A NOVEL INTEGRATED APPROACH FOR CIRCULAR SUPPLIER SELECTION: COMBINING FUZZY SIMPLIFIED BEST WORST METHOD (F-SBWM) AND FUZZY DECISION-MAKING TRIAL AND EVALUATION LABORATORY (FDEMATEL)

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THESIS ACCEPTANCE CERTIFICATE

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Declaration

I hereby state that no portion of work referred to in this dissertation has been submitted in support of an application for another degree or qualification in this or any other University or other institute of learning.

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Abstract

With the growing environmental concerns and heightened public awareness, companies face mounting pressure from governmental bodies and stakeholders to adopt eco-friendly practices. This has driven a significant emphasis on incorporating green principles into daily operations. A vital component of this shift towards environmental responsibility is the careful selection of circular suppliers. The Circular Economy concept focuses on reusing, recycling, or repurposing products and materials, reducing waste and environmental impact. Choosing suppliers aligned with this model becomes essential. These suppliers contribute to waste reduction and resource efficiency. Thus, this study delves beyond standard supplier selection, emphasizing alignment with Circular Economy principles. This research introduces a novel integrated approach that integrates the Fuzzy Simplified Best Worst Method (F-SBWM) and Fuzzy Decision-Making Trial and Evaluation Laboratory (FDEMATEL) to determine the weights of criteria and sub criteria while considering the interdependencies among criteria to resolve supplier selection problem. F-SBWM is used to determine the weights of the criteria and sub criteria without considering the Interdependencies among criteria, while FDEMATEL then addresses the inner dependencies among criteria. Subsequently, the Interdependencies is applied on the initially calculated weights to get the final weights which are ultimately used to evaluate the suppliers. This integrated method aims to overcome prior limitations while effectively leveraging their strengths. The research is in accordance with Sustainable Development Goals (SDGs) including SDG 8, which focuses on promoting decent work and economic growth, and SDG 12, which emphasizes responsible consumption and production. It offers a practical approach for ranking suppliers within the circular supply chain, contributing to sustainable and environmentally responsible practices.

1. Introduction:

With the expansion of the global population and rising consumer demand, the rate of natural resource consumption has accelerated, causing serious environmental harm and a quicker depletion of available resources (Kannan et al., 2020), (Mardan et al., 2019). Supply chains across the globe are proactively rethinking how to control their environmental footprints due to intense globalization, tough competition, and increased customer awareness. Being environmentally conscious is no longer a competitive advantage, but rather a requirement to maintain a business's viability and stakeholders' interest (Govindan et al., 2020). Geissdoerfer et al. (2017) argue that supply chains worldwide are currently reassessing their operational strategies and actively considering the incorporation of circular economy principles into their supply chain management practices. The central concept of the Circular Economy is to optimize the utilization of goods, parts, and resources, with the aim of achieving zero waste. This is accomplished by reintroducing Biological products back into the ecosystem in a safe manner, while the remaining items and products are subjected to repair, recycling, or remanufacturing processes (Farooque et al., 2019). Including CE in the management of supply chains could push sustainability's limits by lowering the demand for virgin materials, which promotes resource circulation and can help supply chains reduce waste and to gain economic and social benefits (Genovese et al, 2017).

Circular Economy is not a new topic in business research but due to the devastating impacts of industrialization and hyper-consumerism, this topic is gaining a considerable amount of attention from many researchers, and serval implications can be found when it comes to integrating environmental consciousness into the traditional supply chain processes (Li et al., 2018; Ghayebloo et al., 2015). In the literature, various applications of supply chain operations combining Circular Economy can be found such as product design, procurement, manufacturing, transportation, and distribution (Nasir et al., 2017) (Nasr et al., 2021). To convert supply chains into circular and closed models, more studies are focusing on combining forward and reverse flows, and suppliers are considered to have a significant role to play in halting environmental deterioration and boosting firms' competitiveness as being at the very start of the supply chain network but only a limited amount of research can be found circular supplier selection. According to the researchers, the effective evaluation and selection of suppliers in the circular economy (CE) context can have a significant effect on lowering environmental harm and the overall supply chain cost (Govindan et al., 2020).

Collaborating with sustainable suppliers and acquiring green and environmentally friendly raw materials are the initial steps in adopting the green supply chain and protecting the environment. Using recyclable and green raw materials reduces waste and utilization of raw materials, provided that the right circular suppliers are chosen (CSS) (Kannan et al., 2020).

Suppliers, who are at the initial stage of the supply chain network, play an important part in halting environmental deterioration and boosting businesses' competitiveness (Mina et al., 2020; Mardan et al., 2019). To safeguard natural resources as well as improve network efficiency and save costs, suppliers should be chosen while applying common and circularity criteria. There is a significant concern among scholars on the process of supplier selection in relation to environmental issues (Gao et al., 2020). When it comes to circular supplier selection, there has been a notable emphasis on economic and environmental issues, while the social dimension, which holds significance within the circular supply chain, has been somewhat neglected. Kannan et al. (2020) have expanded upon existing literature by presenting a conceptual framework that offers a more comprehensive approach to addressing the sustainable circular supplier selection challenge. As depicted in Figure 1, the process of sustainable supplier selection entails the establishment of criteria for supplier evaluation, the allocation of weights to these criteria through the utilization of a robust MCDM technique, the acquisition of supplier data, the evaluation of suppliers using a

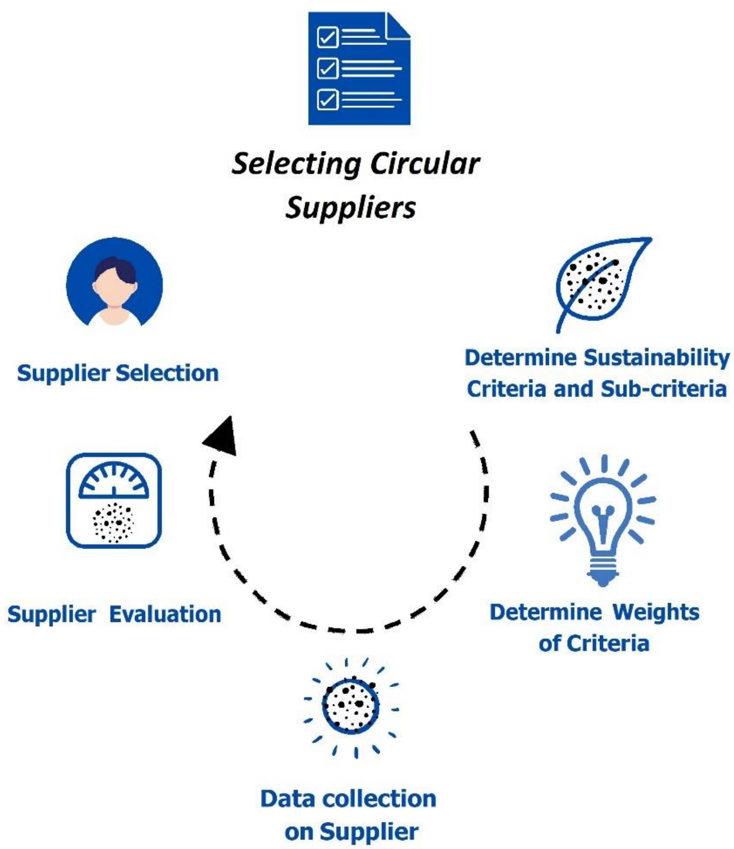


Figure 1: The process of selecting circular suppliers.

reliable methodology, and ultimately, the selection of the most appropriate supplier.

According to Mina et al. (2020), effective circular supplier selection relies on two critical factors: choosing effective criteria and selecting an appropriate method to evaluate suppliers. Because these two elements work best together, ignoring one of them would make the evaluation process ineffective. Hence, the two primary concerns in the supplier selection research revolve around the determination of suitable criteria and sub criteria for the supplier selection process and the determination of the most effective strategy for evaluating vendors.

This research study introduces a unique hybrid strategy that integrates the F-SBWM and the FDEMATEL within the framework of the Circular Economy. The primary objective of this technique is to address the crucial supplier selection process. The methodological framework utilizes the F-SBWM approach in order to ascertain the weights of criterion and sub criteria, so providing a structured basis for Decision Making. The FDEMATEL method is utilized to determine the interrelationships among these criteria and to compute the ultimate weights of sub criteria, hence augmenting the precision and comprehensiveness of the evaluation procedure. The primary objective of this technique is to evaluate and prioritize suppliers based on the chosen criteria and sub criteria, offering decision-makers a strong basis for picking the most appropriate supplier in line with Circular Economy efforts.

This research study presents several noteworthy contributions. The paper presents a novel operational-level hybrid technique that combines the F-SBWM and FDEMATEL. Additionally, this study marks the first case in which the Fuzzy F-SBWM is expanded to include both criteria and sub criteria. Previous research has primarily focused solely on criteria. In addition, this research considers the factors that facilitate supply chains in making a positive impact towards the attainment of the Sustainable Development Goals (SDGs), particularly emphasizing the accomplishment of SDG 8, which focuses on promoting decent work and economic growth, and SDG 12, which emphasizes responsible consumption and production. In order to examine the efficacy of the suggested methodology, a case study was undertaken to assess and choose suppliers within the textile sector of Pakistan.

2. Literature Review:

According to Geissdoerfer et al. (2017), the notion of circular economy encompasses a regenerative approach that aims to diminish the utilization of resources, waste generation, and emissions by effectively managing the material and energy cycles. This goal can be achieved by advocating for resilient design, effective maintenance, repair and reuse strategies, as well as embracing remanufacturing, refurbishment, and recycling practices. According to the studies conducted by Genovese et al. (2017) and Bukhari et al. (2018), the circular economy (CE) has emerged as a viable strategy for attaining sustainability objectives through the substitution of product waste with material reuse and recycling. Nevertheless, the implementation of Circular Economy (CE) necessitates a substantial transformation in the manner in which products, business models, and supply chains (SC) are conceived (Bressanelli et al., 2019). The integration of corporate environment with CE has been observed to have a notable influence on the structure and interactions inside SCs, as highlighted by Farooque et al. (2019) and Batista et al. (2018).

According to Kennedy and Linnenluecke (2022), a prevailing framework for the circular economy (CE) encompasses three primary tactics, namely, narrowing, delaying, and closing resource cycles. Narrowing entails the reduction of resources and commodities necessary to fulfill client demand, a characteristic commonly observed in corporate tactics within the linear economy. According to Lüdeke-Freund et al. (2019), the goal of achieving this can be accomplished by the redesign of products, using strategies that involve the utilization of less resources and the implementation of more efficient production processes. According to Blomsma and Tennant (2020), in order to mitigate the rapid depletion of resources, it is imperative for businesses to prioritize the elongation of product life cycles by adopting recycling, reusing and refurbishment strategies. Bocken et al. (2016) suggest that the deceleration of resource cycles can be achieved by extending the duration of product and material utilization within the economy, while simultaneously optimizing their utilization. It is imperative for organizations to employ highly efficient systems to facilitate the continuous circulation of commodities over extended periods of time.

The ultimate approach towards attaining the circular economy (CE) entails implementing measures to mitigate material leakage from supply chain systems, commonly referred to as completing resource loops. Businesses achieve this by internally gathering material and product waste, together with manufacturing byproducts, with the purpose of utilizing them in their own operations or supplying them as inputs to other businesses' manufacturing processes. The utilization of techniques such as "design for disassembly" is also employed to guarantee that product designs facilitate a seamless transition back into biological and technical cycles, as proposed by Bocken et al. (2016). The European Environment Agency (2016) delineates the fundamental attributes of the circular economy as follows:

1. A diminished reliance on inputs and consumption of resources, achieved through the efficient utilization of energy, basic materials, and natural resources.
2. An increased percentage of recyclable materials and energy (achieved through the substitution of non-renewable materials with renewable ones, responsible material procurement, and material cycle completion).
3. Emission reduction throughout the product life cycle.
4. Decreased material waste and residuals (resulting from the conservation of natural resources).
5. Maintain the market value of commodities, resources, and components (Maria et al., 2021). This is achieved by prolonging the lifespan of products, promoting the reuse of components, and emphasizing recycling.

The shift from a linear to a circular economy cannot be achieved by a sole entity. Therefore, adopting a holistic approach that considers the entire supply chain is a crucial step toward establishing a circular economy (Fehrer & Wieland, 2021). Consequently, a comprehensive reassessment of the entire business ecosystem—encompassing the supply chain that connects suppliers to customers—is imperative to transition towards a circular paradigm pertaining to the manufacturing, selection, and utilization of resources and products (Ghisellini et al., 2016). As per Maria et al. (2021), the integration of the supply chain plays a crucial role in determining the efficacy of the circular economy. The heightened effectiveness of CE is achieved through supply chain integration, which strengthens the links between diverse business activities including design, procurement, production, and distribution. Ensuring the interconnection and coordination of all supply chain activities is crucial for a company to incorporate CE into its overarching philosophy. In a similar vein, external integration with suppliers (SCI) holds equivalent significance as it facilitates businesses in collaborating to pursue shared environmental objectives and planning, establish joint efforts to mitigate or prevent pollution, implement unified purchasing policies and practices, and ultimately reinforce the Circular Economy. For organizations to successfully transition to a circular economy, their supply chains must be internally and externally integrated. External consumer integration can facilitate the resolution of environmental issues, the exchange of information regarding eco-friendly products, and the development of sustainable products in collaboration with customers, according to Wong et al. (2018). Business performance and the environment may both benefit from this type of integration. In the quest for a circular economy, Maria et al. (2021) emphasize the importance of integrating both internal and external aspects of the supply chain, considering it a crucial element.

In addressing the pivotal stakeholders essential for a successful shift to a Circular Economy, suppliers, positioned at the initial stage of the network, play a significant role in determining the overall effectiveness of the system. The cost of procuring primary materials from suppliers constitutes a significant proportion of the overall product cost (Mirzaee et al., 2018). In the same way, suppliers and manufacturers are the primary contributors to environmental degradation. As a result, choosing the right suppliers can reduce costs and environmental impact while encouraging the reuse of discarded materials. The CE mandates that suppliers acquire environmentally sustainable raw materials that possess the qualities of being technically restorative, recoverable, and regenerative (Genovese et al., 2017). This paper's literature review is subdivided into two sections: criteria for selecting suppliers and methodologies used in circular supplier selection problem. The first section focuses specifically on the criteria for selecting supplier, while the subsequent part addresses supplier selection methodologies.

2.1 Criteria for selecting suppliers:

It is imperative to establish appropriate criteria when selecting suppliers; however, the precise criteria utilized are contingent upon the particular business environment (Rashidi et al., 2020). Multi-criteria Decision Making (MCDM) is required to select circular suppliers due to the complexity and contradiction of these criteria (Guarnieri & Trojan, 2019). MCDM offers a framework for structuring decision-making problems and a set of methods for assessing preferences among multiple alternatives. In order to rank the top ten suppliers, Fallahpour et al. (2017) conducted an extensive literature review and pinpointed forty-six criteria covering economic, environmental, and social dimensions. These criteria were then evaluated using fuzzy preference programming and the Fuzzy TOPSIS method. Similarly, Luthra et al. (2017) proposed a set of 22 assessment criteria for the selection of sustainable suppliers by an Indian automotive manufacturer, derived from economic, environmental, and social factors. Goren (2018) examined the process of selecting environmentally, socially, and economically sustainable suppliers in light of the aforementioned factors. As social criteria, Goren considered workplace health and safety and support activities. In regard to environmental criteria, Goren considered resource consumption, eco-friendly product design, and environmental management.

To examine the selection of environment-friendly suppliers, Haeri and Rezaei (2019) opted for both economic and environmental factors. The criteria that were considered in their study were economic and environment. The factors that were considered in the domain of economic factors were delivery, pricing, quality, innovation, and technological capabilities. Selected for the environmental domain were the organization's eco-friendly reputation, resource usage, pollution control measures, pollution generation, and dedication to sustainable management. The method employed in this study was the best-worst method to determine the respective weights of each factor. For the inter-relationship among these factors, gray relational analysis was done.

Ecer and Pamucar (2020) in their research, proposed a novel approach for the sustainable procurement from suppliers catering to the needs of household appliance manufacturers. The methodology incorporated economic factors such as transportation cost, pricing, quality, delivery, and service, additionally, within the environmental criteria were considerations such as environmental expenses, environmental stewardship, pollution management, eco-friendly practices, and environmental expertise. The research employed the Fuzzy BWM methodology to improve the accuracy of their supplier evaluation procedure. In their study, Gao et al. (2020) focused their supplier selection process on economic considerations, including aspects such as technology competency, pricing, and quality. Within the domain of electronics manufacturing, the selection of suppliers is guided by economic factors that comprise several criteria such as gas emissions, environmental certification, waste management, green product offerings, and green competitiveness.

Mina et al. (2021) utilized a comprehensive assessment methodology, incorporating a total of 17 criteria that encompassed both economic and environmental aspects. The researchers utilized Fuzzy Inference Systems (FIS) and Fuzzy Analytic Hierarchy Process (FAHP) methodologies to determine criterion weights, thereby enabling the evaluation of circular providers. Kannan et al. (2020) employed a comprehensive approach that encompassed the economic, environmental, and social aspects. The evaluators integrated a comprehensive set of 16 criteria in their assessment of providers. To assess the significance of these factors, the FBWM was utilized.

