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Fuzzy Analytical Hierarchy Process to Optimize Supply Chain Processes in the Digital Age

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Abstract The rise of e-commerce has profoundly reshaped supply chain management in the apparel industry, increasing pressure on companies to enhance responsiveness, efficiency, and service quality. This study evaluates the influence of e-commerce on key supply chain dimensions using the Fuzzy Analytical Hierarchy Process (FAHP). Six criteria are examined: efficiency, delivery, environmental impact, services, social, and economic factors. Expert judgments, collected from professionals in the apparel sector, reveal that efficiency, delivery, and service quality are the most influential criteria in the digital context. Beyond identifying key priorities, this study provides a structured decision-making framework that supports managers in addressing uncertainty inherent to digital supply chains. The findings also highlight the strategic value of integrating fuzzy MCDM tools to guide future supply chain optimization initiatives. These insights provide strategic guidance for apparel companies seeking to improve supply chain performance and adapt to the evolving demands of online commerce.

Keywords E-commerce, textile supply chain, Fuzzy AHP, logistics, Operational Research (OR), Artificial Intelligence.

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1. Introduction

The "COVID-19" pandemic hit the global economy hard and accelerated the growth of activities such as e-commerce in the apparel industry [1]. During this period, companies faced challenges and opportunities on an unprecedented scale as consumers turned massively to online shopping [2]. The rapid adoption of digital technology in response to this disruption has forced apparel companies to rethink their supply chain strategies to compete [3]. The development of online shopping has put immense pressure on companies to rethink their supply chains, highlighting the need for a fast, resilient, and efficient supply chain [4].
In this evolving market environment, the importance of an agile supply chain has become increasingly apparent. Traditional linear supply chains are being replaced by more dynamic, interconnected networks that must adapt quickly to internal and external disruptions. [5] highlights how pandemics and other global shocks expose vulnerabilities in supply chain structures, particularly in sectors such as apparel where consumer preferences are highly volatile. Companies are now prioritizing factors such as efficiency, product delivery, and service to ensure smooth operations and on-time delivery, which is critical to customer satisfaction in leading digital markets [6].
While the importance of these business factors is recognized, there are significant weaknesses in the integration of environmental, economic, and social considerations into the apparel supply chain sustainability and lifestyle factors are generally recognized quality practices, but are not prioritized according to short-term performance measures, particularly speed and efficiency of fulfillment and delivery [7]. also [8] emphasizes that developing resilient supply chains is no longer optional but essential, given the recurrence of global disruptions such as pandemics, climate change, and geopolitical tensions. In response, companies are increasingly prioritizing agility,

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distribution efficiency, and customer service to overcome these challenges while balancing cost efficiency.

This study aims to address these gaps by analyzing the impact of e-commerce on the apparel supply chain using a multi-criteria decision-making process called the Fuzzy Analytical Hierarchy Process (FAHP), which combines fuzzy logic with traditional AHP methods. This allows for a more nuanced analysis of complex and common objects, making it ideal for researching standards and their relevance to global supply chain studies. This study develops a systematic management system for assessing their relative importance and provides actionable insights for companies seeking to optimize their e-commerce supply chain by evaluating six key criteria: efficiency, distribution, environmental factors, services, social factors, and economic considerations. The study provides insight into the complexities of the modern apparel supply chain. It also offers practical recommendations for companies seeking to meet the twin challenges of speed and sustainability in e-commerce-dominated markets.

This paper is divided into five sections. Section 1 briefly introduces the study, outlining the current e-commerce and supply chain development state. Section 2 provides an in-depth literature review focusing on how e-commerce reshapes supply chain management, with logistics, sustainability, and consumer preferences implications. Section 3 details the method and data collection used in the research. Section 4 presents the results of this study and provides an in-depth analysis of the results, highlighting an empirical case study for the Tunisian apparel industry. Finally, Section 5 provides a discussion, summarizing the study's contribution to supply chain management.

2. Literature review: overview of key criteria

Since the advent of e-commerce, it has consistently acted as a transformative force within the apparel supply chain. Along with the opportunities it has created, this transformation has also presented a significant number of challenges. By synthesizing various investigations with previous research, this analysis will focus on several elements that appear to be rationally significant in the influence of e-commerce as one of the criteria. These elements include changes in supply chain efficiency, resource management methods, changes in distribution, consumer satisfaction, and sustainability considerations. Each of these elements is examined in terms of its significance and implications for modern apparel supply chain management, providing a comprehensive overview of the changes.

2.1. Efficiency criterion

The integration of e-commerce into supply chain management has fundamentally transformed the operations and effectiveness of supply chains on a global scale. We examine the main findings of studies investigating the link between e-commerce product offerings and efficiency. Firms gain productivity by combining resources to enhance organizational capabilities [9]. Several studies highlighted the transformative effects of e-commerce to enhance supply chain efficiency. The flexibility facilitated by e-commerce platforms simplifies operations, reduces processing time, and increases overall efficiency. E-commerce had a profound impact on the dynamics of supply chains.

In their analysis, [10] study of Amazon's supply chain showed how e-commerce integration enabled the company to achieve impressive efficiency and customer satisfaction through advanced data analytics and automated warehousing techniques. Amazon's use of predictive analytics and machine learning is an example of e-commerce's ability to transform supply chain efficacity to optimize inventory levels and delivery methods. Moreover, the study conducted by [11] revealed that the implementation of research-based e-commerce strategies has a direct and positive impact on the supply chain. The authors posit that integrating e-commerce into the supply chain has the potential to effect transformative changes in traditional business frameworks, revitalize operational dynamics, and elevate overall efficiency and effectiveness. This infusion of e-commerce has the potential to emulate how human innovation and adaptability reshape systems for the better, thereby fostering a more agile and responsive supply chain environment. These challenges have been elucidated in several studies, such as that by [12], who proposed open innovation and solutions for MSMEs actors to enhance the value of certain e-payment services, e-commerce

services, and MSME supply chain efficacy indicators to expedite the digitalization process. The utilization of e-payments in MSMEs enhances the quality and accuracy of transactions, thereby reducing costs and improving efficiency. The implementation of e-commerce services within MSMEs has the potential to enhance operational efficacy and introduce novel business models. E-payment services facilitate transactions, particularly during the pandemic caused by the novel Coronavirus.
Given this context, it is evident that e-commerce influences supply chain efficiency. Therefore, the first criterion:
C1: efficiency criterion

