VERİMLİLİK DERGİSİ
JOURNAL OF PRODUCTIVITY

Evaluation of Barriers to Digital Transformation in Maritime Logistics Based on A Spherical Fuzzy Multi-Criteria Decision-Making Framework

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ABSTRACT

Purpose: The objective of this study is to identify and prioritize the barriers to the adoption of digital transformation in order to ensure more efficient and effective operation of the maritime logistics sector.

***Methodology*:** The Spherical Fuzzy Analytical Hierarchy Process (SF-AHP) method, which gives successful results in modelling uncertainty and uses Spherical fuzzy sets (SFSs), is used to rank the barriers affecting adoption of digital transformation according to their importance.

Findings: In the application part of the study, firstly the barriers in the adoption of digital transformation were determined and as a result of expert evaluations, the barriers were ranked according to their importance by applying the steps of the method. When the results obtained from the study were examined, 'Technology' is the most important barrier category (B1) (0.341) for the adoption of digital transformation in maritime logistics, followed by the main barrier categories related to "Security" (B4) (0.266), "Environment" (B3) (0.223) and "Organisation" (B2) (0.171) respectively.

Originality: This study represents a pioneering effort in the field of maritime logistics, as it is the first to identify and prioritize the barriers to digital transformation that impede operational efficiency.

Keywords*:* Digital Transformation, Barrier, Spherical Fuzzy Set, AHP.

JEL Codes: D81, L91, O31.

Küresel Bulanık Çok Kriterli Karar Verme Çerçevesine Dayalı Olarak Denizcilik Lojistiğinde Dijital Dönüşümün Önündeki Engellerin Değerlendirilmesi

ÖZET

Amaç: Bu çalışmanın amacı, deniz lojistik sektörünün daha verimli ve etkin çalışmasını sağlamak için dijital dönüşümün benimsenmesinin önündeki engelleri tespit etmek ve önceliklendirmektir.

***Yöntem*:** Belirsizliğin modellenmesinde başarılı sonuçlar veren ve küresel bulanık kümeleri kullanan Küresel Bulanık Analitik Hiyerarşi Süreci (SF-AHP) yöntemi, dijital dönüşümün benimsenmesini etkileyen engelleri önem derecelerine göre sıralamak için kullanılmıştır.

Bulgular: Çalışmanın uygulama kısmında öncelikle dijital dönüşümün benimsenmesindeki engeller belirlenmiş ve uzman değerlendirmeleri sonucunda yöntemin adımları uygulanarak engeller önem derecelerine göre sıralanmıştır. Çalışmadan elde edilen sonuçlar incelendiğinde, deniz lojistiğinde dijital dönüşümün benimsenmesi için en önemli engel kategorisinin (B1) (0,341) 'Teknoloji' olduğu, bunu sırasıyla "Güvenlik" (B4) (0,266), "Çevre" (B3) (0,223) ve "Organizasyon" (B2) (0,171) ile ilgili ana engel kategorilerinin takip ettiği görülmüştür.

Özgünlük: Bu çalışma, operasyonel verimliliği engelleyen dijital dönüşümün önündeki engelleri tespit edip önceliklendirmesi bakımından deniz lojistiği alanında öncü bir çabayı temsil etmektedir.

Anahtar Kelimeler*:* Dijital Dönüşüm, Bariyer, Küresel Bulanık Küme, AHP.

JEL Kodları: D81, L91, O31.

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DOI: 10.51551/verimlilik.1526042
Research Article | Submitted: 01.08.2024 | Accepted: 26.09.2024
Cite: Tatar, V. (2025). "Evaluation of Barriers to Digital Transformation in Maritime Logistics Based on A Spherical Fuzzy Multi-Criteria Decision-Making Framework", *Verimlilik Dergisi,* Productivity for Logistics (SI), 29-44.

1. INTRODUCTION

The digital century has recently changed the competitive dynamics of many businesses, including the logistics sector (Raza et al., 2023). Sustainable and efficient maritime transportation is essential to the world economy's continuous growth (Vujičić et al., 2020). The implementation of digital transformation has the potential to yield benefits for the maritime transport chain, such as enhanced business operations, reduced environmental impacts, and optimized cargo management (Jović et al., 2022). Digital transformation (DT) innovates the processes of traditional business models, providing opportunities for visibility and transparency, operational efficiency and integration and collaboration (Kache and Seuring, 2017; Tijan et al., 2021).

The global logistics industry, which had a market size of approximately 9.41 trillion US dollars in 2023, is expected to exceed 14.08 trillion U.S dollars by 2028 (Statista, 2024). Despite the rising costs of logistics, the sector is not adequately addressing the challenges of digitalisation in terms of sustainability (Parhi et al., 2022). Maritime logistics is a complex system that encompasses many interrelated factors. Therefore, the maritime industry, which deals with a large number of documents and procedures, needs the implementation of DT in the context of faster, more efficient and lower costs, operationally and commercially (Yang, 2019). The implementation of digital transformation in maritime companies, which encompasses concepts such as "Artificial Intelligence", "Internet of Things", "Cloud Computing", "Blockchain" and "Cybersecurity" related to Industry 4.0, will be important indicators in terms of customer satisfaction, environmental protection, cost efficiency, improved service quality and operational efficiency (Ichimura et al., 2022).

Maritime logistics, which integrates the global supply chain concept into maritime transportation, is an indispensable part of the global economy. In a competitive environment, shipping companies focus on key performance indicators ─ such as quality, speed, reliability, flexibility and cost (Panayides and Song, 2013). Digital technologies will enable more efficient operations in ports by shortening ship docking and waiting times at the terminal. In addition, it will reduce energy consumption and greenhouse gas emissions by optimizing ship arrival times by providing up-to-date meteorological information to the ship crew (Fruth and Teuteberg, 2017). The success of digital transformation in maritime logistics depends not only on the adoption of modern technologies but also on the cooperation of other stakeholders in the maritime transportation ecosystem (Heilig et al., 2017). Maritime logistics, which is important in terms of sea and land connection, is of great importance for maritime enterprises to use digital transformation in their business models in order to achieve sustainable goals and use their resources efficiently (Del Giudice et al., 2022). The maritime industry is undergoing a period of transition in order to adapt to the challenges of digital transformation. This transformation is focused on optimising cargo handling, streamline maritime procurement and logistics processes, enhancing efficiency, safety and reduce environmental effect (Babica et al., 2020).

