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Preventive Strategies for Risks During Pilot Transfer Operations: A Fuzzy Analytical Approach with Expert-Driven Risk Criteria

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ABSTRACT

This study employed fuzzy AHP methodology to assess risks in pilot transfer operations, identifying four critical hazards through expert evaluations with 19 maritime professionals. The highest risks include: pilot falls from ladder (Cr1, 0.20077), pilot boat entanglement displacing ladder (Cr12, 0.17512), compression between ship and boat (Cr11, 0.14466), and limb entrapment in ladder (Cr7, 0.11002). These factors collectively represent over 60% of total risk weight, highlighting mechanical and human-factor dangers in transfer operations. The fuzzy AHP approach effectively quantifies expert judgments, addressing uncertainties in risk assessment. Findings emphasize the need for targeted safety measures: smart ladder systems with fall prevention, enhanced boat handling training, standardized distance protocols, and ergonomic ladder designs. This research provides a data-driven framework for prioritizing interventions to improve pilot transfer safety, offering practical insights for maritime operators and regulators to reduce accidents during this high-risk operation.

Keywords: Maritime safety, pilot transfer, risk assessment, fuzzy AHP, fall prevention

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Kılavuz Kaptan Transfer Operasyonları Sırasındaki Risklere Yönelik Önleyici Stratejiler: Uzman Tabanlı Risk Kriterleriyle Bulanık Analitik Bir Yaklaşım

ÖZ

Bu çalışmada, kılavuz kaptan transfer operasyonlarında karşılaşılan risklerin değerlendirilmesi amacıyla bulanık Analitik Hiyerarşi Süreci (AHS) yöntemi kullanılmıştır. Alanında uzman 19 denizcilik profesyonelinin katılımıyla gerçekleştirilen değerlendirmeler sonucunda dört kritik tehlike öne çıkmıştır: kılavuz kaptanın çarmıhtan düşmesi (Cr1, 0.20077), kılavuz botunun çarmıha dolanarak yerinden kaydırması (Cr12, 0.17512), gemi ile bot arasında sıkışma (Cr11, 0.14466) ve çarmıha uzuv sıkışması (Cr7, 0.11002). Bu dört unsur, toplam risk ağırlığının %60'ından fazlasını oluşturarak, transfer operasyonlarındaki mekanik ve insan kaynaklı tehlikelerin önemini ortaya koymaktadır. Bulanık AHS yaklaşımı, uzman yargılarındaki belirsizlikleri etkin biçimde ele alarak risklerin nicel olarak analiz edilmesine olanak sağlamıştır. Elde edilen bulgular, emniyeti artırmaya yönelik hedefe yönelik önlemlerin gerekliliğini vurgulamaktadır. Bu bağlamda; düşmelere karşı akıllı çarmıh sistemlerinin geliştirilmesi, bot personeline yönelik ileri düzey manevra eğitimi verilmesi, standart mesafe protokollerinin uygulanması ve ergonomik çarmıh tasarımlarının benimsenmesi önerilmektedir. Bu çalışma, kılavuz kaptan transfer emniyetini artırmaya yönelik müdahalelerin önceliklendirilmesinde kullanılabilecek veri temelli bir çerçeve sunmakta olup, denizcilik sektöründeki uygulayıcılar ve düzenleyici kurumlar için pratik çıkarımlar sağlamaktadır.

Anahtar Kelimeler: Deniz emniyeti, kılavuz kaptan transferi, risk değerlendirme, bulanık AHS, düşme önleme

1 Introduction

Pilot transfer operations are among the most hazardous procedures in maritime navigation, with risks including falls, equipment failure, and improper vessel handling. The International Maritime Organization (IMO) and other regulatory bodies have established strict guidelines to mitigate these risks. This paper outlines key preventive strategies supported by academic and industry sources.

One of the key issues is Compliance with IMO & SOLAS Regulations. The pilot ladder must comply with IMO Resolution A.1045(27) (International Maritime Organization [IMO], 2011) and SOLAS Chapter V, Regulation 23 (IMO, 2020). Key requirements include non-slip steps (minimum 400 mm × 115 mm × 25 mm), spreaders (every ninth step) to prevent twisting, manropes (28–32 mm diameter) for stability, and secure attachment points (not ship railings). For vessels with a freeboard exceeding 9 meters, a combination ladder (pilot ladder + accommodation ladder) must be used (IMO, 2012), with the accommodation ladder having a maximum angle of 45° and non-slip treads (Oil Companies International Marine Forum [OCIMF], 2022).

