essentially contested concept (Korhonen et al. 2018) – making its use as a managerial decision tool difficult; even though circularity assessment has not been systematically engaged as a business decision tool, especially within supply chain management.

This study is motivated by efforts of private and public organisations in applying and developing circular purchasing and procurement standards; or attempting to develop performance measures that can be applied to this situation.[1] These practices and measures are used for supplier and materials selection reasons; and are still in development or refinement. Clear guidance is needed for practitioners, but also for researchers, for metrics development and models for circular procurement including supplier selection.

Supplier selection is a critical and strategic decision within supply chain management (Sarkis and Talluri 2002). In the sustainable supply chain management literature, extensive work exists on models or tools for production – and consumption – responsible suppliers (Kannan 2018; Luthra et al. 2017; Zimmer, Fröhling, and Schultmann 2016). Although sustainability performance metrics have informed circular supplier selection, circularity may not be the best for sustainability efforts and may impose contradicting impact on circularity. That is, treating sustainable supply chains as synonymous with circular supply chains can cause the wrong choices and methods to be applied.

The research contributions of this study are manifold. First, CE practices that may have positive or negative effects on sustainability attributes are rarely delineated in the literature and in various investigations. CE practice may simultaneously have positive and negative impacts on sustainability (Dantas et al. 2021). For example, material usage reduction – source reduction and a staple of business sustainability – may serve at cross purposes to the circular economy business model. Although

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several frameworks and methods considering the interrelationships between CE practices and sustainability exist in supply chain management (for example, Genovese et al. 2017), few studies exist that focus on supplier selection methods with a balanced positive and negative relationship perspective amongst the performance measurement variables (Merli, Preziosi, and Acampora 2018; Bai et al. 2019).

Second, existing studies mainly purport a positive promotion of CE practices and sustainability (Abad-Segura et al. 2021; Geng, Sarkis, and Ulgiati 2016; De Lima, Seuring, and Sauer 2021), with the negative effect – measures and practices that may weaken sustainability – have not been fully considered. These negative impacts make the selection of CEC suppliers more complex and uncertain, given that existing methods do not consider these possibilities and may not represent a realistic outlook to solving the supplier selection problem. This additional complexity is ostensibly related to decision-maker preference tensions and tradeoffs associated with various attributes, as well as complementary relationships or tensions associated with balancing CE and sustainability performance at multiple levels of analysis.

Third, no study has systematically considered differences between circular supplier selection from sustainable supplier selection; nor have any studies provided a comprehensive circularity assessment to facilitate effective circular supplier selection and management. Effective circular suppliers can enhance circularity for the focal firm internally and externally to supply chain networks – and may not necessarily enhance sustainability. Addressing this issue is one of our objectives and contributions to the literature on supplier selection. By incorporating the tensions and tradeoffs between sustainability and CE performance measurements in supplier selection, our study extends the current literature – central to supplier selection – to supplier portfolio evaluation and monitoring with the goal of circularity improvement.

In this paper, we introduce a group decision-making method by integrating the best-worst method (BWM), regret theory (RT), and dual hesitant fuzzy sets (DHFS) for circular economy and circularity (CEC) supplier evaluation and selection. Each of these specific tools is introduced in the method to deal with limitations and complement other techniques. DHFS is introduced to address divergent or conflicting opinions among decision-makers in an uncertain environment. RT provides a regret-rejoice value by solving a group decision-making problem that incorporates decision-maker risk aversion psychological characteristics (Bell 1982); an issue that has not been addressed in supplier selection literature. We advance novel DHFS to deal with the diverse tradeoffs in relationships (Zhao, Xu, and Liu 2016) to facilitate consistent operations among opposite relationship functions; and strengthen BWM application. We extend DHFE-BWM to determine the attribute weights by modifying the objective function and integrating a dual hesitant fuzzy element (DHFE). These are methodological contributions to the supplier selection literature.

The proposed methodology, DHFE-RT provides an opportunity to accommodate decision-maker psychological behaviour under uncertain environments while simultaneously capturing divergent or even conflicting opinions of different functional teams or individual decision-makers. In summary, this multistep group decision-making method can support CEC supplier selection problems effectively by involving decision-maker risk aversion characteristics, integrating divergent personal opinions and balancing conflicting benefit tradeoffs among decision-makers, and considering uncertainties in the macro, meso, and micro decision-making environments.

The remainder of the paper begins with a background on circular economy principles, procurement, and supplier selection with an emphasis on the type of performance and selection criteria used. This background provides an evidence-based argument on the need for these tools and measures. The industry is currently challenged by this issue and is seeking solutions. We seek to offer one avenue to help practitioners of circular procurement in this paper.

2. Background

The circular economy (CE) may not be synonymous with sustainability; it may or may not be driven by environmental principles but has been primarily associated with economic principles. Additionally, it has altered and differed in levels of analysis. Academic investigations and practical applications have supported this multi-level analysis of CE (Ghisellini, Cialani, and Ulgiati 2016). At the macro level, economies and global communities are establishing and promoting standards and policies to better understand the opportunities and challenges in CE advancement (Geng, Sarkis, and Bleischwitz 2019). At the meso level, eco-industrial parks and supply chain consortiums work on circularity strategic management and outcomes such as partner formation, re-use applications and resources continuity (Susur, Hidalgo, and Chiaroni 2019). At the micro-level, firms and individuals can engage in CE-oriented products and services production and consumption activities (Jabbour et al. 2019).

This section, derived from both academic and evidence-based – practical – reflections, serves as the foundation of this study for circularity-based supplier selection. We initially introduce the extant definitions of CE from the academic literature and present our CE definition used in this study. We then will use practical evidence from globally recognised CE practitioners, such as the International Standards Organization (ISO), the Ellen Macarthur Foundation (EMF) and other organisations to support the development and need for procurement and supplier selection metrics and methods. Building on this evidential need, we then present an overview of the current state-of-the-art for CE or circularity-based supplier selection. A critical analysis of existing decision methods for circular supplier selection and management is also provided. This critical analysis shows that what is being considered may not be appropriate; and the techniques used require additional improvements.

2.1. Defining the circular economy

The definition of CE has not reached a consensus (Korhonen et al. 2018). More than 100 different definitions of the CE exist in the academic literature (Kirchherr, Reike, and Hekkert 2017) and professional journals, though the underlying philosophy appears to be that CE is more sustainable than the current linear economic system (Table 1).

Many CE definitions exist in the extant literature. A summary of the top-cited definitions is presented in Table 1. These definitions have coalesced around one definition by the Ellen MacArthur Foundation (EMF), the one that informed our study, 'CE is a continuous positive development cycle that preserves and enhances natural capital, optimises resource yields, and minimises system risks by managing finite stocks and renewable flows.' Confusion has the potential to undermine the CE concept and various parties including policymakers, scholars and civil society representatives have started to mobilise efforts to help mitigate emerging concerns (Dewick et al. 2020). Such concerns include contestable understanding, fuzzy indicators, inadequate information and a need for government policy and regulatory oversight.

For years, the contention of the circular economy remains a 'contested concept' (Korhonen et al. 2018; Schröder et al. 2019). While the concept provokes design thinking in various industrial sectors and business practices, its objectives and core value propositions remain debatable and contentious.

Lack of definitional consensus makes circularity measurement challenging. Multiple analysis levels – macro, meso, or micro – also results in varying conceptual metrics dimensions. Since various measurements exist for the multiple perspectives (Moraga et al. 2019; Saidani et al. 2019), inconsistency exists when companies in different sectors and regions decide on what circularity practices they should or should not adopt.

Performance measures and indicator fuzziness can be mitigated through circularity performance metrics for CE – bringing some clarity to a broader scope and multiple perspectives, a CE performance measure typology. This fuzziness makes the organisational circularity performance information generation process complex and difficult (Kirchherr et al. 2018). The complexity increases further given no international agreed-upon standards due to the lack of government and regulatory policy – definitions for CE vary by region and country (Geng et al. 2013).

The absence of consistent and coherent quality information for CE application also means there are challenges for academic research advancement. In the next section, we review practical – using real-world evidence – needs for CE principles to inform sourcing activities and especially supplier selection.

2.2. Empirical evidence for circular procurement needs

As population increases, economies increase natural resources usage to meet socio-economic development demands. Globally, organisations are under enormous strain to refine manufacturing, production, and consumptions cycles to accommodate resource shortages and waste emissions upsurge. Industrial initiatives aim to break the current linear economic models and resort to circular economic models. Policies and pilot projects for circular procurement are meant to help advance the transition. Practical evidence of circular procurement policies, projects and programmes appear in Table 2. Table 2 provides the policy or project, major performance metrics, and the source for additional information. We summarise some of these. This list is not exhaustive but meant to be exemplary and practical evidence for the adoption of circular procurement. Most of these policies and projects are still in their early stages of development; further evidencing the need for investigation on this topic. We now briefly review these programmes.

At the local governmental level – Nantes, France promotes procurement policy with the integration of circular economy objectives. This effort is part of Nantes' Responsible Purchasing Promotion Scheme (RPPS). This policy is exemplary for macro-level performance metrics particularly in procurement dimensions, including resources optimisation and regeneration, for example, optimising collection and reusage of small equipment and biowaste,

Table 1. Circular economy definitions.

Paper	Definition
Kumar et al. (2020)	'Circular economy focuses on value optimisation by smart management of human and natural resources to explore the social and environmental implications of manufacturing in present and future scenarios.'
Nasir et al. (2017, 444)	'Circular economy is defined as an economic paradigm where resources are kept in use as long as possible, with maximum value extracted from them; the paradigm has its conceptual root in industrial ecology, emphasising the benefits of recycling waste materials and by-products.'
Kirchherr, Reike, and Hekkert (2017, 224)	'A circular economy describes an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations.'
Geissdoerfer et al. (2017, 766)	'CE, a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops.'
Ghisellini, Cialani, and Ulgiati (2016, 16)	'Circular economy is defined in line with The Ellen Macarthur Foundation vision (2012), as a system that is designed to be restorative and regenerative.'
Stahel (2016, 435)	'A "circular economy" would turn goods that are at the end of their service life into resources for others, closing loops in industrial ecosystems and minimising waste. It would change economic logic because it replaces production with sufficiency: reuse what you can, recycle what cannot be reused, repair what is broken, remanufacture what cannot be repaired.'
Gregson et al. (2015, 9)	'The circular economy seeks to stretch the economic life of goods and materials by retrieving them from post-production consumer phases. This approach too valorises closing loops but does so by imagining object ends in their design and by seeing ends as beginnings for new objects.'
Haas et al. (2015, 765)	'The circular economy (CE) is a simple, but convincing, strategy, which aims at reducing both input of virgin materials and output of wastes by closing economic and ecological loops of resource flows.'
Ma et al. (2014, 506)	'A circular economy is a mode of economic development that aims to protect the environment and prevent pollution, thereby facilitating sustainable economic development.'
Park, Sarkis, and Wu (2010, 1496)	'The CE policy seeks to integrate economic growth with environmental sustainability, with one element relying on new practices and technological developments, similar to the application of environmental modernisation technology.'
Xue et al. (2010, 1296)	'Circular economy is the outcome of over a decade's efforts to practice sustainable development by the international communities and is the detailed approach towards sustainable development … '
Yang and Feng (2008, 814)	'Circular economy is an abbreviation of Closed Materials Cycle Economy or Resources Circulated Economy' (…) 'The fundamental goal of circular economy is to avoid and reduce wastes from sources of an economic process, so reusing and recycling are based on reducing.'

Source: Adapted from (Prieto-Sandoval, Jaca, and Ormazabal 2018).

and incorporating life-cycle assessments into public procurement.

The Netherlands has initiated national-level circular procurement projects. In 2013, the Dutch government established the Circular Procurement Green Deal to accelerate the transition to a circular economy by raising the proportion of circular procurement to 10% by 2020. The ambition of the Cabinet is to realise a 50% reduction in the use of primary raw materials (minerals, fossil and metals) by 2030. Ultimately, the government-wide programme aims at developing a nation-wide circular economy by 2050. The performance metrics include wastage of raw materials prevention by maximising the reusability of products and materials and by minimising value destruction.