The Analytical Hierarchy Process (AHP) is a frequently employed multi-criteria decision-making methodology, devised by Saaty (1977), for addressing intricate decision-making challenges (Kumar and Pant, 2023). It is a systematic approach to the prioritisation, ranking and evaluation of criteria and sub-criteria in accordance with the main goal. The traditional AHP approach is insufficient for addressing the absence of information or ambiguity in decision-maker (DM) judgments (Özkan et al., 2022). To address this limitation, the spherical fuzzy set (SFS) theory proposed Kahraman and Kutlu Gündoğdu (2018) is integrated into the AHP framework. The SFS methodology entails the definition of a fuzzy membership function on a spherical surface, accompanied by the independent assignment of function inputs to a larger domain. This approach affords decision-makers the flexibility to express ambivalence during the evaluation process (Dogan, 2021; Kutlu Gündoğdu and Kahraman, 2020a).

The current research study aims to address the above academic area and provide guidance to maritime industry managers by identifying and prioritising the potential barriers to the implementation of digital transformation practices by using the spherical fuzzy AHP (Kutlu Gündoğdu and Kahraman, 2020b) approach within the scope of the relevant literature review. In this context, the contributions of this study are as follows:

(1) This study identifies and constructs a hierarchical structure of the barriers to the adoption of DT in the maritime logistics sector, based on a comprehensive literature review.

(2) The proposal of a set of valid barriers to the implementation of digitalization in maritime logistics from the perspective of key stakeholders.

(3) To the best of the author's knowledge, this is the first study to utilize the AHP method based on SFS to evaluate the barriers in the digital transformation process in the maritime logistics sector. The spherical fuzzy AHP method was utilized to the determination of the relative importance of the criteria.

(4) In order to aggregate the judgement data of individual experts, a method based on the SWAM operator is employed to generate an aggregate evaluation matrix.

(5) The proposed approach will serve as a reference for experts and practitioners in the maritime logistics sector, offering crucial insights for the implementation of DT technologies.

(6) A comparative analysis was conducted to ascertain the robustness and applicability of the proposed methodology.

The rest of the manuscript is organized as follows: In Section 2, the barriers to adopting digital transformation are reviewed. Section 3 includes the introductory definitions and preliminary information on SFS and AHP methodology. Section 4 employs SF-AHP method to an illustration of an application. Subsequently, a comparative analysis is conducted in Section 4.1, while managerial implications are presented in Section 4.2. Finally, conclusions in Section 5.

2. LITERATURE REVIEW

The term "digitalization" is a key factor in the creation of new business models that aim to enhance business productivity and sustainability through the utilization of digital technologies within businesses (Ahmad et al., 2021; Jović et al., 2022). Fruth and Teuteberg (2017) emphasized reducing costs and protecting the environment by optimizing fleet controls with Big Data and digital transformation. Kechagias et al. (2022) highlighted that the maritime industry faces cyber risks with the increase in technological developments. Ahmad et al. (2021) posited that blockchain technology can be employed to effect the permanent and transparent recording of changes in the ownership or movements of shipments, cranes, and internal logistics vehicles. Port call optimization with the aid of digitalization is one of the crucial short-term steps that can considerably lower the CO_2 emissions of maritime transportation in the framework of international efforts towards the decarbonization of shipping (UNCTAD, 2020). Blockchain technologies facilitate safe and secure communication amongst supply chain participants in addition to enabling quick and dependable engagement within a broader network (Wei et al., 2019: 235). The maritime industry's quick adoption of IoT technology will make the management of fundamental operations such as ship monitoring, greenhouse gas emissions control, maintenance planning and safety more effective (Plaza-Hernández et al., 2021). The adoption of new digital technologies and automated systems raises the standard of strategic planning and communication strategies, workforce working conditions, and maritime supply chain stakeholders' productivity (Parola et al., 2021). Kozak-Holland and Procter (2020) point out that the Information Technology (IT) department of businesses has important duties to overcome the challenges of digital transformation. Tsiulin et al. (2023) have identified and summarized the challenges associated with the implementation of blockchain technology in the maritime industry and sea ports.

Cost is one of the major barriers to adoption of digital transformation technologies. The most important of these costs is the high cost of the initial investment. The payment of a significant amount of funds to a technology provider for work on a 'private blockchain' is a risk that could hamper its implementation in the maritime industry (Zhou et al., 2020). The willingness of the user to switch to the new system is significantly and negatively influenced by varying conversion costs due to economic risks, evaluation costs, learning costs and consumer acceptance (Ho and Hsu, 2020). The conservative culture of decision makers in maritime companies is another barrier to the adoption of digital transformation (Gausdal et al., 2018, Zhou et al., 2020). In addition to the adaptation of digital technologies, the implementation of secure systems that ensure the protection of the organisational infrastructure and operating systems against cyber attacks is imperative (Fruth and Teuteberg, 2017; Tijan et al., 2021). The implementation of DT requires the utilisation of distinct skill sets and the involvement of individuals within the organisational structure who possess a different set of competencies compared to those who are more experienced and adhere to more traditional (Raza et al., 2023). The potential for significant organisational change raises concerns among senior managers about their organisations' capacity to embrace such a transformative shift. These leaders perceive a lack of requisite knowledge, tools and commitment within their organisations to navigate the complexities of such a profound change (Mugge et al., 2020). Another managerial obstacle is the resistance of managers and employees due to not having the necessary skills (Durão et al., 2019). The country-specific nature of regulations in the field of maritime transport also gives rise to difficulties in the implementation of new Technologies (Tijan et al., 2021). Stakeholders at the maritime sector (e.g., shippers, consignees, shipping agents) face obstacles to digital transformation operations that other businesses experience, such as lack of awareness, absence of effective strategies and initiatives, and lack of resources for successful digital transformation (Tan and Sundarakani, 2021; Tijan et al., 2021, Raza et al., 2023). Table 1 presents the identified barriers, their classifications, and the authors who employed these barriers in their respective studies.