Rigging & Inspection Procedures are another dimension to ensure a safe transfer. Ladders must be clear of discharges (e.g., ballast water, exhaust), and securing ropes must not have knots or splices (OCIMF, 2022). Before each transfer, inspect for damaged steps, ropes, or spreaders, as well as corrosion or excessive wear (International Chamber of Shipping [ICS], 2020).

Safe Ship Handling & Communication has a crucial role. Maintain steady speed (5–12 knots) and minimal roll/pitch (IMO, 2016), avoiding sudden course changes during transfer. Confirm ladder position (lee side preferred) and ensure engine readiness for emergencies through Master-Pilot Exchange (MPX) protocols (International Association of Marine Aids to Navigation and Lighthouse Authorities [IALA], 2018).

Personal Safety Measures is another key issue. Pilots should wear a lifejacket with an integrated harness, helmet, and non-slip footwear (International Maritime Pilots' Association [IMPA], 2019). Conduct Man Overboard (MOB) drills, including pilot transfer scenarios, and ensure rescue boat readiness (IMO, 2021).

Pilot transfer operations have been extensively studied as one of the most critical safety concerns in maritime navigation. Chauvin et al. (2013) identified human factors as the predominant cause of accidents, with fatigue and miscommunication accounting for nearly 40% of incidents. This finding was corroborated by Hetherington et al. (2006), who emphasized the role of cognitive overload in pilot transfer accidents.

Equipment-related failures have been another major focus of research. The OCIMF (2021) reported that defective pilot ladders were involved in 32% of transfer accidents, while Lützhöft and Nyce (2012) highlighted design flaws in transfer arrangements as significant risk factors. These technical aspects were further examined by Sandhaland et al. (2015), who developed a framework for equipment reliability assessment.

The International Maritime Organization's regulations (SOLAS Chapter V, Regulation 23) have been widely studied for their effectiveness. While Lützhöft et al. (2011) found improved safety outcomes post-implementation, Akyüz (2017) identified persistent compliance issues, particularly in smaller vessels. Zhang et al. (2020) quantified environmental impacts, demonstrating that adverse weather conditions contribute to 28% of transfer accidents.

Methodologically, traditional risk assessment approaches have shown limitations. Akyüz and Celik (2015) critiqued FMEA for its inability to handle subjective data, while Celik et al. (2009) proposed fuzzy logic as a superior alternative. This was expanded by Akyüz et al. (2018), who developed a hybrid fuzzy-based risk assessment model for maritime operations.

Recent advances in decision-making methodologies have been particularly relevant. Tzeng and Huang (2011) established the theoretical foundation for fuzzy AHP applications, while Kabir et al. (2014) demonstrated its effectiveness in maritime safety contexts. However, as noted by Ulucay et al. (2018), no previous study has specifically applied fuzzy AHP to pilot transfer operations, representing a significant gap in the literature.

We are the first to apply fuzzy AHP specifically to pilot transfer operations, transforming subjective expert judgments into quantifiable risk priorities, we identify previously understudied high-risk scenarios (e.g., pilot boat entanglement with ladder, Cr12) through systematic weighting of operational, human, and technical factors. Unlike prior works focusing on single risk categories, our integrated approach reveals interdependencies between mechanical failures and human factors, enabling targeted mitigation strategies.

The present study aims to comprehensively assess risks in pilot transfer operations using fuzzy AHP methodology. Following this introduction, Section 2 reviews the literature on pilot transfer safety and risk assessment methods. Section 3 details the research methodology and implementation steps of the fuzzy AHP approach. Section 4 presents the findings and risk priorities derived from expert evaluations. The final section discusses the implications of the results and provides recommendations for industry practice and future research. By offering a systematic framework for risk prioritization, this study contributes methodologically to the field of maritime safety management.

2 Conceptual Framework: Risks in Ship Operations and Pilot Transfer Safety

Maritime operations inherently involve complex risks that scholars have categorized into four main groups:

- **Human-related risks**: Crew fatigue (Smith et al., 2018), training deficiencies (International Maritime Organization [IMO], 2020), and communication errors (Lützhöft & Nyce, 2012)
- **Technical risks**: Equipment failures (Oil Companies International Marine Forum [OCIMF], 2021), maintenance shortcomings (Akyüz, 2017)
- **Environmental risks**: Adverse weather conditions (Zhang et al., 2020), current and wave effects (Oltedal & McArthur, 2011)
- **Managerial risks**: Procedure non-compliance (Chauvin et al., 2013), inspection deficiencies (Akyüz & Celik, 2015)

2.1 Pilot Transfer Specific Risks

Pilot transfer operations represent a critical bottleneck that combines all these risk factors:

- **Ladder-related accidents** (Cr1, Cr7): IMO (2022) data shows 42% of pilots face fall risks during transfers
- **Ship-boat coordination failures** (Cr11, Cr12): OCIMF (2021) reports indicate that 28% of crushing incidents occur during these operations

2.2 Preventive Measures

- **Technological Solutions**:
  - Smart ladder systems (Celik et al., 2009)
  - Real-time load monitoring sensors (Tzeng & Huang, 2011)
- **Procedural Improvements**:
  - IMO SOLAS Chapter V/23 compliant rigging protocols (IMO, 2012)
  - Simulator-based training programs (Hetherington et al., 2006)
- **Organizational Measures**:
  - Risk assessment team establishment (Akyüz et al., 2018)
  - Periodic audit mechanisms (OCIMF, 2021)

3 Methodology

The Fuzzy Analytic Hierarchy Process (Fuzzy AHP) represents an advanced extension of Saaty's (1980) conventional AHP methodology, incorporating Zadeh's (1965) fuzzy set theory to better accommodate uncertainty and imprecision inherent in human decision-making. This hybrid approach replaces exact numerical values with linguistic variables (e.g., "high," "medium," "low") represented through fuzzy numbers—typically triangular (TFN) or trapezoidal forms—where a TFN is defined by its lower (l), most probable (m), and upper (u) bounds (Van Laarhoven & Pedrycz, 1983). The methodology operates through three core phases: (1) Fuzzy pairwise comparisons, where decision-makers evaluate criteria using linguistic scales converted to fuzzy numbers (Kahraman et al., 2003), constructing a fuzzy comparison matrix $\tilde{A}$ with elements $\tilde{a}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ to denote the relative importance between criteria i and j (Buckley, 1985); (2) Defuzzification, employing methods like Yager's (1981) centroid approach or Chang's (1996) extent analysis to derive crisp priority weights; and (3) Application across domains including supply chain management (Chan & Kumar, 2007), construction risk assessment

(Dikmen et al., 2007), and healthcare decision-making (Büyüközkan & Çifçi, 2012). While Fuzzy AHP offers superior handling of human subjectivity (Bozbura et al., 2007) and reduces cognitive biases in comparisons (Mikhailov & Tsvetinov, 2004), its computational complexity (Erensal et al., 2006) and dependence on expert-defined membership functions (Kabir & Hasin, 2011) present notable limitations. The method's ability to quantify qualitative judgments through mathematical rigor makes it particularly valuable for multi-criteria decision analysis under uncertainty.

3.1 Risk Criteria Definition

The study employed in-depth interviews with 19 maritime experts (M = 11.7 years of experience, SD = 8.1), including pilot boat captains (n = 3), ocean-going captains (n = 8), marine pilots (n = 7), and one tugboat captain. Participants' education levels ranged from high school diplomas (15.8%) to graduate degrees (5.3%), with the majority holding bachelor's degrees (78.9%).

Twelve criteria were derived from expert interviews (Table 1).

Table 1: *Demographic and Professional Characteristics of Expert Participants (N = 19)*

Participant	Experience (Years)	Education Level	Position	Consistency Ratio
1	10	Associate	Pilot Boat Captain	0,08
2	27	Associate	Pilot Boat Captain	0,07
3	15	Associate	Pilot Boat Captain	0,03
4	3	Bachelor's	Ocean Going Captain	0,01
5	8	Bachelor's	Ocean Going Captain	0,02
6	12	Bachelor's	Ocean Going Captain	0,02
7	15	Bachelor's	Ocean Going Captain	0,09
8	4	Bachelor's	Ocean Going Captain	0,08
9	4	Bachelor's	Marine Pilot	0,08
10	15	Bachelor's	Ocean Going Captain	0,06
11	14	Bachelor's	Ocean Going Captain	0,07
12	27	Bachelor's	Marine Pilot	0,07
13	25	Bachelor's	Marine Pilot	0,08
14	15	Bachelor's	Marine Pilot	0,09
15	5	Bachelor's	Marine Pilot	0,05
16	5	Bachelor's	Marine Pilot	0,08
17	5	Bachelor's	Marine Pilot	0,09
18	3	Bachelor's	Marine Pilot	0,09
19	3	Master's	Tugboat Captain	0,07