Despite various forms of circular economy models and initiatives, there has not been a global consensus on the agenda, frameworks, supporting tools and standardised performance metrics for the broader implementation of activities of all levels, to maximise the contribution to sustainable development. Proposed by France in June 2018, a new technical committee was formed and accepted by ISO: the ISO/TC 323-circular economy. The objective of this standards-setting committee is to develop standardised deliverables for organisations wishing to implement circular economy projects, including commercial organisations, public services, and not-for-profit organisations. Some evaluation dimensions are derived from current TCs, such as eco-design, life cycle assessment in ISO/TC 207 Environmental management and sustainable procurement (ISO 20400: 2017 – Sustainable procurement); but CE was viewed differently and needed its own structure alluding to the issue that CE is not necessarily a sustainability concept alone.

Another evidentiary example is the electronics industry – through the Green Electronics Council (GEC) – seeking to develop electronics circularity purchasing standards. These efforts are still in early stages but include a variety of practices such as product attributes, vendor commitment dimensions, and transformational circularity dimensions.

The performance reporting and management for CE is challenging without standardisation and common definitions – as evidenced by ISO and GEC. The Global Reporting Initiative (GRI) has launched new global standards for sustainability reporting that particularly integrates circularity concerns. GRI 306 (Effluents and Waste) sets out reporting standards that help organisations better understand, assess, and manage waste impacts. The draft GRI Waste Standard recognises that the linear, 'take-make-waste' approach is contributing towards a global waste crisis. As the world moves to a more circular

Table 2. Circular procurement in practice.

Policy and projects	Performance metrics	Sources
Responsible Purchasing Promotion Scheme (RPPS) - Nantes, France	• Organic food in school restaurants • Establishing Forest Stewardship Council (FSC) standards • 100% of significant wood purchases, certified and eco-friendly cleaning products • Recycled or certified paper • Progressive elimination of plant protection products	• https://ec.europa.eu/environment/gpp/pdf/news_alert/Issue74_Case_Study_148_Nantes.pdf
Circular Procurement Green Deal - Netherlands	• Reduce total amount of materials • Reduce non-renewable virgin input • Extend the use/lifetime of products • Optimise the potential Reuse of products & components • Optimise the potential Recycling of products & materials	• https://www.circle-economy.com/news/green-deal-circular-procurement
ISO/TC 323 circular economy	• Sharing economy • Sustainable finance • Sustainable cities and communities • Innovation management • Blockchain and distributed ledger technologies • Greenhouse gas management and related activities • Life cycle assessment • Environmental performance evaluation • Environmental labelling • Environmental auditing and related environmental investigations • Environmental management systems • Quality management and quality assurance • Environmental standardisation for electrical and electronic products and systems	• https://www.iso.org/committee/7203984.html
Green Electronics Council – Purchaser Guide for Circularity	• Focus on longevity, reuse and recyclability (LRR) • Product attributes on LRR metrics • Vendor commitment to renewable energy, and LRR metrics • Transformational activities - Changing supply chain - External engagement - Public commitment - Internal operational behaviours	• https://greenelectronicscouncil.org/workshop/
GRI 306, 308	• GRI 306 - Water discharge by quality and destination - Waste by type and disposal method - Significant spills - Transport of hazardous waste - Water bodies affected by water discharges and/or runoff • GRI 308 o Percentage of new suppliers that were screened using environmental criteria o Number of suppliers assessed for environmental impacts. o Number of suppliers identified as having significant actual and potential negative environmental impacts. o Significant actual and potential negative environmental impacts identified in the supply chain. o Percentage of suppliers identified as having significant actual and potential negative environmental impacts with which improvements were agreed upon as a result of assessment. o Percentage of suppliers identified as having significant actual and potential negative environmental impacts with which relationships were terminated as a result of assessment.	• https://www.globalreporting.org/standards/media/1013/gri-306-effluents-and-waste-2016.pdf • https://www.globalreporting.org/standards/media/1015/gri-308-supplier-environmental-assessment-2016.pdf
CGRI (Circularity Gap Reporting Initiative)	• Extracted resources • End-of-life stage of material input and output • Waste: mining waste, unregistered waste, and landfilled waste • Cycled resources • Consumption footprint • …	• https://www.circularity-gap.world/
Ellen Macarthur Foundation - Toronto Circular Economy Procurement Implementation	• Economic o cost savings for the city, waste reduction savings • Environmental o the percentage of waste diverted from landfill, CO2 savings, percentage of recycled content, raw materials avoided • Social o number of associated jobs created, number of city staff who have received circular economy training, asset sharing activities	• https://www.ellenmacarthurfoundation.org/case-studies/creating-systemic-change-through-public-purchasing-power

economy, in which waste should be treated as an input material for production, new corporate reporting standards – and by extension performance measures – are required. In addition, GRI 308 is seeking to include circularity dimensions for supplier environmental assessment – strengthening the move towards circularity in supplier management and sourcing. These standards will help companies better understand and measure the waste impacts of the entire supply chain networks, disclosing reliable and comparable data that ultimately supports better decisions.

The circularity gap reporting initiative (CGRI) highlights the uniqueness of reporting standards focusing on circularity. Based on their global investigation in 2020, the world is now 8.6% circular. CGRI proposes a global circularity gap metric (CGM) to all firms of all countries to identify business models, organisational behaviours, and individual habits to evaluate the social progress and ecological footprint of humankind. CGM aims to store and measure circularity progress, track circularity changes over time, and complete trends analyses. Such consistent measurement frameworks should inform governments and businesses alike to engage in uniform goal setting and guide future action, including supply chain management.

Based on the critical reflections from both academic research and practical applications, we summarised the core dimensions and factors at the macro, meso and micro levels. The factors, their descriptions and sources are presented in Table 3. These categories and metrics provide a comprehensive set of metrics and measures that can be utilised in supplier selection, monitoring, and development for circularity. We show how they will be used in a methodology introduced later is this paper. Initially, before introducing our methodology, we provide an overview of the literature for circularity supplier selection decision methods in the next subsection.

2.3. Decision methods for circular supplier selection and management

Table 4 summarises the existing decision methods that claim to help circular supplier selection and management decisions. Most of the studies utilise techniques such as multi-criteria decision-making, surveys, and case studies. These studies have investigated supplier selection at the micro-level – within individual organisations. Only a few existing studies focus on inter-organisational and supply chain multi-stakeholder value creation. The existing methods deal with group decision making but few of them consider interrelationships – conflicts, tensions, and cognitive differences – among a group of decision-makers. Considering the subjectivity and limitations of these methods, an integrated group decision-making method along with robustness checks are needed.

CEC supplier selection may involve multiple functions, partners, and even stakeholders. Given that uncertainty and complexity rise in CEC supplier selection problems, group decision support is important. There are some methods that have been applied to support group decision-makers or multi-stakeholder sustainability decision-making (Bai et al. 2019; Bai and Sarkis 2019). These methods help group decision-makers evaluate multiple criteria, consider differing opinions, and rank alternatives. However, few studies consider the conflicting interests and opinions of a decision-maker in the evaluation and decision-making process. A decision-maker may have diverse and often conflicting opinions across similar performance metrics on a given alternative. This characteristic makes achieving group agreement or consensus on these elements very challenging. For example, a decision-maker may believe that CE practices increase the recycling of materials and while simultaneously consuming more energy. This can be considered as one of the limitations of existing studies on group decision-making methods, and in the supplier selection literature in general – but particularly for circular economic supplier selection modelling. Group decision-making methods should discuss trade-offs between differing opinions between decision-makers and conflicting opinions of decision-makers rather than just trying to balance between different criteria.

In addition, although various techniques have been applied to facilitate supplier selection processes under the CE theme, few of them incorporate pure CE dimensions – many confound sustainability dimensions with CE dimensions. Most decision-making methods tend to be based on a set of attributes, ignore the positive and negative relationship between these alternatives and the attributes. For example, CE practices of suppliers do not necessarily form environmental protection, some even have a negative impact on environmental protection.

Group decision-making psychological characteristics are important when evaluating the CEC supplier selection decision – especially when group members have differing and conflicting opinions towards contested concepts such as CE. A joint DHFS, BWM, and RT method can support the CEC supplier selection problem in a group decision environment with positive and negative relationships among attributes and alternatives, while offering solutions in uncertain environments. Some related BWM or RT methods use hesitant fuzzy sets (HFS). For example, Li, Wang, and Hu (2019) improves the ability of BWM by extending it to fuzzy preference relations. Liu et al. (2019) introduce the interval Pythagorean fuzzy operator and the distance

Table 3. Proposed CE core dimensions and factors.

Level of analysis	Dimensions	Factors	Description – Examples	Sources
MACRO LEVEL (city, region, nation and beyond) and **MESO-LEVEL** (eco-industrial parks)	• Sharing economy • Sustainable development • Urban/industrial symbiosis	1. Use of byproducts	The supplier supports and engages public and regional physical exchange of materials, energy, water and byproducts as alternative raw materials or energy sources for industrial operations.	Moreau et al. (2017); Veleva and Bodkin (2018); Geng et al. (2012).
		2. Economic prosperity	The supplier will impact and enhance future inter- and intra- organisational regional CE economic competitiveness.	Moreau et al. (2017); Preston (2012); Stahel (2013).
		3. Effective governance systems	The supplier is involved in CE regional and eco-industrial park policy-standards setting and development.	McDowall et al. (2017); Govindan and Hasanagic (2018)
		4. Industrial leadership	The supplier is an industrial institutional entrepreneur to help organisations adopt and participate in CE practices.	Geng, Mansouri, and Aktas (2017); Raj et al. (2019); Kouhizadeh, Zhu, and Sarkis (2020).
		5. Social and Environmental Sustainable Development	The supplier supports social and environmental sustainable development using CE principles and aligning with Sustainable Development Goals (SDGs).	De Mattos and De Albuquerque (2018); Ranta, Aarikka-Stenroos, and Mäkinen (2018); Takhar and Liyanage (2019).
MESO LEVEL (eco-industrial parks) and **MICRO LEVEL** (products, companies, consumers)	• Closed material cycles	6. Material recycling	The supplier focuses on material recycling optimisation in its business processes.	Allwood (2014); Pacelli et al. (2018).
		7. Material reuse	The supplier extends the usage and reusage of input (procured) materials.	Allwood (2014); Korhonen et al. (2018); Preston (2012).
		8. Renewable materials	The supplier primarily uses renewable materials in business processes.	De Angelis, Howard, and Miemczyk (2018); Mishra, Hopkinson, and Tidridge (2018).
		9. Non-renewable virgin input	The supplier is reducing the use of non-renewable material as virgin input in business processes.	Hoogmartens, Eyckmans, and Van Passel (2018); MacArthur (2013); Andersen (2007).
	• Closed production cycles	10. Technological and Infrastructure	The supplier has suitable information technology (IT) and digital systems in place to support a circular business model.	Bai et al. (2019); Mishra et al. (2019).
		11. CE orientated organisational policy	The supplier has a CE specific mission and objectives in its organisational strategic planning.	Dubey et al. (2019); Govindan and Hasanagic (2018); Weetman (2016).
		12. CE related employee training	The supplier has tailored employee training that entails implementing circular economy in a specific function or business unit.	Jabbour et al. (2019); Ünal, Urbinati, and Chiaroni (2019); Zhu, Geng, and Lai (2010).
		13. Resource efficiency	The supplier emphasises resource efficiency improvement in its business processes.	Welfens, Bleischwitz, and Geng (2017); Taranic, Behrens, and Topi (2016); Tukker (2015).
		14. Systems risks	The supplier has specific processes for identifying, assessing, and managing system risks related to the transition to a circular economy.	MacArthur (2013); Franco (2017); Gaustad et al. (2018).
		15. Potential reuse of products & components	The supplier focuses on products & components reusage optimisation in its business processes.	Allwood (2014); Giurco et al. (2014); De los Rios and Charnley (2017).
	• Closed consumption cycles	16. Use/lifetime of products	The supplier promotes and contributes to product lifecycle extension in product consumption stage.	Lacy, Long, and Spindler (2020); Graedel et al. (2019); Alcayaga, Wiener, and Hansen (2019).
		17. CE related consumer training	The supplier has tailored consumer training that entails implementing circular economy in a specific function or business unit.	Ünal, Urbinati, and Chiaroni (2019); Preston (2012); Heyes et al. (2018).
		18. Potential recycling of products	The supplier's practices contribute to products recycling at the consumption stage.	Govindan and Hasanagic (2018); Allwood (2014); Lacy and Rutqvist (2016).
		19. Incentive mechanism for recycling and reuse (products and packaging) for stakeholders	The supplier has involved in incentive mechanism for products and/or packaging recycling and reusage for stakeholders, for example customers.	Fischer and Pascucci (2017); Spring and Araujo (2017); Giurco et al. (2014).

