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A Decision-Support Framework for Supply Chain Cooperation under Asymmetric Information: Integrating AHP and Repeated Game Theory for Punishment Mechanism Design

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ABSTRACT

Variations in knowledge among partners within a supply chain can sometimes lead to untrustworthy behaviour, undermining sustained collaboration. This study introduces a multi-criteria framework incorporating the Analytic Hierarchy Process (AHP) to develop robust punishment mechanisms in repeated game contexts, aiming to preserve cooperation when one participant possesses less information than the other. The framework conceptualises supply chains as repeated games and evaluates a range of punitive strategies with respect to their economic outcomes, associated risks, enforceability, and fairness. By employing AHP, these evaluation criteria are systematically structured and weighted, ensuring that the selected policies effectively deter opportunistic behaviour while retaining overall benefits. To address imperfect information, the model explicitly incorporates information asymmetry when analysing firm strategies. The practical applicability of this approach is demonstrated through numerical simulations and a real-world case study, highlighting improvements in supply chain stability, collective profitability, and trust among partners. Results suggest that integrating multi-criteria decision-making with game-theoretic punishment designs enables managers to mitigate risks and foster cooperative behaviour across the supply chain. Consequently, this methodology offers an enhanced tool for supply chain management and decision sciences, providing a structured, data-driven basis for aligning diverse objectives within complex organisational networks. By combining insights from repeated games with a rigorous analytical framework, the proposed approach supports more informed managerial and engineering decisions for the formulation of joint strategies.

1. Introduction

In today's increasingly interconnected global business environment, the success of organizations largely depends on effective collaboration within supply chains. Companies rely on external partners to achieve cost reductions, improved service, innovation, and responsiveness to market demands [5]. Beyond contractual agreements, successful collaboration requires trust, integrity, and

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a shared commitment among all parties [4]. Despite the potential for synergy, supply chain relationships frequently face difficulties due to conflicting interests, differing strategies, and, most critically, asymmetric information [19]. Uneven data sharing can foster opportunistic behaviour, undermining trust and cooperation [25]. Sustained cooperation is particularly vital over the long term, as stable interactions are necessary for high performance across the supply chain [12].

Scholars frequently employ repeated game theory to model and regulate strategic interactions under uncertainty [11]. In this framework, firms are represented as decision-makers whose actions over multiple periods influence future behaviour [16]. The anticipation of future rewards or sanctions acts as a mechanism to encourage compliance, even in the absence of formal enforcement measures [32]. The effectiveness of repeated games in sustaining cooperation depends on the credibility and clarity of the punishment threats [23]. Implementing these mechanisms in practical contexts is challenging due to difficulties in detecting defections, delays in enforcement, diverse organisational priorities, and incomplete information [31]. Information asymmetry further complicates assessment, as it may be unclear whether breaches of trust are intentional or arise from miscommunication, hindering equitable enforcement [9].

Consequently, decision-makers must evaluate punishment policies against multiple criteria, including economic impact, likelihood of occurrence, ease of enforcement, and perceived fairness [14]. Excessively harsh penalties risk provoking conflict and damaging relationships Safarzadeh et al. [27], whereas overly lenient approaches may permit continued opportunistic behaviour [28]. In complex supply chains involving numerous heterogeneous actors, nuanced judgement and contextual understanding are essential [13]. Given the dynamic nature of supply networks, punishment frameworks must also remain adaptable to evolving conditions [2]. Comprehensive evaluation should integrate multiple perspectives to identify mechanisms that are effective, feasible, and contextually appropriate [7].

This research presents a multi-criteria framework that combines the AHP with repeated game theory to design suitable punishment strategies for supply chains characterised by information asymmetry. The method models supply chain interactions as repeated games and apply AHP to prioritise and rank potential punitive strategies according to key criteria, including economic outcomes, risk exposure, enforceability, and fairness. By integrating expert knowledge and empirical data, the framework allows managers to select punishment mechanisms that are both effective and aligned with organisational objectives. Furthermore, the model incorporates the influence of information asymmetry on strategic decisions and outcomes. Validation through numerical simulations and real-world case studies demonstrates that this approach enhances supply chain stability, promotes joint profitability, and strengthens inter-firm trust. By uniting these two approaches, the framework provides a robust decision-support tool for managing the complexities of modern supply chains in a structured, evidence-based manner.