2.2. Delivery criterion

The advent of e-commerce has dramatically transformed the apparel supply chain, precipitating substantial shifts in delivery, efficiency, and customer engagement as consumer behavior increasingly gravitates towards online shopping.
In response, businesses are adapting their supply chain management strategies to align with these changes [13]. By studying these shifts, researchers can identify both the benefits and challenges associated with e-commerce. One of the major impacts of e-commerce on the apparel supply chain is delivery efficiency. E-commerce systems facilitate the adoption of Direct-Consumer (D2C) deals, simplifying the delivery process by bypassing traditional retailer intermediaries. According to a study by [14], D2C models reduce the number of touchpoints in the supply chain, reducing costs and accelerating delivery times. This performance is complicated by sophisticated inventory management systems providing real-time stock-level data and customer demand. These systems allow apparel companies to maintain optimal inventory levels, reducing oversales and excess inventory. E-commerce has increased the need for speed and agility in the apparel supply chain. Consumers now expect faster delivery options, forcing apparel companies to optimize their logistics. The research of [15] provided a comprehensive analysis of the logistics and delivery methods used by e-commerce companies in China. The research examined the methods of classifying e-commerce transactions using AHP and entropy value methods. The TOPSIS method is then used to validate the model, which provides valuable management insights for logistics and delivery professionals. According to a report by [16], A considerable number of prominent e-commerce enterprises have their origins in China. In 2013, the global e-commerce landscape, based on gross merchandise value, was dominated by China's Alibaba Group, along with the USA's Amazon and eBay, as reported by the United Nations Conference on Trade and Development (UNCTAD) in 2015. E-marketplaces have transformed the connections between buyers and suppliers, revitalizing essential business interactions and opening avenues to previously untapped markets. However, alongside these opportunities, businesses must also navigate a range of challenges, including integration, security, and antitrust concerns, akin to travelers charting their course through a complex and evolving landscape. A study conducted by [17] investigated the influence of e-commerce expansion on the delivery of fashion and beauty stores. The research specifically scrutinized alterations in offline store dynamics in Seoul, Korea, attributed to the rise of online transactions. Particularly, the COVID-19 pandemic has heightened reliance on or accelerated the transition from traditional brick-and-mortar retail to online retail. The study found that location is a key factor in the retail business and plays a significant role in determining the absolute and relative value of a store.
The multifaceted impact of e-commerce on energy consumption and export marketing strategies underscores its diverse effects on the contemporary business environment. This leads to our next criterion:
C2: delivery criterion

2.3. Environment criterion

The environmental impact of e-commerce has been the subject of extensive study, which has revealed a complex array of positive and negative effects. E-commerce has the potential to reduce the environmental footprint by consolidating products and reducing the number of physical storefronts, which in turn leads to a reduction in energy consumption and carbon emissions associated with transportation and construction projects.
The environment is further enhanced by the increased profitability of e-commerce, as highlighted by [18], which requires transportation and other applications. Furthermore, it provides power consumption in data centers that support e-commerce platforms [19], representing a significant environmental burden. Several studies highlighted the impact of e-commerce on the supply chain environment. Although e-commerce can improve delivery

alternatives, the convenience of home delivery has increased carbon emissions. Increased ”last-cycle” deliveries, which often deliver smaller items directly to customers' homes, present inefficiencies and additional vehicle emissions. A study by [20] suggested that despite optimization of the e-commerce delivery, especially in urban areas, the increased frequency of personal package delivery has resulted in a notable contribution to traffic congestion and carbon emissions. Similarly, [21] examined various aspects of the e-commerce supply chain, including packaging, transportation, returns, and disposal. The environmental impact of e-commerce is difficult to measure due to the limited data available on its effects. In response to the growing demand for sustainable practices in e-commerce, businesses are implementing strategies to reduce waste and enhance sustainability. However, the increasing consumer expectation for expedited delivery is contributing to an increase in transportation-related emissions. Despite the challenges, companies are implementing creative solutions to minimize waste and promote sustainability. The concept of e-commerce and its environmental impact in the apparel sector has been previously investigated in other studies, including the one conducted by [22]. The researchers examined shopping behaviors and the impact of e-commerce on the urban environment, utilizing an econometric model to calculate the number of miles traveled by vehicles and the emissions produced in cities. The study addressed the potential for overestimation in the assessment of reductions in externalities associated with shopping behaviors. This was achieved by employing a multinomial logit model at both the micro and macro levels, using data from the 2016 American Time Use Survey (ATUS). In their examination of the environmental consequences of e-commerce, authors such as [23] employed two validated conceptual models. In Model 1, the adoption of e-commerce is influenced by green consumerism, which in turn shapes individuals' environmental attitudes. In Model 2, a notable shift is observed, as positive environmental attitudes are no longer indicative of the propensity to use e-commerce. Although e-commerce presents opportunities for environmental benefits through enhanced logistics and diminished physical retailing, these are frequently counterbalanced by challenges about packaging, delivery, and energy consumption. Consequently, a balanced approach is essential to fully realize its potential.

In light of the aforementioned evidence, it is reasonable to conclude that e-commerce has an impact on the environment. Therefore, the third criterion is:

C3: environment criterion

2.4. Service criterion

The advent of e-commerce has had a profound impact on customer satisfaction within the supply chain, ushering in a new era of growth and heightened expectations. One of the principal ways in which e-commerce enhances the quality of services is through its convenience and accessibility. Moreover, e-commerce platforms frequently furnish consumers with comprehensive product data, analysis, and comparisons, thereby facilitating informed decision-making.

