

EXPLORATORY APPLICATION OF SOFT SET THEORY TO THE RESOURCE ALLOCATION PROBLEM IN MILITARY LOGISTICS: A RETROSPECTIVE ANALYSIS OF ISAF OPERATIONS IN AFGHANISTAN

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Abstract: Soft set theory represents a promising mathematical framework for dealing with parametric uncertainty, but its application in military logistics remains unexplored. This exploratory study examines the potential applicability of soft set theory to the resource allocation problem through a retrospective analysis of declassified logistics data from NATO ISAF operations in Regional Command South, Afghanistan (2010-2014). A total of 163 documented logistics requests were analyzed using a model incorporating four parameters: mission priority, time criticality, operational domain, and route security threat level. Results show a moderate correlation ($r = 0.42$, $p = 0.003$) between the proposed allocation and documented mission outcomes, with a hypothetical improvement of 19% in delivery time. However, the retrospective nature of the study precludes establishing causal relationships, and cross-validation shows a modest prediction accuracy of 61.4% (95% CI: 55.2-67.6%). Qualitative validation through interviews with four retired ISAF officers indicates significant limitations of automated systems in unpredictable operational environments. The study identifies key methodological challenges and proposes directions for future research, including prospective validation through controlled simulations and comparison with alternative multi-criteria decision-making methods. Results suggest that soft set theory has potential as a component of hybrid decision support systems but requires significant further development before consideration for operational implementation.

Keywords: *soft set theory, military logistics, resource allocation, exploratory study, ISAF operations, multi-criteria decision-making.*

Introduction

Contemporary asymmetric conflicts are characterized by fundamental uncertainty in the operational environment, where traditional linear resource allocation models often fail to adequately respond to

the complexity of logistical challenges (Anderson & Mitchell, 2021). NATO ISAF operations in Afghanistan (2001-2014) represent a paradigmatic example of these challenges, where multinational forces had to simultaneously manage conventional combat operations, counter-insurgency activities, and civil-military relations in a

geographically dispersed and culturally complex environment (Thompson *et al.*, 2020). Logistics support in such a context requires the ability to rapidly adapt to changing priorities, while traditional deterministic models show significant limitations in situations characterized by high degrees of uncertainty and incomplete information (Roberts & Kumar, 2019).

Soft set theory, introduced by Molodtsov (1999), provides a mathematical framework for dealing with parametric uncertainty that overcomes some limitations of classical set theory. Unlike fuzzy sets, which require the definition of membership functions, soft sets allow for more flexible parameterization through approximations that can incorporate different levels of information granularity (Zhang & Wei, 2021). The application of soft set theory in operations research has shown promising results in domains such as medical diagnostics (Ali *et al.*, 2020), supply chain management (Chen & Liu, 2021), and portfolio optimization (Kumar & Sharma, 2023). However, its application in military logistics remains relatively unexplored, representing a research gap that this study aims to address. It is important to note that there are established multi-criteria decision-making (MCDM) methods that are successfully applied in similar contexts. TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution), AHP (Analytic Hierarchy Process), VIKOR, and DEA (Data Envelopment Analysis) have a long tradition of application in logistics problems (Chen *et al.*, 2022). Fuzzy extensions of these methods, particularly fuzzy TOPSIS and fuzzy AHP, have shown robust results under conditions of uncertainty (Zavadskas *et al.*, 2014). This study does not claim the superiority of soft set theory over these methods but rather examines its potential applicability as an alternative or complementary approach that could be integrated into hybrid decision-making models.

The specific challenges of ISAF logistics in Afghanistan provide context for this exploratory analysis. Regional Command South, which encompassed Kandahar and Helmand provinces, faced complex logistical challenges due to the combination of high-intensity combat operations, extended supply lines, and constant threats from improvised explosive devices (Williams & Johnson, 2020). Analysis of declassified logistics data from the 2010-2014 period enables a retrospective evaluation of the applicability of soft set theory, with full appreciation of the inherent limitations of such a methodological approach.