The primary aim of this study is to develop and validate a framework that supports the selection of appropriate punishment strategies for repeated supply chain interactions, particularly under conditions of unequal information access. By integrating AHP with repeated game theory, the framework provides managers with a systematic means to assess the economic efficiency, risk implications, enforceability, and perceived fairness of various punitive measures. Ultimately, the framework seeks to reinforce long-term collaboration, deter opportunistic behaviour, enhance supply chain resilience, and cultivate trust across multiple organisational partners.

2. Related Works

The literature presents a wide variety of strategies and approaches designed to enhance collaboration among SC partners. These methods offer structured mechanisms to promote cooperative behaviour; however, they generally assume that all participants have access to the same information and seldom account for fairness or enforceability. While such approaches may improve trust and transparency, their implementation is frequently costly or computationally intensive. Although MCDM tools such as AHP and TOPSIS have been employed in partner assessment and risk management, their application to strategic decision-making within SCs remains limited. As illustrated in Table 1, there is currently no integrated methodology that combines repeated games, multiple criteria, and genuine asymmetric information to formulate practical, validated punishment frameworks suitable for dynamic SC environments.

Table 1:
Comparison of Existing Game-Theoretic and Decision-Making Approaches for Supply Chain Cooperation

Author(s)	Techniques Involved	Advantages	Disadvantages
Zhou et al. [33]	Evolutionary game in construction SC finance	Captures co-creation dynamics and evolving partner roles	Sector-specific; limited applicability beyond construction
Zhang et al. [32]	Evolutionary game for LNG trade cooperation	Analyses coordination in shipping and trading under energy constraints	Restricted to LNG context; low generalizability
Fan et al. [8]	Opinion dynamics with probabilistic linguistic uncertainty	Enhances group decision-making under ambiguous information	Not focused on SCs or game-theoretic punishment mechanisms
Feng et al. [10]	Dynamic evolutionary game for green building materials	Encourages sustainable strategies and stabilises market behaviour	Confined to low-carbon building sector; limited broader applicability
Hashemi et al. [15]	Cooperative game integrated with genetic algorithm	Improves land valuation by fostering cooperative behaviour	Domain-specific to agriculture; does not address repeated interactions or enforcement mechanisms

Zhou et al. [33] employed an evolutionary game analysis to examine value co-creation within construction SC finance. Their model captures the relationships among stakeholders and demonstrates how financial mechanisms shape collaborative behaviour throughout the project lifecycle. The study emphasises that successful cooperation in construction projects, which involve substantial investments, relies on aligning incentives and financial arrangements. However, while effective in construction contexts, the model lacks generalisability to other SC domains. Similarly, Zhang et al. [32] applied an evolutionary game framework to explore trading and shipping cooperation in the LNG import SC amid global energy shortages. The model illustrates how different SC actors respond to energy supply constraints and market fluctuations, providing insights into sustaining collaboration under resource limitations. Nevertheless, the model's design is specific to the LNG sector, limiting its broader applicability to other SC contexts.

Fan et al. [8] developed an opinion dynamics model utilising probabilistic uncertain linguistic information to enhance group decision-making. By addressing uncertainty in language, managers can more accurately express preferences, improving collective decisions in ambiguous scenarios. Despite these advantages, the study is not grounded in SC modelling or game-based punishment strategies and primarily contributes to decision theory rather than cooperative SC management. Feng et al. [10] proposed a dynamic evolutionary game model focused on promoting low-carbon building materials within the green construction market. The framework examines the influence of regulatory policies and market forces on stakeholder behaviour over time, encouraging stable and sustainable strategies. Although it offers valuable perspectives on SC sustainability, it primarily addresses environmental policy implementation and does not integrate multi-criteria evaluation or enforcement mechanisms necessary for broader SC collaboration.

Hashemi et al. [15] combined cooperative game theory with genetic algorithm optimisation to enhance agricultural land valuation in consolidation projects. Their hybrid model improves fairness and cooperation among landowners and planners, refining allocation processes. Despite its innovation, the approach is context-specific to agriculture and does not consider repeated interactions or punishment mechanisms relevant to strategic SC behaviour. Existing studies thus exhibit several limitations, including industry-specific focus, partial consideration of multi-criteria decision-making, minimal treatment of information asymmetry, and limited modelling of enforcement and fairness in cooperative strategies. To address these gaps, our proposed framework integrates repeated game theory with robust MCDM modelling. Unlike prior work, which often assumes symmetric information or concentrates on a single sector, this framework explicitly incorporates asymmetric information prevalent in SCs and evaluates punishment mechanisms across multiple dimensions, including economic performance, risk, enforceability, and fairness.