As stated in [24], the implementation of effective logistics and the availability of robust warehousing capacity are crucial for meeting the demands of today's customers in terms of rapid delivery. Furthermore, the incorporation of sophisticated tracking technologies affords customers the ability to monitor the status of their orders in real-time, thereby enhancing transparency and fostering trust in the e-commerce process. The study conducted by [25], revealed that, in the context of online shopping services, customers prioritize assurance and safety above all other considerations. The reliability of these services is regarded as a pivotal determinant of their quality. Notably, there is a divergence of opinion about the features of e-commerce services, which suggests that customers have disparate preferences concerning these aspects. Moreover, apparel manufacturing with a focus on customer satisfaction, a women's clothing e-commerce company employs the invaluable tool of sentiment analysis to rapidly obtain insights into customer attitudes. This facilitates more optimal product selection and strategic decision-making. By establishing a connection with the emotional state of customers, the company can gain insight into their preferences and dislikes regarding products, which in turn allows for the implementation of a strategy that is both attentive and customer-focused. The authors of the study [26] examined the emotional analysis of customer comments, addressing services across various aspects, including quality, customer service, and returns/refunds. Such a system enables customers to share their experiences while simultaneously facilitating the identification of challenges inherent to the clothing procurement process by the company. In conclusion, this strategy, which is focused on the customer, and which makes use of sentiment analysis, plays a vital role in improving the shopping

platform for women. It establishes a space that connects with and caters to its clientele. As [27] notes, the crux of e-commerce logistics lies in the quality of service provided by logistics companies, a facet that is rich in various dimensions. To investigate this, they employed smart sensor technology for data mining and analysis along with online evaluation surveys. In the context of e-commerce, businesses can enhance the quality of their services and cultivate enduring customer loyalty by prioritizing key factors such as quality, trust, system functionality, and operational efficiency. These elements are not merely transactional; rather, they form the core of customer experiences, shaping perceptions and behaviors that are crucial for the success of e-commerce enterprises.
By embodying these qualities, businesses can foster not just transactions but also genuine connections, thereby establishing a bond that extends beyond the digital realm. This leads to our next criterion:
C4: Services criterion

2.5. Social criterion

The advent of e-commerce has transformed the dynamics of customer-business interactions, prompting a fundamental reevaluation of customer relationship management strategies. The integration of e-commerce into social criterion has emerged as a pivotal area of interest for researchers and practitioners alike, all united by the common objective of nurturing enhanced customer loyalty, satisfaction, and, ultimately, the success of the business [28].
In a study focusing on enhancing e-commerce impacts through customer relationship management, [29] indicated that communication and data collection constraints are mitigated through the Web-based production of goods and services. By leveraging technologies such as database management, data warehousing, and data mining, the Web serves as a facilitator for interaction with customers and suppliers, as well as for data collection and analysis processes. Additionally, as emphasized by [30], social criterion entail a series of practices, technologies, and strategies utilized to oversee and analyze customer interactions and data throughout the entire customer lifecycle. The ultimate objective is to enhance business relationships and ensure customer satisfaction. Moreover, several authors, including [31], have underscored that the implementation of e-commerce in supply chain management (SCM) is propelled by the strategic and tactical importance of supply chain assessment in e-commerce environments, characterized by information availability and changing market dynamics. Moreover, additional research, such as that conducted by [32], indicates that e-commerce is exerting a considerable influence on social service. In the current data-driven business environment, the fundamental objective of social service capabilities is to act as a reliable and trusted partner for companies. By conducting a more thorough examination of customer data, social service can serve as a guiding compass for a company's decision-making processes. Beyond the mere transactional aspect, it is about developing a comprehensive understanding of customer needs and responding to them in a manner that fosters long-lasting, mutually beneficial relationships. The advent of e-commerce has brought about a radical transformation in the realm of social service within the context of supply chains, particularly within the apparel industry. This transformation is characterized by an increased reliance on data, personalization, and customer service.
These developments contribute to the efficiency of the supply chain, despite the necessity for considerable investment in technology and security.This leads to our next criterion:
C5: Social criterion

2.6. Economic criterion

The global supply chain landscape has been transformed by the advent of e-commerce, with the emergence of new costs that companies must navigate to remain competitive. E-commerce systems facilitate operational efficiency and effective inventory management, thereby reducing the necessity for physical outlets.
A comprehensive analysis of recent research and key findings reveals how e-commerce is reshaping value systems in the supply chain. Moreover, as [33] notes, sustained investment in technology infrastructure, including e-commerce platforms and cyber-security systems to safeguard against fraud and data breaches, represents a substantial ongoing expense. Such technological investments are essential for the optimization of online marketing channels and the protection of customer information.

Table 1. The summary of method approaches applied in relevant studies.

References	Applied areas	Method approaches	Criteria					
			C1	C2	C3	C4	C5	C6
[34]	High and IT-intensity sectors	Tucker-Lewis Index (TLI) and Normed Fit Index (NFI)	✓					
[35]	Cloud computing company in the US	The Beer Game	✓	✓				
[36]	US manufacturing company	Student test		✓				
[37]	Supply chain	Econometric model	✓					
[38]	Consumer Internet transaction	Web-based surveys,Partial Least Squares,PLS-Graph and AMOS (NFI)				✓		
[39]	China's delivery of goods and services	Web-based surveys,Partial Least Squares, PLS-Graph and AMOS		✓		✓		✓
[40]	Distribution system.	Panel Data Model		✓				
[41]	Electronic banking services	Single-channel and a dual channel distribution system	✓					
[42]	E-commerce market	SCOR model and Cronbach's alpha				✓		
[43]	U.Sconsulting, and manufacturing	SCommon Method Bias and Cronbach's alpha and scale composite reliability						✓
[16]	E-commerce platforms and logistics service providers	Stackelberg game theory		✓				
[44]	Manufacturing Industry	Panel regression models						✓
[45]	E-commerce shopping	Equamax rotation method and OLS regression analysis				✓		
[15]	The electronic mall at JD.com (Jing-Dong)	AHP and TOPSIS		✓				
[25]	E-commerce services	The Keizer–Meyer–Olkin test				✓		
[23]	Retail sector	The Heterotrait-Monotrait ratio of correlations (HTMT)		✓	✓			
[26]	Ecommerce domain	R programming				✓		
[27]	Mobile E-Commerce Platform	Apriori algorithm and K-means algorithm				✓		
[12]	MSMEs in Indonesia	Multiple linear regression analysis	✓					
[30]	Jordanian pharmaceutical companies	Confirmatory Factor Analysis (CFA)					✓	
[32]	E-commerce enterprises in China	Common Method Bias (CMB)					✓	

Abbreviations: Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Supply Chain Operations Reference (SCOR).