Table 4. Decision methods for circular supplier selection and management.

Paper	Circular economy dimensions	Circularity performance metrics	Measurements	Paper type	Methodology	Level of analysis
Prosman and Sacchi (2018)	Circular supplier selection in close loop supply chain management	Environmental impact	• Product flows • Induced transport • Waste handling • Usability of discarded products	Empirical	Case study, sequential life cycle assessment	Micro Level
Bai et al. (2019)	Sustainable supplier selection in industry 4.0	Industry 4.0	• Technological and Infrastructure • Positive organisational culture towards implementation of industry 4.0	Empirical	Multi-criteria decision-making (best-worst method' (BWM) and VIKOR)	Micro Level
Kannan et al. (2020)	Circular supplier selection in close loop supply chain management	Sustainability dimensions	• Economic (Cost, quality, delivery, reputation, technology and flexibility) • Social (occupational health and safety systems, stockholders' rights, employees' rights, job creation, information disclosure) • Circular (Air pollution, eco-friendly materials, environmental standards, recycling, clean technologies, packaging)	Empirical	Fuzzy best-worst method and the interval VIKOR technique	Micro Level
Govindan et al. (2020)	Circular supplier selection in close loop supply chain management	Circular, quality and on-time delivery	• Air pollution • Environmental standards • Eco-friendly raw materials • Eco-design • Eco-friendly packaging • Eco-friendly transportation • Clean technology	Empirical	Fuzzy analysis network process (FANP), fuzzy decision-making trial and evaluation laboratory (FDEMATEL), and multi-objective mixed-integer linear programming (MOMILP) models	Micro Level
Witjes and Lozano (2016)	Sustainable public procurement and sustainable business models	Recovery value	• Raw materials • Waste price per service	Conceptual	Grounded Theory	Macro Level
Dubey et al. (2019).	Supplier relationship management for circular economy	Sustainability dimensions	/	Conceptual	Survey	Micro Level
Guarnieri and Trojan (2019)	Circular supplier selection in sustainable supply chain management	Social, Ethical and Environmental criteria	• Environmental impact • Diversity • Security • Human rights • Smaller suppliers • Environmental costs • Managerial skills • Image green, ...	Empirical	Multi-criteria decision-making	Micro Level
Sousa-Zomer et al. (2018)	Cleaner production	Clean production process	• Products durability • Waste • Environmental impact in supplier selection • Reduction of material usage • Product installation simplification • Manufacturing efficiency • Natural resources reduction • Green products • Recyclability • Information sharing • Energy-saving equipment	Empirical	Case study	Micro Level
Koh et al. (2017)	Supply chain resource sustainability	Resource utilisation and management	• Social resources utilisation • Economic resources utilisation • Environmental resources utilisation	Conceptual	/	Micro Level
Zhao, Zhao, and Guo (2017)	Eco-industrial parks	Sustainability dimensions	• Economic • Social • Environmental • Ecological industry construction • Management level	Empirical	Multi-criteria decision-making	Meso Level
Shih et al. (2018)	Eco-Innovation in Circular Agri-Business	Closed-loop sustainable supply chain	• Water management • Relationships with suppliers • Knowledge sharing • Environmental management systems • New product and service development	Empirical	Fuzzy-VIKOR	Micro Level
Genovese et al. (2017)	Sustainable economy	Relationships between ecological systems and economic growth	• Direct, indirect and total lifecycle emissions • Waste recovered • Virgin resources use • Carbon maps	Empirical	Case study	Macro Level
He and Ma (2010)	Supplier selection in reverse logistics	Environmental impact	/	Empirical	Multi-criteria decision making	Micro Level

measurement, and the deviation model that is combined with the BWM to determine the weights of criteria. Mi and Liao (2019) investigate the BWM with hesitant fuzzy information and three different models to derive the priorities of criteria are developed with respect to diverse objectives. These example studies show that these methodologies need to be integrated to enhance group fuzzy input contexts – but limitations exist. First, these methods are not effectively combined with DHFS to consider the conflicting opinions of a decision-maker. Second, these methods increase complexity and make BWM's parsimonious advantages disappear, which is not conducive to practical application. Consequently, solving an MCDM problem entirely with DHFS information, with a simple calculation process, can help make these evaluations become more efficient. No supplier selection model uses all three, and none of the CEC supplier selection models are quite as extensive.

To conclude, the novelty and contributions of the proposed multistep group decision-making method for CEC supplier selection are manifold. We effectively: (1) involve decision-maker risk aversion characteristics; (2) integrate divergent personal and personality opinions; (3) balance conflicting benefit tradeoffs among decision-makers, and (4) consider uncertainties at the macro, meso, and micro decision-making levels.

3. Methodology

In this section, to set the stage we present general definitions and functions of DHFS, BWM, and RT. $X = \{x_1, x_2, \dots, x_n\}$ is used to denote the reference set throughout this paper.

3.1. Dual hesitant fuzzy set (DHFS)

Dual hesitant fuzzy set (DHFS) methodology is a popular extension of HFS (Torra and Narukawa 2009; Zhu, Xu, and Xia 2012). It is used to represent and address uncertainty originating from decision maker hesitancy (doubt) in providing their alternative preferences. It also presents membership degrees and non-membership degrees using paired possible values. DHFS has also been extended to provide the degrees that one alternative is preferred or non-preferred to another alternative (Zhao, Xu, and Liu 2016). In this paper, we study various opposing relationships based on this latter DHFS approach.

This approach is of practical value since decision teams consisting of several experts have varying cognitive emphasis and information. For example, they may provide varying information on an attribute's importance or non-importance to another attribute when determining attribute weight. They may also divulge that one alternative has positive and negative impact on attributes when determining an alternative's performance. We now provide various definitions that are necessary for the execution of the methodology.

Definition 3.1: A DHFS A on X is defined in terms of a positive function $h_A(x_i)$ and a negative function $g_A(x_i)$, when applied to X; both return a subset of values in [0, 1],

$$A = \{< x_i, h_A(x_i), g_A(x_i) > | x_i \in X\} \tag{1}$$

where the pair $d(x_i) = \{h(x_i), g(x_i)\}$ is called a dual hesitant fuzzy element (DHFE) and represents the possible positive and negative degrees of the element $x \in X$ to A. $\gamma \in h(x_i)$ and $\eta \in g(x_i)$ have the conditions: $\gamma^+ \in h(x_i)^+ = \cup \max\{\gamma\}$, $\eta^+ \in g(x_i)^+ = \cup \max\{\eta\}$, $0 \le \gamma$, $\eta \le 1$, and $0 \le \gamma^+ + \eta^+ \le 1$.

The basic operations of DHFE are different between the membership and non-membership of DHFE. But, in our circumstances, the positive and negative impact information should be treated in a fair manner (Zhao, Xu, and Liu 2016). Therefore, new operations are needed for DHFEs.

Definition 3.2: Let $d_1 = \{h_1, g_1\}$ and $d_2 = \{h_2, g_2\}$ be any two DHFEs, the basic operations of DHFSs are defined as follows for $\gamma_1 \in h_1$, $\gamma_2 \in h_2$, $\eta_1 \in g_1$, and $\eta_2 \in g_2$:

$$d_1 \oplus d_2 = \cup\left\{\left(\frac{\gamma_1\gamma_2}{\gamma_1\gamma_2 + (1-\gamma_1)(1-\gamma_2)}\right), \left(\frac{\eta_1\eta_2}{\eta_1\eta_2 + (1-\eta_1)(1-\eta_2)}\right)\right\}; \tag{2}$$

$$d_1 \otimes d_2 = \cup\{(\gamma_1\gamma_2, \eta_1\eta_2\}; \tag{3}$$

$$\lambda d_1 = \left\{\frac{{\gamma_1}^\lambda}{{\gamma_1}^\lambda + (1-\gamma_1)^\lambda}, \frac{{\eta_1}^\lambda}{{\eta_1}^\lambda + (1-\eta_1)^\lambda}\right\}; \tag{3}$$

$$d_1{}^\lambda = \{{\gamma_1}^\lambda, {\eta_1}^\lambda\}; \tag{4}$$

Definition 3.3: The score function of a DHFE d_1 is defined in expression (5):

$$s(d_1) = \frac{1}{l(h_1)}\sum_{\gamma \in h_1}\gamma - \frac{1}{l(g_1)}\sum_{\eta \in g_1}\eta \tag{5}$$

where $l(h_1)$ and $l(g_1)$ are the number of values for positive degrees h_1 and negative degrees g_1 of DHFEs d_1.

Definition 3.4: The variance degree between DHFEs d_1 and d_2 is defined by expression (6):

$$D(d_1, d_2) = \frac{1}{2}\left[\frac{1}{l_h}\sum_{\gamma_1 \in h_1, \gamma_2 \in h_2}(|\gamma_1 - \gamma_2|)\right.$$

$$+\frac{1}{l_g}\sum_{\eta_1\in g_1,\eta_2\in g_2}(|\eta_1-\eta_2|)\Bigg] \quad (6)$$

where $l_h = \max\{l(h_1), l(h_2)\}$ and $l_g = \max\{l(g_1), l(g_2)\}$.

Definition 3.5: Let $d = (d_1, d_2, \ldots, d_n)$ be a set of DHFEs, then a symmetric dual hesitant fuzzy weighted averaging (SDHFWA) operator is defined as:

$$\mathrm{SDHFWA}_w(d) = \sum_{i=1}^{n}(w_i \otimes d_i)$$
$$= \cup\left\{\left(\frac{\prod_{i=1}^{n}\gamma_i^{w_i}}{\prod_{i=1}^{n}\gamma_i^{w_i}+\prod_{i=1}^{n}(1-\gamma_i)^{w_i}}\right),\left(\frac{\prod_{i=1}^{n}\eta_i^{w_i}}{\prod_{i=1}^{n}\eta_i^{w_i}+\prod_{i=1}^{n}(1-\eta_i)^{w_i}}\right)\right\} \quad (7)$$

where $w = (w_1, w_2, \ldots, w_n)^T$ is the weight vector of $d = (d_1, d_2, \ldots, d_n)$ with $w_i \in [0, 1]$, and $\sum_{i=1}^{n} w_i = 1$.

3.2. The best-worst method

The best-worst method (BWM) is the recently developed multi-criteria decision making (MCDM) method to determine attribute weights (Rezaei 2015). BWM has uses pairwise comparison data in a technique that can reduce the risk of inconsistency and ensures the accuracy of judgment by constructing a structured comparison method (Bai et al. 2019). Most studies extend the BWM from crisp number to fuzzy numbers, using techniques such as HFS, intuitionistic fuzzy numbers (IFN), interval two-type fuzzy numbers (IT2FN), and triangular fuzzy numbers (TFN), each of which can more effectively model real-world applications (Mi and Liao 2019).

DHFS is selected mainly because it can effectively express the ambiguity and hesitancy among a group of decision-makers and can express the positive and negative cognitive information of the decision-maker for the same attribute or alternative. Traditional BWM is applied as follows (Rezaei 2015):

(1) Construct the decision criteria system with a set of attributes $\{c_j | j = 1, \ldots, m\}$.
(2) Determine the best (most important) attribute B and the worst (least important) attribute W.
(3) Develop the reference comparisons with the best and worst attributes based on a score between 1 and 9.
(4) Build the mathematical programming model and solve optimal weights of the attributes.

3.3. Regret theory

Regret theory (RT) (Bell 1982) uses a bivariate utility function to involve unexpected utility models. Decision-makers are concerned with their payoff (positive impact), but also about their potential risks or losses (negative impact). It incorporates decision-maker regret if they make a wrong decision that losses are bigger than payoffs; and rejoice if they make the right decision that losses are smaller than payoff (Bai and Sarkis 2019). In RT, decision-makers avoid selecting the optimal solution that has a less negative impact, which will cause them greater regret.