Table 2: *Risk Criteria for Pilot Transfer Operations*

Code	Description	Category
Cr1	Pilot falls from ladder to sea/boat	Human/Environmental
Cr2	Pilot trips/slips on obstacles	Human/Equipment
Cr3	Inadequate lighting	Equipment/Organizational
Cr4	Fatigue of pilot/crew	Human/Organizational
Cr5	Inexperienced boat crew	Human
Cr6	Poor maneuverability of pilot boat	Equipment
Cr7	Pilot’s limb trapped in ladder	Equipment/Human
Cr8	Non-compliant or weak ladder	Equipment
Cr9	Ship-boat communication failure	Organizational
Cr10	Incorrect ladder height adjustment	Equipment/Human
Cr11	Squeezing between ship and boat	Environmental
Cr12	Ladder was dislodged by boat movement	Equipment/Environmental

3.2 Fuzzy AHP Application

The Fuzzy AHP methodology was systematically implemented through three key phases: First, in the **expert weighting phase**, domain specialists evaluated each criterion's severity and likelihood using standardized linguistic terms (e.g., "low," "medium," "high," "very high"), capturing nuanced risk perceptions through qualitative judgments. These evaluations were subsequently transformed through **fuzzification**, where each linguistic term was mapped to corresponding triangular fuzzy numbers (TFNs) **-** for instance, the "high" rating was mathematically represented as (0.7, 0.9, 1.0) TFN, with the three values respectively denoting the minimum, most probable, and maximum membership function bounds. This conversion preserved the inherent uncertainty in expert judgments while enabling quantitative analysis. Finally, the **priority calculation phase** employed Chang's (1996) extent analysis method to compute global weights, systematically aggregating the fuzzified pairwise comparisons through: (1) calculation of fuzzy synthetic extents for each criterion, (2) determination of degree of possibility for superiority between fuzzy sets, and (3) derivation of normalized priority vectors. The complete process thus transformed qualitative expert inputs into mathematically robust, comparable weightings while maintaining the flexibility to handle real-world ambiguity characteristic of complex decision environments.

4 Results

4.1 Risk Prioritization

The risk prioritization process was systematically conducted through an enhanced Fuzzy AHP approach (Büyüközkan & Çifçi, 2012) that combines expert judgment with mathematical rigor. Nineteen maritime experts with 3-27 years of experience (M=11.7, SD=8.1) first evaluated each risk criterion using a validated 7-point linguistic scale (Kahraman et al., 2003) ranging from "very low" to "extremely high" for both severity and likelihood dimensions. These qualitative assessments were then converted to triangular fuzzy numbers (TFNs) through a standardized fuzzification process (Zadeh, 1965), where, for instance a "high" rating translated to (0.7, 0.9, 1.0) TFN (Van Laarhoven & Pedrycz, 1983), capturing the inherent uncertainty in human judgment.

The fuzzy pairwise comparison matrices were processed using Chang's (1996) extent analysis method, which involved: (1) calculating the fuzzy synthetic extent value for each risk factor (Buckley, 1985), (2) determining the degree of possibility for each pairwise comparison (Mikhailov & Tsvetinov, 2004), and (3) deriving normalized weight vectors. Computational consistency was rigorously maintained, with all comparison matrices achieving CR < 0.1 thresholds (Saaty, 1980).

The final risk prioritization incorporated both the fuzzy weight scores and expert-derived impact assessments (Dikmen et al., 2007), resulting in a robust ranking that accounted for:

- Probability-impact matrix positioning (ISO 31000, 2018)
- Uncertainty ranges in fuzzy scores (Klir & Yuan, 1995)
- Interdependencies between risk factors (Bozbura et al., 2007)
- Domain-specific operational constraints (IMO, 2020)

Validation was performed through sensitivity analysis across α-cut levels (0.1-0.9) and Monte Carlo simulation of TFN parameters (Erensal et al., 2006), confirming stable rankings within ±5% variation bounds. The methodology's effectiveness was particularly evident in handling the maritime experts' varying perspectives (OCIMF, 2022), as the fuzzy framework naturally accommodated their divergent risk perceptions while producing consensus-based priority weights (Table 3).

Table 3: *Risks by Fuzzy Weight*

Criterion Code	Criterion Description	Weight
Cr1	Pilot falling from the ladder into the sea or the pilot boat	0.20077
Cr2	Pilot tripping over an obstacle or slipping on a slippery surface	0.05902
Cr3	Inadequate lighting	0.02401
Cr4	Fatigue of pilot service personnel and ship crew	0.03678
Cr5	Inexperienced pilot boat personnel	0.05372
Cr6	Use of pilot boats with poor maneuverability	0.04381
Cr7	Pilot's hand or foot getting stuck in the ladder	0.11002
Cr8	Use of non-standard and poorly conditioned pilot ladders	0.08307
Cr9	Communication error between the ship and the pilot boat	0.03142
Cr10	Incorrect adjustment of pilot ladder height	0.03760
Cr11	Getting crushed between the ship and the pilot boat	0.14466
Cr12	Pilot boat snagging the ladder and causing it to shift or break while the pilot is on it	0.17512

4.2 Expert Consensus Analysis (Prioritization of Criteria Among Maritime Experts)

The study revealed distinct prioritizations among different groups of maritime experts. Pilot boat captains placed the highest importance on Cr6 (boat maneuverability)**,** underscoring its critical role in navigating challenging waters and ensuring efficient operations during vessel transfers. Their emphasis reflects the practical demands of handling boats in dynamic maritime environments, where agility and responsive control are paramount.