2.2 Supplier selection methods:

Multi-Criteria Decision Making (MCDM) approaches are of significant importance in the process of supplier evaluation, as they offer a structured approach for the assessment and selection of suppliers, taking into account many criteria. Prominent methods within the realm of Multiple Criteria Decision Making (MCDM) frequently applied in this context include the Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Best Worst Method (BWM), TOPSIS/FTOPSIS, Fuzzy Inference System (FIS), data envelopment analysis (DEA)/fuzzy DEA, VIKOR, and hybrid MCDM approaches (Mina et al., 2020).

Moreover, several scholars have adopted hybrid approaches, integrating MCDM approaches and mathematical models to determine the most optimal selections, as demonstrated in the studies conducted by Govindan et al. (2020) and Wu et al. (2019). An inventive hybrid strategy was presented by Hashemi et al. (2015) to prioritize green suppliers. It integrated the use of Gray Relation Analysis (GRA) with the Analytic Network Process (ANP). The researchers utilized the Analytic Network Process (ANP) methodology to effectively capture the interdependencies between criteria in their study. Additionally, Grey Relational Analysis (GRA) technique was employed to address and include uncertainties within the model. In order to rank suppliers in the automotive industry, the following six critical factors were considered: pricing, quality, technology, environmental impact, resource utilization, and management dedication. Darabi and Heydari (2016) suggested a ranking methodology for green suppliers using an interval-valued fuzzy entropy algorithm in a parallel inquiry. The research verified the efficacy of their approach by utilizing data from a study conducted by Kannan et al. (2013). This study involved the evaluation of three suppliers based on various factors, including quality, pricing, technology capabilities, delivery, and environmental competency standards. The validation conducted in this study demonstrated the resilience and effectiveness of their methodology.

In their study, Luthra et al. (2017) proposed a comprehensive approach aimed at assessing the sustainability of suppliers within the operational environment of an Indian manufacturer. 22 different measures including social, environmental, and economic aspects were identified as part of the research's methodology. The researchers utilized the Analytical Hierarchy Process (AHP) in order to determine the relative significance of these criteria. Subsequently, the VIKOR approach was employed to evaluate and prioritize providers according to the predetermined criteria.

Guarnieri and Trojan (2019) presented a novel supplier selection methodology that places particular emphasis on ethical responsibility in the textile industry. As part of the methodology, suppliers were assessed using the ELECTRE-TRI method, and criteria weights were assigned using the AHP method. In their study, Khan et al. (2018) presented an innovative approach to evaluate the sustainability of suppliers within the vehicle manufacturing sector in Pakistan. The researchers utilized the fuzzy Shannon entropy technique to assign weights to the criteria and incorporated the fuzzy inference system (FIS) to rank providers according to the predetermined criteria.

Li et al. (2019) proposed the utilization of a novel technique called Rough cloud TOPSIS to effectively prioritize sustainable suppliers in situations characterized by uncertainty. The authors conducted a comparative analysis of the proposed methodology. In evaluating suppliers, Azadeh et al. (2016) proposed a hybrid approach integrating Taguchi, DEA, and Simulation (CLSC). Supplier assessment in this method considered five factors: price, delivery time, production capability, service, and technology. Meanwhile, Rashidi and Cullinane (2019) combined Fuzzy DEA and Fuzzy TOPSIS methodologies to appraise supplier performance in their study. The results of their research provide empirical support for the superior effectiveness of the TOPSIS approach over DEA. Additionally, Hendiani et al. (2020) offered a new fuzzy version of the best-worst method for choosing sustainable suppliers. The methodology employed by the researchers involves the utilization of trapezoidal fuzzy membership functions to effectively tackle the issue of uncertainty inside uncertain situations. Kannan et al. (2020) conducted a comprehensive research endeavor comprising in which The Fuzzy BWM was initially utilized to allocate weights to the criteria. Subsequently the Interval VIKOR approach was utilized to evaluate the supplier performance. In order to ascertain the efficacy of their suggested methodology, a practical case study was undertaken. In contrast, Mina et al. (2021) employed a different methodology. The researchers employed the Fuzzy Inference System to assign weights to the criteria and implemented the FTOPSIS method to assess the suppliers in their research framework.

A notable contribution in this area/domain made by Wan et al. (2021) is worth mentioning here. This paper provides a critical evaluation of the extension of the Fuzzy BWM proposed by Guo and Zhao, as well as other related extensions that have been influenced by their work on the Fuzzy BWM. The primary focus of the critique centers on the erroneous utilization of mathematical operations pertaining to triangular fuzzy numbers (TFNs). The approach proposed by Guo and Zhao has faced criticism due to its flaws in dealing with multiplication and subtraction operations involving Type-2 Fuzzy Numbers (TFNs), as well as erroneous comparisons between them. The Fuzzy BWM and GITrFBWM approaches have faced criticism because of their inability to effectively handle the crucial matter of improving the consistency of reference comparisons between criteria. These critiques highlight the significance of precise mathematical operations and the need to enhance consistency in reference comparison when dealing with fuzzy numbers in order to maintain the validity of outcomes.

GITrF BWM, as proposed in the study by Wan et al. (2021), aims to address these concerns and offers a more adaptable and accurate method for multi-criteria Decision Making. In this regard, The Fuzzy Simplified Best Worst Method (F-SBWM) employed in the present study is worth mentioning as it demonstrates resilience to the criticisms outlined by Wan et al. (2021). F-SBWM employs a simplified approach for identifying the best and worst alternatives based on fuzzy numbers, as proposed by Amiri et al. (2022), without employing the mathematical model under critique.

The literature on circular supplier selection problems is concisely summarized in Table 1.

2.3: Summary of Literature and Gap Analysis in Circular Supplier Selection Problem

Table 1: Summary of circular supplier selection problem

Author(s)/ Year	Criteria	Sub criteria	Technique / Approach
Lo et al. (2018)	Economic	Quality of product, innovation capability, service flexibility, labor intensive, reputation, financial stability, safety of information	BWM and fuzzy TOPSIS
	Environmental	Environmental performance, eco- friendly manufacturing, green logistics	
Abdel-Baset et al. (2019)	Economic	Product cost, revenue on product, cost of transportation	ANP and VIKOR
	Environmental	Management of waste, eco-friendly manufacturing techniques, sustainable packaging and labeling practices	
	Social	Safety and well-being of workers, transparency in information disclosure, compliance with ethical and legal obligations	

Mishra et al. (2019)	Economic	Technological expertise, product/service quality, adaptability, financial strength, innovation culture	Hesitant fuzzy WASPAS
	Environmental	Systematic approach to environmental management, environmentally conscious design, adoption of green technologies, development of eco-friendly products,	
		Commitment to sustainable practices	
Bai et al. (2019)	Social	Well-being and safety of workers, community impact through training and education, stakeholders' influence,	NRS, TOPSIS and VIKOR
		Management system for occupational health and safety, protection of employees' interests and rights	
		Protection of stakeholders' rights, transparency in disclosing information, ethical employment practices	
Li et al. (2019)	Economic	Cost, prompt delivery, quality and flexibility	Rough cloud TOPSIS
	Environmental	Green production, development, green design, green procurement, and green logistics.	
	Social	Respecting employee rights, ensuring safe and healthy working environments, and adhering to human rights values, engaging in philanthropic or community activities, promoting fair trading and opposing corruption	
Rashidi and Cullinane (2019)	Economic	Cost of providing service, utilization of energy and resources, quality of the rendered services	Fuzzy DEA and fuzzy TOPSIS
	Environmental	System of environmental management	
	Social	Workers' health and safety, societal accountability	
Hendiani et al. (2020)	Economic	Cost, flexibility, reliability of delivery, quality of the rendered services, supply capacity, state of the relationships, and service	Fuzzy best-worst method
	Environmental	Participation in green activities, environmental knowledge, compliance with environmental regulations and policies	
Kannan et al. (2020)	Economic	Cost, reputation, technology, quality, delivery, and flexibility	FBWM and Interval VIKOR
	Circular	The use of sustainable raw resources, observing environmental regulations, air pollution, the use of sustainable technology, packaging made from recyclable materials	

	Social	The rights of workers and investors, health and safety, creation of jobs, Information sharing	
Govindan et al. (2020)	Economic	System of quality control, prior clients' satisfaction, standard of post-purchase assistance, timely and productive output, time allocation, time of delivery	FAHP, FDEMATEL and FANP
	Environmental	Environmental norms, air pollution, clean technology, sustainable raw material, eco-friendly transportation, and design	
Mina et al. (2021)	Economic	Lead time, delivery, post-purchase servicing, quality control, technology capabilities, facilities and capacities, financial capability, and flexibility	FIS, FAHP and FTOPSIS
	Environmental	Emissions of greenhouse gases, observance of environmental laws and guidelines, green packaging use, Using environmentally friendly technologies recyclable and environmentally benign raw materials	
Proposed Approach	Economic	Cost, Lead time, Quality, Reputation, Flexibility, Production Capacity	F-SBWM and FDEMATEL
	Environmental	GHG emissions, Adherence to environmental regulations and standards, Green packaging, Use of recyclable materials, Clean Technology, Design of products to reuse	
	Social	Employee's Health and safety, Job creation, The rights stakeholders, Information disclosure	

3. Problem definition:

To address the gap in the current literature, this study proposes an enhanced and inclusive method for selecting suppliers that incorporates circular economy principles and sustainability. The proposed approach is designed to assist organizations in making better-informed decisions and enhancing their supply chain sustainability performance.

3.1 Research questions

This research seeks to provide answers to the following research questions:

1. What are the sustainable criteria and sub criteria that should be considered in the supplier selection process for a circular economy?

2. What is an effective approach to establish relative importance (weights) of sustainable criteria and sub criteria in a circular supplier selection problem?
3. How can the interdependencies among the criteria be determined and applied to the weights of criteria and sub criteria?
4. What can be an effective approach/ method to evaluate the suppliers based on the selected criteria and sub criteria?
5. How can the proposed integrated approach be applied to evaluate and select sustainable circular suppliers in a real-world case study scenario?

4. Proposed novel integrated approach for selection of circular suppliers:

Although the circular supplier selection issue has been studied in detail in the literature, this study attempts to fill a methodological gap as shown in Figure 2. Using thorough literature research, the initial step in this process is to develop sustainable criteria and sub criteria for supplier selection. The second step involves utilizing the F-SBWM to assign weights to the criterion and sub criteria without taking into account the interdependencies among the criteria. The consistency ratio is calculated in the third step to determine if the CR falls within an acceptable range. As suggested by Mina et al. (2021) and Kannan et al. (2020), the fourth step involves calculating the interdependency among criteria using FDEMATEL approach. The fifth stage involves calculation of final weights by applying the inter dependency matrix to criteria weights which were calculated in stage 2. In the final stage, suppliers are assigned individual scores based on each sub criteria, and the evaluation of suppliers is determined by the highest mean score.

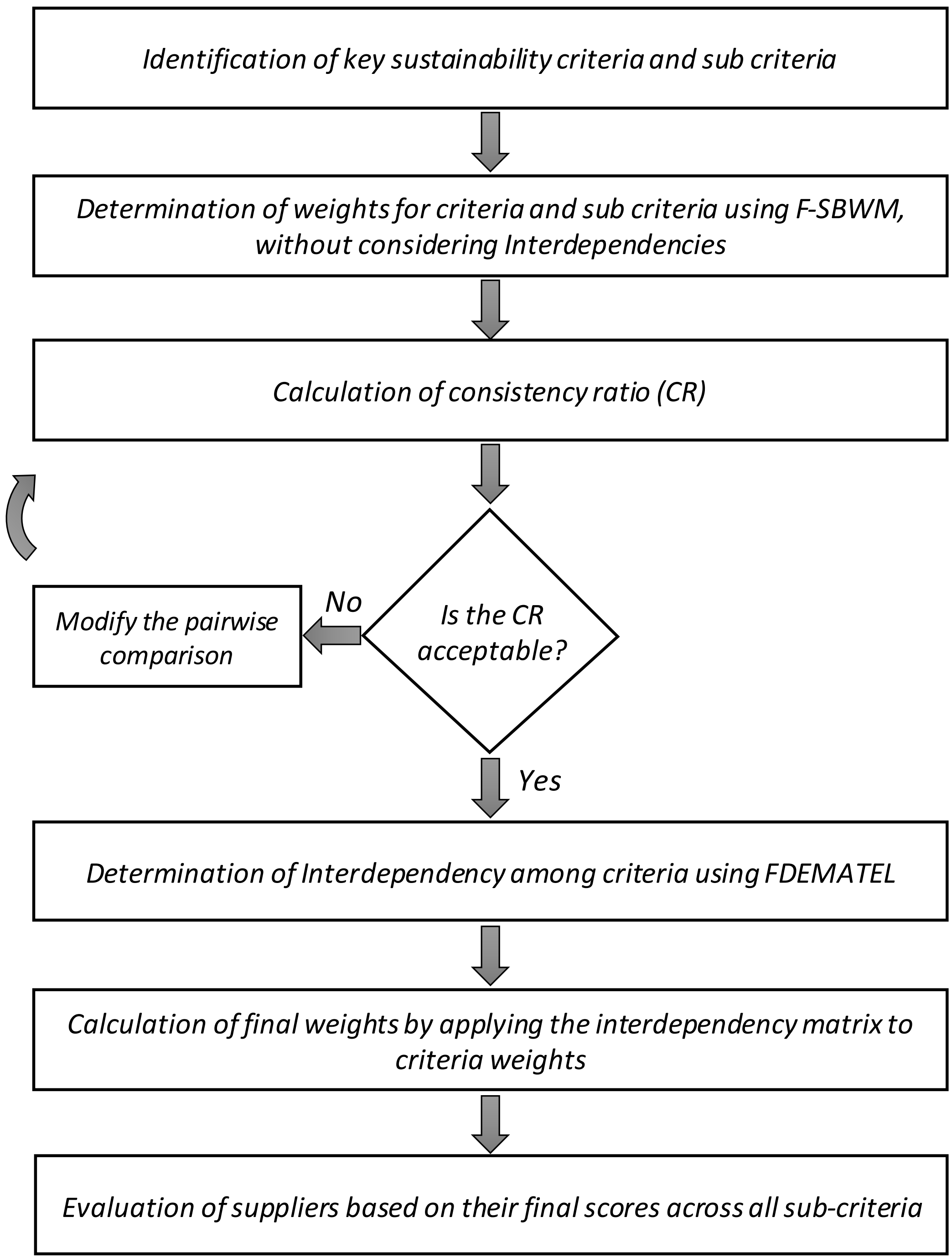


Figure 2: Flowchart of the Proposed Novel Integrated Approach

A detailed breakdown of each stage is as follows:

4.1 Identifying key sustainability criteria and sub criteria:

In the first phase of this study, a comprehensive assessment of the existing literature, coupled with expert input is carried out to identify the key criteria and sub criteria relevant to the circular supplier selection problem. After careful evaluation of literature and with the help of expert opinion economic, circular, and social variables are identified as the key decision criteria for the process of evaluating and selecting suppliers. In addition, the sub criteria linked to each of these core criteria have been derived. Table 2 presents a comprehensive compilation of the criteria and their respective sub criteria, offering a thorough depiction of the insights derived from the extant literature. The sub criteria C1-C6 has a direct or indirect impact on SDG 12, which is centered on the promotion of responsible consumption and production. The sub criteria S1-S3 have a direct or indirect impact on SDG 8, which focuses on promoting decent employment and economic development.