Definition 3.6: Let $\Delta v = v_1 - v_2$ be the difference among the utility values (v_1 and v_2) of two objects (x_1 and x_2), then the regret–rejoice function $R(\Delta v)$ is defined as follows:

$$R(\Delta v) = 1 - e^{-\gamma \Delta v} \quad (8)$$

where γ refers to a decision-maker's risk aversion coefficient. The greater the value of γ, the greater the degree of decision-maker risk aversion. $R(\Delta x) < 0$ denotes the regret value or $R(\Delta x) > 0$ denotes the rejoice value if decision-makers select object x_1 instead of object x_2.

4. Model application

This section will demonstrate the application of the proposed methodology in a CEC supplier selections context from the perspective of a focal firm.

4.1. An illustrative supplier selection scenario

To provide practical insights, a hypothetical scenario is provided with some variation in supplier selection and for exemplary purposes. A manufacturing firm has carefully examined the performance of all suppliers during the past two years. To further promote CE development, an eco-industrial park organisation – given its positioning as a CE company – has shortlisted the top 5 suppliers that claim to some level of circular economy practice. Their CE oriented performance has been summarised below:

Supplier 1: This supplier has been actively leading a CE knowledge-sharing consortium within its communities. The supplier also engages with other suppliers in establishing CE-related governance systems, policies, standards for a better circularity ecosystem for the eco-industrial park. This supplier has a long history of outstanding environmental performance and quality management. But the operational flows including material, resources, and information have not been transparent. The percentage of its non-renewable virgin input is still higher than its CE objective. Technological digital systems have not been updated to enable real-time data sharing and managing, which remains a major barrier to broader CE strategic planning.

Supplier 2: This supplier has been working with the firm for years even before the development of the eco-industrial park. This supplier has established a solid relationship with all firms using quality raw material sourcing, competitive pricing, and reliability assurance. This supplier has been engaged in corporate social responsibility and sustainability programmes with the adoption of various environmental standards and social reputational recognition in its industry. Though it emphasises material reduction and efficiency, the circularity philosophy has not fully penetrated its operational activities. The use of byproducts, or material recycling and reuse, or product lifecycle extension is not implemented in its supply chain networks.

Supplier 3: This supplier engages with upstream suppliers and downstream manufacturers by incorporating physical exchanges of materials, energy, water, and by-products as alternative raw materials or energy sources in its operational activities. It promotes closed-loop energy and resources-sharing platform within other eco-industrial park members. Whilst major strides have been made in improving resource sharing and exploring new forms of renewable energy. Less thought has been given to systematically managing material leakage and waste disposal. Its current system is still based on consumption rather than on the restorative use of non-renewable resources. Though the material chain is advanced to a circularity design at the meso level, it imposes significant losses of value along with the production and consumption chain.

Supplier 4: This supplier promotes a high level of industry 4.0 integration, with the installation of suitable information technology (IT) and digital systems in place to support a circular business model on a large scale. Through the convergence of the Internet-of-things (IoT) at its manufacturing process level, its internal operations are highly equipped with smart production systems, additive manufacturing, selective waste collection, waste sorting, and waste treatment. The mission of this supplier is to establish CE organisational culture and cultivate its employees and consumers to be better understand the benefits of circular economy at macro, meso, and micro levels. To enhance the effectiveness of implementing CE practices in the entire supply chain ecosystem, this supplier has established incentive mechanisms for various CE activities for stakeholders, such as introducing consumer rewards programmes for packaging recycling and material reuse.

Supplier 5: This supplier delivers reliable responsiveness to customer orders and service queries efficiently with a structured process through their chain of command. They remain competitive on price with their rivals, deliver undamaged products, and provide training and information as required. They are also capable of fulfilling emergent orders as well reducing the need to work with numerous suppliers. This supplier also seeks quality accreditation from various regulating bodies. Continuous improvement has been monitored in its material quality and employee professionalism. The supplier has not yet committed to a clear circular economy agenda.

4.2. Methodological elicitation

In this section, the integrated BWM, RT, DHFE method is applied to evaluate and select a CEC-supportive supplier using the illustration application. The proposed CEC supplier evaluation and selection method incorporates eight steps.

Step 1: Construct the CEC decision system.

The decision system for CEC supplier evaluation and selection is defined by $T = (S, C)$, where $S = \{s_1, s_2, \dots, s_n\}$ is a set of n CEC suppliers, $C = \{c_1, c_2, \dots, c_m\}$ is a set of m circular economy dimensions and circularity performance attributes.

In our case, the illustrative focal company considers uses three supply chains experts $E = \{E_e | e = 1, \dots, 3\}$ who will evaluate the five candidate CEC suppliers $S = \{s_i, i = 1, 2, \dots, 5\}$ based on the 19 CEC attributes $A = \{a_j, j = 1, 2, \dots, 19\}$. All CEC attributes come from both academic investigations and practical applications summarised in Table 3.

Step 2: Determine the best and the worst CE attribute for each expert.

In this step each expert E_e evaluates which attribute a_j is the best and the worst for the CEC supplier evaluation problem. In our case, the best and worst CEC attributes of each expert are shown in Table 5.

Step 3: Evaluate the important and non-important relationships among the CEC attributes.

Each expert E_e provides linguistic judgments for evaluating the important and non-important relationships among the CEC attributes. This process will be divided into four sub-steps. First, each expert E_e specifies which CEC attribute is the most important over all CEC attributes using 9-stage measurement scale that result in a Best-to-Others (BO) matrix $A^e_{BO} = \{a^e_{Bi} | i = 1, \dots, 19\}$.

Second, each expert E_e determines the importance of all CEC attributes to the best CEC attribute that

Table 5. The best and worst CEC attributes determined by each expert.

Experts	The best attribute	The worst attribute
Expert1	$a15$ (RPC)	$a17$ (CT)
Expert2	$a1$ (BP)	$a12$ (ET)
Expert3	$a16$ (LP)	$a9$ (NVI)

results in an Others-to-Best (OB) matrix $A^e_{OB} = \{a^e_{iB} | i = 1, \ldots, 19\}$. This relationship indicates the non-importance of the best CEC attribute to all CEC attributes.

Third, each expert E_e also determines the importance of all CEC attributes over the worst CEC attribute that results in an Others-to-Worst (OW) matrix $A^e_{OW} = \{a^e_{iW} | i = 1, \ldots, 19\}^T$. Finally, each expert E_e evaluates the worst CEC attribute's importance over all CEC attributes that results in a Worst-to-Others (WO) matrix $A^e_{WO} = \{a^e_{iW} | i = 1, \ldots, 19\}^T$. For treating vagueness in decision maker assessments, a fuzzy scale table corresponding to the linguistic judgments is shown in Table 6.

In our case, the equally important value of $a1$ (BP) attribute to the $a15$ (RPC) attribute is transformed into an importance value for expert E_1; or is assigned a value: $a^1_{B1} = 1 = (1{,}1)$. In addition, the equally important value of $a15$ (RPC) attribute to the $a1$ (BP) attribute is transformed into a non-important number for expert E_1 is given as: $a^1_{1B} = 1 = (1{,}1)$. In our example case, the BO matrix, OB matrix, OW matrix and WO matrix for the three experts are presented in Tables 7 and 8.

Step 4: Calculate the crisp weights w^*_i for each CEC attribute

This step is comprised of two sub-steps.

Step 4.1: the DHFE weights of the CEC attributes are calculated by solving the DHFE-BWM optimisation model for each expert E_e using expression (9).

$$\min \max_j \{D(h(w^e_B) - a^e_{Bj} \otimes h(w^e_j)),$$
$$D(a^e_{jB} \otimes g(w^e_B) - g(w^e_j)),$$
$$D(h(w^e_j) - a^e_{jW} \otimes h(w^e_W)),$$
$$D(a^e_{Wj} \otimes g(w^e_j) - g(w^e_W))\} \quad (9)$$

s.t.

$$d(w^e_j) = \{h(w^e_j) = (\gamma^{e-}_j, \gamma^{e+}_j), g(w^e_j) = (\eta^{e-}_j, \eta^{e+}_j)\},$$
$$0 \le \gamma^{e-}_j \le \gamma^{e+}_j \le 1,$$
$$0 \le \eta^{e-}_j \le \eta^{e+}_j \le 1,$$
$$\sum_{j=1}^{m} (\gamma^{e+}_j + \eta^{e+}_j) = 1,$$

Table 8. The OW matrix and WO matrix for experts.

	OW matrix			WO matrix		
Type	Expert 1	Expert 2	Expert 3	Expert 1	Expert 2	Expert 3
Worst	*a*17	*a*12	*a*9	*a*17	*a*12	*a*9
*a*1	(7,8)	(8,9)	(6,7)	(0,0)	(0,0)	(0,0)
*a*2	(7,8)	(5,6)	(6,7)	(0,0)	(0,0)	(0,0)
*a*3	(6,7)	(4,5)	(5,6)	(0,0)	(1,2)	(0,0)
*a*4	(4,5)	(6,7)	(5,6)	(1,2)	(0,0)	(0,0)
*a*5	(6,7)	(5,6)	(4,5)	(0,0)	(0,0)	(1,2)
*a*6	(5,6)	(4,5)	(3,4)	(0,0)	(0,0)	(1,2)
*a*7	(5,6)	(3,4)	(4,5)	(0,0)	(1,1)	(1,1)
*a*8	(5,6)	(4,5)	(3,4)	(0,0)	(1,2)	(1,2)
*a*9	(7,8)	(6,7)	(1,1)	(1,2)	(0,0)	(1,1)
*a*10	(8,9)	(7,8)	(6,7)	(0,0)	(0,0)	(0,0)
*a*11	(6,7)	(6,7)	(7,8)	(0,0)	(0,0)	(0,0)
*a*12	(2,3)	(1,1)	(1,2)	(2,3)	(1,1)	(1,1)
*a*13	(3,4)	(2,3)	(1,2)	(2,3)	(1,2)	(1,1)
*a*14	(4,5)	(3,4)	(5,6)	(1,2)	(1,2)	(0,0)
*a*15	(8,9)	(7,8)	(6,7)	(0,0)	(0,0)	(0,0)
*a*16	(7,8)	(6,7)	(8,9)	(0,0)	(0,0)	(0,0)
*a*17	(1,1)	(1,2)	(2,3)	(1,1)	(1,1)	(1,1)
*a*18	(4,5)	(3,4)	(2,3)	(0,0)	(0,0)	(1,1)
*a*19	(5,6)	(3,4)	(4,5)	(1,1)	(1,1)	(1,1)

Table 6. Linguistic judgments and their corresponding fuzzy values.

	DHFE-BWM		DHFE-RT	
Human judgments	Linguistic important	Linguistic non-important	Performance	Fuzzy value
0		Not Non-important (NNI)	Not applicable	(0,0)
1	Equal importance (EqI)	Equal Non-importance (ENqI)	Absolutely Low	(1,1)
2	Weak importance (WI)	Weak Non-important (WNI)	Very Low	(1,2)
3	Little importance (LI)	Little Non-important (LNI)	Low	(2,3)
4	Moderate importance (MI)	Moderate Non-important (MNI)	Medium Low	(3,4)
5	Moderate plus importance (MpI)	Moderate plus Non-important (MpNI)	Medium	(4,5)
6	Strong importance (SI)	Strong Non-important (SNI)	Medium High	(5,6)
7	Strong plus importance (SpI)	Strong plus Non-important (SpNI)	High	(6,7)
8	Very strong importance (VsI)	Very strong Non-important (VsNI)	Very High	(7,8)
9	Extreme importance (ExI)	Extreme Non-important (ExNI)	Absolutely High	(8,9)

Table 7. The BO matrix and OB matrix for experts.