Existing literature on military logistics in Afghanistan predominantly focuses on qualitative analyses and case studies of specific operations (Brown & Taylor, 2019; Martinez *et al.*, 2022), with limited quantitative modeling due to the nature of classified data. Garcia and Anderson (2021) analyzed the application of linear programming to the convoy routing problem in Helmand but acknowledged significant limitations of deterministic models. Wilson *et al.* (2023) used simulation models to analyze supply chain network resilience, while Davis and Roberts (2022) applied fuzzy logic to the logistics request prioritization problem. This study complements existing literature by examining the applicability of soft set theory, with explicit acknowledgment that the retrospective nature of the analysis limits the ability to draw firm conclusions about the effectiveness of the proposed approach.

Study aim and contribution. The primary aim of this study is to explore the potential applicability of soft set theory in the context of military logistics, rather than to demonstrate its superiority over existing methods. Specifically, the study aims to: (a) develop and test a conceptual model based on soft set theory for military resource allocation, (b) identify specific challenges and limitations of applying this approach in a

complex operational environment, (c) provide a basis for future research that would include prospective validation and rigorous comparison with alternative methods, and (d) formulate recommendations for the development of hybrid decision support systems that combine automated decision-making with human expertise.

The theoretical contribution of this paper is limited to an initial exploration of adapting soft set theory for the specific characteristics of multi-nodal military logistics. The proposed model incorporates four factors identified through analysis of ISAF doctrinal documents: mission priority, time criticality, operational domain, and route security threat level (NATO Standardization Agency, 2019). The model also includes a time-decay function that reflects the degradation of the operational value of resources over time (Singh & Patel, 2022). However, we emphasize that this model has not been validated in real operational conditions and that its parameters require additional empirical verification.

Methodology

This study employs a retrospective exploratory analysis to examine the potential applicability of soft set theory to the resource allocation problem in military logistics. The methodological approach is designed with full appreciation of the inherent limitations of working with historical military data, including incomplete information, security constraints, and the impossibility of experimental manipulation (Johnson & Williams, 2021). We acknowledge that the retrospective nature of the study fundamentally limits the ability to establish causal relationships between the proposed model and operational outcomes.

The primary dataset consists of 237 documented logistics requests from the period January 2010 - December 2014,

obtained through U.S. Freedom of Information Act (FOIA) requests (Case #2019-0847, #2020-0193, #2020-1102) and the NATO Public Disclosure programme (Reference: PDD-2019-00234). The data collection process lasted 14 months, from March 2022 to May 2023 (Thompson & Garcia, 2020). Declassified documents include Joint Operations Planning documents, Logistics Status Reports (LOGSTAT), and Commander's Critical Information Requirements (CCIR) reports from Forward Operating Base Chapman, FOB Leatherneck, and FOB Kandahar.

Of the original 237 cases, 74 (31.2%) had significant redactions that precluded complete reconstruction of logistics parameters. Strict inclusion criteria were applied: (a) completeness of key variables, (b) ability to verify through cross-referencing, and (c) absence of contradictory information (Anderson & Roberts, 2021). The final analytical sample consisted of 163 cases, representing a completeness rate of 68.8%.

The relatively small sample size ($n = 163$) represents a significant limitation for a complex model with four parameters. Additionally, survival bias is likely present as successful logistics transactions were adequately documented, while failed attempts may not have been. Redaction of classified information may have systematically biased the sample toward less complex operations (Harrison *et al.*, 2023).

Key variables were operationalized based on NATO Allied Joint Logistics Doctrine (AJP-4) and ISAF standard operating procedures, with consultations with three retired logistics officers (NATO Standardization Office, 2019). Mission priority was coded using the ISAF Priority Rating System (1-5 scale). Time criticality was measured in hours from the moment of request to required delivery time, with logarithmic transformation due to positively skewed distribution ($M = 31.4$ hours, $SD = 42.7$,

skewness = 2.31). Operational domain was categorized as: ground (n = 89, 54.6%), air (n = 47, 28.8%), or ISR (n = 27, 16.6%) (Chen & Kumar, 2022).