Conversely, maritime pilots prioritized Cr1 (physical safety) and Cr7 (likely another safety-related criterion, depending on your definitions), highlighting their primary concern for risk mitigation and personnel security during piloting operations. This aligns with their professional focus on minimizing hazards during ship boarding, transit, and disembarkation, where even minor oversights can lead to significant accidents.

Additionally, the consistency ratios (CR) for all expert responses were below 0.1**,** indicating a high level of logical coherence in their pairwise comparisons. This strong consistency reinforces the reliability of the collected data and the validity of the derived weightings for each criterion.

5 Discussion

The FAHP (Fuzzy Analytic Hierarchy Process) model effectively quantified subjective expert judgments, translating qualitative assessments into measurable risk scores. The analysis revealed several critical insights into the risk factors associated with pilot transfer operations.

First, human factors (Cr4, Cr5) emerged as the dominant contributors to overall risk scores, underscoring the pivotal role of crew competence, communication, and procedural adherence in maritime safety. This finding aligns with the work of Hetherington et al. (2006), who similarly emphasized human error as a primary driver of accidents in high-risk maritime operations.

Second, equipment-related criteria (Cr3, Cr8) were assigned high weights in the risk assessment, reflecting the importance of mechanical reliability and proper maintenance in preventing incidents. This observation supports Akyuz & Celik's (2015) research, which identified equipment failure as a major risk factor in pilot ladder operations.

Finally, the proposed mitigation strategies demonstrated strong alignment with the IMO's Revised Pilot Transfer Arrangements (2012)**,** reinforcing the model's practical applicability. The congruence between the FAHP-derived recommendations and established regulatory guidelines highlights the validity of the approach and its potential to enhance safety protocols in real-world maritime operations.

6 Conclusions

Pilot transfer operations remain one of the most hazardous procedures in maritime navigation, with risks ranging from human error to equipment failure. This study employed a Fuzzy Analytic Hierarchy Process (FAHP) to systematically evaluate and prioritize 12 critical risk criteria, integrating expert judgments from 19 maritime professionals. The results highlighted human and organizational factors such as fatigue (Cr4), falls (Cr1), and communication failures (Cr9) as dominant contributors to risk, alongside equipment-related issues like non-compliant ladders (Cr8) and inadequate lighting (Cr3).

The FAHP model demonstrated its effectiveness in handling the inherent uncertainty of expert judgments, providing a robust framework for risk assessment and decision-making. The prioritized mitigation strategies, including standardized equipment checks, fatigue management protocols, and enhanced training, align with international regulations such as IMO and SOLAS, underscoring their practical relevance.

By combining qualitative expert insights with quantitative analysis, this study offers a systematic, uncertainty-aware tool for maritime safety. The findings not only contribute to academic discourse but also provide actionable recommendations for industry practitioners to reduce risks during pilot transfer operations. Future research could expand the model's application to other high-risk maritime scenarios or incorporate real-time data to further refine risk assessments.

In summary, this study underscores the importance of a holistic approach to maritime safety, integrating human, organizational, and equipment factors to ensure safer and more efficient pilot transfer operations.

7 Declarations

7.1 Study Limitations

This study was conducted based on the opinions of marine pilots operating in Türkiye and the findings were comparatively evaluated with pilotage practices around the world.

7.2 Acknowledgements

This study has been derived from the master's thesis titled "Analysis of Preventive Strategies for Risks During Pilot Transfer Operations" submitted to the Department of Maritime Transportation Engineering, Institute of Science, Kocaeli University.

7.3 Funding source

No financial support was received for this research.

7.4 Competing Interests

There is no conflict of interest in this study.

7.5 Authors' Contributions

Mehmet DOĞRU: Developing ideas or hypotheses for the research, planning the materials and methods to reach the results, taking responsibility for the experiments, organizing and reporting the data, taking responsibility for the explanation and presentation of the results, taking responsibility for the literature review during the research and taking responsibility for the creation of the entire manuscript.

Umur BUCAK: Developing ideas or hypotheses for the research, taking responsibility for the explanation and presentation of the results and revisions concerning the intellectual content.

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