By leveraging AHP to systematically rank criteria, the methodology provides a rigorous tool for designing credible punishment strategies that sustain long-term cooperation in complex and uncertain SC environments. It extends applicability across industries while simultaneously supporting balanced decision-making across technical, economic, and human resource considerations. The framework demonstrates how actors with unequal knowledge can interact over repeated periods, enabling the development of deterrent mechanisms to prevent opportunistic behaviour. By unifying previously separate considerations—information asymmetry, multi-criteria evaluation, enforcement, and fairness—into a single approach, the framework promotes equitable, resilient, and enduring SC collaboration.

In summary, prior research offers various game-theoretic and decision-based approaches to enhance SC cooperation, including evolutionary games in construction finance and LNG trading, opinion dynamics in group decision-making, and cooperative game–genetic algorithm hybrids in agriculture. While informative, these studies remain largely sector-specific, assume symmetric information, and rarely integrate MCDM evaluation or enforcement mechanisms. This paper advances the literature by presenting a unified framework that combines repeated game theory, asymmetric information modelling, and AHP. By prioritising economic performance, risk, enforceability, and fairness, the framework facilitates the creation of credible, adaptive punishment strategies that maintain long-term collaboration across diverse SC networks, thereby strengthening data-driven decision-making in complex, information-intensive SC environments.

3. AHP-Based Punishment Model for Supply Chains

The study proposes a multi-stage system designed to support SCs facing information asymmetry in fostering cooperation and trust. The initial stage conceptualises the SC as a repeated game, encouraging firms to maintain collaboration by anticipating the consequences of their recurring decisions. Overall payoffs for each participant are quantified using a discounted utility function, which emphasises the value of engagement within an industry alliance. During this phase, various types of sanctions are formulated, including tit-for-tat, fixed-duration penalties, and grim-trigger strategies. These punishment mechanisms are intended to deter opportunistic behaviour and reinforce confidence among partners. Decision-makers can select the most appropriate response based on the severity and reversibility of any defection. The operational flow of the proposed methodology is illustrated in Figure 1.

At this stage, an MCDM approach grounded in AHP is employed to prioritise and structure the selection of punishment strategies. A hierarchical framework is constructed, using economic performance, risk probability, enforceability, and fairness as primary criteria. Each alternative is compared with others to derive normalised weights through eigenvalue calculations, which are then applied to rank the strategies systematically. In the final phase, the framework incorporates mechanisms to address uncertainty, utilising probabilistic assessments, trust metrics, and adaptive thresholds tailored to specific contexts. These features enable differentiation between deliberate violations and inadvertent errors, ensuring that all punishment decisions are objective and data-driven. By integrating repeated game theory, AHP-based decision-making, and detailed treatment of asymmetric information, the model offers a practical and novel solution to enhance SC reliability, joint benefits, and strategic alignment under complex and uncertain conditions.