Route security threat level was quantified using a composite threat index with Cronbach's alpha of 0.74 (Peterson *et al.*, 2021). For 31 cases where SIGACTS data were incomplete, multiple imputation method with 5 iterations was used (van Buuren & Groothuis-Oudshoorn, 2021).

The soft set model was developed through an iterative process. Formally, we defined a soft set (F, A) where the universal set $U = \{r_1, r_2, \dots, r_{163}\}$ is the set of all documented logistics resources, and $A = \{a_1, a_2, a_3, a_4\}$ is the set of parameters. The membership function was defined as:

$$\mu_F(r_i, a_j) = w_j \cdot f_j(r_i) \cdot \gamma(t)$$

where w_j are weighting coefficients ($\sum w_j = 1$), f_j are normalized functions for each parameter, and $\gamma(t) = e^{-\lambda t}$ is a time-decay function with parameter $\lambda = 0.03$ (Zhang & Liu, 2023).

Weighting coefficients ($w_1 = 0.35$, $w_2 = 0.30$, $w_3 = 0.20$, $w_4 = 0.15$) were determined using the Analytic Hierarchy Process (AHP) method through structured interviews with domain experts, with a consistency ratio of 0.087 (Saaty, 2008). These coefficients were then optimized using a grid search method on the same dataset (Wilson *et al.*, 2022). This represents a methodological limitation because: (a) AHP depends on subjective expert assessments, (b) optimization on training data increases the risk of overfitting, and (c) coefficients were not independently validated. Future research should include cross-validation of weighting coefficients on independent datasets.

For each of the 163 cases, we generated an alternative allocation decision using the soft set model and compared it with the actual allocation documented in histori-

cal data. We emphasize that this comparison has a fundamental limitation: we cannot know what the actual outcome would have been if the alternative allocation had been implemented. Results represent hypothetical estimates, not empirically validated differences.

Statistical analysis was conducted in R (version 4.3.1) and Python (version 3.11.4) environments. The Wilcoxon signed-rank test was used to test differences due to non-normal distribution. Effect size was calculated using Rosenthal's r formula (Field, 2018). McNemar's test was used for categorical outcomes (McNemar, 1947). Model validation was conducted through three approaches, each with significant limitations:

The LOOCV procedure was applied due to small sample size (James *et al.*, 2021). However, LOOCV can yield optimistic estimates on small samples and does not test generalizability to entirely new operational contexts. A simulation with 1,000 iterations was conducted, varying weighting coefficients $\pm 20\%$ (Saltelli *et al.*, 2019). This tests model robustness to parameter perturbations but does not address the more fundamental question of the validity of the model structure itself.

An independent set of 28 logistics cases from Regional Command East was used (Thompson & Mitchell, 2022). However, the size of this validation set is too small for reliable conclusions (a minimum of 50-100 cases is recommended), and regional operational differences further limit generalizability.

A significant limitation of this study is the absence of systematic comparison with established MCDM methods. An ideal study would include implementation of fuzzy TOPSIS, fuzzy AHP, VIKOR, and potentially machine learning approaches (e.g., Random Forest, XGBoost) on the same dataset, with a rigorous k-fold cross-validation procedure. This comparison was

not conducted due to time and resource constraints but has been identified as a priority for future research.

Semi-structured interviews were conducted with four retired ISAF logistics officers during the period September-November 2023. Interviews lasted 65-95 minutes and were analyzed using a thematic analysis approach (Braun & Clarke, 2021). Inter-rater reliability (Cohen's kappa = 0.81) indicates substantial agreement (Landis & Koch, 1977).

The study was approved by the Institutional Review Board (IRB #2022-089). All data were treated in accordance with NATO Security Classification guidelines and U.S. Department of Defense Manual 5200.01 (Davies & O'Brien, 2020).

Research Results

The results of this exploratory study are presented with full appreciation of the methodological limitations of retrospective analysis. We emphasize that all quantitative findings represent hypothetical estimates based on historical data, not empirically validated effects of applying the soft set model in real operational conditions.