Expert	best	*a*1	*a*2	*a*3	*a*4	*a*5	*a*6	*a*7	*a*8	*a*9	*a*10	*a*11	*a*12	*a*13	*a*14	*a*15	*a*16	*a*17	*a*18	*a*19
BO matrix																				
Expert 1	*a*15	(1,1)	(2,3)	(2,3)	(4,5)	(3,4)	(1,2)	(1,2)	(5,6)	(5,6)	(1,2)	(4,5)	(4,5)	(5,6)	(2,3)	(1,1)	(1,2)	(8,9)	(4,5)	(4,5)
Expert 2	*a*1	(1,1)	(1,2)	(1,2)	(3,4)	(4,5)	(2,3)	(2,3)	(6,7)	(7,8)	(1,2)	(3,4)	(3,4)	(6,7)	(3,4)	(1,1)	(2,3)	(7,8)	(5,6)	(4,5)
Expert 3	*a*16	(2,3)	(2,3)	(2,3)	(3,4)	(4,5)	(1,2)	(1,2)	(4,5)	(4,5)	(1,1)	(4,5)	(3,4)	(8,9)	(3,4)	(1,2)	(1,1)	(8,9)	(4,5)	(5,6)
OB matrix																				
Expert 1	*a*15	(1,1)	(1,2)	(1,2)	(2,3)	(0,0)	(1,2)	(1,2)	(0,0)	(0,0)	(1,2)	(0,0)	(0,0)	(0,0)	(1,2)	(1,1)	(1,2)	(0,0)	(0,0)	(0,0)
Expert 2	*a*1	(1,1)	(1,1)	(1,1)	(1,2)	(0,0)	(1,2)	(1,2)	(0,0)	(0,0)	(1,2)	(1,2)	(0,0)	(0,0)	(1,2)	(1,1)	(1,1)	(0,0)	(0,0)	(1,2)
Expert 3	*a*16	(1,1)	(1,2)	(1,1)	(1,2)	(0,0)	(1,1)	(1,1)	(0,0)	(0,0)	(1,1)	(1,2)	(0,0)	(0,0)	(1,1)	(1,1)	(1,1)	(0,0)	(0,0)	(0,0)

$$\sum_{j=1}^{m} \gamma_j^{e+} = \frac{a_{Bj}^{e+} + a_{jW}^{e+}}{a_{Bj}^{e+} + a_{jW}^{e+} + a_{jB}^{e+} + a_{Wj}^{e+}},$$

$$\sum_{j=1}^{m} \eta_j^{e+} = \frac{a_{jB}^{e+} + a_{Wj}^{e+}}{a_{Bj}^{e+} + a_{jW}^{e+} + a_{jB}^{e+} + a_{Wj}^{e+}}.$$

where $d(w_j^e) = \{h(w_j^e) = (\gamma_j^{e-}, \gamma_j^{e+}), g(w_j^e) = (\eta_j^{e-}, \eta_j^{e+})\}$ represents the weight result in DHFE form, which can represent importance $h(w_j^e)$ and non-importance $g(w_j^e)$. Expression $\sum_{j=1}^{m}(\gamma_j^{e+} + \eta_j^{e+}) = 1$ indicates that the total weight is 1.

$$\sum_{j=1}^{m} \gamma_j^{e+} = \frac{a_{Bj}^{e+} + a_{jW}^{e+}}{a_{Bj}^{e+} + a_{jW}^{e+} + a_{jB}^{e+} + a_{Wj}^{e+}}$$

and

$$\sum_{j=1}^{m} \eta_j^{e+} = \frac{a_{jB}^{e+} + a_{Wj}^{e+}}{a_{Bj}^{e+} + a_{jW}^{e+} + a_{jB}^{e+} + a_{Wj}^{e+}}$$

indicate that the proportion of total importance weight and non-importance weight is consistent with the proportion of experts' evaluation.

In our case, the DHFE weights for each CEC attribute a_j and expert E_e are obtained, as shown in Table 9. The consistency ratio ξ^* is small, hence the comparisons are highly consistent and reliable.

***Step 4.2*:** We then determine a crisp weight w_j for all the experts E_e using expression (10).

$$w_j = \frac{[\sum_{e=1}^{E} s(d(w_j^e))]}{\sum_{j=1}^{m}\sum_{e=1}^{E} s(d(w_j^e))} \tag{10}$$

In our case, as an example, the crisp weight (w_1^*) for attribute (BP) is:

$$w_1^* = \frac{[\sum_{e=1}^{E} s(d(w_1^e))]}{\sum_{j=1}^{m}\sum_{e=1}^{E} s(d(w_j^e))} = \frac{0.187}{2.002} = 0.093.$$

The crisp weights are shown in the last column of Table 9.

Step 5: Evaluate the positive and negative impact of each supplier on CEC attributes

Each expert E_e is asked to evaluate each CEC attribute a_j for each supplier $s_i$in this step. First, each expert E_e is asked to evaluate the positive impact p_{ij}^e of each supplier s_i on CEC attribute a_j using a 10-level measurement scale (Not applicable, Very Low-Very High). A fuzzy scale table corresponding to the linguistic judgments is shown in Table 6. Second, each expert E_e is asked to evaluate the negative impact n_{ij}^e of each supplier s_i on CEC attribute c_j using 10-level measurement scales. This step will result in one DHFE matrix $d(x_{ij}^e)$ for each expert.

$$d(x_{ij}^e) = \begin{cases} \left\{\left(\frac{p_{ij}^e}{10}\right), \left(\frac{n_{ij}^e}{10}\right)\right\} & \text{if } p_{ij}^{e+} + n_{ij}^{e+} \le 10 \\ \left\{\left(\frac{p_{ij}^e}{10(p_{ij}^{e+} + n_{ij}^{e+})}\right), \left(\frac{n_{ij}^e}{10(p_{ij}^{e+} + n_{ij}^{e+})}\right)\right\} & \text{other} \end{cases} \tag{11}$$

In our case, expert E_1 thinks that supplier s_1 has 'Very Low' positive level on attribute a_1 and assigns a fuzzy value of (1,2). He also thinks that supplier s_1 has a 'Very High' negative level on attribute a_1 and then assigned a fuzzy value of (7,8). $\max p_{1,1}^1 + \max n_{1,1}^1 = 10$, which results in: $d(x_{1,1}^{e=1}) = \{VL, VH\} = \{(0.1, 0.2)\ (0.7, 0.8)\}$.

Table 9. The CEC attributes weights for the 3 experts using DHFE-BWM.

	DHFE weights			Crisp weights
Attributes	Expert1	Expert2	Expert3	Integration
$a1$	{(0.041,0.062)(0.005,0.008ïijĽ}	{(0.059,0.059)(0.007,0.008ïijĽ}	{(0.097,0.097)(0.006,0.007ïijĽ}	0.093
$a2$	{(0.042,0.061)(0.003,0.012ïijĽ}	{(0.024,0.024)(0.007,0.008ïijĽ}	{(0.097,0.097)(0.006,0.007ïijĽ}	0.075
$a3$	{(0.037,0.056)(0.003,0.005ïijĽ}	{(0.024,0.024)(0.007,0.008ïijĽ}	{(0.035,0.035)(0.006,0.007ïijĽ}	0.044
$a4$	{(0.017,0.042)(0.004,0.007ïijĽ}	{(0.095,0.095)(0.007,0.008ïijĽ}	{(0.035,0.035)(0.006,0.007ïijĽ}	0.070
$a5$	{(0.035,0.058)(0.001,0.007ïijĽ}	{(0.05,0.05)(0.007,0.008ïijĽ}	{(0.023,0.023)(0.007,0.007ïijĽ}	0.050
$a6$	{(0.033,0.051)(0.003,0.012ïijĽ}	{(0.028,0.028)(0.007,0.008ïijĽ}	{(0.026,0.026)(0.007,0.007ïijĽ}	0.037
$a7$	{(0.033,0.051)(0.003,0.012ïijĽ}	{(0.028,0.028)(0.007,0.008ïijĽ}	{(0.026,0.026)(0.007,0.007ïijĽ}	0.037
$a8$	{(0.014,0.037)(0.001,0.007ïijĽ}	{(0.012,0.012)(0.007,0.008ïijĽ}	{(0.015,0.015)(0.007,0.007ïijĽ}	0.017
$a9$	{(0.014,0.036)(0.003,0.004ïijĽ}	{(0.032,0.032)(0.007,0.008ïijĽ}	{(0.015,0.015)(0.006,0.007ïijĽ}	0.027
$a10$	{(0.045,0.068)(0.003,0.012ïijĽ}	{(0.1,0.1)(0.007,0.008ïijĽ}	{(0.098,0.098)(0.006,0.007ïijĽ}	0.116
$a11$	{(0.022,0.049)(0.001,0.007ïijĽ}	{(0.095,0.095)(0.007,0.008ïijĽ}	{(0.035,0.079)(0.006,0.007ïijĽ}	0.085
$a12$	{(0.009,0.034)(0.001,0.006ïijĽ}	{(0.017,0.017)(0.007,0.008ïijĽ}	{(0.017,0.017)(0.007,0.007ïijĽ}	0.019
$a13$	{(0.011,0.011)(0.005,0.006ïijĽ}	{(0.012,0.012)(0.007,0.008ïijĽ}	{(0.009,0.009)(0.007,0.007ïijĽ}	0.006
$a14$	{(0.012,0.012)(0.003,0.003ïijĽ}	{(0.015,0.015)(0.007,0.008ïijĽ}	{(0.035,0.035)(0.006,0.007ïijĽ}	0.022
$a15$	{(0.047,0.067)(0.002,0.01ïijĽ}	{(0.124,0.124)(0.007,0.008ïijĽ}	{(0.101,0.101)(0.006,0.007ïijĽ}	0.131
$a16$	{(0.041,0.062)(0.003,0.012ïijĽ}	{(0.095,0.095)(0.007,0.008ïijĽ}	{(0.111,0.111)(0.007,0.007ïijĽ}	0.118
$a17$	{(0.005,0.005)(0.004,0.007ïijĽ}	{(0.011,0.011)(0.007,0.008ïijĽ}	{(0.011,0.011)(0.006,0.008ïijĽ}	0.003
$a18$	{(0.015,0.042)(0.001,0.007ïijĽ}	{(0.014,0.014)(0.007,0.008ïijĽ}	{(0.015,0.015)(0.007,0.007ïijĽ}	0.019
$a19$	{(0.022,0.049)(0.001,0.002ïijĽ}	{(0.015,0.015)(0.007,0.008ïijĽ}	{(0.023,0.023)(0.006,0.007ïijĽ}	0.029
ξ^*	5.97	7.25	4.87	

Table 10. The DHFE number for CEC attributes of suppliers for all experts.