The findings of the research conducted by [11] indicate that e-commerce has the potential to significantly reduce supply chain costs by enhancing information visibility. This improvement enables companies to strategically implement centralized fleets and efficient picking zones, thereby optimizing operational efficiency in the e-commerce sector. Several studies have examined the impact of e-commerce on apparel supply chain costs. E-commerce has had a significant impact on the cost structure of the apparel supply chain, creating new efficiencies and significant additional costs. One notable impact of e-commerce is the reduction in costs associated with maintaining physical stores. According to a study by [46], e-commerce enables retailers to reduce many of the costs associated with physical stores, such as rent, utilities, and store staff. According to de [47], costs also affect the environmental impact of e-commerce. The increased waste and carbon footprint associated with traditional deliveries has led companies to invest in sustainable practices and environmentally friendly packaging solutions. These investments benefit the environment and increase the cost structure of the entire supply chain. E-commerce can streamline some aspects of the apparel supply chain and reduce some costs, but it also introduces additional costs in terms of logistics technology, returns management, and packaging, making cost management a means of effectively balancing these factors. It takes observational thinking. Therefore, we propose our final criterion:
C6: Economic criterion.

The main objective of this study is to investigate the impact of e-commerce on supply chain management. After a comprehensive review of the literature, we extract the criteria cited in the literature, which are: efficiency **(C1)**, delivery **(C2)**, environment **(C3)**, services **(C4)**, social **(C5)**, and economic **(C6)**. Table 1 provides a literature review of the e-commerce sector in terms of criteria, methodological approaches, and application areas over the past decade and the gaps provided by current research. Gaps in current research have been indicated. As can be seen, the main MCDM methods used in logistics outsourcing problems are the Analytic Hierarchy Process (AHP), the Technique of Order Prioritization based on the Similarity of Ideal Solutions (TOPSIS), the Econometric Model, and other MCDM methods.

To strengthen the relevance and robustness of the evaluation framework, the six selected criteria—efficiency, delivery, environmental impact, services, social, and economic factors—were retained following a focused and comparative review of recent studies in e-commerce and textile supply chain management. This literature synthesis highlighted the recurring importance of these dimensions in assessing digital transformation within the apparel sector, particularly regarding operational performance, sustainability requirements, and customer-oriented service enhancements. To ensure that the selected criteria accurately reflect real-world priorities, the final set was further reviewed and validated by industry experts with significant experience in the textile domain. Their feedback confirmed the practical relevance, completeness, and alignment of the criteria with current industry challenges, thereby reinforcing the scientific grounding and applicability of the evaluation model.

3. Method and data collection

A qualitative study was conducted to investigate the impact of e-commerce on supply chain management in the apparel industry. The quantitative method provides specific ways to measure the impact of e-commerce, which is why structured survey instruments (combined with semi-structured interviews) have become popular research tools. Semi-structured interviews were chosen because they are widely recognized as an effective method for gathering in-depth information on the impact of e-commerce. 18 experts were carefully selected to participate in the interviews. The selection was based on multiple factors: their years of professional experience, the strategic or operational positions they occupy, and their specific expertise in the textile industry, including company directors, store managers, logistics and marketing managers, human resource managers, and product and quality control managers Leveraging their extensive knowledge, these experts reviewed and validated the criteria identified through an extensive literature review, ensuring that the selected evaluation factors were both theoretically grounded and practically relevant for real-world decision-making.The combination of structured survey instruments and expert interviews provided a robust framework for examining the subtle impact of e-commerce on supply chain

management in the fashion industry. This integrated approach ensured that the data collected was both quantitative and qualitative, providing a comprehensive view of how e-commerce is changing supply chain practices in this sector. The findings of this study are expected to provide valuable insights for apparel industry participants seeking to optimize the performance of their supply chains in the digital age. The following table 2 provides information on the interviews.

Table 2. Information on interviewees

Number	*Company*	*Post*	*Duration(min)*
1	Paris Confection	Manager	68
2	Hammadi Abid	Logistics manager	74
3	Exist	Sales and Marketing manager	58
4	Decathlon	Team Leader	66
5	Tuto Sport	Store Manager	68
6	Oasis Fashion	Store Manager	52
7	Peak Tunisia	Sales force expert	56
8	Hummel	E-commerce manager	65
9	Heni Collection	HR and Quality manager	61
10	Mazzaro Milano	Store Manager	66
11	Baton Rouge	Store Manager	73
12	Kontakt	Product Manager	65
13	Anta Sport	HR manager	71
14	Zen Tunisia	Customer Relationships manager	57
15	Omiz	Sales assistant	54
16	Mabrouk	Store Manager	52
17	Barsha	Store manager	70
18	Karizma promo	Manager	76

3.1. Sampling

The purpose of these interviews was to gather detailed information about the impact of e-commerce on various supply chain activities. The semi-structured format provided a balance between systematic data collection and the flexibility to explore the unique perspective of each respondent. Qualitative analysis of the interview responses revealed key trends and relationships, highlighting improvements in inventory management, order fulfillment efficiency, supplier collaboration, customer satisfaction, customer relationship management, and supply chain costs by emphasizing the adoption of e-commerce. This comprehensive approach provided an in-depth understanding of how e-commerce reshapes supply chain management in the apparel industry.

Table 3 presents that after reviewing the literature and identifying key criteria for assessing the impact of e-commerce on supply chains, we formulated three specific objectives for questions for each criterion. Based on the six key themes of efficiency, delivery, environment, service, service, social, and economic, we were guided by these objectives to develop 18 focused interview questions. Each question corresponds directly to its purpose, allowing for a detailed exploration of the operational, environmental, and business changes brought about by customer-centric e-commerce. This structured approach ensures that the interview questions effectively address each criterion, providing interviewees with comprehensive insights.

The flowchart in Figure 1, summarizes the methodological framework adopted in this study, outlining the sequential steps followed to assess the impact of e-commerce on the apparel supply chain. It visually presents the process from criteria selection and FAHP application to consistency verification, weight determination, and final analysis of results.