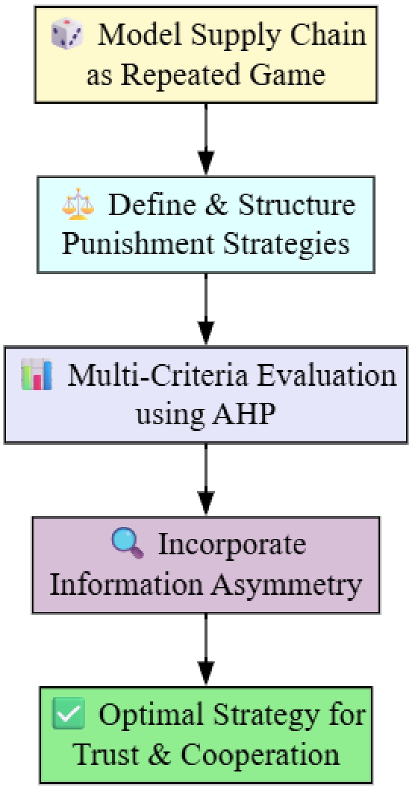

Fig.1: Proposed Flow Diagram

3.1 Modelling the Supply Chain as a Repeated Game

The initial step involves conceptualising the SC as a repeated game, where firms engage collaboratively over multiple periods rather than in a single interaction. In this framework, each SC participant is treated as a rational decision-maker, whose choices depend both on current circumstances and anticipated future outcomes. This modelling approach highlights that firms operating in such markets rely on long-term relationships and established trust to guide their behaviour [17]. By framing interactions as a repeated game, the model demonstrates how the use of rewards and punishments promotes cooperation and discourages opportunistic actions, particularly under conditions of asymmetric information [21]. Sustained cooperation arises from the participants' preference to avoid future penalties by adhering to collaborative strategies. The payoff U_i to firm i for firm i is shown in equation (1).

$$U_I = \sum_{t=0}^{\infty} \delta^t u_i(a_1^t, a_2^t, \dots, a_n^t) \quad (1)$$

Here, $u_i(a_1^t, a_2^t, \dots, a_n^t)$ is the reward for firm i at period t from acting based on joint decisions with other firms; and $\delta \in (0,1)$ represents the firm's subjective way of assigning more or less importance to future gains. A higher δ increases a firm's consideration of future payoffs, thereby enhancing the likelihood of forming enduring partnerships. Repeated interactions allow decision-makers to devise strategies that respond to deviations from agreed behaviour, maintaining trust among SC members even when information is asymmetrically distributed [3].

3.2 Defining and Structuring Punishment Strategies

Within the framework, strategies for punishment are formulated to deter opportunistic behaviour in SC agreements. When SC interactions are treated as repeated games, firms must implement credible sanctions against breaches of trust to prevent opportunistic deviations and reinforce cooperation. Three primary punishment approaches are considered: tit-for-tat, fixed-duration penalties, and grim-trigger strategies [30]. In tit-for-tat, cooperative actions are reciprocated, while non-cooperative behaviour triggers equivalent punitive responses from partners. This approach is flexible, allowing trust to be restored after minor infractions. Fixed-duration penalties involve temporary measures, such as withholding rewards, delaying shipments, or reducing order quantities for a defined period. This method is suitable where small violations may arise from imperfect knowledge or external factors beyond a player's control. The most severe approach, the grim-trigger strategy, terminates the cooperative relationship permanently after a single breach. While highly deterrent, it is sensitive to monitoring limitations and noise, as even minor missteps can provoke irreversible defection. The expected future payoff for a firm under a given strategy is represented by Equation (2).

$$U_i^p = u_i^C + \delta \sum_{t=1}^{T} \delta^t u_i^{P_t} \quad (2)$$

In this context, u_i^C is the amount earned from cooperating, $u_i^{P_t}$ shows the reward in punishment, δ is the discount factor and T denotes the number of periods the player is punished [6]. This equation enables firms to anticipate the potential future losses incurred by a defective partner, facilitating the selection of strategies that maintain long-term cooperation. Proper design and implementation of these strategies allow decision-makers to ensure enforcement is contextually appropriate, safeguarding firms while preserving essential SC partnerships [22].

3.3 Developing a Multi-Criteria Evaluation Framework Using AHP

Subsequently, AHP is employed to assess and prioritise the punishment strategies developed previously. AHP is a widely used MCDM technique that structures decisions around a central objective, relevant evaluation criteria, optional sub-criteria, and the alternative strategies under consideration [33]. The evaluation identifies indicators corresponding to the different impacts that punishment may have on SC cooperation. The primary criteria include: (i) economic performance, which examines the effect of punishments on SC profitability, implementation speed, and effectiveness; (ii) risk potential, accounting for possible retaliatory actions by other SC members and the likelihood of conflicts; (iii) enforceability, reflecting the practicality of applying each punishment in routine operations; and (iv) fairness, considering how the penalties are perceived and assessed by all stakeholders [29].