Table 2: Selected criteria and sub criteria for circular supplier selection

Criteria	Sub criteria	Description	References
Economic	Cost (E1)	Expense of production or service provision	Kannan et al. (2020); Memari et al. (2019); Mohammed et al. (2019)
(EC)	Lead Time (E2)	Time to complete a process or deliver	Mina et al. (2020); Qazvini et al. (2019); Goren (2018); Dobos & Vorosmarty (2014)
	Quality (E3)	Standard of excellence in products or services	Nasr et al. (2021); Rashidi and Cullinane (2019); Kannan (2018)
	Reputation (E4)	Collective perception and image	Nasr et al. (2021); Kellner et al. (2019); Lo et al. (2018); Ghadimi et al. (2018);
	Flexibility (E5)	Adaptation to change and responsiveness	Nasr et al. (2021); Guarnieri and Trojan (2019); Kannan (2018); Luthra et al. (2017)

	Production Capacity (E6)	Maximum output within a timeframe	Mina et al. (2020); Goren (2018)
Circular (CR)	GHG Emissions (C1)	Greenhouse gas releases impacting climate	Mina et al. (2020); Kannan et al. (2020); Azimifard et al. (2018); Vahidi et al. (2018)
	Adherence to environmental standards (C2)	Environmental rule compliance	Govindan et al. (2020); Mina et al. (2020); Rashidi and Saen (2018); Kannan (2018)
	Green Packaging (C3)	Eco-friendly packaging choices	Govindan et al. (2020); Kannan et al. (2020); Qazvini et al. (2019); Chatterjee et al. (2018)
	Use of Recyclable Materials (C4)	Using Materials that are recyclable	Nasr et al. (2021); Mina et al. (2020); Govindan et al. (2020); Memari et al. (2019); Kannan (2018)
	Clean Technology (C5)	Environmentally friendly tech	Govindan et al. (2020); Kannan et al. (2020); Mina et al. (2020); Li et al. (2019); Goren (2018)
	Design of products to reuse (C6)	Products designed for multiple uses	Nasr et al. (2021); Govindan et al. (2020); Kannan (2018)
Social (SC)	Employee's Health and Safety (S1)	Ensuring staff well-being and workplace safety	Kannan et al. (2020); Memari et al. (2019); Luthra et al. (2017); Ghadimi et al. (2018), Goren et al. (2018)
	Job Creation (S2)	Generating employment opportunities for people	Nasr et al. (2021); Kannan et al. (2020); Tiwari et al. (2019); Rashidi and Cullinane (2019)
	The rights of stockholders (S3)	Protecting the interests and rights of shareholders	Nasr et al. (2021); Kannan et al. (2020); Rashidi and Cullinane (2019); Luthra et al. (2017)
	Information disclosure (S4)	Transparent sharing of relevant company information	Kannan et al. (2020); Xu et al. (2019); Bai et al. (2019); Mohammed et al. (2019)

4.2 Determination of weights without considering interdependencies using F-SBWM

This stage involves the allocation of weights to criteria and sub criteria while not taking into account the interdependencies between criteria. This stage can be further divided into distinct steps. The important relationships and mathematical operators related to Triangular Fuzzy Numbers within the proposed approach are detailed as follows (Amiri et al., 2022):

$$\bar{A} = (a^L, a^M, a^U)$$

$$\bar{B} = (b^L, b^M, b^U)$$

$$\bar{A} + \bar{B} = (a^L + b^L, a^M + b^M, a^U + b^U)$$

$$\bar{A} - \bar{B} = (a^L - b^U, a^M - b^M, a^U - b^L)$$

$$\bar{A} * \bar{B} \cong (a^L b^L, a^M b^M, a^U b^U)$$

$$\bar{A} \div \bar{B} \cong \left(\frac{a^L}{b^U}, \frac{a^M}{b^M}, \frac{a^U}{b^L}\right)$$

$$\frac{1}{\bar{A}} \cong \left(\frac{1}{a^U}, \frac{1}{a^M}, \frac{1}{a^L}\right)$$

$$\bar{A} * \lambda \cong (a^L\lambda, a^M\lambda, a^U\lambda), where\ \lambda \geq 0$$

Key notations which are adopted and extended from the work of Amiri et al., (2022), to be employed throughout different steps in this stage are presented in Table 3 below:

Table 3: Important notations used in F-SBWM

Notation	**Description**
C_i	The ith criterion from the criteria set
$\bar{P}_{Bj}$	The degree of preference for best criterion in relation to the jth criterion, represented as TFN
$\bar{P}_{jW}$	The degree of preference for jth criterion in relation to the worst criterion, represented as a Triangular Fuzzy Number
P_{Bj}^L	The lower threshold of the Triangular Fuzzy Number linked to the preference for best criterion in relation to the jth criterion
P_{Bj}^M	The central value of the Triangular Fuzzy Number linked to the preference for the best criterion over the jth criterion

P_{Bj}^{U}	The upper threshold of the Triangular Fuzzy Number linked to the preference for the best criterion over the jth criterion
P_{jW}^{L}	The lower threshold of the Triangular Fuzzy Number linked to the preference for the jth criterion over the worst criterion
P_{jW}^{M}	The central value of the Triangular Fuzzy Number linked to the preference for the jth criterion over the worst criterion
P_{jW}^{U}	The upper threshold of the Triangular Fuzzy Number linked to the preference for the jth criterion over the worst criterion
$\widetilde{w}_j'$	The weight given to the jth criteria in the best to others reference comparisons
$\widetilde{w}_j'\ (E)$	The weight given to the jth sub criteria within economic criterion in the best to others reference comparisons
$\widetilde{w}_j'\ (S)$	The weight given to the jth sub criteria within social criterion in the best to others reference comparisons
$\widetilde{w}_j'\ (C)$	The weight given to the jth sub criteria within circular criterion in the best to others reference comparisons
$\widetilde{w}_j''$	The weight given to the jth criteria in the others to worst reference comparisons
$\widetilde{w}_j''(E)$	The weight given to the jth sub criteria within economic criterion through others to worst reference comparisons
$\widetilde{w}_j''(S)$	The weight given to the jth sub criteria within social criterion through others to worst reference comparisons
$\widetilde{w}_j''(C)$	The weight given to the jth sub criteria within circular criterion through others to worst reference comparisons
w_j^{L}	The lower threshold of the Triangular Fuzzy Number linked to the weight of the jth criterion
w_j^{M}	The lower value of the Triangular Fuzzy Number linked to the weight of the jth criterion
w_j^{U}	The upper threshold of the Triangular Fuzzy Number linked to the weight of the jth criterion

$\widetilde{w}_B'$	The weight given to the best criterion in the best to others reference comparisons
$\widetilde{w}_W''$	The weight given to the worst criterion in the others to worst reference comparisons
$\widetilde{w}_j^*$	The final weight given to the jth criterion
$\widetilde{w}_j^*(E)$	The final weight given to the jth sub criteria within economic criterion
$\widetilde{w}_j^*(S)$	The final weight given to the jth sub criteria within social criterion
$\widetilde{w}_j^*(C)$	The final weight given to the jth sub criteria within circular criterion
CR	Consistency Ratio

The sequential breakdown of this stage is as follows:

4.2.1: Determination of the best and the worst criteria:

The initial step in F-SBWM involves determining the decision criteria in terms of C_i and identifying the best criteria and the worst criteria.

4.2.2: Establishing the preference of the best criterion over other criteria:

The next step involves determination of preference of the best criteria over the other criteria using linguistic terms and Triangular Fuzzy Numbers in the format of $\bar{P}_{Bj} = \left(P_{Bj}^L, P_{Bj}^M, P_{Bj}^U\right)$. Table 4 adopted from Amiri et al., (2020), displays a list of linguistic terms and their corresponding TFN values. These TFNs provide the necessary basis for experts in determining preferences during the decision-making process.

4.2.3: Establishing the other to worst criteria preferences:

This stage entails determination of the relative importance of each criterion in relation to worst criterion in the form of $\bar{P}_{jW} = \left(P_{jW}^L, P_{jW}^M, P_{jW}^U\right)$ through the utilization of linguistic terms and Triangular Fuzzy Numbers.

Table 4: Linguistic terms used for evaluation of criteria (Amiri et al., 2020)

Linguistic terms		Fuzzy Scale
Equally important	EI	(1,1,1)
Weakly important	WI	(1,2,3)
Moderate importance	MI	(2,3,4)
Moderate plus importance	MP	(3,4,5)
Strong importance	SI	(4,5,6)
Strong plus importance	SP	(5,6,7)
Very strong importance	VS	(6,7,8)
Extreme importance	EX	(7,8,9)

4.2.4: Calculating criteria weights based on best to other reference comparisons:

In this step, the preference of each criterion is established by employing the reference comparisons, where the best criterion is compared against the other criteria in the form of $\widetilde{w}_j' = (w_j^L, w_j^M, w_j^U)$. To determine the best criterion's preference in comparison with each of the other criteria, the Equation (1) is used. As a result, the weight of the best criterion ($\widetilde{w}_B'$) is attained. Subsequently, the weights of the remaining criteria are assessed by replacing the weight of the best criterion in equation (2).

$$\sum_j \frac{1}{\bar{P}_{Bj}} \widetilde{w}_B' = 1 \Rightarrow \widetilde{w}_B' = \frac{1}{\sum_j \bar{P}_{Bj}} \qquad (1)$$

$$\widetilde{w}_B' - \bar{P}_{Bj}\widetilde{w}_j' = 0 \Rightarrow \bar{P}_{Bj}\widetilde{w}_j' = \widetilde{w}_B' \Rightarrow \widetilde{w}_j' = \frac{\widetilde{w}_B'}{\bar{P}_{Bj}} \; \forall \; j \qquad (2)$$

4.2.5: Calculating criteria weights based on other to worst reference comparisons:

In this step, the others to worst reference comparisons are employed to determine the weights of each criterion in the terms of $\overline{w}_j'' = (w_j^L, w_j^M, w_j^U)$. Using Equation (3), the preference of each criterion is assessed in relation to the worst criteria. As a result, the weight of the worst criterion is determined. Subsequently, by replacing the worst criterion's weight into Equation (4), the weights of the other criteria are determined.

$$\sum_j \widetilde{w}_W'' \bar{P}_{jW} = 1 \Rightarrow \widetilde{w}_W'' = \frac{1}{\sum_j \bar{P}_{jW}} \qquad (3)$$

$$\widetilde{w}_j'' - \overline{P}_{jW}\widetilde{w}_W'' = 0 \Rightarrow \widetilde{w}_j'' = \overline{P}_{jW}\widetilde{w}_W'' \quad \forall\, j \qquad (4)$$

4.2.6: Calculation of Ultimate Decision Criteria Weights:

The final step within this stage entails the computation of the final weights assigned to the decision criteria. These final weights are derived by utilizing Equation (5).

$$\widetilde{w}_j^* = \left(\frac{\widetilde{w}_j' + \widetilde{w}_j''}{2}\right) \qquad (5)$$

4.3 Calculation of consistency ratio (CR):

The next stage in the proposed approach is the calculation of consistency ratio to assess the reliability of the weights obtained through F-SBWM approach. In Decision Making processes that rely on pairwise comparisons, calculating the consistency rate is imperative. If the consistency ratio falls outside an acceptable range, it signifies that the results might be unreliable. In such cases, experts are required to revisit their preferences and comparisons to enhance consistency. Therefore, in this stage the consistency ratio is measured by using Equation (6). The closer the value of CR is to zero, the more consistent the comparisons are (Kannan et al., 2020). However, achieving perfect consistency in pairwise comparisons can be challenging, particularly when dealing with many decision criteria. Some scholars assert that a CR below 0.1 represents the threshold for acceptance. They propose that values surpassing this threshold demand a meticulous review and potential adjustments to expert preferences. On the other hand, a contrasting viewpoint is advocated by an alternative group of researchers who argue for a more rigorous CR threshold of less than 0.05 (Pant et al., 2022).

$$CR = \sum_j \left|\widetilde{w}_j' + \widetilde{w}_j''\right|^2 \qquad (6)$$

4.4 Determination of Interdependencies among criteria using FDEMATEL:

In this stage, the FDEMATEL is used to determine the interdependencies among the criteria. To achieve this, this stage is further segregated into following steps:

4.4.1: Impact Assessment:

In this step, experts are tasked with visually mapping out the influence of criteria on each other based on their experience and knowledge.

4.4.2: Developing the Matrix of Criteria Impacts:

After assessing the impacts of criteria, the next step entails providing the experts with the pairwise comparison matrix and a table of linguistic terms as shown in Table 5 which is adopted from the research of Govindan et al., (2020). This makes it possible to evaluate how different criteria affect one another, which eventually leads to the development of a fuzzy direct-relation matrix.

Table 5: Table of Linguistic terms for FDEMATEL (Govindan et al., 2020)

Linguistic Terms	Fuzzy scales
None	(0,0,0.1)
Very low	(0.1,0.2,0.3)
Low	(0.2,0.3,0.4)
More or less low	(0.3,0.4,0.5)
Medium	(0.4,0.5,0.6)
More or less good	(0.5,0.6,0.7)
Good	(0.6,0.7,0.8)
Very good	(0.7,0.8,0.9)
Excellent	(0.8,0.9,1)

4.4.3: Normalization of the matrix:

The next step is to normalize the resultant matrix by using equation 7 (Govindan et al., 2020).

$$\bar{A}_{ij} = (l_{ij}, m_{ij}, u_{ij}) \text{ and } s = \frac{1}{max_{1\leq i\leq n}\sum_j u_{ij}}, \text{then } \tilde{X} = s \times \bar{A} \qquad (7)$$

4.4.4: Generation of the Fuzzy Relation Matrix:

In this step, the complete fuzzy relation matrix is constructed, by applying Equation (8). Here, the symbol "I" in the equation represents the identity matrix. Consequently, the matrix $\tilde{X}_{ij}$ undergoes a conversion into three separate defuzzified matrices. These three matrices consist of entries corresponding to low, middle, and high values of triangular fuzzy numbers.

$$X_1 = \begin{bmatrix} 0 & l_{12} & \dots & l_{1n} \\ l_{21} & 0 & \dots & l_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ l_{n1} & l_{n2} & \dots & 0 \end{bmatrix}, X_2 = \begin{bmatrix} 0 & m_{12} & \dots & m_{1n} \\ m_{21} & 0 & \dots & m_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m_{n1} & m_{n2} & \dots & 0 \end{bmatrix}, X_3 = \begin{bmatrix} 0 & u_{12} & \dots & u_{1n} \\ u_{21} & 0 & \dots & u_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u_{n1} & u_{n2} & \dots & 0 \end{bmatrix}$$

$$\tilde{T} = \tilde{X}(I - \tilde{X})^{-1}, \tilde{T} = \begin{bmatrix} \tilde{t}_{11} & \tilde{t}_{12} & \dots & \tilde{t}_{1n} \\ \tilde{t}_{21} & \tilde{t}_{22} & \dots & \tilde{t}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{t}_{n1} & \tilde{t}_{n2} & \dots & \tilde{t}_{nn} \end{bmatrix} where \ \tilde{t}_{ij} = \left(l'_{ij}, m'_{ij}, u'_{ij}\right) then, Matrix\left[l'_{ij}\right] =$$

$$X_l(I - X_l)^{-1}, Matrix\left[m'_{ij}\right] = X_m(I - X_m)^{-1}, Matrix\left[u'_{ij}\right] = X_u(I - X_u)^{-1} \quad (8)$$

(Govindan et al., 2020)

4.4.5 Calculation of the Interdependency Matrix:

The final step involves calculating the interdependency matrix. To do this, the total fuzzy relation matrix undergoes defuzzification and normalization by using Equations (9) and (10)

$$Defuzzy\left(t_{ij}\right) = \frac{t_{ij}^{a} + 4t_{ij}^{b} + t_{ij}^{c}}{6} \quad (9)$$

$$Normalized\ Defuzzy\left(t_{ij}\right) = \frac{Defuzzy\left(t_{ij}\right)}{\sum_i Defuzzy\left(t_{ij}\right)} \quad (10)$$

(Govindan et al., 2020)

4.5 Calculation of final weights by applying the inter dependency matrix to criteria weights:

The previous stage's interdependency matrix is applied to the criteria weights obtained in phase 2 section 5.2.6. After applying the interdependency matrix to the criteria weights the final weights of the criteria are obtained with the consideration of interdependency among them. The weights obtained at this stage align with both expert preference for the priority of criteria weights and the interdependencies between them.

4.6 Evaluation of suppliers based on their final scores across all sub criteria:

At this concluding stage, experts are given a questionnaire to assign scores to each supplier against all sub criteria. Table 6 lists the linguistic terms and their related Triangular Fuzzy Numbers. Combined expert opinions on each sub-criterion are obtained using table 6. To get the final score for each supplier, the weights of the sub criteria are multiplied with their corresponding score and the sum of weighted score is attained. As a result, the suppliers with the highest scores are designated as qualified suppliers.

Table 6: Linguistic terms used for supplier ranking (Dagdeviren and Yüksel, 2010)

Linguistic values for positive sub-factors	Linguistic values for negative sub-factors	Triangular fuzzy numbers	The mean of fuzzy numbers
Very weak	Very strong	(0,0,0)	0
Weak	Strong	(0,0.167,0.333)	0.167
Weak-Mid	Mid-Strong	(0.167,0.333,0.5)	0.333
Mid	Mid	(0.333,0.5,0.667)	0.5
Mid-Strong	Weak-Mid	(0.5,0.667,0.833)	0.667
Strong	Weak	(0.667,0.833,1)	0.833
Very strong	Very weak	(1,1,1)	1

5. Validation of F-SBWM and its integration with F-DEMATEL in Circular Supplier Selection:

F-SBWM and the FDEMATEL techniques are validated using numerical examples from earlier research papers in this section. The goal is to examine the effectiveness of the proposed approach in establishing the weights of criterion and sub criteria in the context of a Multi-criterion Decision Making (MCDM) problem for supplier selection. To achieve this, the case study data, preferences, and the linguistic table from the research conducted by Kannan et al. (2020) have been employed. This is done to facilitate a comparative analysis of the effectiveness between the FBWM and the F-SBWM and to determine the role of interdependency while determining criteria weights.

5.1 Stage 1: Identification of sustainable criteria and sub criteria:

Table 7 displays the criteria and sub criteria taken from the case study conducted by Kannan et al. (2020), serving as a reference for the validation of the proposed approach. In the research of Kannan et al. (2020), the primary criteria are economic, circular, and social and the corresponding sub criteria are detailed in Table 7.

Table 7: Criteria and Sub criteria for Supplier selection (Kannan et al., 2020)

Criteria	Sub criteria
Economic (EC)	Cost (EC1), Quality (EC2), Delivery (EC3), Reputation (EC4), Technology (EC5), Flexibility (EC6)
Social (SC)	Health and safety (SC1), The rights of stockholders (SC2), The rights of employees (SC3), Job creation (SC4), Information disclosure (SC5)
Circular (CR)	Air pollution (CR1), Use of eco-friendly raw materials (CR2), Respecting environmental standards (CR3), Implementation of clean technologies (CR4), Use of recyclable material in packaging (CR5)

5.2 Stage 2: Determining criteria and sub-criteria weights without considering Interdependencies:

This stage can further be divided into the following steps.