Table 1. Identified barriers to adopting DT in the maritime sector

Barrier type	*Barriers*	*References*
Technology (B1)		
B11	Cost	Ho and Hsu (2020), Zhou et al. (2020)
B12	Conservatism	Gausdal et al. (2018), Zhou et al. (2020)
B13	Decreased cyber security levels	Fruth and Teuteberg (2017), Tijan et al. (2021)
Organisation (B2)		
B21	Lack of sufficient human resources	Raza et al. (2023)
B22	Lack of knowledge	Mugge et al. (2020)
B23	Employees' and managers' resistance to change	Durão et al. (2019)
B24	Inadequate or absent regulations	Tijan et al. (2021)
Environment (B3)		
B31	Lack of coordination and cooperation in the partner ecosystem	Raza et al. (2023), Tan and Sundarakani (2021), Tijan et al. (2021)
B32	Laws and regulations	Zhou et al. (2020)
B33	Government/policy-makers support	Tijan et al. (2021)
Security (B4)		
B41	Information system insecurity	Nguyen et al. (2019), Sarker et al. (2021)
B42	Data protection and security breach	Cichosz et al. (2020)
B43	Lack of information security management	Gebremeskel et al. (2023)

This study sought to address this gap in the literature by employing a multi-criteria decision-making (MCDM) technique based on the spherical fuzzy-AHP (SF-AHP) (Kutlu Gündoğdu and Kahraman, 2020b) method to rank the barriers to digital transformation in maritime logistics. A total of thirteen barriers were identified and grouped into four main categories. The SF-AHP was then utilized to determine the relative weights and ranks of each barrier. Table 2 summarizes the prominent studies in the literature.

Table 2. Literature review summary

Author(s)	*Aim of the study*	*Methods used*
Heilig et al. (2017)	To identify current potentials and barriers, an overview of the development and status of digital transformation in modern seaports	Game theory
Tijan et al. (2021)	A summarized model of the drivers, factors, and barriers for digital transformation in maritime transport	Literature review
Bocayuva (2021)	Port cybersecurity aanalyzed in view of digital transformation	-
Jović et al. (2022)	A model of the factors that influence the digital transformation in the maritime transport sector	Literature review and Questionnaire survey
Parhi et al. (2022)	A total of fifteen enabling factors for the implementation of sustainable logistics 4.0 are identified and subjected to critical evaluation, with particular emphasis on firms at disparate levels of digitalization	F-AHP, DEMATEL
Tsiulin et al. (2023)	To identify and summarize the challenges of blockchain implementation in the maritime industry and sea ports	Literature review and previous research findings
Raza et al. (2023)	To examine in liner shipping companies, the current digital maturity levels, the opportunities afforded by digitalisation and the underlying challenges that impede its implementation in the liner shipping segment within the broader maritime logistics industry. It also identifies the essential leading strategies of digitalisation in this segment	Semi-structured interviews
Hamidi et al. (2024)	A three-stage digital maturity model that is designed to effectively gauge digital preparedness within the context of maritime logistics industries	F-AHP, F-TOPSIS
Utama et al. (2024)	To develop the digital transformation maturity model for ports	Literature review and Focus Group Discussion

3. METHODOLOGY

3.1. Spherical Fuzzy Sets: Preliminaries

The theory of fuzzy sets was first proposed by Zadeh (1965) as a way to deal with the doubt and ambiguity that frequently accompanies decision-making processes. The spherical fuzzy set (SFS) approach, which builds upon the foundations of Neutrosophic set (NS) and Pythagorean fuzzy set (PyFS), was firstly introduced by Kutlu Gündoğdu and Kahraman (2019a). This novel approach offers a robust framework for navigating the inherent ambiguity of data. SFS represents a novel expansion of the fuzzy set concept, offering a means of expressing the degree of membership, non-membership, and hesitancy as perceived by experts (Liu et al., 2023). Figure 1 depicts the historical development of fuzzy sets.

Figure 1. The history of the development of fuzzy sets

Spherical Fuzzy Sets (SFSs) afford decision-makers a more expansive domain of preference, and each of them is also able to ascertain their degree of hesitancy within the context of a spherical fuzzy environment (Donyatalab et al., 2022). In spherical fuzzy sets, the sum of the squares of the three parameters (membership, non-membership and hesitancy) can be in the interval [0, 1], while each can be defined independently in the interval [0, 1] (Kutlu Gündoğdu and Kahraman (2019b). This section presents the preliminary concepts of SFSs (Kutlu Gündoğdu and Kahraman, 2019b; Donyatalab et al., 2022).

Definition 1: The definition of an SFs, $\tilde{T}_s$, of the universe of discourse U is as follows (Equation 1):

$$\tilde{T}_s = \left\{ \langle u, \left(\beta_{\tilde{T}_s}(u), \gamma_{\tilde{T}_s}(u), \delta_{\tilde{T}_s}(u) \right) \rangle \mid u \in U \right\} \tag{1}$$

Where $\beta_{\tilde{T}_s}: U \to [0,1]$, $\gamma_{\tilde{T}_s}: U \to [0,1]$, $\delta_{\tilde{T}_s}: U \to [0,1]$, and

For each, $\beta_{\tilde{T}_s}(u), \gamma_{\tilde{T}_s}(u), and\ \delta_{\tilde{T}_s}(u)$ are the degree of membership, non-membership, and hesitancy of u to $\tilde{T}_s$, respectively (Equation 2).

$$0 \le \beta_{\tilde{T}_s}^2(u) + \gamma_{\tilde{T}_s}^2(u) + \delta_{\tilde{T}_s}^2(u) \le 1 \quad (u \in U) \tag{2}$$

Definition 2: The following section presents the computations for the basic operators defined in the context of SFS. The operators are defined as follows Equations 3-6.