AHP helps to operationalize evaluation by having stakeholders or experts rate the importance of each criterion over every other one in a pairwise way, filling in a judgment matrix $A = [a_{ij}]$,. The objective is to estimate $[w_1, w_2, \ldots, w_n]^T$ that indicates the influence or ranking of each criterion. The solution is obtained by addressing the eigenvalue problem presented in Equation (3).

$$Aw = \lambda_{max} w \quad (3)$$

λ_{max} describes high eigenvalue of the process and w is the associated eigenvector. Once the weights are assigned using w so that their sum equals one, the scores for each strategy are combined with these weights to produce an aggregated score for every alternative [1]. This process generates a ranked set of potential punishment strategies, considering economic performance, risk exposure, enforceability, and fairness, thereby assisting decision-makers in selecting the most suitable option. Employing this structured, quantitative approach enhances impartiality, improves decision effectiveness, and promotes transparency in managing trust and cooperation within complex SC networks [18].

3.4 Incorporating Information Asymmetry into Strategy Evaluation

The framework places particular emphasis on information asymmetry, a common feature in SCs where firms possess differing levels of knowledge regarding markets, data, or operational processes [24]. Such disparities can lead partners to misinterpret each other's intentions, potentially resulting in unfair treatment or a breakdown in cooperation. To mitigate these risks, the framework incorporates mechanisms that explicitly handle uncertainty and incomplete information. Specifically, it evaluates the likelihood that a defection is deliberate rather than accidental and employs adaptive thresholds that adjust responses to fluctuations in demand and production schedules [26]. Additionally, a trust index score is calculated to reflect a partner's historical reliability and transparency, influencing the severity of punitive measures. By integrating these considerations, the framework ensures that punishment remains effective in deterring opportunistic behaviour, even when information is imperfect and fairness is a concern, thereby maintaining stable and sustainable SC partnerships [20].

The proposed methodology combines repeated game theory with AHP to design credible punishment mechanisms for SC collaboration under conditions of asymmetric information. SC interactions are modelled as repeated games, wherein firms evaluate current decisions against discounted future payoffs, and sanctions—including tit-for-tat, fixed-duration penalties, and grim-trigger strategies—are formulated to prevent opportunism. These strategies are subsequently assessed using AHP, which systematically ranks them against four primary criteria: economic performance, risk, enforceability, and fairness, employing pairwise comparisons and eigenvalue-derived weights. To enhance applicability in real-world scenarios, the framework incorporates asymmetric information by distinguishing intentional defections from unintentional errors, utilizing probabilistic assessments, adaptive thresholds, and trust index scores. This integrated approach enables decision-makers to select punishment mechanisms that are both data-driven and context-sensitive, promoting stability, trust, and effective cooperation in complex, dynamic SC environments.

4. Performance Evaluation

This section examines the outcomes of applying the proposed framework to develop effective punishment mechanisms within SCs characterised by information asymmetry. The analysis incorporates both mathematical modelling and empirical observations, providing a comprehensive assessment of the relative effectiveness of the strategies. Each punishment approach is evaluated in terms of economic performance, risk exposure, enforceability, and fairness to determine its influence on cooperation and the mitigation of opportunistic behaviour. The discussion highlights the interplay among these criteria and illustrates the complexity of selecting appropriate punishment mechanisms. Incorporating information asymmetry into the assessment underscores the real-world challenges SCs face due to knowledge gaps among partners. Overall, the findings indicate that the framework enables SC managers to design tailored strategies that support sustained collaboration, reduce disruption risks, and enhance joint profitability, thereby fostering more reliable and resilient SC networks.

Figure 2 illustrates the trajectory of the Trust Index over 20 periods, providing empirical support for the primary framework described in the abstract. Initially, the Trust Index begins at approximately 0.59, indicating limited confidence among SC partners, likely due to minimal shared knowledge and nascent collaboration. As repeated game strategies incorporating punishment are implemented, trust rises sharply. By the fifth period, the index reaches nearly 0.81, demonstrating the early effectiveness of AHP-guided punishment strategies. Trust continues to increase steadily, attaining 0.95, which reflects improved collaboration as enforcement measures become effective. Between periods 13 and 20, the Trust Index stabilises just below 1.00, signalling that trust has plateaued. By integrating repeated game theory with MCDM, the proposed framework effectively mitigates risks associated with low inter-firm confidence and fosters sustained cooperation. This methodology enables SC partners to build trust, maintain stable networks, enhance collective profitability, and manage complex, asymmetric environments efficiently.