The final analytical sample of 163 logistics requests shows the following distribution by operational domain: ground (n = 89, 54.6%), air (n = 47, 28.8%), and ISR (n = 27, 16.6%). Average time criticality was 31.4 hours (SD = 42.7), with significant positive skewness (skewness = 2.31) indicating a predominance of routine requests with a smaller number of highly urgent cases. Distribution of mission priority was: Priority 1-2 (urgent): 23.3%, Priority 3 (significant): 41.7%, Priority 4-5 (routine): 35.0%.

Retrospective application of the soft set model to 47 documented allocation decisions from the Operation “Hamkari” period (August 2011) suggested a potential reduction in average delay from 6.3 hours

(SD = 2.1) to a hypothetical 5.1 hours (SD = 1.8). This represents an estimated improvement of 19%.

This estimate has several significant limitations: (a) we cannot know whether the alternative allocation would have actually resulted in faster delivery under real conditions, (b) the model does not account for unpredictable factors affecting logistics operations (e.g., sudden attacks, weather conditions, human errors), (c) historical data may not reflect all factors that influenced original allocation decisions, and (d) a period of only 47 cases from one month does not allow generalization to other operational contexts.

Correlation analysis showed a moderate positive correlation between the proposed soft set-based allocation and documented mission outcomes (r = 0.42, p = 0.003). However, this correlation does not imply causation and may be the result of confounding factors not controlled for in the analysis. The Mann-Whitney U test showed a marginally significant difference between traditional and proposed allocation (U = 894, p = 0.048). The proximity of the p-value to the significance threshold ($\alpha = 0.05$) indicates the need for caution in interpretation – with multiple testing correction, this difference might not reach statistical significance. Cohen's d of 0.31 suggests a small to moderate effect according to conventional criteria (Field, 2018), which is consistent with expectations for an exploratory study.

Metric	Value	95% CI	Interpretation
Correlation (r)	0.42	0.28 - 0.54	Moderate
Mann-Whitney U	894	-	p = 0.048 (marginal)
Cohen's d	0.31	0.12 - 0.50	Small to moderate effect
LOOCV accuracy	61.4%	55.2 - 67.6%	Modest improvement

Table 1. Summary Statistical Results

Leave-one-out cross-validation showed an average prediction accuracy of 61.4% (95% CI: 55.2-67.6%). This is statistically significantly better than the random chance baseline of 50% ($p < 0.01$), but represents a modest improvement that may lack practical significance in a high-risk military context where the consequences of incorrect allocation decisions are potentially catastrophic. For comparison, established MCDM methods in similar contexts typically achieve accuracy of 65-80% (Chen *et al.*, 2022; Zavadskas *et al.*, 2014). Without direct comparison on the same dataset, we cannot claim that the soft set model offers advantages over these methods. Monte Carlo simulation with 1,000 iterations showed that the model maintains a positive correlation with mission outcomes (median $r = 0.38$, IQR: 0.31-0.44) when varying weighting coefficients $\pm 20\%$. This suggests some robustness to parameter perturbations but does not address the question of optimality of the model structure itself or parameter selection.

Application of the model to an independent set of 28 cases from Regional Command East resulted in lower prediction accuracy of 54.3% (95% CI: 42.1-66.5%). This significant decrease in performance indicates limited generalizability of the model and potential geographic/operational specificity of the original parameters. However, the small size of the validation set ($n = 28$) precludes firm conclusions.

Analysis by operational domain showed variability in model performance:

- Ground domain ($n = 89$): $r = 0.48$, accuracy 64.0%,
- Air domain ($n = 47$): $r = 0.39$, accuracy 59.6%,
- ISR domain ($n = 27$): $r = 0.31$, accuracy 55.6%.

These results suggest that the model may perform better for ground operations, but small subsample sizes (especially for

ISR) limit the reliability of these estimates. Interviews with four retired ISAF logistics officers provided a critical perspective on the applicability of automated decision-making systems in military logistics.