Addition:

$$\tilde{T}_s \oplus \tilde{P}_s = \left\{ \sqrt{\beta_{\tilde{T}_s}^2 + \beta_{\tilde{P}_s}^2 - \beta_{\tilde{T}_s}^2 . \beta_{\tilde{P}_s}^2}, \gamma_{\tilde{T}_s}^2 . \gamma_{\tilde{P}_s}^2, \sqrt{\left(\left(1 - \beta_{\tilde{P}_s}^2\right) \delta_{\tilde{T}_s}^2 + \left(1 - \beta_{\tilde{T}_s}^2\right) \delta_{\tilde{P}_s}^2 - \delta_{\tilde{T}_s}^2 . \delta_{\tilde{P}_s}^2 \right)} \right\} \tag{3}$$

Multiplication:

$$\tilde{T}_s \otimes \tilde{P}_s = \left\{ \beta_{\tilde{T}_s}^2 . \beta_{\tilde{P}_s}^2, \sqrt{\gamma_{\tilde{T}_s}^2 + \gamma_{\tilde{P}_s}^2 - \gamma_{\tilde{T}_s}^2 . \gamma_{\tilde{P}_s}^2}, \sqrt{\left(\left(1 - \gamma_{\tilde{P}_s}^2\right) \delta_{\tilde{T}_s}^2 + \left(1 - \gamma_{\tilde{T}_s}^2\right) \delta_{\tilde{P}_s}^2 - \delta_{\tilde{T}_s}^2 . \delta_{\tilde{P}_s}^2 \right)} \right\} \tag{4}$$

Multiplication by a scalar:

$$\tilde{T}_s \otimes x = \left\{ \sqrt{1 - \left(1 - \beta_{\tilde{T}_s}^2\right)^x}, \gamma_{\tilde{T}_s}^x, \sqrt{\left(1 - \beta_{\tilde{T}_s}^2\right)^x - \left(1 - \beta_{\tilde{T}_s}^2 - \delta_{\tilde{T}_s}^2\right)^x} \right\} \quad (5)$$

x. Power of $\tilde{T}_s$:

$$\tilde{T}_s^x = \left\{ \beta_{\tilde{T}_s}^x, \sqrt{1 - \left(1 - \gamma_{\tilde{T}_s}^2\right)^x}, \sqrt{\left(1 - \gamma_{\tilde{T}_s}^2\right)^x - \left(1 - \gamma_{\tilde{T}_s}^2 - \delta_{\tilde{T}_s}^2\right)^x} \right\} \quad (6)$$

Definition 3: The definition of Spherical Weighted Arithmetic Mean $(SWAM)_{\omega=}(\omega_1, \omega_1, \ldots, \omega_n); \sum_{i=1}^{n} \omega_i = 1$ is as follows (Equation 7):

$$\text{SWAM}_\omega (\tilde{T}_{s1}, \tilde{T}_{s2}, \ldots, \tilde{T}_{sn}) = \omega_1 \tilde{T}_{s1} + \omega_2 \tilde{T}_{s2} + \ldots + \omega_n \tilde{T}_{sn}$$

$$= \left\{ \sqrt{1 - \prod_{i:1}^{n} \left(1 - \beta_{\tilde{T}_{si}}^2\right)^{\omega_i}}, \prod_{i:1}^{n} \gamma_{\tilde{T}_{si}}^{\omega_i}, \sqrt{\prod_{i:1}^{n} \left(1 - \beta_{\tilde{T}_{si}}^2\right)^{\omega_i} - \prod_{i:1}^{n} \left(1 - \beta_{\tilde{T}_{si}}^2 - \delta_{\tilde{T}_{si}}^2\right)^{\omega_i}} \right\} \quad (7)$$

3.2. Spherical Fuzzy AHP (SF-AHP)

Step 1: The initial stage of the process involves the establishment of a hierarchical structure.

Step 2: A spherical fuzzy pairwise comparison matrix $\tilde{\boldsymbol{P}} = [\tilde{\boldsymbol{P}}_{ij}]_{nxn}$ is constructed using the information obtained from the decision makers. The linguistic terms defined in Table 3, are used to express the opinions of decision makers. $\tilde{P} = [\tilde{P}_{ij}]_{nxn}$ is calculated using Equation 8.

$$\tilde{P} = [\tilde{P}_{ij}]_{nxn} = \begin{bmatrix} 1 & \tilde{T}_{12} & \ldots & \tilde{T}_{1n} \\ \tilde{T}_{21} & 1 & \cdots & \tilde{T}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{T}_{n1} & \tilde{T}_{n2} & \ldots & 1 \end{bmatrix} \text{ where } i = j = 1,2, \ldots, n \text{ and } \tilde{T}_{ij} = (\beta_{\tilde{T}_{ij}}, \gamma_{\tilde{T}_{ij}}, \delta_{\tilde{T}_{ij}}). \quad (8)$$

Table 3. The scale of SF linguistic terms

Linguistic Terms	*Spherical Fuzzy Numbers (SFNs)* (β, γ, δ)	*Score Index (SI)*
Absolutely more importance (AMI)	(0.9, 0.1, 0.0)	9
Very high importance (VHI)	(0.8, 0.2, 0.1)	7
High importance (HI)	(0.7, 0.3, 0.2)	5
Slightly more importance (SMI)	(0.6, 0.4, 0.3)	3
Equal importance (EI)	(0.5, 0.4, 0.4)	1
Slightly low importance (SLI)	(0.4, 0.6, 0.3)	1/3
Low importance (LI)	(0.3, 0.7, 0.2)	1/5
Very low importance (VLI)	(0.2, 0.8, 0.1)	1/7
Absolutely low importance (ALI)	(0.1, 0.9, 0.0)	1/9

Source: Kutlu Gündoğdu and Kahraman (2020b)

The score indices (SI) in Table 3 are calculated using the Equations 9 and 10.