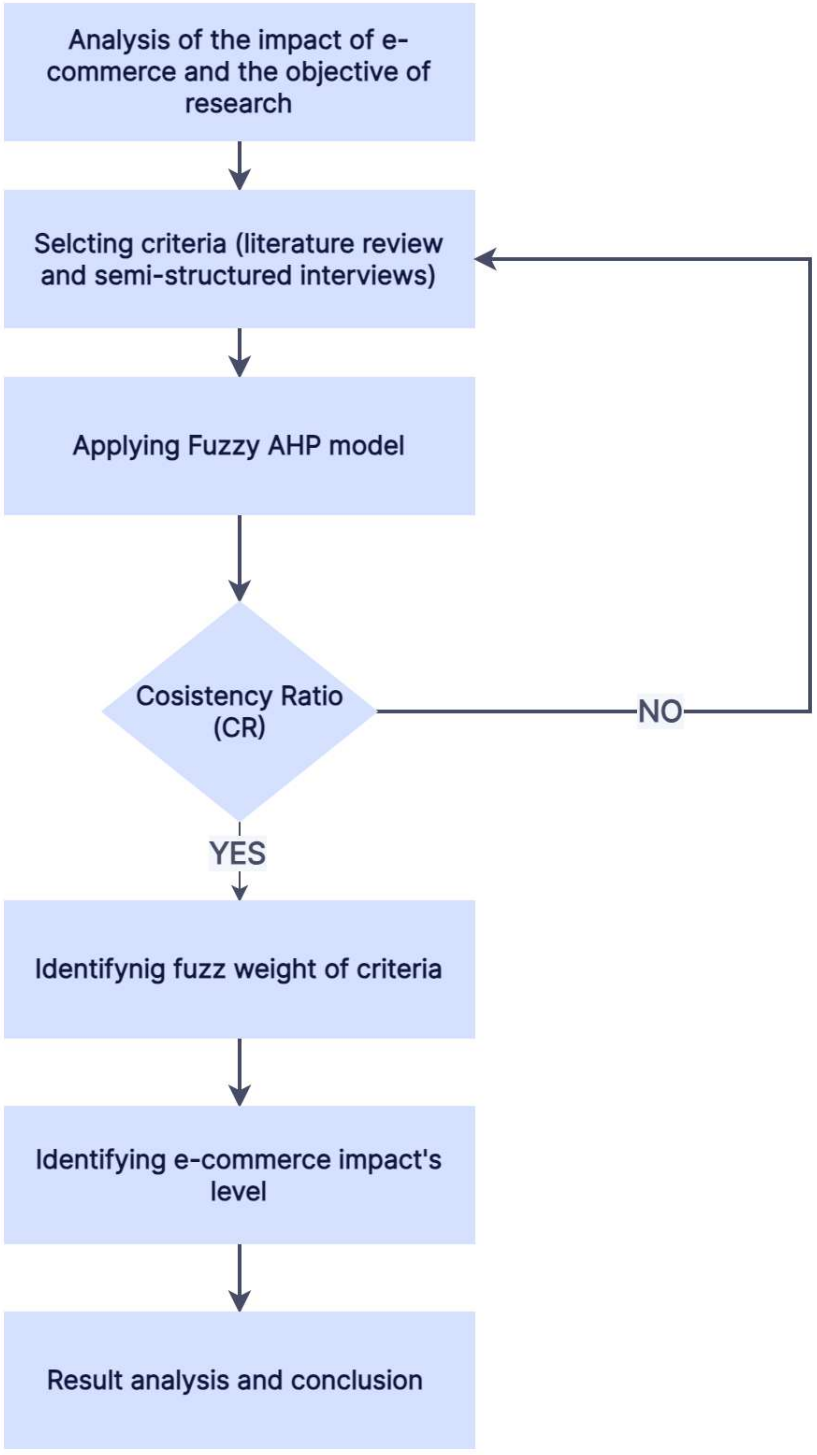

Figure 1. Fuzzy AHP flowchart

Table 3. Guided inquiries for sampling: criteria and associated questions.

Efficiency (C1)	
Question objectives	***Inquiries***
Supply chain efficiency	Have you noticed any changes in the way your textile supply chain operates since you made e-commerce part of your strategy?
Order processing	What impact does e-commerce have on order processing speed?
Accuracy of demand planning	Can you identify a process where e-commerce has improved the efficiency of your supply chain?
Delivery (C2)	
Question objectives	***Inquiries***
Rapidity of delivery	How have you adapted online sales to manage your distribution process?
Ease of delivery	Have online sales made it easier or harder to deliver products to customers?
Returns and exchanges management	Have you encountered any additional difficulties in distributing products?
Environment (C3)	
Question objectives	***Inquiries***
-Reduction of carbon footprint	Do you think selling online is more environmentally friendly than selling in physical stores?
Use of recycled materials	What measures have you adopted to make your operations more environmentally friendly?
Reduction of plastic waste	Has the switch to e-commerce had an impact on your environmental footprint?
Service (C4)	
Question objectives	***Inquiries***
Customer satisfaction	What effect do you think e-commerce has on customer satisfaction?
User experience on the platform	Have you received any positive or negative feedback from your customers about the convenience of online shopping?
Responsiveness to customer feedback	Do you take into account complaints received from your customers' apartments after online transactions?
Social (C5)	
Question objectives	***Inquiries***
Customer service efficiency	What techniques and tools can you use to take account of your customer's wishes and expectations?
Engagement on social networks	How is your customer relationship management linked to a data platform?
Loyalty program	What effect does e-commerce have on customer loyalty?
Economic (C6)	
Question objectives	***Inquiries***
Operational cost reduction	Have you noticed any cost savings since integrating e-commerce into your business?
Engagement on social networks	How is your customer relationship management linked to a data platform?
Return on investment	What specific costs do you associate with e-commerce in the textile sector, such as packaging, handling, or delivery?

4. Data analysis and result

4.1. Fuzzy AHP

According to [48] fuzzy set theory was proposed to solve uncertain Multi-Criteria Decision Methods (MCDM) problems. A Triangular Fuzzy Number (TFN) is defined as (a, b, c) representing the lower boundary, the middle value, and the upper boundary, respectively, as shown in figure Equation 1.

$$\mu(\frac{x}{\widetilde{F}}) = \begin{cases} (x-a)/(b-a), a \leq x \leq b \\ (c-x)/(c-b), b \leq x \leq c \\ 0, Otherwise \end{cases} \tag{1}$$

The representative of each level of membership function is presented in Equation 2.

$$\tilde{F} = \left(F^{l(y)}, F^{r(y)}\right) = [a + (b-a)y, c + (b-c)y], y \in [0, 1] \tag{2}$$

Where $Fl(y), Fr(y)$ are two sides of the fuzzy number. AHP extension of the Fuzzy AHP process overcomes the shortcomings of AHP and solves many MCDM problems in fuzzy situations. Table 5 shows the linguistic description of fuzzy dimension and distributed TFN. The FAHP methods are presented below. Each linguistic term was converted into a triangular fuzzy number (TFN) to quantify the uncertainty inherent in human judgment. This conversion allows for the incorporation of expert vagueness and subjectivity into the Fuzzy AHP calculations. For instance, the term "Weak importance" is represented by the TFN (1, 2, 3), while "Very important" is represented by (6, 7, 8). By applying this linguistic-to-numerical transformation, the method can systematically compute the priority weights of criteria while reflecting the degree of fuzziness in expert evaluations.