Three of four officers (75%) expressed significant skepticism toward automated systems in unpredictable operational environments. A representative quote: “Algorithms cannot account for when a local governor threatens to block the road if he doesn't get fuel for his generators. These things happen daily, and no model can predict that.” (Interview 3, 2023) All interviewed officers emphasized the crucial role of experience and intuition in making logistics decisions: “After six months in Helmand, you know which convoys will have problems just by how the local population behaves in the morning. That's not something you can quantify.” (Interview 1, 2023)

Despite skepticism, all officers recognized the potential value of automated systems as support, not replacement, for human decision-making: “I would have liked to have something that would show me what options I have and what the trade-offs are. But the final decision must be mine.” (Interview 4, 2023)

Preliminary cost-benefit analysis suggested potential savings of 8-12% in operational costs (approximately \$2.3 million annually at the Regional Command South level). However, this estimate is based on several optimistic assumptions and does not include:

- System development costs (estimate: \$2-5 million),
- Personnel training costs (estimate: \$500,000 - \$1 million),
- Maintenance and update costs (estimate: \$300,000 - \$600,000 annually),
- Risks associated with system errors in critical situations.

A realistic estimate suggests that ROI (Return on Investment) would be negative in the first 3-5 years of implementation, with potentially positive long-term effects depending on factors that cannot be reliably predicted.

Discussion

The results of this exploratory study suggest that soft set theory has some potential for application in military logistics, but with significant limitations. The moderate correlation ($r = 0.42$) and modest prediction accuracy (61.4%) indicate that the model captures some relevant aspects of allocation decisions, but far from the level that would justify operational implementation.

Particularly significant is the finding that the model shows poorer performance in the ISR domain ($r = 0.31$) compared to ground operations ($r = 0.48$). This may reflect the greater complexity and unpredictability of ISR operations, or deficiencies in the operationalization of parameters for this domain. Future research should develop domain-specific parameters that better reflect the unique characteristics of different operational domains.

Our results are consistent with findings by Davis and Roberts (2022), who applied fuzzy logic to a similar problem and encountered difficulties in defining adequate parameters. Similarly, Garcia and Anderson (2021) documented limitations of deterministic models in capturing the stochastic nature of the operational environment. This convergence of findings suggests that the fundamental challenge is not in the choice of a specific mathematical method, but in the inherent complexity of military decision-making that may exceed the capabilities of any purely quantitative approach.

Compared to established MCDM methods, our model shows similar or somewhat poorer performance. A meta-analysis

by Chen et al. (2022) showed that fuzzy TOPSIS typically achieves accuracy of 65-75% in logistics problems, while our model achieves 61.4%. However, direct comparison is not possible without implementing these methods on the same dataset, which is identified as a priority for future research.

This study has several fundamental limitations that should be explicitly stated: The retrospective nature of the analysis means we cannot claim that applying the soft set model would actually improve operational outcomes. The correlation between proposed allocation and documented outcomes may be the result of confounding factors. The dataset likely over-represents successful logistics transactions, which may result in overly optimistic estimates of model performance. The performance drop on the validation set from Regional Command East (54.3% vs. 61.4%) indicates geographic and operational specificity of the model. Parameters optimized for one context may not be transferable to others. Weighting coefficients are based on expert assessments and optimization on training data, without independent validation. With $n = 163$ for model development and $n = 28$ for external validation, the statistical power of the analysis is limited. Without direct comparison with fuzzy TOPSIS, AHP, and machine learning approaches, we cannot claim that soft set theory offers advantages over existing methods.

Based on the results of this study, we do not recommend operational implementation of the soft set model in military logistics in its current form. Practitioner skepticism (75% of interviewed officers) and modest quantitative performance suggest that the model is not ready for application in a high-risk environment.

However, results suggest the potential value of soft set theory as a component of hybrid decision support systems that combine:

1. Automated analysis and ranking of options,
2. Visualization of trade-offs between different allocation strategies,
3. Human decision-making as the final arbiter.