For AMI, VHI, HI, SMI, and EI

$$SI = \sqrt{\left|100 \times \left(\left(\beta_{\tilde{U}_s} - \delta_{\tilde{U}_s}\right)^2 - \left(\gamma_{\tilde{U}_s} - \delta_{\tilde{U}_s}\right)^2\right)\right|} \quad (9)$$

For EI; SLI; LI; VLI; and ALI;

$$SI^{-1} = 1 \Big/ \sqrt{\left|100 \times \left(\left(\beta_{\tilde{U}_s} - \delta_{\tilde{U}_s}\right)^2 - \left(\gamma_{\tilde{U}_s} - \delta_{\tilde{U}_s}\right)^2\right)\right|} \quad (10)$$

Step 3: The pairwise comparison matrix is checked for consistency. The defuzzified crisp numbers are subjected to a comparison with the SFNs presented in Table 3, with the use of Saaty's scale. Then Saaty's classical consistency formula is employed. The spherical fuzzy pairwise comparison matrix is deemed consistent if the consistency ratio (CR) is smaller than 0.1.

Step 4: Calculate the spherical fuzzy local weights for each criterion. The weighted arithmetic mean is utilized to compute the spherical fuzzy weights; the spherical weights of each criterion is determined using the SWAM operator given in Equation 7.

Step 5: Use the score function *(S)* in Equation 11 to defuzzify the criteria weights and then Equation 12 to normalize to determine the final weights (Kutlu Gündoğdu and Kahraman, 2020b).

$$S(\tilde{\omega}_j^s) = \sqrt{\left|100 \times \left[\left(3\beta_{\tilde{T}_s} - \frac{\delta_{\tilde{T}_s}}{2}\right)^2 - \left(\frac{\gamma_{\tilde{T}_s}}{2} - \delta_{\tilde{T}_s}\right)^2\right]\right|} \quad (11)$$

$$\tilde{\omega}_j^s = \frac{S(\tilde{\omega}_j^s)}{\sum_{j=1}^{n} S(\tilde{\omega}_j^s)} \quad (12)$$

4. AN ILLUSTRATION OF AN APPLICATION

The proposed method is an application to identify and determine the relative importance of barriers in the digital transformation process of companies in maritime logistics; more details are provided in following. Following a comprehensive literature review, a decision team consisting of three decision makers (DM1, DM2, DM3) experienced in maritime logistics is formed during the data collection process. In this context, four barriers (Technology (B1), Organisation (B2), Environment (B3), and Security (B4)) and 13 sub-barriers were determined based on expert opinions and literature review. Figure 2 illustrates this hierarchy, which comprises all identified barriers and sub- barriers.

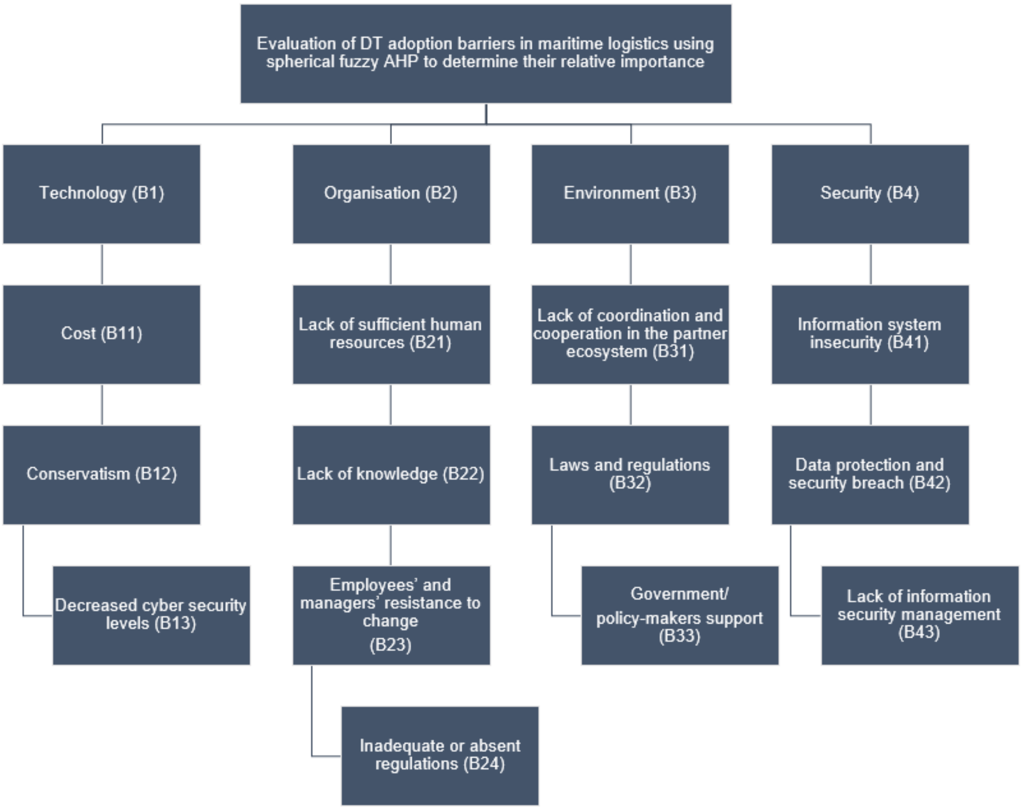

Figure 2. The developed decision hierarchy of barriers to adopting DT in maritime logistics

The CRs of the pairwise comparison matrices are computed in accordance with the corresponding numerical values in the classical AHP method for the linguistic scale delineated in Table 3. The pairwise comparisons and the computed spherical weights ($\tilde{\boldsymbol{\omega}}^s$) and crisp weights ($\overline{\boldsymbol{\omega}}^s$) are presented in Tables 4-13 including their CRs. In Table 14, the local and global weights of each sub-barrier are presented.