Table 4. Linguistic variable values in FAHP model [49].

Level	Linguistics Variables	Corresponding TFNs
1	Equal importance	(1, 1, 1)
2	Weak importance	(1, 2, 3)
3	Not bad	(2, 3, 4)
4	Preferable	(3, 4, 5)
5	Importance	(4, 5, 6)
6	Fairly importance	(5, 6, 7)
7	Very important	(6, 7, 8)
8	Absolute	(7, 8, 9)
9	Perfect	(8, 9, 10)

A simplified example illustrating the application of the Fuzzy AHP method is presented in Table 3. This example demonstrates how expert judgments were aggregated and transformed into priority weights. Eighteen experts, carefully selected based on their years of experience, the positions they occupy, and their specific expertise in the textile industry, reviewed and validated the criteria identified through an extensive literature review.

Table 5. Illustrative example of Fuzzy AHP application for three criteria.

Criteria	C1: Operational Efficiency	C2: Delivery Performance	C3: Customer Service
Aggregated TFN	(4.24, 5.29, 6.32)	(1, 1.41, 1.73)	(4.24, 5.29, 6.32)
Defuzzified Value	5.28	1.38	5.28
Priority Weight	0.44	0.12	0.44

Step 1: Suppose that a decision group has Kexperts. An integrated fuzzy pairwise comparison matrix can be formulated using the geometrical aggregation, as mentioned in Equation 3.

$$\widetilde{D}\begin{pmatrix} 1 & \widetilde{f_{12}} & \cdots & \widetilde{f_{1n}} \\ \widetilde{f_{21}} & 1 & \cdots & \widetilde{f_{2n}} \\ \cdots & \cdots & \cdots & \cdots \\ \widetilde{f_{n1}} & \widetilde{f_{n2}} & \cdots & 1 \end{pmatrix} = \begin{pmatrix} 1 & \widetilde{f_{12}} & \cdots & \widetilde{f_{1n}} \\ 1/\widetilde{f_{21}} & 1 & \cdots & \widetilde{f_{2n}} \\ \cdots & \cdots & \cdots & \cdots \\ 1/\widetilde{f_{n1}} & \widetilde{f_{n2}} & \cdots & 1 \end{pmatrix} \tag{3}$$

$$\text{where } \tilde{f}_{ij} = \begin{cases} \tilde{9}^{-1}, \tilde{8}^{-1}, \tilde{7}^{-1}, \tilde{6}^{-1}, \tilde{5}^{-1}, \tilde{4}^{-1}, \tilde{3}^{-1}, \tilde{2}^{-1}, \tilde{1}-1, \tilde{1}, \tilde{2}, \tilde{3}, \tilde{4}, \tilde{5}, \tilde{6}, \tilde{7}, \tilde{8}, \tilde{9} \text{ such that } i \neq j \\ 1 \text{ such that } i = j \end{cases}.$$

Step 2: The fuzzy geometric mean of each criterion is computed by Equation 4.

$$\widetilde{r_i} = \left(\prod_{j=1}^{n} \widetilde{f_{ij}}\right)^{\frac{1}{n}} \; such\; that\; i = 1, 2, ..., n \tag{4}$$

Step 3: The fuzzy weight of each criterion is computed by Equation 5.

$$\tilde{w}_i = \tilde{r}_i(\times)\left(\tilde{r}_1(+)\tilde{r}_2(+)\ldots(+)\tilde{r}_n\right)^{-1} \tag{5}$$

Step 4: Defuzzify the fuzzy weight using the average weight criteria Mi, as shown in Equation 6.

$$M_i = \frac{\widetilde{w_1}(+)\widetilde{w_2}(+)\ldots(+)\widetilde{w_n}}{n} \tag{6}$$

Step 5: The normalized weight criteria Ni is computed by Equation 7.

$$N_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \tag{7}$$

The impact of e-commerce on the apparel supply chain can be investigated as a Multi-Criteria Decision Method (MCDM), considering several qualitative and quantitative factors. It is based on a generalized framework or multicriteria method selection. This paper proposes a multi-criteria optimization model, FAHP, to evaluate the impact of e-commerce on the apparel supply chain.

In this study, we employ the Fuzzy AHP method to assess the influence of e-commerce on the apparel supply chain. The evaluation is based on six primary criteria: efficiency, delivery, environmental impact, service, social and economic. In the initial phase of the study, 18 semi-structured interviews were conducted to gather expert judgments.

In the first stage, FAHP is used to analyze and estimate the significant fuzzy weight of each criterion. The criteria are based on recent relevant research and a review of expert interviews, which means effectiveness, delivery, service level, environmental, social, and economic. In addition to the economic aspects, service providers are expected to increase customer satisfaction by delivering services on time and maintaining a high level of service. Consequently, the list of 6 criteria is defined, including efficiency (supply chain performance), delivery (delivery time), economic (logistics costs and financial stability), service level (service quality, reliability, loyalty, flexibility, and responsiveness), environmental (pollution, environmental legislation, and green operations) and social (customer relationship management).

4.2. Result and Empirical case study

To check the consistency ratio in applying the FAHP model, an example of the calculation of the five main criteria is presented in the following FAHP procedure, which are efficiency (C1), delivery (C2), environment(C3), services

Table 6. The initial comparison matrix of FAHP model

Criteria	Efficiency (C1)	Delivery (C2)	Environment (C3)	Services (C4)	Social (C5)	Economic (C6)
Efficiency (C1)	(1,1,1)	(2,3,4)	(1,2,3)	(3,4,5)	(4,5,6)	(1,2,3)
Delivery (C2)		(1,1,1)	(1,1,1)	(1,2,3)	(2,3,4)	(1,2,3)
Environment (C3)			(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
Services (C4)				(1,1,1)	(1,2,3)	(1,1,1)
Social (C5)					(1,1,1)	(1,1,1)
Economic (C6)						(1,1,1)

Table 7. The integrated fuzzy comparison matrix of the FAHP model.