5.2.1: Determination of the best and the worst criteria from the given set

Kannan et al. (2020) determined Economic and Circular as the best and worst criteria, respectively. Additionally, EC1, CR2, and SC1 were determined as the best sub criteria, while EC6, CR5, and SC5 were regarded as the worst sub criteria.

5.2.2: Establishing best to other preferences:

According to Kannan et al. (2020) the priorities for best to other criteria and sub criteria are as follow:

Fuzzy BTO preferences for criteria: [(1, 1, 1), (0.667, 1, 1.5), (1.5, 2, 2.5)]

Fuzzy BTO preferences for sub criteria within economic criterion:

[(1, 1, 1), (0.667, 1, 1.5), (1.5, 2, 2.5), (0.667, 1, 1.5), (1.5, 2, 2.5), (2.5, 3, 3.5)]

Fuzzy BTO preferences for sub criteria within social criterion:

[(1, 1, 1), (0.667, 1, 1.5), (0.667, 1, 1.5), (1.5, 2, 2.5), (2.5, 3, 3.5)]

Fuzzy BTO preferences for sub criteria within circular criterion:

[(0.667, 1, 1.5), (1, 1, 1), (2.5, 3, 3.5), (1.5, 2, 2.5), (3.5, 4, 4.5)]

5.2.3: Establishing others to worst preferences:

According to Kannan et al. (2020) the priorities for other to worst criteria and sub criteria are as follow:

Fuzzy OTW preferences for criteria: [(1.5, 2, 2.5), (0.667, 1, 1.5), (1, 1, 1)]

Fuzzy OTW preferences for sub criteria within economic criterion:

[(2.5, 3, 3.5), (1.5, 2, 2.5), (0.667, 1, 1.5), (1.5, 2, 2.5), (0.667, 1, 1.5), (1, 1, 1)]

Fuzzy OTW preferences for sub criteria within social criterion:

[(2.5, 3, 3.5), (1.5, 2, 2.5), (1.5, 2, 2.5), (0.667, 1, 1.5), (1, 1, 1)]

Fuzzy OTW preferences for sub criteria within circular criterion:

[(2.5, 3, 3.5), (3.5, 4, 4.5), (0.667, 1, 1.5), (1.5, 2, 2.5), (1, 1, 1)]

5.2.4: Calculating criteria weights based on best to other reference comparisons:

After obtaining the best-to-other and others-to-worst fuzzy vectors, the next step is the calculation of weights, $\tilde{w}_j'$ using the best-to-other preferences that were determined in Step 2 of this stage. In this example, the weights are computed initially for the criteria and subsequently for the sub criteria within each criterion.

$\tilde{w}_j'$ For Criteria:

The weight of the best criterion is determined through Equation (1).

$$\tilde{w}_1' = \frac{1}{\frac{1}{(1,1,1)} + \frac{1}{(0.667,1,1.5)} + \frac{1}{(1.5,2,2.5)}} = \frac{1}{(2.067,2.5,3.167)}$$

$$\tilde{w}_1' = (0.316, 0.40, 0.484)$$

Subsequently, by substituting the weight $\overline{w}_1'$ into Equation (2), the weights of the remaining criteria are obtained.

$$\widetilde{w}_2' = \frac{\widetilde{w}_1'}{\overline{P}_{12}} = \frac{(0.316, 0.40, 0.484)}{(0.667, 1, 1.5)} = (0.211, 0.40, 0.725)$$

$$\widetilde{w}_3' = \frac{\widetilde{w}_1'}{\overline{P}_{13}} = \frac{(0.316, 0.40, 0.484)}{(1.5, 2, 2.5)} = (0.126, 0.20, 0.323)$$

Using the same method as described above, the weights for the sub criteria within each criterion are determined.

$\widetilde{w}_j'$ for sub criteria within economic criterion:

$$\boldsymbol{\widetilde{w}_1'(E)} = (0.175, 0.231, 0.293)$$

$$\widetilde{w}_2'(E) = (0.117, 0.231, 0.439)$$

$$\widetilde{w}_3'(E) = (0.07, 0.116, 0.195)$$

$$\widetilde{w}_4'(E) = (0.117, 0.231, 0.439)$$

$$\widetilde{w}_5'(E) = (0.07, 0.116, 0.195)$$

$$\widetilde{w}_6'(E) = (0.05, 0.077, 0.117)$$

$\widetilde{w}_j'$ for sub criteria within social criterion:

$$\boldsymbol{\widetilde{w}_1'(S)} = (0.198, 0.261, 0.332)$$

$$\widetilde{w}_2'(S) = (0.132, 0.261, 0.497)$$

$$\widetilde{w}_3'(S) = (0.132, 0.261, 0.497)$$

$$\widetilde{w}_4'(S) = (0.079, 0.131, 0.221)$$

$$\widetilde{w}_5'(S) = (0.057, 0.087, 0.133)$$

$\widetilde{w}_j'$ for sub criteria within circular criterion:

$$\widetilde{w}_1'(C) = (0.174, 0.325, 0.583)$$

$$\tilde{\boldsymbol{w}}'_{\boldsymbol{2}}(\boldsymbol{C}) = (0.26{,}0.325{,}0.389)$$

$$\tilde{w}'_3(C) = (0.075{,}0.109{,}0.156)$$

$$\tilde{w}'_4(C) = (0.104{,}0.163{,}0.259)$$

$$\tilde{w}'_5(C) = (0.058{,}0.082{,}0.111)$$

5.2.5: Calculating criteria weights based on others to worst reference comparisons:

After calculating weights, $\tilde{w}'_j$, of all criteria and sub criteria, the next step involves the determination of weights, $\tilde{w}''_j$, utilizing the fuzzy preferences representing the priorities of other criteria over the worst criterion. In this example, the weights $\tilde{w}''_j$ are computed initially for the criteria and subsequently for the sub criteria within each criterion.

$\tilde{w}''_j$ For Criteria:

The weight of the worst criterion is determined by using Equation (3).

$$\tilde{w}''_3 = \frac{1}{(1.5, 2, 2.5) + (0.667, 1, 1.5) + (1, 1, 1)} = \frac{1}{(3.167{,}4.0{,}5.0)}$$

$$\tilde{w}''_3 = (0.20, 0.25, 0.32)$$

Subsequently, by replacing the weight of the worst criterion into Equation (4), the weights of the remaining criteria are determined.

$$\tilde{w}''_1 = (1.5, 2, 2.5) * (0.20, 0.25, 0.32) = (0.30, 0.50, 0.79)$$

$$\tilde{w}''_2 = (0.667, 1, 1.5) * (0.20, 0.25, 0.32) = (0.13, 0.25, 0.47)$$

Using the same method as described above, the weights for the sub criteria within each criterion are determined.

$\tilde{\boldsymbol{w}}''_{\boldsymbol{j}}$ for sub criteria within economic criterion:

$$\tilde{w}''_1\ (E) = (0.2{,}0.3{,}0.447)$$

$$\tilde{w}''_2\ (E) = (0.12{,}0.2{,}0.32)$$

$$\widetilde{w}_3'' (E) = (0.054,0.1,0.192)$$

$$\widetilde{w}_4'' (E) = (0.12,0.2,0.32)$$

$$\widetilde{w}_5'' (E) = (0.054,0.1,0.192)$$

$$\boldsymbol{\widetilde{w}_6''} (\boldsymbol{E}) = (0.08,0.1,0.128)$$

$\widetilde{w}_j''$ for sub criteria within social criterion:

$$\widetilde{w}_1'' (S) = (0.228,0.334,0.489)$$

$$\widetilde{w}_2'' (S) = (0.137,0.223,0.349)$$

$$\widetilde{w}_3'' (S) = (0.137,0.223,0.349)$$

$$\widetilde{w}_4'' (S) = (0.061,0.112,0.21)$$

$$\boldsymbol{\widetilde{w}_5''} (\boldsymbol{S}) = (0.091,0.112,0.14)$$

$\widetilde{w}_j''$ for sub criteria within circular criterion:

$$\widetilde{w}_1'' (C) = (0.193,0.273,0.382)$$

$$\widetilde{w}_2'' (C) = (0.27,0.364,0.491)$$

$$\widetilde{w}_3'' (C) = (0.052,0.091,0.164)$$

$$\widetilde{w}_4'' (C) = (0.116,0.182,0.273)$$

$$\boldsymbol{\widetilde{w}_5''} (\boldsymbol{C}) = (0.077,0.091,0.11)$$

5.2.6: Calculating Ultimate Weights of Criteria and Sub criteria:

In this step, the final weights of criteria and sub criteria are computed using Equation (5). In this example, the final weights are first determined for the criteria and then for the sub criteria within each criterion. The crisp values of the final weights are determined using equation $\widetilde{w}_j^* = \frac{L+4M+U}{6}$ (Amiri et al., 2022).

Final weights ($\tilde{w}_j^*$) For Criteria:

The final weights of the criteria are determined using equation (5) as follow:

$$\tilde{\boldsymbol{w}}_{\mathbf{1}}^* = \left(\frac{\tilde{w}_1' + \tilde{w}_1''}{2}\right) = \frac{(0.316, 0.40, 0.484) + (0.30,0.50,0.79)}{(2,2,2)} = (0.31,0.45,0.64)$$

$$\tilde{w}_2^* = \frac{(0.211,0.40,0.725) + (0.13,0.25,0.47)}{(2,2,2)} = (0.17,0.33,0.60)$$

$$\tilde{w}_3^* = \frac{(0.126,0.20,0.323) + (0.20,0.25,0.32)}{(2,2,2)} = (0.16,0.23,0.32)$$

Final weights after defuzzification:

$$\tilde{\boldsymbol{w}}_{\mathbf{1}}^* = \mathbf{0.45}$$

$$\tilde{\boldsymbol{w}}_{\mathbf{2}}^* = \mathbf{0.33}$$

$$\tilde{\boldsymbol{w}}_{\mathbf{3}}^* = \mathbf{0.22}$$

Using the same method as described above, the weights for the sub criteria within each criterion are determined.

Final weights ($\tilde{w}_j^*$) for sub criteria within economic criterion:

$$\tilde{w}_1^*(E) = (0.188,0.266,0.37) \Rightarrow \quad \bar{w}_1^*(E) = 0.25$$

$$\tilde{w}_2^*(E) = (0.119,0.216,0.379) \Rightarrow \quad \bar{w}_2^*(E) = 0.22$$

$$\tilde{w}_3^*(E) = (0.062,0.108,0.194) \Rightarrow \quad \bar{w}_3^*(E) = 0.11$$

$$\tilde{w}_4^*(E) = (0.119,0.216,0.379) \Rightarrow \quad \bar{w}_4^*(E) = 0.22$$

$$\tilde{w}_5^*(E) = (0.062,0.108,0.194) \Rightarrow \quad \bar{w}_5^*(E) = 0.11$$

$$\tilde{w}_6^*(E) = (0.065,0.089,0.123) \Rightarrow \quad \bar{w}_6^*(E) = 0.09$$

Final weights ($\tilde{w}_j^*$) for sub criteria within social criterion:

$$\widetilde{w}_1^*(S) = (0.213,0.298,0.41) \Rightarrow \quad \overline{w}_1^*(S) = 0.30$$

$$\widetilde{w}_2^*(S) = (0.134,0.242,0.423) \Rightarrow \quad \overline{w}_2^*(S) = 0.24$$

$$\widetilde{w}_3^*(S) = (0.134,0.242,0.423) \Rightarrow \quad \overline{w}_3^*(S) = 0.24$$

$$\widetilde{w}_4^*(S) = (0.07,0.121,0.216) \Rightarrow \quad \overline{w}_4^*(S) = 0.12$$

$$\widetilde{w}_5^*(S) = (0.074,0.1,0.137) \Rightarrow \quad \overline{w}_5^*(S) = 0.10$$

Final weights ($\widetilde{w}_j^*$) for sub criteria within circular criterion:

$$\widetilde{w}_1^*(C) = (0.183,0.299,0.483) \Rightarrow \quad \overline{w}_1^*(C) = 0.31$$

$$\widetilde{w}_2^*(C) = (0.265,0.344,0.44) \Rightarrow \quad \overline{w}_2^*(C) = 0.34$$

$$\widetilde{w}_3^*(C) = (0.063,0.10,0.16) \Rightarrow \quad \overline{w}_3^*(C) = 0.10$$

$$\widetilde{w}_4^*(C) = (0.11,0.172,0.266) \Rightarrow \quad \overline{w}_4^*(C) = 0.17$$

$$\widetilde{w}_5^*(C) = (0.068,0.086,0.111) \Rightarrow \quad \overline{w}_5^*(C) = 0.08$$

5.3 Stage 3: Calculation of Consistency Ratio (CR):

This stage involves the calculation of consistency ratios for all criterion and sub criteria are within each of the criterion. The consistency ratio is crucial for assessing the dependability and consistency of the results obtained. In this example, the CR for the criteria and for all the sub criteria within each criterion is computed using equation (6). The aim of this analysis is to determine the reliability and consistency of the calculated weights. To use equation 6, all $\overline{w}_j'$ and $\overline{w}_j''$ are converted into defuzzified weights using $\frac{L+4M+U}{6}$.

Consistency Ratio (CR) for Criteria:

$$Consistency\,Ratio = |0.4 - 0.515|^2 + |0.423 - 0.268|^2 + |0.208 - 0.253|^2 = 0.039$$

Consistency Ratio for sub criteria within economic criterion:

$$Consistency\,Ratio = |0.232 - 0.308|^2 + |0.246 - 0.207|^2 + |0.121 - 0.107|^2 + |0.246 - 0.207|^2 + |0.121 - 0.107|^2 + |0.079 - 0.101|^2 = \mathbf{0.010}$$

Consistency Ratio for sub criteria within social criterion:

$$Consistency\ Ratio = |0.262 - 0.341|^2 + |0.279 - 0.229|^2 + |0.279 - 0.229|^2 + |0.137 - 0.119|^2 + |0.089 - 0.112|^2 = \mathbf{0.012}$$

Consistency Ratio for sub criteria within circular criterion:

$$Consistency\ Ratio = |0.342 - 0.278|^2 + |0.324 - 0.369|^2 + |0.110 - 0.096|^2 + |0.169 - 0.186|^2 + |0.082 - 0.092|^2 = \mathbf{0.007}$$

The calculated consistency ratios for all criteria and sub criteria fall below the threshold of 0.05, which proves that there is a significant degree of consistency in the derived weights.

5.4 Stage 4: Comparative Analysis of criteria and sub-criteria weights: F-SBWM vs. FBWM:

In this section a comparative assessment of the weights obtained by the Fuzzy Simplified Best Worst Method (F-SBWM) and weights obtained by the Fuzzy Best Worst Method (FBWM) is conducted. The analysis is structured into four distinct parts to ensure a full evaluation. Initially, the weights of the criteria are compared, followed by a further comparison of the weights of sub criteria within each criterion.

5.4.1 Weights comparison for Criteria:

This section contains a comparative analysis of the criteria weights derived from the F-SBWM proposed in this study against the weights found by Kannan et al. (2020) using FBWM, as shown in Table 8. Figure 3 provides a visual illustration that also provides evidence that the F-SBWM approach produces criteria weights that are equally consistent as compared to the weights obtained from the FBWM. Also, F-SBWM demonstrates a lower Consistency Ratio in comparison to the FBWM, hence guaranteeing enhanced consistency in the derived weights.

Table 8: Criteria results comparison between FBWM and F-SBWM

	FBWM		F-SBWM	
Criteria	**Weights**	**Rank**	**Weights**	**Rank**
Economic	0.42	1	0.45	1
Social	0.33	2	0.33	2
Circular	0.25	3	0.22	3
CR	**0.057**		**0.039**	

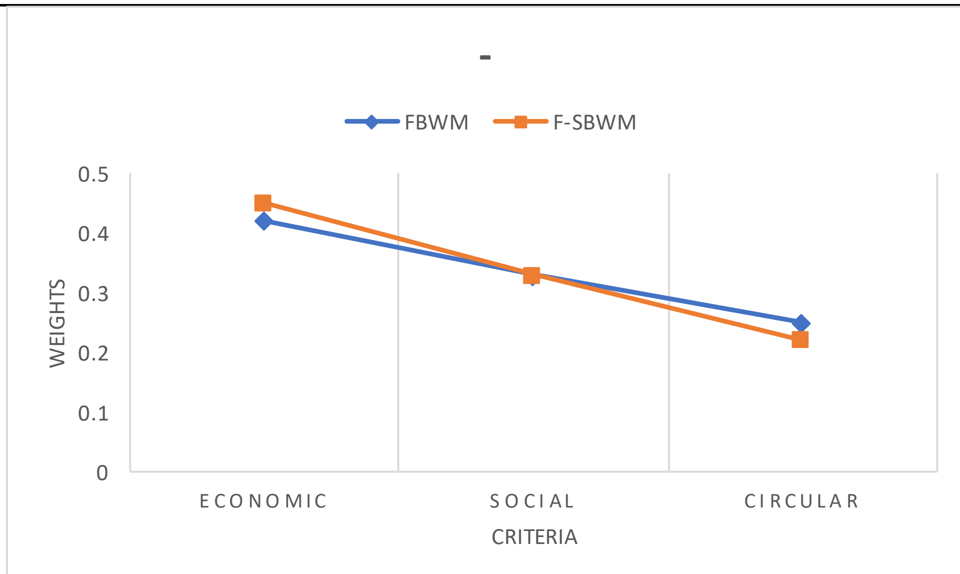


Figure 3: Illustration of criteria weights comparison between FBWM and F-SBWM

5.4.2 Comparative Assessment of Sub criteria Weights within the Economic criterion:

This section contains a comparative analysis of the relative weights assigned to the sub criteria within the economic criterion, as shown in Table 9. The observed discrepancy is evident when comparing the weightings derived using the F-SBWM with those acquired by Kannan et al. (2020) through the utilization of the Fuzzy FBWM. Figure 4 provides an illustration that supports the analysis, and highlights that the F-SBWM approach produces equally reliable and consistent results while determining the sub criteria weights, as compared to the FBWM method. Furthermore, it is important to acknowledge that F-SBWM demonstrates a lower Consistency Ratio in this analysis as well, which highlights that F-SBWM shows a higher level of consistency in the computed weights.