Table 4. Pairwise comparison of main barriers

Main Barriers		*B1*	*B2*	*B3*	*B4*
DM1	B1	EI	VHI	HI	SMI
CR= 0.044	B2	VLI	EI	SLI	LI
	B3	LI	SMI	EI	SLI
	B4	SLI	HI	SMI	EI
DM2		B1	B2	B3	B4
CR= 0.085	B1	EI	HI	SMI	HI
	B2	LI	EI	SLI	LI
	B3	SLI	SMI	EI	EI
	B4	LI	HI	EI	EI
DM3		B1	B2	B3	B4
CR= 0.064	B1	EI	AMI	VHI	HI
	B2	ALI	EI	SLI	LI
	B3	VLI	SMI	EI	SLI
	B4	LI	HI	SMI	EI

Table 5. Spherical weights of the main barriers

Main Barriers		$\tilde{\omega}^s$		$\bar{\omega}^s$
B1	0.69	0.31	0.25	0.341
B2	0.37	0.61	0.29	0.171
B3	0.48	0.50	0.32	0.223
B4	0.55	0.42	0.30	0.266

Table 6. Pairwise comparison of “Technology related” barriers

Technology		*B11*	*B12*	*B13*
DM1	B11	EI	LI	SMI
CR=0.057	B12	HI	EI	VHI
	B13	SLI	VLI	EI
DM2		B11	B12	B13
CR=0.033	B11	EI	SLI	SMI
	B12	SMI	EI	HI
	B13	SLI	LI	EI
DM3		B11	B12	B13
CR=0.006	B11	EI	SLI	SMI
	B12	SMI	EI	VHI
	B13	SLI	VLI	EI

Table 7. Spherical weights of the “Technology related” barriers

Technology		$\tilde{\omega}^s$		$\bar{\omega}^s$
B11	0.50	0.47	0.33	0.319
B12	0.65	0.33	0.27	0.434
B13	0.40	0.57	0.31	0.247

Table 8. Pairwise comparison of “Organisation related” barriers

Organisation		*B21*	*B22*	*B23*	*B24*
DM1	B21	EI	HI	LI	SMI
CR=0.091	B22	LI	EI	VLI	SLI
	B23	HI	VHI	EI	HI
	B24	SLI	SMI	LI	EI
DM2		B21	B22	B23	B24
CR=0.052	B21	EI	VHI	SLI	SMI
	B22	VLI	EI	VLI	SLI
	B23	SMI	VHI	EI	HI
	B24	SLI	SMI	LI	EI
DM3		B21	B22	B23	B24
CR=0.060	B21	EI	VHI	SLI	SMI
	B22	VLI	EI	VLI	SLI
	B23	SMI	VHI	EI	SMI
	B24	SLI	SMI	SLI	EI

Table 9. Spherical weights of the “Organisation related” barriers

Organisation		$\tilde{\omega}^s$		$\overline{\omega}^s$
B21	0.60	0.40	0.28	0.287
B22	0.36	0.62	0.28	0.164
B23	0.67	0.32	0.26	0.329
B24	0.48	0.50	0.32	0.220

Table 10. Pairwise comparison of “Environment related” barriers

Environment		*B31*	*B32*	*B33*
DM1	B31	EI	LI	VLI
CR=0.056	B32	HI	EI	SLI
	B33	VHI	SMI	EI
		B31	B32	B33
DM2	B31	EI	LI	ALI
CR=0.025	B32	HI	EI	SLI
	B33	AMI	SMI	EI
		B31	B32	B33
DM3	B31	EI	VLI	ALI
CR=0.070	B32	VHI	EI	SLI
	B33	AMI	SMI	EI

Table 11. Spherical weights of the “Environment related” barriers

Environment		$\tilde{\omega}^s$		$\overline{\omega}^s$
B31	0.34	0.64	0.28	0.198
B32	0.58	0.40	0.29	0.354
B33	0.71	0.28	0.25	0.447

Table 12. Pairwise comparison of “Security related” barriers

Security		*B41*	*B42*	*B43*
DM1	B41	EI	VHI	HI
CR=0.057	B42	VLI	EI	SLI
	B43	LI	SMI	EI
		B41	B42	B43
DM2	B41	EI	AMI	HI
CR=0.025	B42	ALI	EI	SLI
	B43	LI	SMI	EI
		B41	B42	B43
DM3	B41	EI	AMI	SMI
CR=0.000	B42	ALI	EI	SLI
	B43	SLI	SMI	EI

Table 13. Spherical weights of the “Security related” barriers

Security		$\tilde{\omega}^s$		$\overline{\omega}^s$
B41	0.73	0.27	0.23	0.470
B42	0.38	0.59	0.31	0.227
B43	0.50	0.48	0.33	0.302

“Technology” is the most important barrier category (B1) (0.341) for the adoption of digital transformation in maritime logistics, followed by the main barrier categories related to “Security” (B4) (0.266), “Environment” (B3) (0.223) and “Organisation” (B2) (0.171) respectively. Subsequently, the relative importance weights of the specific barriers were calculated. Additionally, global preference weights of the specific barriers were calculated, and their corresponding relative importance order or ranks were determined. Further details are provided in Table 14. Furthermore, the ranking results of the global weights of the calculated barriers are presented in Figure 3.

Table 14. Local and global weights of each sub-barrier

Barrier Type	*Main Barrier Weight*	*Local Weights*	*Global Weights*	*Rank*
B1	0.341			
B11		0.319	0.109	3
B12		0.434	0.148	1
B13		0.247	0.084	5
B2	0.171			
B21		0.287	0.049	10
B22		0.164	0.028	13
B23		0.329	0.056	9
B24		0.220	0.038	12
B3	0.223			
B31		0.198	0.044	11
B32		0.354	0.079	7
B33		0.447	0.100	4
B4	0.266			
B41		0.470	0.125	2
B42		0.227	0.060	8
B43		0.302	0.080	6