Criteria	Efficiency (C1)	Delivery (C2)	Environment (C3)	Services (C4)	Social (C5)	Economic (C6)
Efficiency (C1)	(1,1,1)	(2,3,4)	(1,2,3)	(3,4,5)	(4,5,6)	(1,2,3)
Delivery (C2)	(1/4, 1/3,1/2)	(1,1,1)	(1,1,1)	(1,2,3)	(2,3,4)	(1,2,3)
Environment (C3)	(1/3, 1/2,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
Services (C4)	(1/5,1/4,1/3)	(1/3,1/2,1)	(1,1,1)	(1,1,1)	(1,2,3)	(1,1,1)
Social (C5)	(1/6,1/5,1/4)	(1/4,1/3,1/2)	(1,1,1)	(1/3,1/2,1)	(1,1,1)	(1,1,1)
Economic (C6)	(1/3,1/2,1)	(1/3,1/2,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)

(C4), social (C5) and economic (C6). The initial and integrated fuzzy comparison matrix of the FAHP model is shown in Tables 6 and 7, respectively.

To obtain the initial vector of the five principal parameters of the FAHP model, a normalized pairwise comparison matrix is computed by dividing each number into a column. The figure is the sum of its columns. Then, the critical vector is determined by averaging the row of the entries in the normalized matrix, as seen in Table 8.

Table 8. The normalized comparison matrix of FAHP model.

	C1	C2	C3	C4	C5	C6	weight
C1	0.36	0.383	0.267	0.363	0.4	0.285	0.380000
C2	0.119	0.128	0.133	0.182	0.24	0.143	0.190000
C3	0.18	0.254	0.133	0.091	0.16	0.143	0.145000
C4	0.09	0.064	0.267	0.091	0.04	0.143	0.120000
C5	0.071	0.042	0.067	0.182	0.08	0.143	0.100000
C6	0.18	0.129	0.133	0.091	0.08	0.143	0.169000
Sum	1	1	1	1	1	1	1

Table 9. The Random Consistency Index (RCI) [49]

Order	1	2	3	4	5	6	7	8	9	10	11	12	13	14
R.I	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57

The largest eigenvector ($\lambda_{\max}$) is computed to determine the consistency index (CI), the random index (RI), and the consistency ratio (CR), as below.

$$\begin{bmatrix} 0.36 & 0.383 & 0.267 & 0.363 & 0.4 & 0.285 \\ 0.119 & 0.128 & 0.133 & 0.182 & 0.24 & 0.143 \\ 0.18 & 0.254 & 0.133 & 0.091 & 0.16 & 0.143 \\ 0.09 & 0.064 & 0.267 & 0.091 & 0.04 & 0.143 \\ 0.071 & 0.042 & 0.067 & 0.182 & 0.08 & 0.143 \\ 0.18 & 0.129 & 0.133 & 0.091 & 0.08 & 0.143 \end{bmatrix} \times \begin{bmatrix} 0.380000 \\ 0.190000 \\ 0.145000 \\ 0.120000 \\ 0.100000 \\ 0.169000 \end{bmatrix} = \begin{bmatrix} 2.509 \\ 1.255 \\ 1.226 \\ 0.796 \\ 0.661 \\ 1.057 \end{bmatrix}$$

$$\begin{bmatrix} 2.509 \\ 1.255 \\ 1.226 \\ 0.796 \\ 0.661 \\ 1.057 \end{bmatrix} \setminus \begin{bmatrix} 0.380000 \\ 0.190000 \\ 0.145000 \\ 0.120000 \\ 0.100000 \\ 0.169000 \end{bmatrix} = \begin{bmatrix} 6.6044 \\ 6.6042 \\ 6.6046 \\ 6.6041 \\ 6.6045 \\ 6.6043 \end{bmatrix} \quad (8)$$

Formula (8) indicates that the division is performed to compute the average value obtained after multiplying each row of the normalized comparison matrix by the weight vector. This average represents the maximum eigenvalue ($\lambda_{\max}$), which is required to assess the consistency of the judgments.
There are six main criteria. Therefore, we get n=6. Consequently, lmax et CI are computed as below

$$\lambda_{\max} = \frac{6.6044 + 6.6042 + 6.6046 + 6.6041 + 6.6045 + 6.6043}{6} = 6.6044 \quad (9)$$

$$CI = \frac{\lambda_{max} - n}{n-1} = \frac{6.6044 - 6}{6-1} = 0.12089 \quad (10)$$

Such that n=6, we get RI = 1.24 and the consistency ratio (CR) is computed below.

$$CR = \frac{CI}{RI} = \frac{0.12089}{1.24} = 0.0974 \quad (11)$$

Based on the result, $CR = 0.0974 < 1$ Hence, the pairwise comparison matrix is consistent, and the result of the FAHP model is satisfactory. Then, other criteria are computed using the same procedure.

Table 10. The relative significant fuzzy weights of each criterion of the FAHP model.

	Geometric Mean			**Fuzzy weight**			**MI**	**Normalized**
C1	1,6983813	2,4928829	3,2031009	0,1991674	0,3668515	0,6120426	0,405605	0,3616431
C2	0,8908987	1,2578124	1,6188704	0,1044748	0,1850991	0,3093308	0,2069028	0,1844774
C3	0,8312896	0,8908987	1	0,0974845	0,1311042	0,1910782	0,1442813	0,1286432
C4	0,6357075	0,7937005	0,9983263	0,0745488	0,1168006	0,1907584	0,1326536	0,1182758
C5	0,4861411	0,566351	0,7071068	0,0570093	0,083344	0,1351127	0,096061	0,0856493
C6	0,6910423	0,7937005	1	0,0810378	0,1168006	0,1910782	0,136058	0,1213112
Sum	5,2334605	6,795346	8,5274045				1,1215617	1

Table 11. Ranking level of criteria

	P1	P2	P3	P4	P5	P6	level	%
Efficacy (C1)	0.1185201	0.0340811	0.0866232	0.0164603	0.0114986	0.0770238	0.34420715	34%
Delivery (C2)	0.0380343	0.0418581	0.0427324	0.0446354	0.0106482	0.0321882	0.21009672	21%
Environment (C3)	0.0230733	0.0233184	0.0181475	0.0190355	0.011763	0.0264579	0.12179558	12%
Services (C4)	0.0127133	0.0131997	0.0184798	0.1065818	0.018269	0.0172008	0.18644451	19%
Social (C5)	0.0086606	0.0071487	0.0118397	0.0094642	0.0116546	0.0108739	0.05964167	6%
Economic (C6)	0.0096131	0.0077001	0.0112997	0.005195	0.0277185	0.0162886	0.07781438	8%

A fuzzy AHP analysis indicates that apparel suppliers impacted by e-commerce must prioritize development, delivery, and service to maintain competitiveness. This is despite the current products' environmental, economic, and social factors playing a secondary role in increasing consumer awareness. These results were carefully evaluated by our 18 experts, who confirmed that the computed weights are consistent with real-world priorities, providing assurance regarding the reliability and robustness of the findings.