Table 9: Results comparison of sub criteria within economic criterion

	FBWM		F-SBWM	
Sub Criteria	**Weights**	**Rank**	**Weights**	**Rank**
EC1	0.26	1	0.25	1
EC2	0.2	2	0.22	2
EC3	0.11	5	0.11	4
EC4	0.2	3	0.22	3
EC5	0.12	4	0.11	5
EC6	0.09	6	0.09	6
CR	**0.043**		**0.01**	

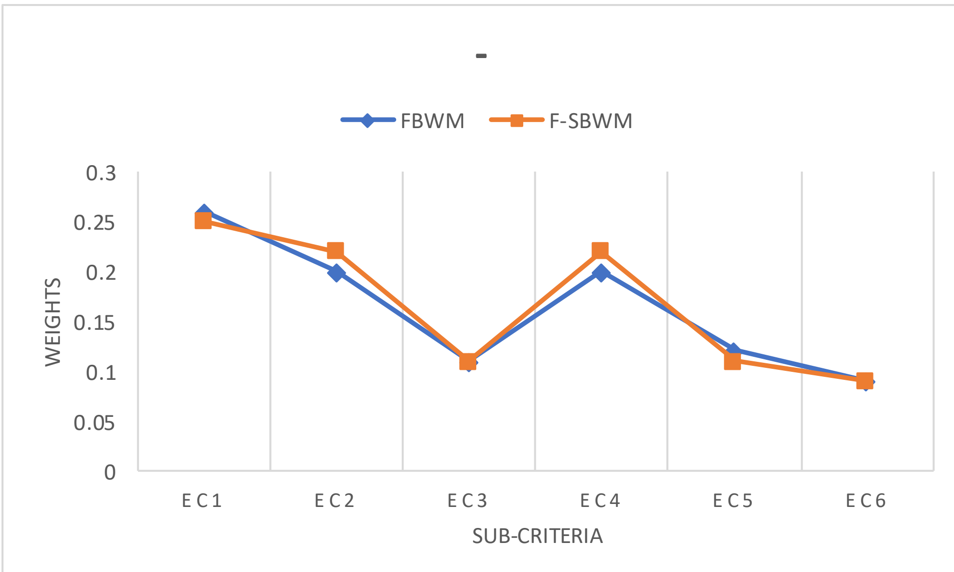


Figure 4: Comparative illustration of sub criteria weights within the economic criterion

5.4.3 Comparative assessment of sub criteria weights within the social criterion:

This section provides a comparative evaluation of the relative weights assigned to the sub criteria within the economic criterion, as shown in Tale 10. The present analysis highlights the differences between the weights derived from the F-SBWM and the weights obtained by Kannan et al. (2020) through the utilization of the FBWM. Additionally, Figure 5 provides an illustration that supports the analysis, and highlights that the F-SBWM approach produces equally reliable and consistent results while determining the sub criteria weights, as compared to the FBWM method. Furthermore, it is important to acknowledge that F-SBWM demonstrates a lower Consistency

Ratio in this analysis as well, which highlights that F-SBWM shows a higher level of consistency in the computed weights.

Table 10: Results comparison of sub criteria within social criterion

	FBWM		F-SBWM	
Sub Criteria	**Weights**	**Rank**	**Weights**	**Rank**
SC1	0.30	1	0.3	1
SC2	0.23	2	0.24	2
SC3	0.23	3	0.24	3
SC4	0.13	4	0.12	4
SC5	0.11	5	0.1	5
CR	**0.043**		**0.012**	

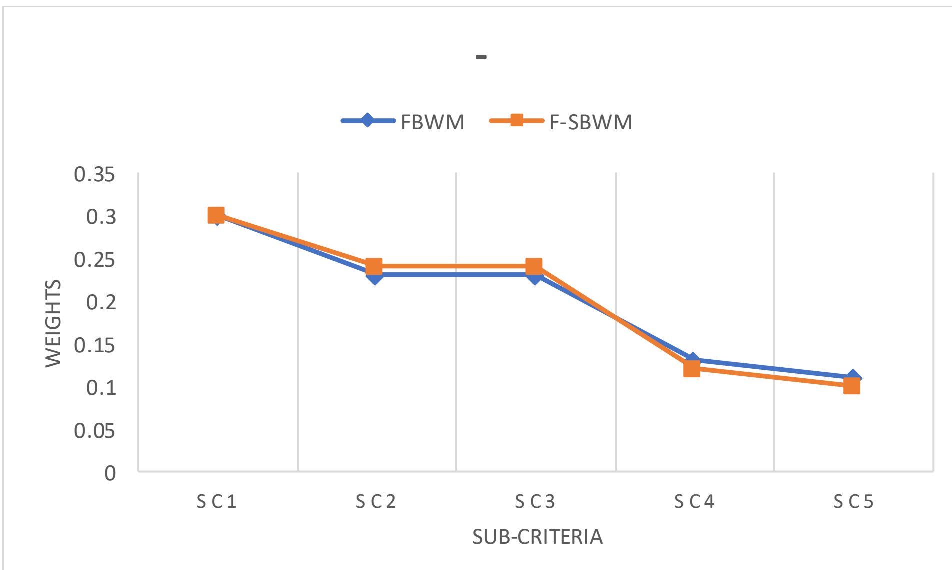


Figure 5: comparative illustration of sub criteria weights within social criterion

5.4.4 Comparative illustration of Sub criteria Weights within Circular criterion:

In this section a thorough comparative analysis of the weights obtained for the sub criteria inside the circular criterion, as shown in Table 11. The table highlights the discrepancy between the sub criteria weights obtained from the suggested F-SBWM and those obtained by Kannan et al. (2020) utilizing the FBWM. Figure 6 provides a visual illustration, which demonstrates that the results obtained from F-SBWM method are equally consistent and reliable, as compared to the FBWM method. Moreover, F-SBWM exhibits a lower Consistency Ratio in this analysis as well, thereby emphasizing the greater level of consistency in the derived weights.

Table 11: Results comparison of sub criteria within circular criterion

	FBWM		F-SBWM	
Sub Criteria	**Weights**	**Rank**	**Weights**	**Rank**
CR1	0.28	2	0.31	2
CR2	0.34	1	0.34	1
CR3	0.11	4	0.1	4
CR4	0.18	3	0.17	3
CR5	0.09	5	0.08	5
CR	**0.037**		**0.007**	

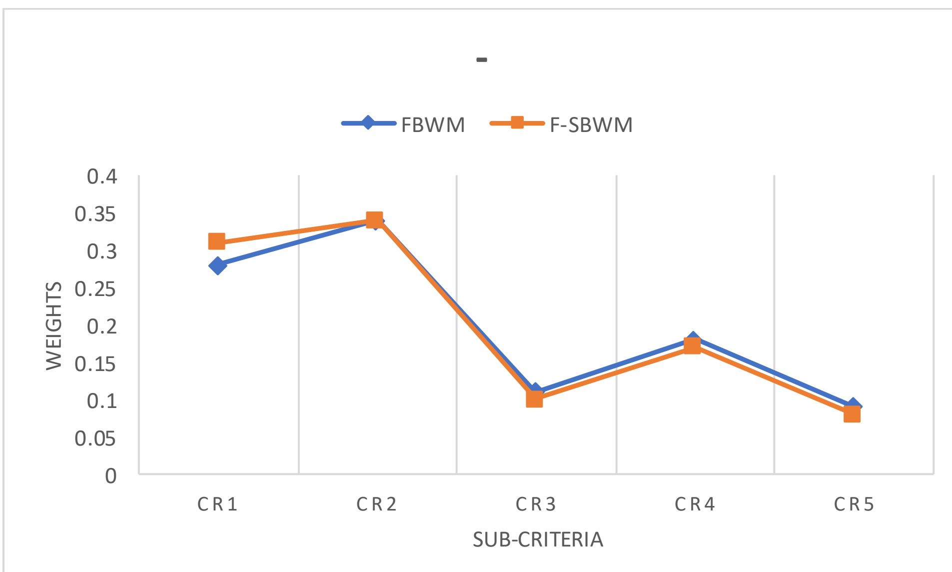


Figure 6: Comparative illustration of Sub criteria weights within circular criterion

All the comparative analyses conducted in this section provide evidence in favor of the Fuzzy Simplified Best Worst Method (F-SBWM) within the domain of Multi-Criteria Decision Making (MCDM) problems. The F-SBWM methodology has demonstrated its reliability and consistency to assign weights to the criteria and sub criteria in MCDM problems that involve several criteria and subsequent sub criteria, all without the need for complex mathematical modeling. Furthermore, The Fuzzy Simplified Best Worst Method (F-SBWM) demonstrates a consistent ability to maintain lower Consistency Ratios, as observed in all comparative assessments. This highlights the superiority of F-SBWM in calculating reliable and consistent weights.

5.5 Stage 5: Determination of Interdependencies among criteria:

At this stage of validation, the objective is to determine the interdependencies among criteria by employing FDEMATEL method. These interdependencies are then applied to the previously obtained criteria weights, allowing for an evaluation of the influence of interdependencies on the initial weighting of criteria and sub criteria.

5.5.1 Impact assessment and formation of criteria's impacts matrix:

The evaluation of the criteria impacts at this stage is based on the work of Govindan et al. (2020) for the purpose of validation. Table 12 displays the matrix of criteria impacts.

Table 12: Criteria's Impacts Matrix adopted from Govindan et al. (2020)

Criteria	EC	SC	CR
EC	-	(0.6,0.7,0.8)	(0.1,0.2,0.3)
SC	(0.1,0.2,0.3)	-	(0.3,0.4,0.5)
CR	(0.1,0.2,0.3)	(0.1,0.2,0.3)	-

5.5.2 Normalizing criteria's impacts matrix:

The normalized matrix is obtained by normalizing the criteria impact matrix using Equation (7). The factor "s" is determined by aggregating the higher values inside each row of Table 12. In the present scenario, the values observed are 1.1 in the first row, 0.8 in the second row, and 0.6 in the third row. The maximum value observed is 1.1, hence the value of s can be calculated as the reciprocal of 1.1, resulting in s = 0.9. Hence, the value of s is 0.9, and it is necessary to do a multiplication operation using the Criteria's Impacts Matrix. Table 13 presents the fuzzy normalized matrix that has been obtained as a result.

Table 13: Normalized Matrix of criteria impacts

Criteria	EC	SC	CR
EC	-	(0.545,0.636,0.727)	(0.091,0.182,0.273)
SC	(0.091,0.182,0.273)	-	(0.273,0.364,0.455)
CR	(0.091,0.182,0.273)	(0.091,0.182,0.273)	-

5.5.3 Formation of the Full Fuzzy Relation Matrix

In this step, Equation 8 is employed to derive the comprehensive fuzzy relation matrix. Initially, the normalized matrix is transformed into three distinct matrices as follows:

$$X_1 = \begin{bmatrix} 0 & 0.545 & 0.091 \\ 0.091 & 0 & 0.273 \\ 0.091 & 0.091 & 0 \end{bmatrix}, X_2 = \begin{bmatrix} 0 & 0.636 & 0.182 \\ 0.182 & 0 & 0.364 \\ 0.182 & 0.182 & 0 \end{bmatrix},$$

$$X_3 = \begin{bmatrix} 0 & 0.727 & 0.273 \\ 0.273 & 0 & 0.455 \\ 0.273 & 0.273 & 0 \end{bmatrix}$$

Subsequently, matrices T_1, T_2, and T_3 are obtained through the equation, $\tilde{T} = \tilde{X}(I - \tilde{X})^{-1}$, where I represent the identity matrix. The resulting matrices are as follows:

$$T_1 = \begin{bmatrix} 0.0799 & 0.6127 & 0.2655 \\ 0.1283 & 0.0983 & 0.3115 \\ 0.1099 & 0.1557 & 0.0525 \end{bmatrix}, T_2 = \begin{bmatrix} 0.2674 & 0.9082 & 0.5613 \\ 0.3369 & 0.3124 & 0.5390 \\ 0.2920 & 0.4042 & 0.2003 \end{bmatrix},$$

$$T_3 = \begin{bmatrix} 0.7796 & 1.6287 & 1.2269 \\ 0.8071 & 0.8805 & 1.0760 \\ 0.7062 & 0.9580 & 0.6287 \end{bmatrix}$$

5.5.4 Calculation of the Interdependency Matrix

In this step equation 9 is used to calculate the interdependency matrix from matrices T_1, T_2, and T_3.

$$Defuzzy\ (t_{11}) = \frac{0.0799 + 4(0.2674) + 0.7796}{6} = 0.322$$

After performing similar calculations for the remaining components, the resulting matrix is as follows:

$$Defuzzy\ (t_{ij}) = \begin{bmatrix} 0.322 & 0.979 & 0.623 \\ 0.381 & 0.371 & 0.591 \\ 0.331 & 0.455 & 0.247 \end{bmatrix}$$

By employing Equation (10), the acquired matrix is subsequently normalized by dividing each element by the sum of its corresponding column. The resulting interdependency matrix is as follows:

$$Interdependency\ Matrix = \begin{bmatrix} 0.311 & 0.542 & 0.426 \\ 0.368 & 0.206 & 0.404 \\ 0.320 & 0.252 & 0.169 \end{bmatrix}$$

5.5.5 Calculation of the final weights:

Following the computation of the Interdependency matrix, the final weights are determined by applying this matrix to the criteria weights obtained in section 6.2.6, as demonstrated below:

$$\begin{bmatrix} 0.311 & 0.542 & 0.426 \\ 0.368 & 0.206 & 0.404 \\ 0.320 & 0.252 & 0.169 \end{bmatrix} \times \begin{bmatrix} 0.45 \\ 0.33 \\ 0.22 \end{bmatrix} = \begin{bmatrix} \mathbf{0.41} \\ \mathbf{0.32} \\ \mathbf{0.27} \end{bmatrix}$$

5.5.6 Comparative Analysis of final weights with and without Interdependency Consideration:

This section entails a comparative examination of the final criteria weights acquired by incorporating interdependency among the criteria, as opposed to the weights achieved through the utilization of F-SBWM without taking interdependency into account, as shown in Table 14. The analysis of Figure 7 demonstrates that the weights of the criteria are influenced by interdependency. In the given instance, it is apparent that the inclusion of interdependency resulted in a reduction in the weights of the economic and social criteria, while concurrently increasing the weight of the circular criterion.

Table 14: comparative assessment of criteria weights, with and without interdependency

Criteria	F-SBWM (without Interdependency)	F-SBWM (with Interdependency)
Economic	0.45	0.41
Social	0.33	0.32
Circular	0.22	0.27
Sum	**1.00**	**1.00**

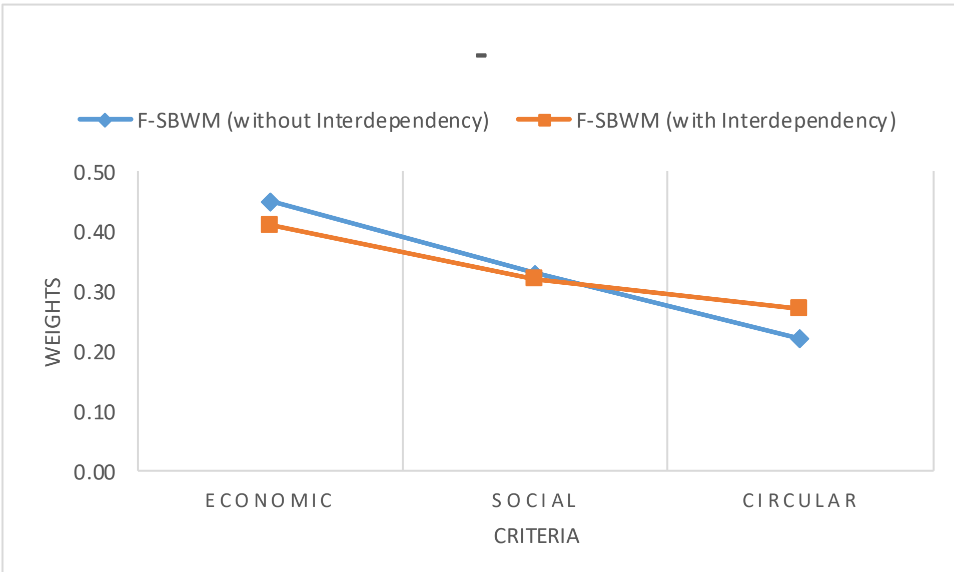


Figure 7: Comparative Illustration of criteria weights

To address the sub criteria, Table 15 presents a comparative examination of the ultimate weights assigned to the sub criteria, considering the interdependency among the criteria, as opposed to the sub criteria weights generated using F-SBWM without considering interdependency. The analysis of Figure 8 demonstrates that there is a substantial impact of interdependency on the weights assigned to the sub criteria.