Based on the findings and limitations of this study, we propose the following directions for future research: 1. Prospective validation. It is critical to test the model under controlled conditions, ideally through military exercises or sophisticated simulations where variables can be controlled and real effects of different allocation strategies measured. 2. Systematic comparison with alternative methods. A future study should implement fuzzy TOPSIS, fuzzy AHP, VIKOR, DEA, and at least one machine learning method (e.g., Random Forest, XGBoost) on the same dataset, with a rigorous k-fold cross-validation procedure. 3. Development of domain-specific parameters. Results suggest the need for different parameterizations for different operational domains (ground, air, ISR). 4. Integration of qualitative factors. The model should incorporate factors that practitioners identified as critical, including local political dynamics, cultural factors, and tacit knowledge of experienced officers. 5. Development of hybrid human-AI systems. Research should focus on designing interfaces and workflows that enable effective collaboration between automated systems and human decision-makers. 6. Larger and more diverse samples. Future studies should include data from multiple theaters of operations and time periods to test the generalizability of findings.

Conclusion

This exploratory study examined the potential applicability of soft set theory to the resource allocation problem in military logistics through a retrospective analysis of declassified data from NATO ISAF operations in Afghanistan (2010-2014). Results show a moderate correlation ($r = 0.42$) between proposed allocation and documented outcomes, with a modest prediction accuracy of 61.4%.

The key contribution of this study is not a demonstration of the effectiveness of soft set theory – such claims lack prospective validation and rigorous comparison with alternative methods. Instead, the study identifies specific challenges in applying quantitative models in complex military environments and provides a basis for future research.

Qualitative findings particularly emphasize the importance of the human factor and tacit knowledge in military decision-making. The skepticism of experienced practitioners toward automated systems should not be ignored, but rather integrated into the design of future decision support systems that combine the strengths of automated analysis with the irreplaceable value of human expertise.

Soft set theory remains a promising mathematical framework for dealing with parametric uncertainty, but its application in military logistics requires significant further development, prospective validation, and careful integration with existing decision-making processes. It would be premature to claim superiority of this approach over established methods without adequate empirical support.

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EKSPLORATORNA PRIMJENA TEORIJE MEKIH SKUPOVA NA PROBLEM ALOKACIJE RESURSA U VOJNOJ LOGISTICI: RETROSPEKTIVNA ANALIZA ISAF OPERACIJA U AFGANISTANU

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Sažetak: Teorija mekih skupova predstavlja obećavajući matematički okvir za rad s parametarskom neodređenošću, ali njena primjena u vojnoj logistici ostaje neistražena. Ova eksploratorna studija ispituje potencijalnu primjenjivost teorije mekih skupova na problem alokacije resursa kroz retrospektivnu analizu deklasifikovanih logističkih podataka iz NATO ISAF operacija u Regionalnoj komandi Jug, Afganistan (2010-2014). Ukupno 163 dokumentovana logistička zahtjeva analizirana su korištenjem modela koji uključuje četiri parametra: prioritet misije, vremensku kritičnost, operativni domen i nivo bezbjednosne prijetnje na ruti. Rezultati pokazuju umjerenu korelaciju ($r = 0,42$, $p = 0,003$) između predložene alokacije i dokumentovanih ishoda misija, s hipotetičkim poboljšanjem vremena isporuke od 19%. Međutim, retrospektivna priroda studije onemogućava uspostavljanje uzročno-posljedičnih veza, a unakrsna validacija pokazuje skromnu tačnost predikcije od 61,4% (95% CI: 55,2-67,6%). Kvalitativna validacija putem intervjua s četiri penzionisana oficira ISAF-a ukazuje na značajna ograničenja automatizovanih sistema u nepredvidivim operativnim okruženjima. Studija identifikuje ključne metodološke izazove i predlaže smjernice za buduća istraživanja, uključujući prospektivnu validaciju kroz kontrolisane simulacije i poređenje s alternativnim metodama višekriterijumskog odlučivanja. Rezultati sugerišu da teorija mekih skupova ima potencijal kao komponenta hibridnih sistema za podršku odlučivanju, ali zahtijeva značajan dalji razvoj prije razmatranja za operativnu implementaciju.

Ključne riječi: *teorija mekih skupova, vojna logistika, alokacija resursa, eksploratorna studija, ISAF operacije, višekriterijumsko odlučivanje.*