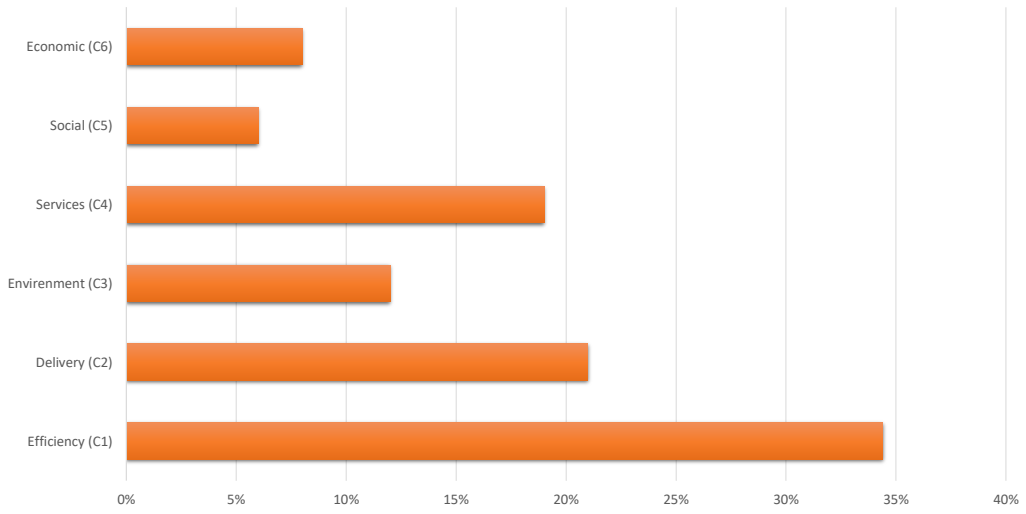

Figure 2. Criteria Weights Computed Using Fuzzy AHP.

5. Discussion

The analysis of apparel supply chains in Tunisia influenced by e-commerce reveals several clear priorities, as demonstrated in Table 11 and Figure 2. As can be observed, operational efficiency (34%) represents a key factor for export operations (21%), emphasizing the necessity for e-commerce companies to meet the high expectations of their customers in terms of speed, reliability, convenience, and intense pressure. In the apparel industry, where demand can fluctuate with seasonal trends and fast fashion cycles, optimizing internal processes and ensuring the timely delivery of products is crucial for customer satisfaction and competitiveness. This is particularly relevant within the context of competing brands.

The service standard (19%) serves to reinforce the significance of a comprehensive e-commerce experience that extends beyond the transaction itself, encompassing aspects such as handling returns and responsive customer support. The service segment is of particular importance in fostering long-term customer loyalty. As customer empowerment increases with the advent of digital channels and the concomitant expectation of impeccable service, companies that excel in this area are likely to gain a competitive advantage.

However, while environmental considerations are accorded a weight of (12%), economic considerations are given 8 weighting, and social considerations a 6 weighting, it is notable that these factors are not given the same level of importance as other considerations. This indicates that, although organizations are conscious of the necessity to address sustainability, financial stability, and ethical practices, these areas are secondary to immediate concerns such as efficacy and the quality of service. The findings of this study indicate that, while operational efficacy, delivery, and service levels remain the primary considerations for fashion brands in the context of e-commerce, sustainability, economic stability, and social responsibility are emerging as increasingly significant factors. As e-commerce continues to transform the apparel industry, companies must adapt their strategies to optimize not only logistics and customer service but also green and ethical practices, in addition to evolving customer expectations.

In the context of e-commerce, the industrialists emphasize the necessity of prioritizing operational efficiencies through the investment in advanced technologies, including automation and Artificial Intelligence (AI) forecasting. This type of problem can be addressed using, Multi-Criteria Decision-Making (MCDM) methods [50, 51, 52, 53] heuristic approaches, such as Dhouib-Matrix, as explored in the works of [54, 55, 56, 57, 58, 59, 60, 61]. Additionally, Neural Networks has been applied in [62, 63, 64, 65], demonstrating the versatility of these approaches in optimizing supply chain operations and decision-making processes. To meet the evolving customer demand for quick services, it is necessary to implement high-quality distribution systems and reliable partnerships with last-mile innovation. It is of the utmost importance to enhance customer service by facilitating returns and providing personalized support to ensure long-term customer loyalty.

Although sustainability and social responsibility currently occupy a relatively low position in the competitive landscape, brands can gain a competitive advantage by embracing green practices and ethical standards. The ability to balance economic and environmental concerns can facilitate compliance, enhance brand reputation, and enable brands to adapt to future changes in consumer behavior, technology, and legislation. This can be achieved by monitoring the rise of the supply chain.

6. Conclusion

The advent of the global pandemic has precipitated a further acceleration of these changes, exposing deficiencies in the traditional supply chain structure, agility, flexibility, and efficiency, and underscoring the imperative for improvement. To effectively navigate this new digital landscape, companies must gain a comprehensive understanding of how e-commerce influences various aspects of supply chains. This includes examining the impact on efficacy, delivery, the environment, customer service, and socioeconomic factors. To respond to this problem, the fuzzy AHP model was used to measure six important criteria for supply chain performance in e-commerce: Efficiency, Delivery, Environmental Impact, Services, Social Factors, and Economic factors gathering expert opinions and analyzing data through this process, we were able to assign a relative weight to each criterion, providing clear priorities for companies involved in e-commerce supply chains. The survey results indicate that

efficiency and delivery performance are the most critical criteria for companies, reflecting the pressure to optimize operations and ensure rapid, reliable logistics in the digital era. Customer service, social responsibility, and environmental concerns are acknowledged but remain less prioritized compared to economic and operational goals. These insights highlight the need for further research on integrating sustainability into supply chain practices, such as reducing carbon emissions and adopting eco-friendly packaging—as well as exploring how emerging technologies (blockchain, IoT, machine learning) can strengthen transparency and efficiency in the apparel supply chain.

Interest Declaration

All authors declare that they have no conflicts of interest.

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