Table 15: Comparative assessment of sub-criteria weights with and without interdependency

Sub criteria	F-SBWM (without Interdependency)	F-SBWM (with Interdependency)
EC1	0.113	0.103
EC2	0.099	0.090
EC3	0.050	0.045
EC4	0.099	0.090
EC5	0.050	0.045
EC6	0.041	0.037
SC1	0.099	0.096
SC2	0.079	0.077
SC3	0.079	0.077
SC4	0.040	0.038
SC5	0.033	0.032
CR1	0.068	0.084
CR2	0.075	0.092
CR3	0.022	0.027
CR4	0.037	0.046
CR5	0.018	0.022
Sum	**1.00**	**1.00**

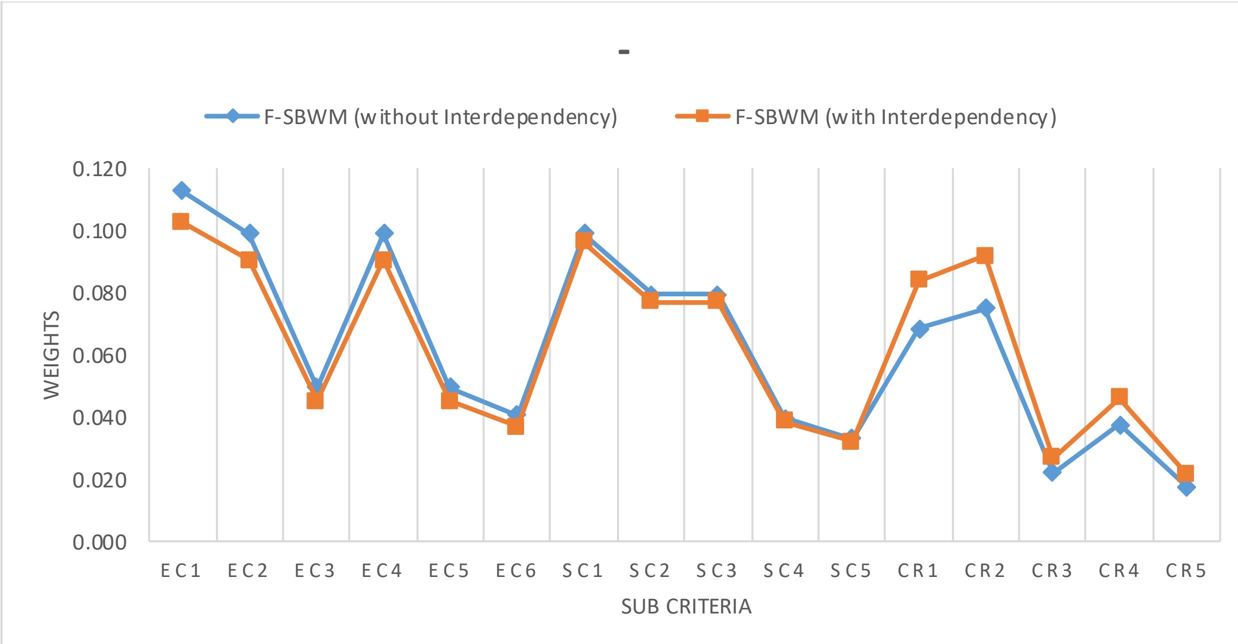


Figure 8: Comparative illustration of sub-criteria weights with and without interdependency

The validation section provides strong evidence supporting the efficacy of integrating F-SBWM and FDEMATEL as a viable approach for determining criteria and sub criteria weights in supplier selection problems. This highlights the need of attaining consistent and dependable weights through the consideration of priority and interdependencies, hence augmenting the process of Decision Making.

6. Case Study

In this section, the proposed methodology is implemented to examine and evaluate the suppliers within the specific context of a textile company located in Pakistan. This textile company specializes in the production of a diverse range of apparel and home textile products, all of these products are manufactured exclusively in Pakistan and subsequently sold to both domestic and international markets. The company's activities are significantly dependent on the acquisition of bulk quantities of essential raw materials, such as cotton, yarn, and polyester. The aforementioned raw materials comprise a substantial proportion of the company's operational expenditures, hence requiring the establishment of strategic and efficient partnerships with suppliers in order to provide a stable and economically viable supply chain. The supplier selection process holds significant importance in guaranteeing the continual fulfillment of the company's production requirements, with a particular focus on maintaining high standards of quality and operational efficiency.

The proposed methodology is utilized to assess the performance of four suppliers within the organization, leveraging the knowledge and insights of a panel consisting of six experts. The panel consists of experts occupying significant positions within the organization, such as the purchasing manager, supply chain director, sales manager, quality compliance manager, operations manager, and supply chain officer. The methodology is executed in a methodical manner, adhering to a sequential procedure, as delineated in the following manner:

6.1 Identification of sustainable criteria and sub criteria for supplier selection:

In this initial phase, the criteria and sub criteria were identified based on an extensive review of relevant literature and a comprehensive analysis of expert opinions, as illustrated in Table 2.

6.2 Determination of weights for criteria and sub criteria without considering Interdependencies using F-SBWM

This phase can further be divided into the following steps.

6.2.1: Determination of the best and the worst criteria from the given set

The experts at this stage were asked to determine the best and the worst criteria and subsequently the best and the worst sub criteria within each criterion. According to the experts Economic and Social are the best and worst criteria, respectively. Additionally, E3, C1, and S1 were determined as the best sub criteria, while E4, C4, and S4 were regarded as the worst sub criteria.

6.2.2: Establishing best to other (BTO) preferences:

At this stage the experts were asked to compare the best criteria with the other criteria and provide reference comparisons using the linguistic terms provided in Table 4. Subsequently, the experts were asked to repeat the same for the sub criteria within each criterion. The obtained expert preferences for best to other criteria and sub criteria are as follow:

Fuzzy BTO preferences for criteria: [(1, 1, 1), (3, 4, 5), (7, 8, 9)]

Fuzzy BTO preferences for sub criteria within economic criterion:

[(1, 2, 3), (3, 4, 5), (1, 1, 1), (5, 6, 7), (4, 5, 6), (2, 3, 4)]

Fuzzy BTO preferences for sub criteria within circular criterion:

[(1, 1, 1), (1, 2, 3), (2, 3, 4), (7, 8, 9), (4, 5, 6), (5, 6, 7)]

Fuzzy BTO preferences for sub criteria within social criterion:

[(1, 1, 1), (4, 5, 6), (2, 3, 4), (7, 8, 9)]

6.2.3: Establishing others to worst (OTW) preferences:

At this stage the experts were asked to compare other criteria with the worst criteria and provide reference comparisons using the linguistic terms provided in Table 4. Subsequently, the experts were asked to repeat the same for the sub criteria within each criterion. The obtained expert preferences for other to worst criteria and sub criteria are as follow:

Fuzzy OTW preferences for criteria: [(7, 8, 9), (2, 3, 4), (1, 1, 1)]

Fuzzy OTW preferences for sub criteria within economic criterion:

[(4, 5, 6), (2, 3, 4), (5, 6, 7), (1, 1, 1), (1, 2, 3), (3, 4, 5)]

Fuzzy OTW preferences for sub criteria within circular criterion:

[(7, 8, 9), (4, 5, 6), (5, 6, 7), (1, 1, 1), (3, 4, 5), (1, 2, 3)]

Fuzzy OTW preferences for sub criteria within social criterion:

[(7, 8, 9), (1, 2, 3), (3, 4, 5), (1, 1, 1)]

6.2.4: Calculating criteria weights based on best to other reference comparisons:

After obtaining the best-to-other and others-to-worst fuzzy vectors from the experts, the next step is the calculation of weights, $\tilde{w}_j'$ using the best-to-other preferences that were determined by the experts. The weights are computed initially for the criteria and subsequently for the sub criteria within each criterion.

$\tilde{w}_j'$ For Criteria:

The weight of the best criterion is determined through Equation (1).

$$\widetilde{w}_1' = \frac{1}{\frac{1}{(1,1,1)} + \frac{1}{(3,4,5)} + \frac{1}{(7,8,9)}} = \frac{1}{(1.311, 1.375, 1.467)}$$

$$\widetilde{w}_1' = (0.677, 0.727, 0.763)$$

Subsequently, by replacing the weight $\overline{w}_1'$ into Equation (2), the weights of the remaining criteria are obtained.

$$\widetilde{w}_2' = \frac{\widetilde{w}_1'}{\overline{P}_{12}} = \frac{(0.677,0.727,0.763)}{(3,4,5)} = (0.135, 0.182, 0.254)$$

$$\widetilde{w}_3' = \frac{\widetilde{w}_1'}{\overline{P}_{13}} = \frac{(0.677,0.727,0.763)}{(7,8,9)} = (0.075, 0.091, 0.109)$$

Using the same method as described above, the weights for the sub criteria within each criterion are determined.

$\widetilde{w}_j'$ for sub criteria within economic criterion:

$$\widetilde{w}_1'(E) = (0.102, 0.204, 0.478)$$

$$\widetilde{w}_2'(E) = (0.061, 0.102, 0.159)$$

$$\boldsymbol{\widetilde{w}_3'(E)} = (0.305,0.408,0.478)$$

$$\widetilde{w}_4'(E) = (0.044,0.068,0.096)$$

$$\widetilde{w}_5'(E) = (0.051,0.082,0.120)$$

$$\widetilde{w}_6'(E) = (0.076,0.136,0.239)$$

$\widetilde{w}_j'$ for sub criteria within circular criterion:

$$\boldsymbol{\widetilde{w}_1'(C)} = (0.323,0.430,0.499)$$

$$\widetilde{w}_2'(C) = (0.108,0.215,0.499)$$

$$\widetilde{w}_3'(C) = (0.081,0.143,0.249)$$

$$\widetilde{w}_4'(C) = (0.036, 0.054, 0.0713)$$

$$\widetilde{w}_5'(C) = (0.054, 0.086, 0.125)$$

$$\widetilde{w}_6'(C) = (0.046, 0.072, 0.100)$$

$\widetilde{w}_j'$ for sub criteria within social criterion:

$$\widetilde{\boldsymbol{w}}_1'(\boldsymbol{S}) = (0.528, 0.603, 0.655)$$

$$\widetilde{w}_2'(S) = (0.088, 0.121, 0.164)$$

$$\widetilde{w}_3'(S) = (0.132, 0.201, 0.327)$$

$$\widetilde{w}_4'(S) = (0.059, 0.075, 0.094)$$

6.2.5: Calculating criteria weights based on others to worst reference comparisons:

After calculating weights ($\widetilde{w}_j'$), of all criteria and sub criteria, the next step involves the determination of weights, $\widetilde{w}_j''$, utilizing the expert's fuzzy preferences representing the priorities of other criteria over the worst criterion. In this example, the weights $\widetilde{w}_j''$ are computed initially for the criteria and subsequently for the sub criteria within each criterion.

$\widetilde{w}_j''$For Criteria:

The weight of the worst criterion is determined by using Equation (3).

$$\widetilde{w}_3'' = \frac{1}{(7,8,9) + (2,3,4) + (1,1,1)} = \frac{1}{(10, 12, 14)}$$

$$\widetilde{w}_3'' = (0.07, 0.083, 0.1)$$

Subsequently, by replacing the weight of the worst criterion into Equation (4), the weights of the remaining criteria are determined.

$$\widetilde{w}_1'' = (7,8,9) * (0.07, 0.083, 0.1) = (0.50, 0.667, 0.9)$$

$$\widetilde{w}_2'' = (2,3,4) * (0.07, 0.083, 0.1) = (0.143, 0.25, 0.4)$$

Using the same method as described above, the weights for the sub criteria within each criterion are determined.

$\tilde{w}_j''$ for sub criteria within economic criterion:

$$\tilde{w}_1''\,(E) = (0.154{,}0.238{,}0.375)$$

$$\tilde{w}_2''\,(E) = (0.077{,}0.143{,}0.250)$$

$$\tilde{w}_3''\,(E) = (0.192{,}0.286{,}0.438)$$

$$\boldsymbol{\tilde{w}_4''}\,(\boldsymbol{E}) = (0.038{,}0.048{,}0.063)$$

$$\tilde{w}_5''\,(E) = (0.038{,}0.095{,}0.188)$$

$$\tilde{w}_6''\,(E) = (0.115{,}0.190{,}0.313)$$

$\tilde{w}_j''$ for sub criteria within circular criterion:

$$\tilde{w}_1''\,(C) = (0.226{,}0.308{,}0.429)$$

$$\tilde{w}_2''\,(C) = (0.129{,}0.192{,}0..286)$$

$$\tilde{w}_3''\,(C) = (0.161{,}0.231{,}0.333)$$

$$\boldsymbol{\tilde{w}_4''}\,(\boldsymbol{C}) = (0.032{,}0.038{,}0.048)$$

$$\tilde{w}_5''\,(C) = (0.097{,}0.154{,}0.238)$$

$$\tilde{w}_6''\,(C) = (0.032{,}0.077{,}0.143)$$

$\tilde{w}_j''$ for sub criteria within social criterion:

$$\tilde{w}_1''\,(S) = (0.389{,}0.533{,}0.75)$$

$$\tilde{w}_2''\,(S) = (0.056{,}0.133{,}0.250)$$

$$\tilde{w}_3''\,(S) = (0.167{,}0.267{,}0.417)$$

$$\boldsymbol{\tilde{w}_4''}\,(\boldsymbol{S}) = (0.056{,}0.067{,}0.083)$$

6.2.6: Calculating Final Weights of Criteria and Sub criteria:

In this step, the final weights of criteria and sub criteria are computed using Equation (5). The final weights are first determined for the criteria and then for the sub criteria within each criterion. The crisp values of the final weights are determined using equation "$Crisp\ value = \frac{L+4M+U}{6}$" .

Final weights ($\tilde{w}_j^*$) For Criteria:

The final weights of the criteria are determined using equation (5) as follow:

$$\tilde{\boldsymbol{w}}_{\boldsymbol{1}}^* = \left(\frac{\tilde{w}_1' + \tilde{w}_1''}{2}\right) = \frac{(0.677,0.727,0.763) + (0.50,0.667,0.9)}{(2,2,2)} = (0.589,0.697,0.831)$$

$$\tilde{w}_2^* = \frac{(0.135,0.182,0.254) + (0.143,0.25,0.4)}{(2,2,2)} = (0.139,0.216,0.327)$$

$$\tilde{w}_3^* = \frac{(0.075,0.091,0.109) + (0.07,0.083,0.1)}{(2,2,2)} = (0.073,0.087,0.104)$$

Final weights after defuzzification:

$$\tilde{\boldsymbol{w}}_{\boldsymbol{1}}^* = \mathbf{0.70}$$

$$\tilde{\boldsymbol{w}}_{\boldsymbol{2}}^* = \mathbf{0.21}$$

$$\tilde{\boldsymbol{w}}_{\boldsymbol{3}}^* = \mathbf{0.09}$$

Using the same method as described above, the weights for the sub criteria within each criterion are determined.

Final weights ($\tilde{w}_j^*$) for sub criteria within economic criterion:

$$\tilde{w}_1^*(E) = (0.128,0.221,0.426) \Rightarrow \quad \bar{w}_1^*(E) = 0.24$$

$$\tilde{w}_2^*(E) = (0.069,0.122,0.205) \Rightarrow \quad \bar{w}_2^*(E) = 0.12$$

$$\tilde{w}_3^*(E) = (0.248,0.347,0.458) \Rightarrow \quad \bar{w}_3^*(E) = 0.34$$

$$\tilde{w}_4^*(E) = (0.041,0.058,0.079) \Rightarrow \quad \bar{w}_4^*(E) = 0.05$$

$$\widetilde{w}_5^*(E) = (0.045,0.088,0.153) \Rightarrow \quad \overline{w}_5^*(E) = 0.09$$

$$\widetilde{w}_6^*(E) = (0.096,0.163,0.276) \Rightarrow \quad \overline{w}_6^*(E) = 0.16$$

Final weights ($\widetilde{w}_j^*$) *for sub criteria within circular criterion:*

$$\widetilde{w}_1^*(C) = (0.275,0.369,0.464) \Rightarrow \quad \overline{w}_1^*(C) = 0.36$$

$$\widetilde{w}_2^*(C) = (0.118,0.204,0.392) \Rightarrow \quad \overline{w}_2^*(C) = 0.22$$

$$\widetilde{w}_3^*(C) = (0.121,0.187,0.291) \Rightarrow \quad \overline{w}_3^*(C) = 0.19$$

$$\widetilde{w}_4^*(C) = (0.034,0.046,0.059) \Rightarrow \quad \overline{w}_4^*(C) = 0.04$$

$$\widetilde{w}_5^*(C) = (0.075,0.120,0.181) \Rightarrow \quad \overline{w}_5^*(C) = 0.12$$

$$\widetilde{w}_6^*(C) = (0.039,0.074,0.121) \Rightarrow \quad \overline{w}_5^*(C) = 0.07$$

Final weights ($\widetilde{w}_j^*$) *for sub criteria within social criterion:*

$$\widetilde{w}_1^*(S) = (0.459,0.568,0.702) \Rightarrow \quad \overline{w}_1^*(S) = 0.56$$

$$\widetilde{w}_2^*(S) = (0.072,0.127,0.207) \Rightarrow \quad \overline{w}_2^*(S) = 0.13$$

$$\widetilde{w}_3^*(S) = (0.149,0.234,0.372) \Rightarrow \quad \overline{w}_3^*(S) = 0.24$$

$$\widetilde{w}_4^*(S) = (0.057,0.071,0.088) \Rightarrow \quad \overline{w}_4^*(S) = 0.07$$

6.3: Calculation of Consistency Ratio (CR)

This phase involves the calculation of consistency ratios for all criteria and sub criteria within each of the criterion. The consistency ratio is crucial at this stage for assessing the dependability and consistency of the results obtained. The CR for the criteria and for all the sub criteria within each criterion is computed using equation (6). To use equation 6, all $\overline{w}_j'$ and $\overline{w}_j''$ are converted into defuzzified weights using $\frac{L+4M+U}{6}$.