Suppliers	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19
Expert 1																			
Supplier 1	[(0.1,0.2) (0.7,0.8)]	[(0.2,0.3) (0.6,0.7)]	[(0.8,0.9) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.2,0.3) (0.6,0.7)]	[(0.1,0.2) (0.7,0.8)]	[(0.1,0.2) (0.7,0.8)]	[(0.1,0.2) (0.7,0.8)]	[(0,0.1) (0.8,0.9)]	[(0.5,0.6) (0.3,0.4)]	[(0.1,0.2) (0.7,0.8)]	[(0.2,0.3) (0.6,0.7)]	[(0.2,0.3) (0.6,0.7)]	[(0.4,0.5) (0.4,0.5)]	[(0.2,0.3) (0.6,0.7)]	[(0,0.1) (0.8,0.9)]	[(0.2,0.3) (0.6,0.7)]	[(0,0.1) (0.8,0.9)]
Supplier 2	[(0,0.1) (0.8,0.9)]	[(0.5,0.6) (0.3,0.4)]	[(0.4,0.5) (0.4,0.5)]	[(0.6,0.7) (0.2,0.3)]	[(0.8,0.9) (0,0.1)]	[(0,0.1) (0.8,0.9)]	[(0,0.1) (0.8,0.9)]	[(0.6,0.7) (0.2,0.3)]	[(0.7,0.8) (0,0.1)]	[(0.1,0.2) (0.7,0.8)]	[(0.2,0.3) (0.6,0.7)]	[(0.2,0.3) (0.6,0.7)]	[(0.7,0.8) (0,0.1)]	[(0.3,0.4) (0.2,0.3)]	[(0.1,0.2) (0.7,0.8)]	[(0.1,0.2) (0.7,0.8)]	[(0,0.1) (0.8,0.9)]	[(0.1,0.2) (0.7,0.8)]	[(0,0.1) (0.8,0.9)]
Supplier 3	[(0.8,0.9) (0,0.1)]	[(0.6,0.7) (0.2,0.3)]	[(0.58,0.67) (0.25,0.33)]	[(0.58,0.67) (0.25,0.33)]	[(0.7,0.8) (0,0.1)]	[(0.3,0.4) (0.5,0.6)]	[(0.4,0.5) (0.4,0.5)]	[(0.6,0.7) (0.2,0.3)]	[(0.7,0.8) (0,0.1)]	[(0.1,0.2) (0.7,0.8)]	[(0.2,0.3) (0.6,0.7)]	[(0.1,0.2) (0.7,0.8)]	[(0.1,0.2) (0.7,0.8)]	[(0.2,0.3) (0.6,0.7)]	[(0.4,0.5) (0.4,0.5)]	[(0.4,0.5) (0.4,0.5)]	[(0.1,0.2) (0.7,0.8)]	[(0.1,0.2) (0.7,0.8)]	[(0,0.1) (0.8,0.9)]
Supplier 4	[(0.5,0.6) (0.3,0.4)]	[(0.64,0.73) (0.18,0.27)]	[(0.8,0.9) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.6,0.7) (0.2,0.3)]	[(0.5,0.6) (0.3,0.4)]	[(0.4,0.5) (0.4,0.5)]	[(0.5,0.6) (0.3,0.4)]	[(0.07,0.08) (0.93,0.93)]	[(0.64,0.73) (0.18,0.27)]	[(0.8,0.9) (0,0.1)]	[(0.4,0.5) (0.4,0.5)]	[(0.4,0.5) (0.4,0.5)]	[(0.4,0.5) (0.4,0.5)]	[(0.4,0.5) (0.4,0.5)]	[(0.8,0.9) (0,0.1)]	[(0.4,0.5) (0.4,0.5)]	[(0.8,0.9) (0,0.1)]
Supplier 5	[(0.1,0.2) (0.7,0.8)]	[(0.4,0.5) (0.4,0.5)]	[(0.4,0.5) (0.4,0.5)]	[(0.4,0.5) (0.4,0.5)]	[(0.6,0.7) (0.2,0.3)]	[(0.2,0.3) (0.6,0.7)]	[(0.1,0.2) (0.7,0.8)]	[(0,0.1) (0.8,0.9)]	[(0,0.1) (0.8,0.9)]	[(0.4,0.5) (0.4,0.5)]	[(0,0.1) (0.8,0.9)]	[(0,0.1) (0.8,0.9)]	[(0.2,0.3) (0.6,0.7)]	[(0.3,0.4) (0.5,0.6)]	[(0.1,0.2) (0.7,0.8)]	[(0.1,0.2) (0.7,0.8)]	[(0,0.1) (0.8,0.9)]	[(0.3,0.4) (0.4,0.5)]	[(0,0.1) (0.8,0.9)]
Expert 2																			
Supplier 1	[(0.6,0.7) (0.1,0.2)]	[(0.8,0.9) (0,0.1)]	[(0.3,0.4) (0.4,0.5)]	[(0.3,0.4) (0.4,0.5)]	[(0.45,0.54) (0.36,0.45)]	[(0.8,0.9) (0,0.1)]	[(0.7,0.8) (0.1,0.2)]	[(0.6,0.7) (0.1,0.2)]	[(0.7,0.8) (0.1,0.2)]	[(0.6,0.7) (0.2,0.3)]	[(0.7,0.8) (0.1,0.2)]	[(0.7,0.8) (0.1,0.2)]	[(0.7,0.8) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.7,0.8) (0,0.1)]	[(0.5,0.6) (0.2,0.3)]	[(0.8,0.9) (0,0.1)]	[(0.6,0.7) (0.2,0.3)]
Supplier 2	[(0.6,0.7) (0.2,0.3)]	[(0.5,0.6) (0.1,0.2)]	[(0.8,0.9) (0,0.1)]	[(0.4,0.5) (0.2,0.3)]	[(0.4,0.5) (0.4,0.5)]	[(0.64,0.73) (0.18,0.27)]	[(0.6,0.7) (0.2,0.3)]	[(0.6,0.7) (0.2,0.3)]	[(0.54,0.64) (0.27,0.36)]	[(0.7,0.8) (0.1,0.2)]	[(0.8,0.9) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.54,0.64) (0.27,0.36)]	[(0.8,0.9) (0,0.1)]	[(0.6,0.7) (0.1,0.2)]	[(0.7,0.8) (0.1,0.2)]	[(0.6,0.7) (0.2,0.3)]	[(0.7,0.8) (0.1,0.2)]	[(0.6,0.7) (0.2,0.3)]
Supplier 3	[(0.4,0.5) (0.4,0.5)]	[(0.6,0.7) (0.2,0.3)]	[(0.5,0.6) (0.3,0.4)]	[(0.55,0.64) (0.270.36)]	[(0.4,0.5) (0.3,0.4)]	[(0.07,0.08) (0.93,0.93)]	[(0.7,0.8) (0,0.1)]	[(0.6,0.7) (0.2,0.3)]	[(0.5,0.6) (0.3,0.4)]	[(0.7,0.8) (0.1,0.2)]	[(0.8,0.9) (0,0.1)]	[(0.7,0.8) (0.1,0.2)]	[(0.5,0.6) (0.1,0.2)]	[(0.8,0.9) (0,0.1)]	[(0.7,0.8) (0,0.1)]	[(0.7,0.8) (0,0.1)]	[(0.7,0.8) (0.1,0.2)]	[(0.7,0.8) (0.1,0.2)]	[(0.6,0.7) (0.2,0.3)]
Supplier 4	[(0.7,0.8) (0.1,0.2)]	[(0.5,0.6) (0.3,0.4)]	[(0.4,0.5) (0.4,0.5)]	[(0.45,0.55) (0.36,0.45)]	[(0.3,0.4) (0.4,0.5)]	[(0.6,0.7) (0.2,0.3)]	[(0.6,0.7) (0.1,0.2)]	[(0.8,0.9) (0,0.1)]	[(0.7,0.8) (0.1,0.2)]	[(0.2,0.3) (0.5,0.6)]	[(0.4,0.5) (0.3,0.4)]	[(0.4,0.5) (0.4,0.5)]	[(0.7,0.8) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.7,0.8) (0,0.1)]	[(0.7,0.8) (0,0.1)]	[(0.4,0.5) (0.4,0.5)]	[(0.7,0.8) (0,0.1)]	[(0.5,0.58) (0.33,0.42)]
Supplier 5	[(0.6,0.7) (0.1,0.2)]	[(0.7,0.8) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.6,0.7) (0.2,0.3)]	[(0.7,0.8) (0,0.1)]	[(0.6,0.7) (0.1,0.2)]	[(0.6,0.7) (0.2,0.3)]	[(0.6,0.7) (0.2,0.3)]	[(0.8,0.9) (0,0.1)]	[(0.3,0.4) (0.2,0.3)]	[(0.5,0.6) (0.2,0.3)]	[(0.8,0.9) (0,0.1)]	[(0.07,0.08) (0.93,0.93)]	[(0.7,0.8) (0.1,0.2)]	[(0.7,0.8) (0.1,0.2)]	[(0.6,0.7) (0.2,0.3)]	[(0.6,0.7) (0.2,0.3)]	[(0.6,0.7) (0.2,0.3)]
Expert 3																			
Supplier 1	[(0.2,0.3) (0.5,0.6)]	[(0.4,0.5) (0.4,0.5)]	[(0.8,0.9) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.3,0.4) (0.4,0.5)]	[(0.2,0.3) (0.5,0.6)]	[(0.2,0.3) (0.5,0.6)]	[(0.3,0.4) (0.5,0.6)]	[(0.2,0.3) (0.6,0.7)]	[(0.7,0.8) (0.1,0.2)]	[(0.2,0.3) (0.5,0.6)]	[(0.4,0.5) (0.4,0.5)]	[(0.4,0.5) (0.4,0.5)]	[(0.6,0.7) (0.2,0.3)]	[(0.3,0.4) (0.4,0.5)]	[(0.2,0.3) (0.6,0.7)]	[(0.3,0.4) (0.4,0.5)]	[(0.2,0.3) (0.6,0.7)]
Supplier 2	[(0.2,0.3) (0.6,0.7)]	[(0.7,0.8) (0.1,0.2)]	[(0.6,0.7) (0.2,0.3)]	[(0.8,0.9) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.2,0.3) (0.6,0.7)]	[(0.2,0.3) (0.6,0.7)]	[(0.8,0.9) (0,0.1)]	[(0.7,0.8) (0,0.1)]	[(0.2,0.3) (0.5,0.6)]	[(0.3,0.4) (0.4,0.5)]	[(0.4,0.5) (0.4,0.5)]	[(0.8,0.9) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.3,0.4) (0.5,0.6)]	[(0.3,0.4) (0.5,0.6)]	[(0.2,0.3) (0.6,0.7)]	[(0.3,0.4) (0.5,0.6)]	[(0.2,0.3) (0.6,0.7)]
Supplier 3	[(0.8,0.9) (0,0.1)]	[(0.6,0.7) (0,0.1)]	[(0.6,0.7) (0.1,0.2)]	[(0.7,0.8) (0.1,0.2)]	[(0.8,0.9) (0,0.1)]	[(0.5,0.6) (0.3,0.4)]	[(0.6,0.7) (0.2,0.3)]	[(0.7,0.8) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.2,0.3) (0.5,0.6)]	[(0.3,0.4) (0.4,0.5)]	[(0.3,0.4) (0.5,0.6)]	[(0.3,0.4) (0.5,0.6)]	[(0.4,0.5) (0.4,0.5)]	[(0.6,0.7) (0.2,0.3)]	[(0.6,0.7) (0.2,0.3)]	[(0.3,0.4) (0.5,0.6)]	[(0.3,0.4) (0.5,0.6)]	[(0.2,0.3) (0.6,0.7)]
Supplier 4	[(0.7,0.8) (0.1,0.2)]	[(0.7,0.8) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.7,0.8) (0,0.1)]	[(0.7,0.8) (0,0.1)]	[(0.7,0.8) (0.1,0.2)]	[(0.6,0.7) (0.2,0.3)]	[(0.6,0.7) (0.1,0.2)]	[(0.7,0.8) (0.1,0.2)]	[(0.8,0.9) (0,0.1)]	[(0.8,0.9) (0,0.1)]	[(0.6,0.7) (0.2,0.3)]	[(0.6,0.7) (0.2,0.3)]	[(0.6,0.7) (0.2,0.3)]	[(0.6,0.7) (0.2,0.3)]	[(0.8,0.9) (0,0.1)]	[(0.6,0.7) (0.2,0.3)]	[(0.8,0.9) (0,0.1)]
Supplier 5	[(0.3,0.4) (0.5,0.6)]	[(0.6,0.7) (0.2,0.3)]	[(0.6,0.7) (0.2,0.3)]	[(0.6,0.7) (0.2,0.3)]	[(0.8,0.9) (0,0.1)]	[(0.4,0.5) (0.4,0.5)]	[(0.3,0.4) (0.5,0.6)]	[(0.2,0.3) (0.6,0.7)]	[(0.2,0.3) (0.6,0.7)]	[(0.63,0.72) (0.18,0.27)]	[(0.2,0.3) (0.6,0.7)]	[(0.2,0.3) (0.6,0.7)]	[(0.4,0.5) (0.4,0.5)]	[(0.5,0.6) (0.3,0.4)]	[(0.3,0.4) (0.5,0.6)]	[(0.3,0.4) (0.5,0.6)]	[(0.2,0.3) (0.6,0.7)]	[(0.6,0.7) (0.2,0.3)]	[(0.2,0.3) (0.6,0.7)]

As an example, the evaluation DHFE matrix of all experts is presented in Table 10.

Step 6: Integrate the CEC performance of supplier with attribute weights.

In this step, we will calculate the integrated CEC performance of each supplier s_i based on the CEC performance $d(x_{ij})$ and crisp weight w_j. This step will result in DHFE matrix $d(\tilde{x}_{ij}^e)$ using expression (12).

$$d(\tilde{x}_{ij}^e) = w_j \cdot d(x_{ij}^e) \tag{12}$$

As an example, the crisp weight w_1 for attribute $a1$ (BP) is 0.093. The attribute $a1$ (BP)$d(x_{ij}^e)$ of each supplier s_i for Expert 1 is {(0.1,0.2)(0.7,0.8)}. Then DHFE integrated CEC performance (a1) $d(\tilde{x}_{1,1}^1)$ of each supplier $s_1$for Expert 1 is $d(\tilde{x}_{1,1}) = w_1 \cdot d(x_{1,1}^1) = \{(0.42)(0.55)\}$ through expression (12).