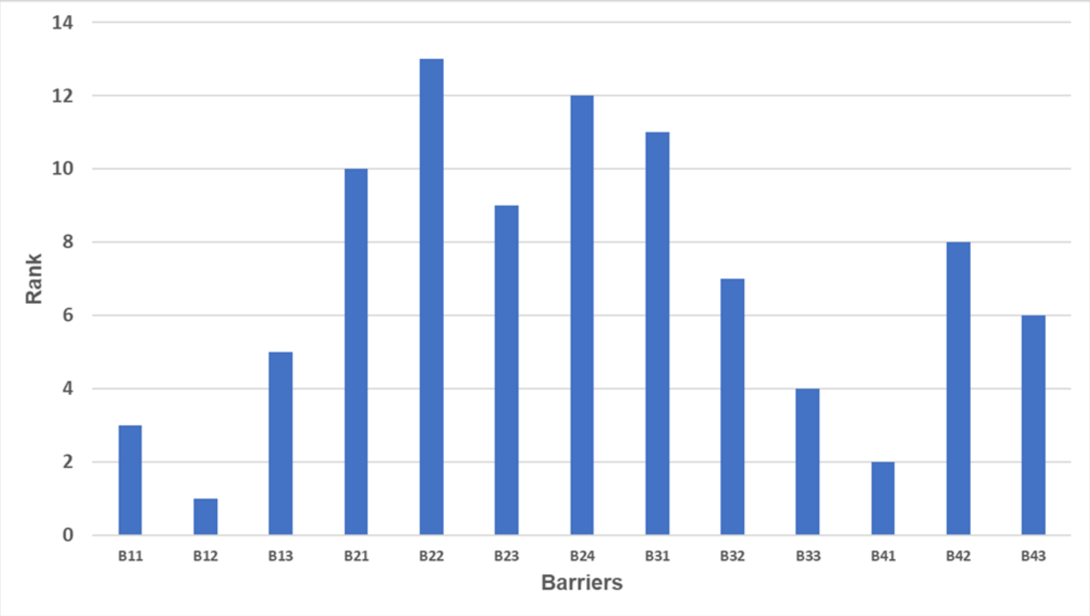

Figure 3. Ranking results of sub-barriers

4.1. Comparative Analysis

In order to ascertain the validity of the proposed method, it was subjected to comparison with the traditional AHP (Method 1) and Fermatean fuzzy AHP (Method 2) (Ayvaz et al., 2024) methods. As illustrated in Table 15, Table 16, Table 17, Table 18 and Table 19, the relative importance assigned to the barriers remains consistent in both the traditional AHP (AHP) and the Fermatean fuzzy AHP (FF-AHP) approaches. Furthermore, Figure 4 presents a comparative analysis of the relative importance weights of the barriers for the proposed method, the traditional AHP, and the FF-AHP, as illustrated graphically.

Table 15. Comparison of weights of the main barriers in SF-AHP, AHP and FF-AHP

	Proposed method	*Method 1*	*Method 2*
Main Barriers	*SF-AHP*	*AHP*	*FF-AHP*
B1	0.341	0.588	0.698
B2	0.171	0.058	0.029
B3	0.223	0.132	0.091
B4	0.266	0.223	0.182

Table 16. Comparison of weights of the Technology sub-barriers in SF-AHP, AHP and FF-AHP

Technology Sub-Barriers	Proposed method SF-AHP	Method 1 AHP	Method 2 FF-AHP
B11	0.319	0.231	0.228
B12	0.434	0.677	0.682
B13	0.247	0.092	0.091

Table 17. Comparison of weights of the Organisation sub-barriers in SF-AHP, AHP and FF-AHP

Organisation Sub-Barriers	Proposed method SF-AHP	Method 1 AHP	Method 2 FF-AHP
B21	0.287	0.270	0.239
B22	0.164	0.054	0.027
B23	0.329	0.551	0.650
B24	0.220	0.125	0.084

Table 18. Comparison of weights of the Environment sub-barriers in SF-AHP, AHP and FF-AHP

Environment Sub-Barriers	Proposed method SF-AHP	Method 1 AHP	Method 2 FF-AHP
B31	0.198	0.064	0.063
B32	0.354	0.282	0.278
B33	0.447	0.654	0.659

Table 19. Comparison of weight of the Security sub-barriers in SF-AHP, AHP and FF-AHP

Security Sub-Barriers	Proposed method SF-AHP	Method 1 AHP	Method 2 FF-AHP
B41	0.470	0.723	0.726
B42	0.227	0.077	0.076
B43	0.302	0.200	0.198

4.2. Managerial Implications

The proposed methodology presents the experts' opinions regarding the main criteria and sub-criteria. The results indicate that technology and security are the two most significant main dimensions of DT. These findings are consistent with those reported in the existing literatüre (Parhi et al., 2022; Hamidi et al., 2024).

The advent of digital transformation has resulted in significant alterations to the structural business models of numerous industries, thereby enhancing the efficiency of business processes. However, it is important to recognise that each sector is confronted with a unique set of challenges and barriers during the digital transformation process. The technology dimension identified by experts as the most significant barrier to the adoption of digital transformation. The author provided a literature review in which four main dimensions (Technology, Organisation, Environment and Security) are considered as the most important factors for the digitalization of an industry. In accordance with expert assessments, the three most significant barriers to digital transformation in maritime logistics are conservatism, information system insecurity, and cost. In contrast to numerous other sectors, the maritime sector is frequently characterised by a familial structure and a networked approach to its stakeholders. This structural form has historically demonstrated a tendency towards conservatism with regard to the incorporation of innovative practices (Raza et al., 2023). The process of digital transformation is one that is gradual and time-consuming, necessitating substantial and effective investments (Utama et al., 2024). Another outcome of this study is the conclusion that information security is a crucial aspect of the digital transformation process. The logistics sector plays a significant role in global trade, engaging with a diverse range of stakeholders. In particular, maritime transportation represents the most highly percentage of all transportation modes. The maritime logistics sector, which handles high-value monetary transfers and large-volume cargo, can be targeted by cyber attacks (Bocayuva, 2021). The high cost and lengthy timeframe associated with digital transformation within the maritime logistics sector place significant responsibility on those in managerial roles. It is therefore incumbent upon maritime logistics companies to adopt a strategic approach to the digital transformation process, ensuring that their capabilities in this regard are clearly defined, that their infrastructure investments are completed, and that they lead the way in corporate innovation.