6.3.1 Consistency Ratio (CR) for Criteria:

$$Consistency\ Ratio = |0.725 - 0.678|^2 + |0.186 - 0.257|^2 + |0.091 - 0.084|^2 = 0.007$$

6.3.2 Consistency Ratio for sub criteria within economic criterion:

$Consistency\ Ratio\ = |0.233 - 0.247|^2 + |0.105 - 0.150|^2 + |0.403 - 0.295|^2 + |0.069 - 0.049|^2 + |0.083 - 0.101|^2 + |0.143 - 0.198|^2 = \mathbf{0.017}$

6.3.3 Consistency Ratio for sub criteria within circular criterion:

$Consistency\ Ratio\ = |0.424 - 0.314|^2 + |0.245 - 0.197|^2 + |0.151 - 0.236|^2 + |0.054 - 0.039|^2 + |0.087 - 0.158|^2 + |0.072 - 0.080|^2 = \mathbf{0.027}$

6.3.4 Consistency Ratio for sub criteria within social criterion:

$Consistency\ Ratio\ = |0.599 - 0.545|^2 + |0.122 - 0.140|^2 + |0.211 - 0.275|^2 + |0.076 - 0.068|^2 = \mathbf{0.007}$

The consistency ratios for all criteria and sub criteria fall below the threshold of 0.05, suggesting a significant degree of consistency in the derived weights. This means that the experts were not required to modify their preferences and the obtained weights for the criteria and sub criteria are consistent. The final sub-criteria weights obtained at this phase using Fuzzy simplified best worst method without considering the interdependency among criteria are displayed in Table 16 and Figure 9.

Table 16:Sub-criteria weights obtained through F-SBWM without interdependencies.

Sub Criteria	E1	E2	E3	E4	E5	E6	C1	C2	C3	C4	C5	C6	S1	S2	S3	S4	Sum
Weights	0.17	0.08	0.24	0.04	0.06	0.11	0.08	0.05	0.04	0.01	0.03	0.01	0.05	0.01	0.02	0.01	**1.00**

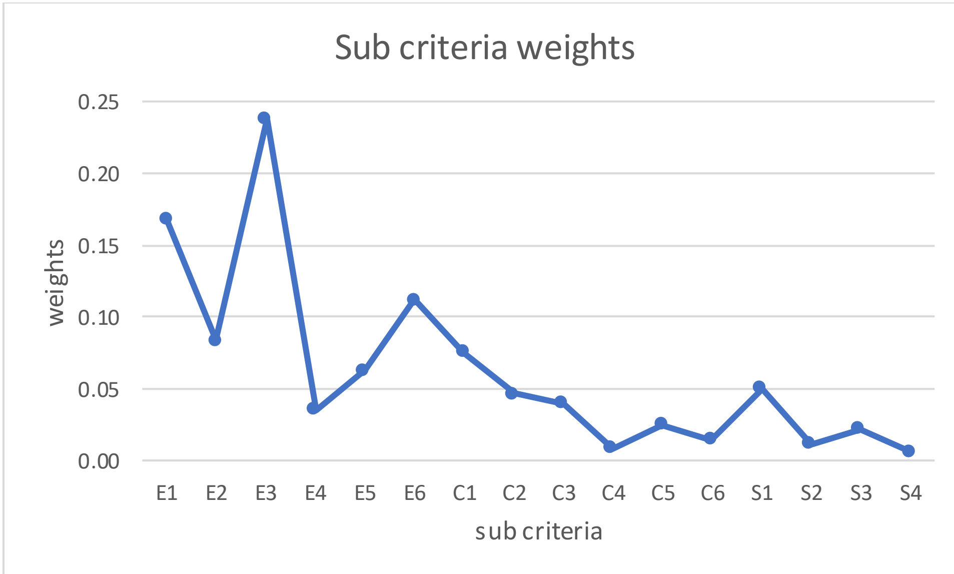


Figure 9: Sub-criteria weights obtained through F-SBWM without considering interdependencies.

6.4 Determination of Interdependencies among criteria:

In this phase of research, the interdependencies among criteria are determined by employing the FDEMATEL method. These interdependencies are then incorporated into the previously established criteria weights, to determine the final weights.

6.4.1 Impact assessment

At this stage the decision makers were asked to graphically present the impact of criteria over each other. The graphical impact assessment provided by the experts are shown in Figure 10.

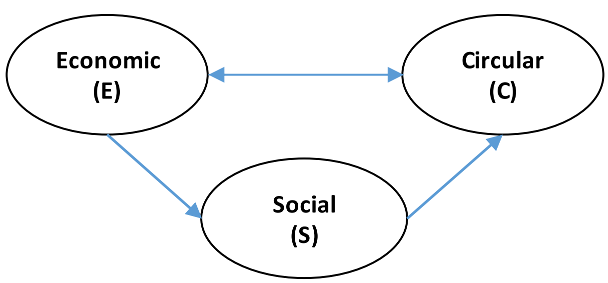


Figure 10: Graphical Impact assessment among criteria

6.4.2 Formation of criteria's impacts matrix.

Based on the impact assessment, the experts were asked to translate these impacts in the fom of TFN by using Table 5. As a result, the criteria's impacts matrix is obtained, as shown in Table 17.

Table 17: Criteria's impact Matrix for the calculation of interdependencies

Criteria	EC	CR	SC
EC	-	(0.4,0.5,0.6)	(0.2,0.3,0.4)
CR	(0.4,0.5,0.6)	-	-
SC	-	(0.1,0.2,0.3)	-

6.4.3 Normalizing criteria's impacts matrix.

As a next step at this stage, the normalized matrix is obtained by normalizing the criteria impact matrix using Equation (7). The factor "s" is determined by aggregating the higher values inside each row of Table 17. In the present scenario, the values observed are 1.0 in the first row, 0.6 in the second row, and 0.3 in the third row. The maximum value observed is 1.0, hence the value of s can be calculated as the reciprocal of 1.0, resulting in s = 01.0. Hence, the value of s is 0.9, and it is necessary to do a multiplication operation using the Criteria's Impacts Matrix. Table 18 presents the fuzzy normalized matrix that has been obtained as a result.

Table 18: Fuzzy normalized matrix for interdependency calculation

Criteria	EC	CR	SC
EC	-	(0.4,0.5,0.6)	(0.2,0.3,0.4)
CR	(0.4,0.5,0.6)	-	-
SC	-	(0.1,0.2,0.3)	-

6.4.4 Formation of the Full Fuzzy Relation Matrix

In this step, Equation 8 is employed to derive the comprehensive fuzzy relation matrix. Initially, the normalized matrix is transformed into three distinct matrices as follows:

$$X_1 = \begin{bmatrix} 0 & 0.4 & 0.2 \\ 0.4 & 0 & 0 \\ 0 & 0.1 & 0 \end{bmatrix}, X_2 = \begin{bmatrix} 0 & 0.5 & 0.3 \\ 0.5 & 0 & 0 \\ 0 & 0.2 & 0 \end{bmatrix},$$

$$X_3 = \begin{bmatrix} 0 & 0.6 & 0.4 \\ 0.6 & 0 & 0 \\ 0 & 0.3 & 0 \end{bmatrix}$$

Subsequently, matrices T_1, T_2, and T_3 are obtained through the equation, $\tilde{T} = \tilde{X}(I - \tilde{X})^{-1}$, where I represent the identity matrix. The resulting matrices are as follows:

$$T_1 = \begin{bmatrix} 0.202 & 0.505 & 0.240 \\ 0.481 & 0.202 & 0.096 \\ 0.048 & 0.120 & 0.010 \end{bmatrix}, T_2 = \begin{bmatrix} 0.289 & 0.778 & 0.417 \\ 0.694 & 0.389 & 0.208 \\ 0.139 & 0.278 & 0.042 \end{bmatrix},$$

$$T_3 = \begin{bmatrix} 0.761 & 1.268 & 0.704 \\ 1.056 & 0.760 & 0.423 \\ 0.317 & 0.528 & 0.127 \end{bmatrix}$$

6.4.5 Calculation of the Interdependency Matrix

In this step equation 9 is used to calculate the interdependency matrix from matrices T_1, T_2, and T_3.

$$Defuzzy\ (t_{11}) = \frac{0.202 + 4(0.289) + 0.761}{6} = 0.353$$

After performing similar calculations for the remaining components, the resulting matrix is as follows:

$$Defuzzy\ (t_{ij}) = \begin{bmatrix} 0.353 & 0.814 & 0.435 \\ 0.719 & 0.420 & 0.225 \\ 0.153 & 0.293 & 0.051 \end{bmatrix}$$

By employing Equation (10), the acquired matrix is subsequently normalized by dividing each element by the sum of its corresponding column. The resulting interdependency matrix is as follows:

$$Interdependency\ Matrix = \begin{bmatrix} 0.288 & 0.533 & 0.612 \\ 0.587 & 0.275 & 0.317 \\ 0.125 & 0.192 & 0.071 \end{bmatrix}$$

6.4.6 Calculation of the final weights

Following the computation of the Interdependency matrix, the final weights of the criteria are determined by applying this matrix to the criteria weights obtained in section 7.2.6, as demonstrated below:

$$\begin{bmatrix} 0.288 & 0.533 & 0.612 \\ 0.587 & 0.275 & 0.317 \\ 0.125 & 0.192 & 0.071 \end{bmatrix} \times \begin{bmatrix} 0.70 \\ 0.21 \\ 0.09 \end{bmatrix} = \begin{bmatrix} \mathbf{0.37} \\ \mathbf{0.49} \\ \mathbf{0.14} \end{bmatrix}$$

6.4.7 Comparative Analysis of final weights with and without Interdependency Consideration

This section entails a comparative analysis of the final criteria weights acquired by incorporating interdependency among the criteria, as opposed to the weights achieved through the utilization of F-SBWM without taking interdependency into account, as shown in Table 19. The analysis of Figure 11 demonstrates that the weights of the criteria are influenced by interdependency. In the given case study, it is apparent that the inclusion of interdependency resulted in a noticeable reduction in the weight of economic criterion while an increase in circular and social criteria.

Table 19: comparison of criteria weight with and without interdependency

Criteria	F-SBWM (without Interdependency)	F-SBWM (with Interdependency)
Economic	0.70	0.37
Circular	0.21	0.49
Social	0.09	0.14
SUM	**1.00**	**1.00**

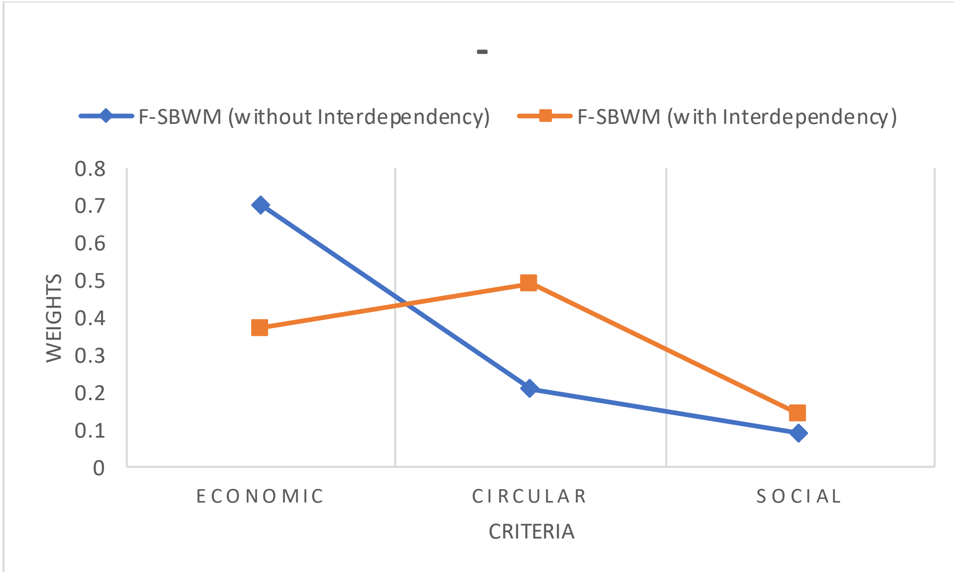


Figure 11: Comparative Illustration of Criteria Weights with and without Interdependency

In case of sub-criteria, Table 20 presents a comparative examination of the ultimate weights assigned to the sub criteria, considering the interdependency among the criteria, as opposed to the sub criteria weights generated using F-SBWM without considering interdependency. The analysis of Figure 12 illustrates that there is a substantial impact of interdependency on the weights assigned to the sub criteria.

Table 20: Comparative analysis of sub-criteria weights with and without interdependency

Sub criteria	F-SBWM (without Interdependency)	F-SBWM (with Interdependency)
E1	0.17	0.09
E2	0.08	0.04
E3	0.24	0.13
E4	0.04	0.02
E5	0.06	0.03
E6	0.11	0.06
C1	0.08	0.18
C2	0.05	0.11
C3	0.04	0.09
C4	0.01	0.02
C5	0.03	0.06
C6	0.01	0.03
S1	0.05	0.08
S2	0.01	0.02
S3	0.02	0.03
S4	0.01	0.01
Sum	**1.00**	**1.00**

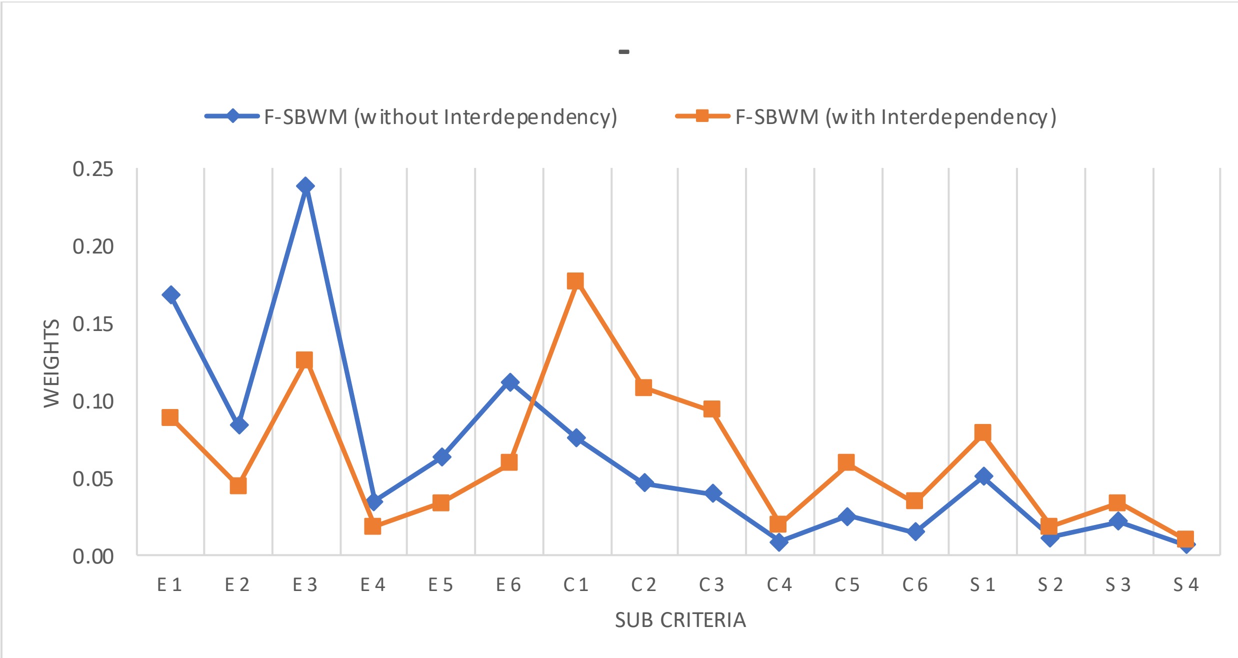


Figure 12: Comparative illustration of sub-criteria weights with and without interdependency

6.5 Evaluation of suppliers based on their final scores across all sub criteria:

At this concluding stage, experts are given a questionnaire to assign scores to each supplier against all the sub criteria. Table 6 lists the linguistic terms and their related Triangular Fuzzy Numbers that have been used to assign scores to the suppliers against all the sub criteria. Combined expert opinions on each sub-criterion are obtained from the panel of experts.

6.5.1 Assigning scores to the suppliers in the form of TFN:

The scores assigned to the suppliers by the panel of experts are highlighted in Table 21.

Table 21: Scores assigned to suppliers in the form of TFN.