Step 7: Calculate the DHFE regret-rejoice value for each supplier.

Using RT and the DHFEs, the regret-rejoice value $d(RG_{ij}^e)$ of attribute a_j of supplier s_i for expert E_e is determined by expression (13):

$$d(RG_{ij}^e) = \{(1 - e^{-\gamma s(h_{ij}^e)}), (1 - e^{-\gamma s(g_{ij}^e)})\} \tag{13}$$

where

$$d(\tilde{x}_{ij}^e) = \{h_{ij}^e, g_{ij}^e\}.$$

For example, the DHFE integrated CEC performance $d(\tilde{x}_{1,1}^1)$ of supplier s_1 is (0.42, 0.55) for attribute $a1$ (BP) and Expert 1. Also assume $\gamma = 0.3$, which is a representative risk aversion coefficient for experts. Then, using expression (5), the rejoice score of $1 - e^{-\gamma s(h_{ij}^e)} = 0.118$, and the regret score of $(1 - e^{-\gamma s(g_{ij}^e)}) = 0.153$.

Step 8: Calculate the crisp regret-rejoice value for each supplier.

In this step we seek to calculate the regret-rejoice value, $T(s_i)$, for each supplier s_i. A higher regret-rejoice value of $T(s_i)$ indicates that the supplier s_i is simultaneously the better rejoice and the less regret; thus, it is a better alternative.

$$T(s_i) = R(s_i) - G(s_i) \tag{14}$$

where $G(s_i) = \sum_{e=1}^{E}\sum_{j=1}^{m} g(R_{ij}^e)$ is the aggregated regret value of supplier s_i and $R(s_i) = \sum_{e=1}^{E}\sum_{j=1}^{m} h(R_{ij}^e)$ is the aggregated rejoice value of supplier s_i.

For example, the aggregated rejoice value of supplier s_1 is $R(s_1) = \sum_{e=1}^{E}\sum_{j=1}^{m} h(R_{1j}^e) = 7.31$ and the aggregated regret value of supplier s_1 is $G(s_1) = \sum_{e=1}^{E}\sum_{j=1}^{m} g(R_{1j}^e) = 6.08$. Then, the regret-rejoice value of $T(s_i)$ of supplier s_1 is $T(s_1) = 7.31 - 6.08 = 1.23$. CEC supplier selection results using the proposed method are shown in Table 11.

The proposed method informs managers of the supplier selection rank order based on supplier circularity performance. The results show that the fourth supplier (s_4) is likely the best supplier with the highest rejoice and least regret. The fourth supplier's CEC performance $d(x_{ij})$ equals to 3.45; and has a higher likelihood possibility $R(s_i)$ value and a higher minimum possible $G(s_i)$ value. The fifth supplier (s_5) is likely the worst-performing supplier with the most regret, least rejoice; its CEC performance score is −0.07. The supplier order ranking – from the best CEC performance to the worst CEC performance – is supplier 4, supplier 3, supplier 1, supplier 2, and supplier 5.

Supplier performance uncertainty may result in varied CEC performance depending on the contextual situation. The results of the proposed method can better inform managers of the possible best performance and the possible worst performance of each supplier. These results are especially helpful to strategic supplier portfolio management. According to DHFE regret-rejoice values shown in Table 11, the positive value $R(s_i)$ represents the possible rejoice value of maximum gain on CEC. Thus, selecting supplier (s_4) will likely result in the maximum gain for CEC with a maximal value of 8.14, if the most advantageous situations occur. Supplier ((s_5)) only likely result in a minimal CEC gain with a value 6.82 in its most advantageous contextual situation. The negative possible $G(s_i)$ represents the most possible regret value of maximum loss on CEC. Thus, selected supplier ((s_4)) will cause the minimum regret loss on CEC with the smallest regret value of 4.69, if the worst contextual situation occurs; while supplier (s_5) results in a maximal loss with a value of 6.89 regret in CEC. This result is sobering because there is a possibility that every supplier, when selected and implemented, will have a worse result in a competitive business or less strict environmental regulatory contextual situation.

We also analyzed the impact of expert fuzzy cognition, conflict cognition, and different experts on the results of supplier rankings in the following sensitivity analysis section. The sensitivity analysis is used to determine the robustness of the results and their implications.

Table 11. The regret-rejoice value for suppliers.

Suppliers	$G(s_i)$	$R(s_i)$	$T(s_i)$
Supplier 1	7.31	6.08	1.23
Supplier 2	6.96	6.05	0.90
Supplier 3	7.93	6.01	1.92
Supplier 4	8.14	4.69	3.45
Supplier 5	6.82	6.89	−0.07

5. Sensitivity analysis

To validate the results above, we further conducted sensitivity analysis from three aspects: variation in methodology, parametric changes, and variations of evaluation. The methodology variation is completed by including or excluding certain methods within the overall methodology – for example, leaving out some DFHE calculation and instead of using crisp numbers. The parametric changes occur for certain values in the method. Variations in the evaluation environments are completed by including or excluding certain decision-makers from the team. The sensitivity analysis is used to determine the robustness of the results and their implications.

5.1. DHFE vs crisp number for weights of CE attributes

We will apply crisp numbers, which do not consider uncertainty and conflicting opinions, using a similar calculation process, to determine whether the weights of CE attributes change. According to the crisp measurement scales in Table 6, these linguistic terms can be converted into a crisp number. We obviously found that the weights of the CE attributes change, as shown in Table 12. Crisp numbers have difficulty expressing uncertain and conflicting opinions for decision-maker judgments and will affect the final ranking results. Hence, the uncertain and conflicting opinions of a decision-maker are very important in the group decision-making method.

5.2. Varying parameter γ

In the initial results, the degree of expert risk aversion parameter was set to 0.3; a relatively common setting.

Table 12. The CE attributes weights for the 3 experts using BWM and crisp numbers.

	DHFE weights			Crisp weights
Attributes	Expert1	Expert2	Expert3	Integration
a1	0.076	0.056	0.062	0.064
a2	0.076	0.069	0.087	0.077
a3	0.069	0.063	0.078	0.070
a4	0.050	0.076	0.078	0.068
a5	0.069	0.069	0.038	0.059
a6	0.062	0.063	0.051	0.059
a7	0.062	0.056	0.063	0.060
a8	0.019	0.023	0.038	0.027
a9	0.031	0.016	0.031	0.026
a10	0.082	0.082	0.087	0.084
a11	0.045	0.076	0.038	0.053
a12	0.042	0.007	0.008	0.019
a13	0.009	0.023	0.005	0.012
a14	0.056	0.056	0.078	0.063
a15	0.082	0.080	0.086	0.082
a16	0.076	0.076	0.104	0.085
a17	0.007	0.016	0.005	0.009
a18	0.049	0.038	0.038	0.042
a19	0.041	0.056	0.023	0.040
ξ	3.34	4.54	3.39	

We now complete a sensitivity analysis to determine the robustness of the solution. First, let γ vary over the range $0.1 \leq \gamma \leq 1.0$, in increments of 0.1. Figure 1 summarises results of this sensitivity analysis. The regret-rejoice values for each supplier do change, some more significantly than others and in differing directions, by varying the parameter value γ (along the horizontal axis). As can be seen in Figure 1, the supplier $\{s_4\}$ is the best supplier for the range of γ values. This result shows that the ranking of suppliers is relatively robust, and the managers can be confident of the supplier CEC evaluation ranking. The attenuation factor γ means the different shapes of the regret and rejoice value function in the behavioural characteristic. Although the regret-rejoice values of suppliers

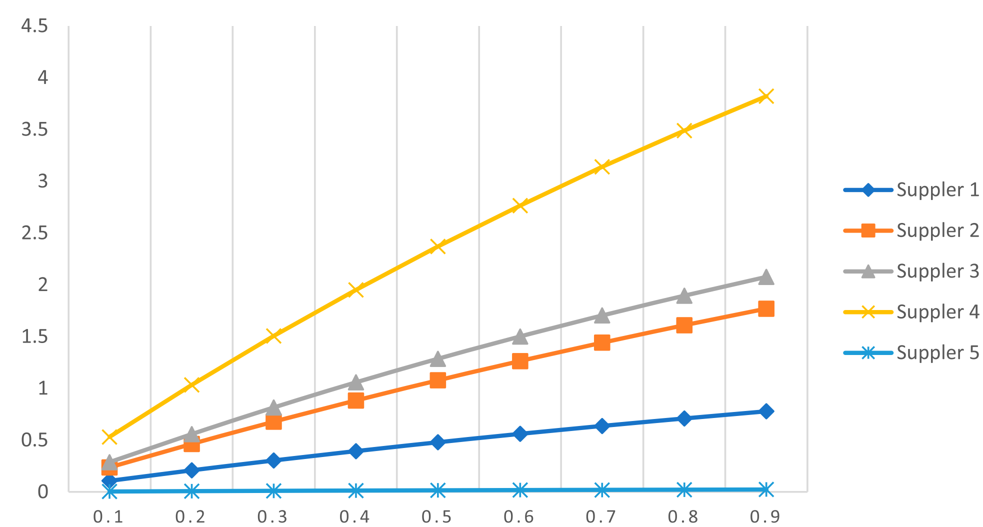

Figure 1. Final regret-rejoice value of suppliers for different γ values.

are significant changes, the ranking results amongst the supplier do not change.

5.3. Sensitivity analysis for experts

The third sensitivity analysis is completed to determine the impact of expert opinions on the results. We will compute the regret-rejoice value of each supplier for each responding expert E_e separately using the same processes as described in section 4. The results of this sensitivity analysis can be found in Table 13 and Figure 2.

The results of the highest-ranked suppliers did not change in each expert's evaluation. Supplier 4 is the most popular CEC supplier in the overall situation, which shows certain stability in expert evaluation.

However, Figure 2 shows that according to three experts, all other supplier rankings show inconsistencies and fluctuations. In the initial case, supplier 5 is the worst CEC supplier and shows relative stability in expert evaluation. According to Experts 1 and 3, supplier 5 ranks worst. In addition, supplier 5's best regret-rejoice value is second according to Expert 2.

Expert 1 and Expert 2 perform a more consistent evaluation, except that suppliers 1 and 2 rank differently. Expert 2 gives a completely inconsistent assessment. Both Expert 2 and Expert 3 are optimistic that the regret-rejoice value for each supplier is bigger than 0. While the regret-rejoice values of the three suppliers are negative and Expert 1 is pessimistic.

In fact, these results show the difficulty of consistency among groups of experts. If only a single specific expert is included in the decision-making process, this may lead to misleading or biased selection results. Therefore, it is necessary to pay attention to the group decision-makers whether to adopt this method and form discussion and consensus after some preliminary evaluations.

Table 13. The regret-rejoice value of suppliers for each expert.

Suppliers	Expert 1	Expert 2	Expert 3	Average
Supplier 1	−0.086	0.217	1.034	0.643
Supplier 2	−0.307	0.669	0.668	0.307
Supplier 3	0.175	0.851	0.850	0.654
Supplier 4	0.600	1.068	1.068	1.016
Supplier 5	−0.700	0.939	0.638	0.191

6. Implications

This study has important methodological and practical implications. Theoretically, the proposed methodology can overcome some existing methodological limitations for supplier selection and evaluation studies. Empirically, the integrated method can be applied by government regulators, eco-industrial parks, and organisations using the proposed metrics and tools – applicable at multiple levels in circular supplier management.