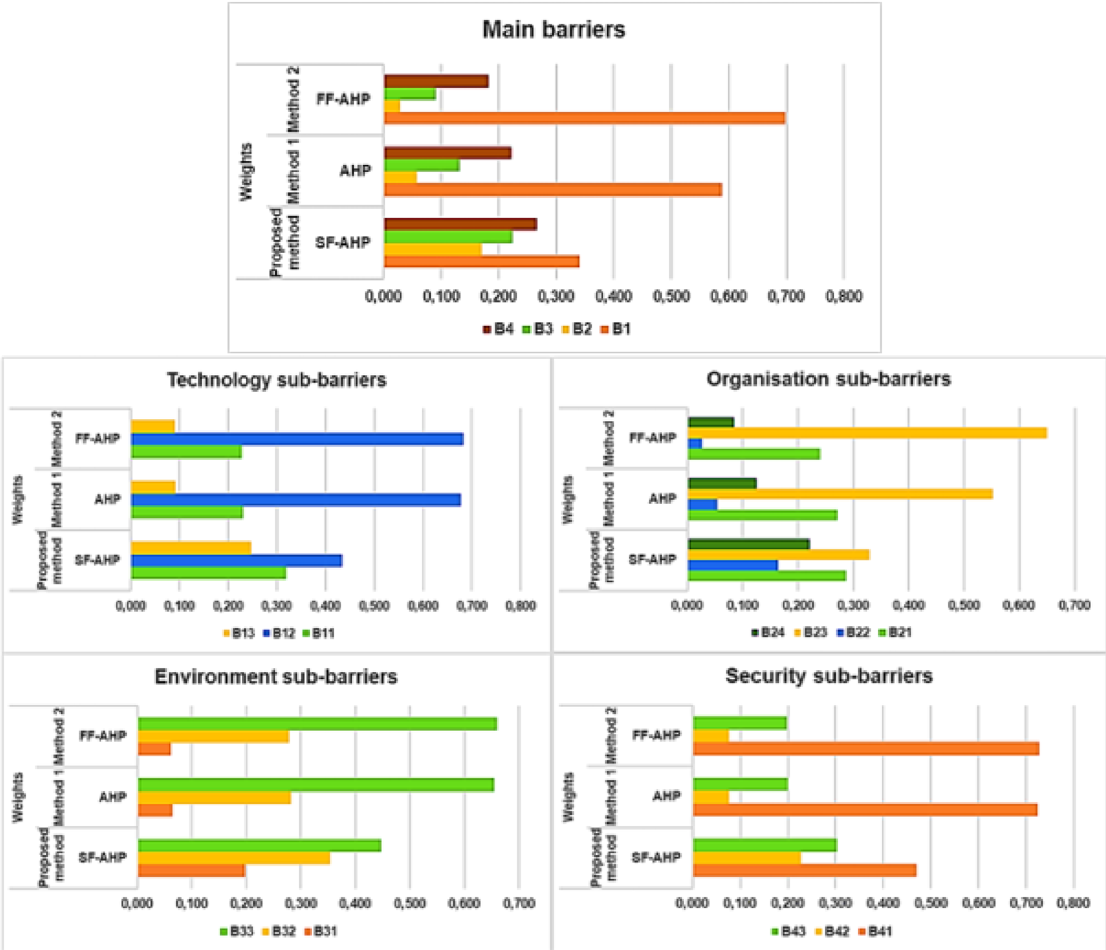

Figure 4. A graphical representation of the comparative analysis results

5. CONCLUSIONS

In the maritime logistics sector, transport operators and port stakeholders are at different phases of the digital transformation (DT) process (Tijan et al., 2021). While some ports, transport companies, etc. have achieved remarkable success in this regard, others have not reached sufficient effectiveness in fully implementing DT throughout the supply chain. Furthermore, the maritime industry is reluctant to assume the risk associated with the adoption of nascent technologies, and its traditionalist culture predisposes decision-makers towards a degree of conservatism (Zhou et al., 2020).

The motivation for this study is derived from the observation that the impediments to the maritime logistics sector's adoption of digital transformation have not been sufficiently evaluated and addressed through the application of diverse methodological approaches. In order to address this gaps, the present study seeks to identify and prioritize the potential barriers that may emerge during the digital transformation of maritime logistics operations. In order to achieve this objective, the author carried out an exhaustive review of the relevant literature.

This study contributes to the field in several ways, offering both theoretical and managerial implications for practitioners, policy makers and researchers involved in this area of research. Firstly, from theoretical point of view, this study identified and ranked four main barriers and 13 related sub-barriers to the adoption of DT in maritime logistics sector. The top five most concerned barriers are; “Conservatism” related to the Technology main barrier, “Information system insecurity” related to the Security main barrier, “Cost” related to the Technology main barrier, “Government/policy-makers support” related to the Environment barrier, and finally “Decreased cyber security levels” related to the Technology main barrier. The proposed approach employs the extended AHP methodology with spherical fuzzy sets (SFS), thus allowing decision makers more flexibility in assigning different values to the degrees of uncertainty in their judgements (degrees of membership, non-membership, and hesitancy degrees).

The main contributions of this study are as follows. First, a hierarchical structure model of the barriers to the adoption of DT in the maritime logistics sector. Secondly, a set of valid barriers to the implementation of digitalization in maritime logistics is proposed from the perspective of key stakeholders. Thirdly, this is the first study to utilize the AHP method based on SFS to evaluate the barriers in the digital transformation process in the maritime logistics sector. Fourth, to aggregate the judgment data of individual experts, a SWAM operator-based method is used to form an aggregate evaluation matrix. Fifth, the proposed approach will serve as a reference for experts and practitioners in the maritime logistics sector and provide crucial insights for the application of DT technologies. And comparative analysis is applied to verify the robustness and applicability of the proposed methodology.

The results of our study indicate that the digital transformation of the maritime logistics sector will be most effective when all stakeholders are encouraged to collaborate. This approach will lead to more efficient and effective operational processes within the sector. For future researches, the proposed method can be compared with different fuzzy set extensions (Pythagorean fuzzy set, picture fuzzy set) and different multi-criteria decision making methods.

Conflict of Interest
No potential conflict of interest was declared by the author.

Funding
Any specific grant has not been received from funding agencies in the public, commercial, or not-for-profit sectors.

Compliance with Ethical Standards
It was declared by the author that the tools and methods used in the study do not require the permission of the Ethics Committee.

Ethical Statement
It was declared by the author that scientific and ethical principles have been followed in this study and all the sources used have been properly cited.

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