SUB-CRITERIA	SUPPLIER 1	SUPPLIER 2	SUPPLIER 3	SUPPLIER 4
E1	(0,0.167,0.333)	(0.333,0.5,0.667)	(0,0.167,0.333)	(0.5,0.667,0.833)
E2	(0.5,0.667,0.833)	(0,0.167,0.333)	(0.667,0.833,1)	(0,0.167,0.333)
E3	(0.5,0.667,0.833)	(0.167,0.333,0.5)	(0,0.167,0.333)	(1,1,1)
E4	(0.333,0.5,0.667)	(0.5,0.667,0.833)	(0,0.167,0.333)	(0.167,0.333,0.5)
E5	(0,0.167,0.333)	(0.333,0.5,0.667)	(0.5,0.667,0.833)	(0.667,0.833,1)

E6	(1,1,1)	(0.5,0.667,0.833)	(0,0.167,0.333)	(0.5,0.667,0.833)
C1	(0.167,0.333,0.5)	(0,0.167,0.333)	(0.333,0.5,0.667)	(0.667,0.833,1)
C2	(0.333,0.5,0.667)	(0.167,0.333,0.5)	(0.167,0.333,0.5)	(0.667,0.833,1)
C3	(0,0.167,0.333)	(0.5,0.667,0.833)	(0.167,0.333,0.5)	(0.333,0.5,0.667)
C4	(0,0.167,0.333)	(1,1,1)	(0.333,0.5,0.667)	(0.5,0.667,0.833)
C5	(0.667,0.833,1)	(0,0.167,0.333)	(0.5,0.667,0.833)	(0.167,0.333,0.5)
C6	(0.333,0.5,0.667)	(0.5,0.667,0.833)	(0.333,0.5,0.667)	(0.667,0.833,1)
S1	(0.167,0.333,0.5)	(0.5,0.667,0.833)	(1,1,1)	(0.333,0.5,0.667)
S2	(0.5,0.667,0.833)	(0,0.167,0.333)	(0.5,0.667,0.833)	(0.333,0.5,0.667)
S3	(0,0.167,0.333)	(0.167,0.333,0.5)	(0.333,0.5,0.667)	(0,0.167,0.333)
S4	(0.167,0.333,0.5)	(0,0.167,0.333)	(0.5,0.667,0.833)	(0,0.167,0.333)

6.5.2 Defuzzification of scores assigned to the suppliers:

As a next step the initially obtained scores are defuzzified as shown in Table 22. The sub criteria weights obtained from previous stage after applying the interdependencies are also given in Table 22 and after this step the weighted scores can be obtained by multiplying the scores with the corresponding sub criteria weights.

Table 22: Defuzzified scores assigned to the suppliers for ranking of suppliers.

Sub-criteria	Weights	Supplier 1	Supplier 2	Supplier 3	Supplier 4
E1	**0.09**	0.167	0.5	0.167	0.667
E2	**0.04**	0.667	0.167	0.833	0.167
E3	**0.13**	0.667	0.333	0.167	1
E4	**0.02**	0.5	0.667	0.167	0.333
E5	**0.03**	0.167	0.5	0.667	0.833
E6	**0.06**	1	0.667	0.167	0.667
C1	**0.18**	0.333	0.167	0.5	0.833
C2	**0.11**	0.5	0.333	0.333	0.833
C3	**0.09**	0.167	0.667	0.333	0.5
C4	**0.02**	0.167	1	0.5	0.667
C5	**0.06**	0.833	0.167	0.667	0.333
C6	**0.03**	0.5	0.667	0.5	0.833
S1	**0.08**	0.333	0.667	1	0.5
S2	**0.02**	0.667	0.167	0.667	0.5
S3	**0.03**	0.167	0.333	0.5	0.167
S4	**0.01**	0.333	0.167	0.667	0.167

6.5.3 Calculation of final Scores

In this step the final scores are calculated by multiplying the defuzzified scores with the corresponding weights of sub criteria. As a result, weighted scores are obtained for each supplier. The weighted scores for each supplier are summed together to determine the final score of each supplier as shown in Table 23.

Table 23: Final weighted scores obtained by suppliers.

Sub-criteria	Supplier 1	Supplier 2	Supplier 3	Supplier 4
E1	0.015	0.045	0.015	0.060
E2	0.027	0.007	0.033	0.007
E3	0.087	0.043	0.022	0.130
E4	0.010	0.013	0.003	0.007
E5	0.005	0.015	0.020	0.025
E6	0.060	0.040	0.010	0.040
C1	0.060	0.030	0.090	0.150
C2	0.055	0.037	0.037	0.092
C3	0.015	0.060	0.030	0.045
C4	0.003	0.020	0.010	0.013
C5	0.050	0.010	0.040	0.020
C6	0.015	0.020	0.015	0.025
S1	0.027	0.053	0.080	0.040
S2	0.013	0.003	0.013	0.010
S3	0.005	0.010	0.015	0.005
S4	0.003	0.002	0.007	0.002
SUM	**0.45**	**0.41**	**0.44**	**0.67**

The suppliers with the highest scores are considered the most preferred suppliers. According to the results obtained, Supplier 4 is the most preferred supplier with the highest score of 0.67, then comes Supplier 1 with the second highest score of 0.45, next is supplier 3 with the score of 0.44 and finally Supplier 2 is the least preferred supplier with the lowest score of 0.41. Figure 13 provides an illustration of the final scores of suppliers and their preference accordingly.

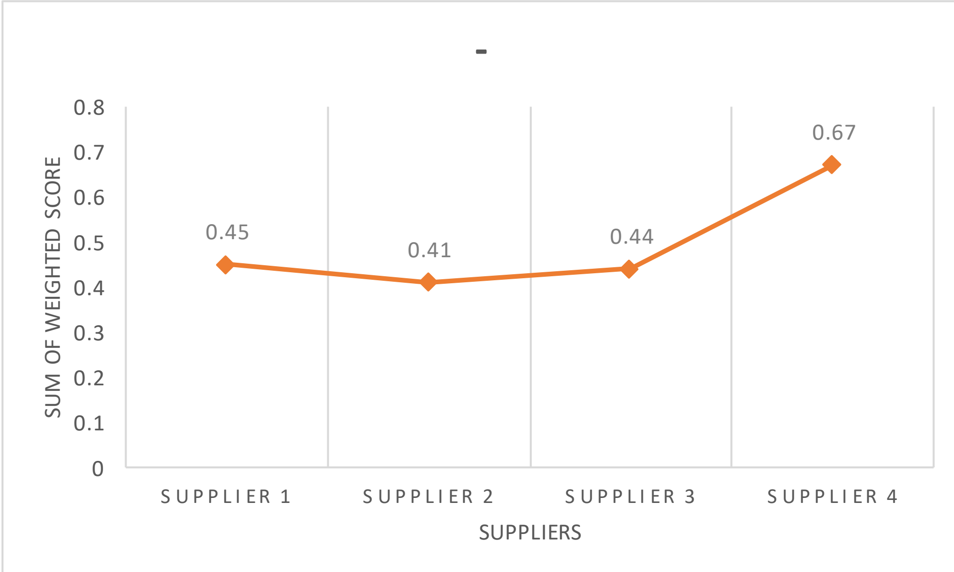


Figure 13: Final weighted scores obtained by suppliers.

7. Findings and Discussion

Based on the results obtained from the case study, through the application of proposed approach, which integrates F-SBWM and FDEMATEL, significant evidence emerges in favor of the proposed methodology. The most crucial aspect highlighted in the results is the change in criteria and sub criteria weights when the interdependency among criteria is considered. The obtained results provide compelling evidence that the consideration of interdependency has a significant influence over criteria and sub criteria weights that ultimately influence the choice of suppliers.

Another important aspect highlighted by the obtained results is the effectiveness and the consistency of F-SBWM in calculating the weights of criteria and sub criteria through a simplified approach that avoids the need for complex mathematical modeling and does not require complex software to obtain weights of criteria and sub criteria. The results obtained through F-SBWM are not only consistent but also reliable, entirely based upon the expert preferences.

Lastly, the application of the proposed methodology in the case study provides enough evidence to support that the integration of F-SBWM with FDEMATEL allows for a more comprehensive attainment of criteria and sub-criteria weights by considering the interdependencies among them and this integration can result in more accurate and robust weight assignments by offering a more holistic and systematic way to handle complex MCDM problems such as supplier selection which involve a wide array of criteria and sub-criteria.

8. Managerial Insights

There are multiple noteworthy managerial implication and insights provided by this research, which are as follow:

Simplified Approach: This research provides the evidence and framework of the effectiveness and consistency of the Fuzzy Simplified Best Worst Method (F-SBWM), which is a simplified and practical approach to obtain weights without the need for complex mathematical modeling or specialized software. Managers can really benefit from adopting such simple and straightforward techniques, especially when dealing with resources or time constraints.

The role of Interdependency among criteria: This research provides evidence to the audience that understanding and consideration for interdependencies among criteria is crucial that significantly impacts the weights assigned to criteria and sub-criteria. Managers should recognize the importance of considering these interdependencies, which can have a substantial influence on supplier selection outcomes.

Integrated approach for weight allocation: The integration of F-SBWM and FDEMATEL enables a more comprehensive assessment of criteria and sub-criteria weights, and this integration offers a systematic and holistic way to manage complex MCDM problems, like supplier selection. Managers can benefit from such integrated methodologies to ensure a more robust and enhanced decision-making process.

Expert Preferences: Relying upon expert preferences as the means for weight allocation ensures reliable and consistent results. Managers should involve experts who possess in-depth understanding and knowledge, to provide input, as their input can enhance the credibility and trustworthiness of the decision-making process.

9. Conclusion and Future Research

This research offers several noteworthy contributions, which are as follows:

A novel Integrated approach: This research introduces a novel integrated approach that combines the F-SBWM with FDEMATEL, which offers a systematic and holistic way to manage complex MCDM problems.

Extension of F-SBWM: A significant contribution of this study is the extension of the F-SBWM to incorporate both criteria and sub-criteria. Previous research had focused only on criteria alone, and this research expands the applicability of F-SBWM to handle more complex MCDM problems and enhances its precision and versatility.

Focus on Sustainable Development Goals: The research recognizes and incorporates the importance of considering the impact of supplier selection on the attainment of Sustainable Development Goals (SDGs). The research emphasizes the achievement of SDG 8 (decent work and economic growth) and SDG 12 (responsible consumption and production) by incorporating sub criteria that align with these goals. This perspective aligns with the global sustainability agenda and demonstrates how supplier selection decisions can contribute to broader societal and environmental objectives.

Empirical Application: In this research a real-world case study within the textile sector of Pakistan is conducted to validate the efficacy of the proposed novel and integrated approach. This practical application provides evidence to the feasibility and applicability of the integrated approach in a specific industry context, providing valuable insights for practitioners and decision-makers.

However, this research is not free from limitations. One of the limitations of this research is the lack of integration with a more effective evaluation technique such as Interval VIKOR. The future direction in this regard is to integrate the proposed methodology with a more effective evaluation technique such as Interval VIKOR to further enhance the supplier evaluation and selection process. Another exciting avenue for the future research is the application of proposed methodology to solve other complex MCDM problems such as location selection problem, mode of transportation selection etc., to further validate the efficacy and versatility of the proposed methodology.

Conclusion:

In conclusion, this research presents a novel integrated approach by integrating F-SBWM with FDEMATEL, to address complex Multi-Criteria Decision-Making (MCDM) problems, with a particular focus on supplier selection. The integration of the F-SBWM with the FDEMATEL offers a systematic and holistic way to manage such intricate decision-making problems. An intriguing aspect of this research is the alignment of the research in promoting Sustainable Development Goals (SDGs), specifically SDG 8 (decent work and economic growth) and SDG 12 (responsible consumption and production). By incorporating sub-criteria that align with these goals, the study underscores the potential for supplier selection decisions to contribute to broader societal and environmental objectives. One of the key findings of this study is the importance of considering interdependencies among criteria which substantially influences the weights assigned to the criteria and sub criteria, ultimately influencing the decision regarding the choice made in supplier selection. Furthermore, the research extends the capabilities of the F-SBWM methodology by incorporating both criteria and sub-criteria. This expansion enhances the reliability and versatility of the F-SBWM, making it applicable to a broader range of MCDM problems.

The empirical application of the proposed methodology in a real-world case study within the textile sector of Pakistan provides evidence of its feasibility and applicability in an industry-specific context. This practical validation offers valuable insights for researchers and decision-makers, demonstrating the utility of the integrated approach. Considering the contribution, this research not only advances the field of MCDM but also enhances the practical relevance of these methodologies in addressing complex decision challenges. As a result, this research invites future research to further explore this integrated methodology by applying and testing it to a broader spectrum of complex multi criteria decision making problems to further validate its effectiveness and versatility.

Appendices:

This section contains the sample questionnaire that have been used to collect preferences from the experts:

1. When selecting suppliers, which of the following criteria do you believe should be the top priority?

   a) Economic b) Circular c) Social

2. In the supplier selection process for the business, which of the following criteria do you consider the least important?

   a) Economic b) Circular c) Social

3. When selecting suppliers, which of the following sub-criteria do you believe should be the top priority?

   a) Cost b) Lead Time c) Quality d) Reputation e) Flexibility
   f) Production Capacity

4. In the supplier selection process for the business, which of the following criteria do you consider the least important?

   a) Cost b) Lead Time c) Quality d) Reputation e) Flexibility
   f) Production Capacity

5. When selecting suppliers, which of the following sub-criteria do you believe should be the top priority?

   a) GHG Emissions b) Adherence to environmental standards
   c) Green Packaging d) Use of Recyclable Materials
   e) Clean Technology f) Design of products to reuse

6. In the supplier selection process for the business, which of the following criteria do you consider the least important?

   a) GHG Emissions b) Adherence to environmental standards
   c) Green Packaging d) Use of Recyclable Materials
   e) Clean Technology f) Design of products to reuse

7. When selecting suppliers, which of the following sub-criteria do you believe should be the top priority?

   a) Employee's Health and Safety b) Job Creation
   c) The rights of stockholders d) Information disclosure

8. In the supplier selection process for the business, which of the following criteria do you consider the least important?

   a) Employee's Health and Safety b) Job Creation
   c) The rights of stockholders d) Information disclosure

9. Using Linguistic Table (1), provide the importance of best criteria over other criteria:

Citeria	Economic (E)	Circular (C)	Social (S)
BTO			

10. Using Linguistic Table (1), provide the importance of other criteria over worst criteria:

Citeria	Economic	Circular (C)	Social (S)
OTW			

11. Using Linguistic Table (1), provide the importance of best criteria over other criteria:

Citeria	Cost (E1)	Lead Time (E2)	Quality (E3)	Reputation (E4)	Flexibility (E5)	Production Capacity (E6)
BTO						

12. Using Linguistic Table (1), provide the importance of other criteria over worst criteria:

Citeria	Cost (E1)	Lead Time (E2)	Quality (E3)	Reputation (E4)	Flexibility (E5)	Production Capacity (E6)
OTW						

13. Using Linguistic Table (1), provide the importance of best criteria over other criteria:

Citeria	GHG Emissions (C1)	Adherence to environmental standards (C2)	Green Packaging (C3)	Use of Recyclable Materials (C4)	Clean Technology (C5)	Design of products to reuse (C6)
BTO						

14. Using Linguistic Table (1), provide the importance of other criteria over worst criteria:

Citeria	GHG Emissions (C1)	Adherence to environmental standards (C2)	Green Packaging (C3)	Use of Recyclable Materials (C4)	Clean Technology (C5)	Design of products to reuse (C6)
OTW						

15. Using Linguistic Table (1), provide the importance of best criteria over other criteria:

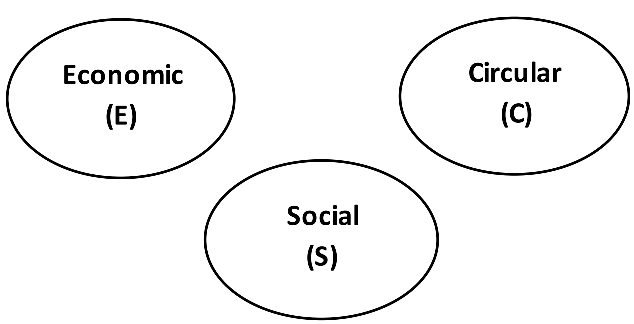
Citeria	Employee's Health and Safety (S1)	Job Creation (S2)	The rights of stockholders (S3)	Information disclosure (S4)
BTO				

16. Using Linguistic Table (1), provide the importance of other criteria over worst criteria:

Citeria	Employee's Health and Safety (S1)	Job Creation (S2)	The rights of stockholders (S3)	Information disclosure (S4)
OTW				

FDEMATEL:

1. Graphically draw the impact of criteria over each another:



2. Using Linguistic Table (2), provide the interdependency of criteria over each another:

Criteria	Economic (E)	Circular (C)	Social (S)
Economic (E)	-		
Circular (C)		-	
Social (S)			-

3. Using Linguistic Table (3), assign score to each supplier against all sub-criteria:

Sub-Citeria	**Supplier 1**	**Supplier 2**	**Supplier 3**	**Supplier N**
Cost (E1)				
Lead Time (E2)				
Quality (E3)				
Reputation (E4)				
Flexibility (E5)				
Production Capacity (E6)				
GHG Emissions (C1)				
Adherence to environmental standards (C2)				
Green Packaging (C3)				
Use of Recyclable Materials (C4)				
Clean Technology (C5)				
Design of products to reuse (C6)				
Employee's Health and Safety (S1)				
Job Creation (S2)				
The rights of stockholders (S3)				
Information disclosure (S4)				

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