First, this methodology not only considers a set of CEC attributes of suppliers, but also considers the positive and negative relationship between CEC attributes and suppliers. Most multi-attribute decision-making methods are based on attribute values to evaluate suppliers (Bottani and Rizzi 2005; Liu and Hai 2005; Barak and Javanmard 2020), which cannot be applied to the evaluation of CEC suppliers. This is mainly due to the uncertainty and even negative impact of CE practices on some CEC attributes – especially sustainability-oriented attributes. As evidenced in pilot circularity programmes of France and the Netherlands, the metrics involve both sustainability and circularity-related attributes. When

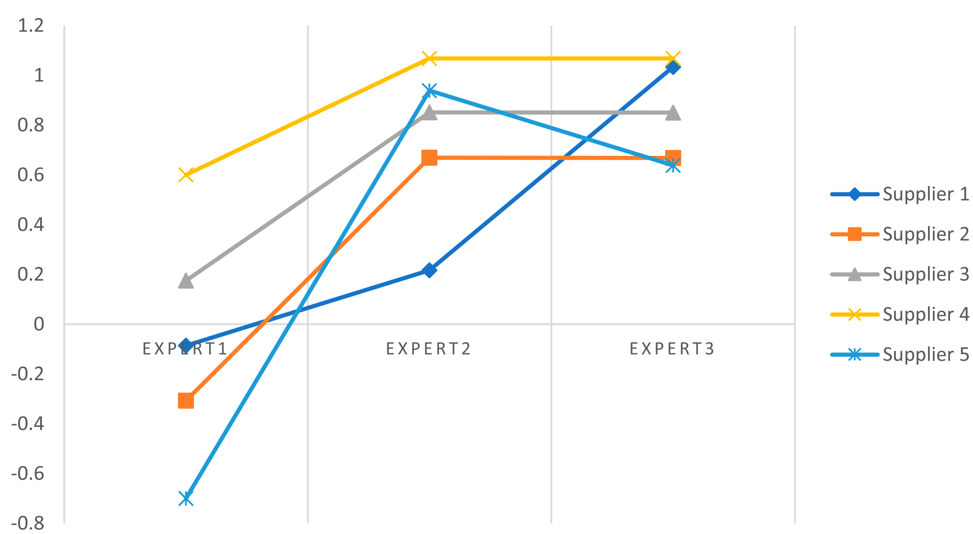

Figure 2. The regret-rejoice value for each supplier across different expert opinions.

evaluating supplier performance, some of the sustainability and circularity attributes have conflicting effects amongst themselves. The proposed method enables managers and decision-makers to evaluate direct relationships between supplier alternatives and CEC attributes, and choose the best supplier more effectively. Decision-makers can apply this method to any flexible set of metrics even when certain metrics are not clearly defined or when the same metrics are measured differently across supply chain actors.

Second, DHFE are used to incorporate complex, uncertain, varying, and conflicting decision-maker opinions and expressions in a group setting. Under many conditions, other fuzzy type data is insufficient to model CEC supplier selection situations because human judgments and preferences often conflict and are in opposite directions and are difficult to estimate with a fuzzy numerical value. The main advancement of DHFE over other HFEs is that it can capture more cognitive information by depicting the possible positive degrees that one alternative is preferred to another, and the possible negative degrees that the alternative is not preferred to another, simultaneously. We also apply DHFE to deal with opposing decision-maker opinions and carry out consistent operations among opposite relationship functions. In traditional DHFE processes different – inconsistent – calculation approaches are used to calculate the relationships (Hao et al. 2020). In this study, we adjust this approach – a contribution – to provide only a single unified analytical expression to calculate the relations. DHFE can integrate information from various decision makers in a formal fuzzy decision-making process to ensure that decision processes are fair and transparent. This approach also shows the importance of DHFE in group decision-making problems through sensitivity analysis – particularly, when there are positive and negative impacts. All these factors affect the weights of attributes. Thus, this DHFE-MCDM successfully considers the various factors in group decision-making problems, including psychological characteristics, fuzzy evaluation, different and conflicting opinions. Those are important topics that should be tackled further in group decision-making problems. Empirically, in any group decision-making environment, diverging decision-maker opinions impact the feasibility and robustness of the method. Circular supplier selection and management involve a dynamic business environment with multiple stakeholders at various levels, with different expertise levels and values related to circularity. These multiple perspectives occur because the CE concept is still unclear, with significant polysemy. The proposed method can accurately incorporate diverging opinions and mitigate social power structures to ensure a robust and consistent solution. This characteristic is especially critical to the practical trustworthiness of results because circularity initiatives involve significant tangible and intangible investments.

Third, RT is used to predict CEC performance of suppliers. RT is used not only to capture behaviour of decision makers under risk and uncertain environments, but also to express the regret value and rejoice value when they select a supplier. In the existing decision analysis methods for supplier selection, the decision maker's behaviour is starting to be considered. However, conflicting cognitive characteristics – e.g. risk aversion level – on the same items by decision makers have not been considered in many studies. In practice, most CE practices do not necessarily result in environmentally friendly practices. That is, CE practices may result in negative cognitive beliefs and effects for some experts. Thus, it is necessary to consider the positive and negative impact of suppliers using the CEC attributes in this decision analysis. RT is introduced to not only consider stakeholder decision behaviour, but also provide regret-rejoice values that can provide detailed information about the degree of regret and the degree of joy for each separate stakeholder or decision-maker.

Fourth, this approach has less computational complexity – time complexity – of DHFE operations required to arrive at a solution. Traditional DHFE operations with additional elements in a DHFS require exponential increases in calculation time. This will increase the complexity of the model, which affects the application of the method in practice, and increases the fuzziness and complexity of the calculation. Thus, the methodology proposed here improves the time complexity – and execution time needed – when compared to other DHFE MCDM approaches.

Hence, this method can prove valuable for group decision-making problems in the CEC by the ability to handle several inter-relationships among attributes and alternatives; while considering the psychological characteristics, fuzzy evaluation, different and conflicting opinions of group decision-makers.

7. Conclusion

Although increasing in organisational and governmental awareness and importance, the circular economy philosophy is still poorly defined and an essentially contested concept. Reducing ambiguity and improvement of evaluation are necessary for more effective progress at all levels. Extensive CE implementation in managerial decision tool development has been challenging due to lack of definitional consensus, fuzzy circularity measurements, and the absence of consistent and coherent quality information at multiple analysis levels – macro, meso, or micro.

This study is motivated by efforts of global private and public organisations in applying and developing circular purchasing and procurement standards; or attempting to develop performance measures that can be applied to organisational supplier selection and management. We review practical – using real-world evidence – needs for CE principles to inform sourcing activities and especially supplier selection. The proposed methodology, DHFE-RT has significant practical implications for managers and policymakers. The integrated method can capture different CE knowledge and value – cognitive intentions towards CE – under complex decision-making environments while simultaneously considering decision-maker risk aversion characteristics, mitigating conflicting benefit tradeoffs among decision-makers, and balancing uncertainties in the decision-making environments. Overall, the applicability of the method provides managers and policymakers an effective and user-friendly tool that enables group decision-making at the micro-, meso- and macro-level with enhanced multi-stakeholder benefits and combined circularity performance. Although applicability exists, whether organisations can find the time to feasibly integrate these tools into their legacy decision and policy-making processes may be difficult. Practitioners and managers may have preferred existing approaches that they are able to understand quickly due to long-time use. Providing new techniques, even simple ones, requires that they move down the learning curve. With multiple approaches and techniques to consider there might be larger barriers to their acceptance.

One of the major issues in decision tools development for CEC supplier selection is the confounding relationships between CEC and sustainability performance metrics. Researchers assume that CE practices are necessarily sustainability-focused, this is not always the case. This confusion has made pure circularity supplier selection management research virtually non-existent. The assumption that sustainability and circularity could be interchanged or integrated can be misleading. The circular economy may not be synonymous with sustainability; it may or may not be driven by environmental principles but has been primarily associated with economic principles. This study initiates discourse and brings a greater awareness for systematically considering the difference of CEC supplier selection from sustainable supplier selection, and provides a comprehensive circularity assessment to facilitate true circular supplier selection and management – a supplier that can enhance circularity for the focal firm internally and externally to supply chain networks.

Most extant circularity supplier selection and management decision-making methods tend to be based on a set of attributes and ignore the positive and negative relationships between these CEC and sustainability performance metrics. In this paper, a group decision-making method is introduced. This method integrates the best-worst method (BWM), regret theory (RT), and dual hesitant fuzzy sets (DHFS) for circular economy and circularity (CEC) supplier evaluation and selection. The improvement of involving RT not only considers stakeholder decision behaviour but also provides the regret-rejoice values. These values provide detailed information about the degree of regret and the degree of rejoicing, and important contribution to this topic's decision-making environment lacking in other studies. We also introduced important adjustments and improvements to the methodologies to address this decision-making environment that allow for more efficient execution of the methodology.

There are also policy and broader CEC standards implications and concerns. From a policymaking perspective, we have seen that there is a confusion that can undermine the CE concept (Dewick et al. 2020). Having explicit CEC supplier performance metrics allows major industrial and other stakeholders – government, civil society, municipalities – to collaborate and further develop more effective and clear measures. Having tools for decision-making to integrate multiple levels and factors is an important step in raising mutual awareness and having a vehicle to apply these performance measurements for holistic circularity. The methods allow for the multi-level analysis which can further open dialogue and communication between policymakers and industry representatives. In fact, some of the early developments for circularity standards have included these multiple stakeholders, and building the decision infrastructure will likely deepen and extend the acceptance of CEC performance metrics leading to long-term institutionalisation of CEC standards.

Although the proposed CE performance metrics and methodology are used for supplier selection and management reasons and the methodological contributions are significant, we also face several limitations in this study. First, although the time complexity is minimal, the overall procedure in the proposed methodology still has some mathematical complexity. The average supply chain manager may not fully comprehend the approach and feel intimidated with the process, although may be happy with the solution. Fuzzy and crisp numbers may arrive at slightly different solutions, but simplification may be needed in some stages to gain broader acceptance. One way of simplifying presentation is to incorporate the technique behind a user-friendly decision support system that makes the process easier to follow. Second, the technique is not applied in a real-world setting, garnering input from practitioners is needed. The illustrative example is heavily dependent on perception, although this perception uncertainty is captured by fuzzy numbers, the variations can be very great, and the results can be directly and greatly influenced. Sensitivity analysis can work in this environment, but the variations can cause managers not to trust the numbers. These are only some of the potential issues, which occur for various techniques that use multiple stages and soft computing methodologies.

These limitations and the remedies identified set the foundation for future research. First, the methodology – although simplified and necessary for appropriate decision-making – is relatively complex. Additional simplifications or guidance for management are needed. Future research can seek to improve this method by testing a variety of other approaches that may fit into various stages. Critical examination and investigation of these variations can be conducted.

Second, the study proposed here – although informed and driven by practical empirical evidence and needs – still requires additional testing and validation of its feasibility in a practical setting. The researchers have discussed the need for such tools and metrics with various agencies that are developing the tools. The question of complexity may arise, adjustments may be needed to allow the technique to be more accessible – given initial feedback. As in most sustainability and circular economy research – research is ahead of practice and these models and research can serve the purpose of further adoption of these practices in the industry and government practice (Pagell and Shevchenko 2014).

Third, although the proposed method incorporates group decision-makers – multiple stakeholders within a complex supply chain network. We did not consider the supply chain structure and the strategic position of each stakeholder within supply chains. Future studies can add another methodological underpinning by incorporating the supply chain structure of different decision-making environments, for enhanced practical significance and broader applications.

Overall, CE still evolving and important – with a significant impact on resources, supply chain, and operations management. Future guidance is needed for practitioners and researchers, to advance metrics development, models for circular procurement at multiple levels, and generally building scientific consensus on CE principles. This research is useful for government regulators, eco-industrial parks, and organisations with the tools and metrics applicable at multiple levels. We provide a foundation in this paper for further development and refinement opportunities for making CE an effective, organisational, social, and environmental aspiration.

Note

1. Examples include the European Union's efforts on circular procurement: https://ec.europa.eu/environment/gpp/circular_procurement_en.htm; the Green Electronics Council efforts to develop circularity purchasing guides: https://greenelectronicscouncil.org/resources-guidance/; https://greenelectronicscouncil.org/workshop/; and professional organizations: https://www.cips.org/knowledge/procurement-topics-and-skills/sustainability/circular-economy/. Additional empirical evidential needs are discussed later in the paper.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article.

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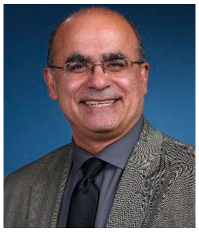

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