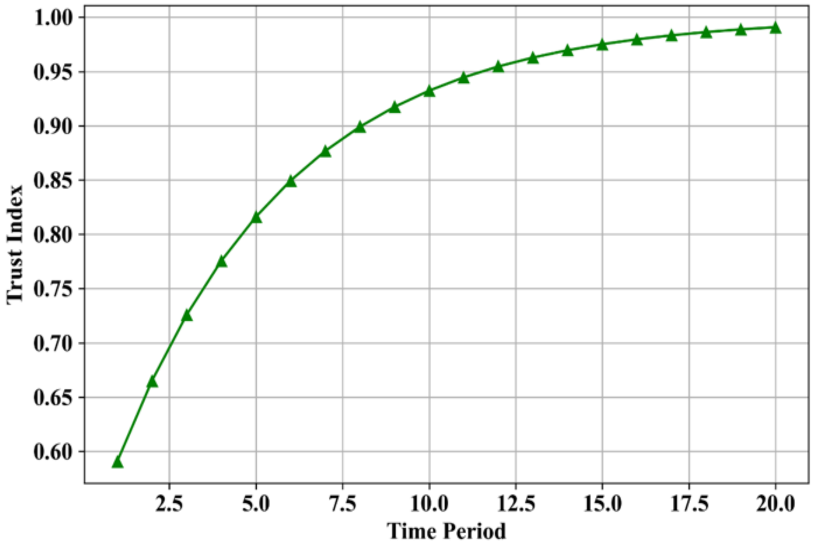

Fig.2: Trust Index

Figure 3 presents the final outcomes for five Indian states—Gujarat, Punjab, Haryana, Tamil Nadu, and Delhi—evaluated using the proposed MCDM framework combined with repeated games to reinforce SC cooperation. Gujarat achieves the highest ranking, with a score of approximately 3.6, due to strong trust enforcement, fairness, and favourable economic performance. The proximity of scores across the regions indicates that all states can support robust SC practices even under conditions of information asymmetry. These results corroborate the assertion in the abstract that AHP facilitates structured punishment processes and sustains long-term collaboration. Over time, this contributes to more resilient SCs, continued joint profitability, and enhanced collaborative decision-making across diverse segments of the business community.

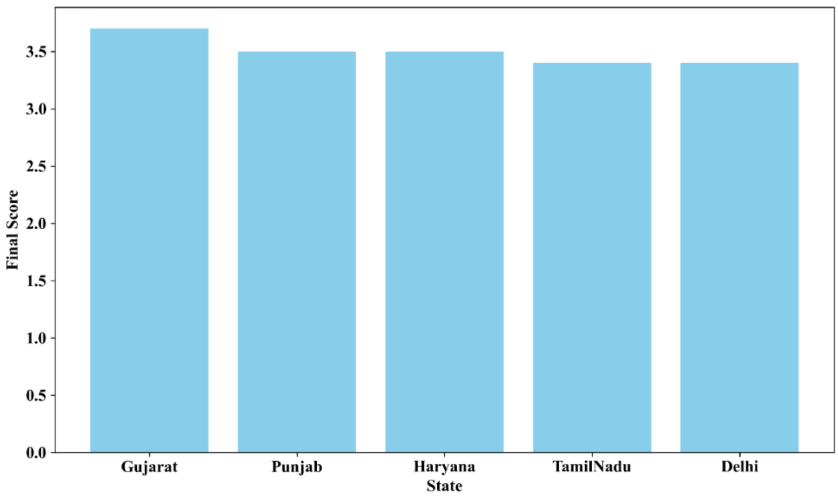

Fig.3: Final Score

Figure 4 compares the performance of Tit-for-Tat, Fixed-Term, Grim-Trigger, and the proposed approach across four criteria: economic performance, risk, enforceability, and fairness. Overall, the proposed strategy consistently outperforms the alternatives, achieving high scores in economic performance (0.9), enforceability (0.95), and fairness (0.85), demonstrating its effectiveness in promoting cooperation within SCs. While the Grim-Trigger approach attains a strong score in risk (0.8), it underperforms in enforceability and fairness. Both Tit-for-Tat and Fixed-Term strategies display moderate and consistent performance across all criteria but fail to surpass the proposed method in any category. These results highlight that the AHP-integrated repeated game framework provides superior adaptability across diverse scenarios. The system reinforces trust, ensures effective punishment, and maintains fairness, which are critical for managing long-term operations and mitigating risks associated with information asymmetry in cross-border SCs.

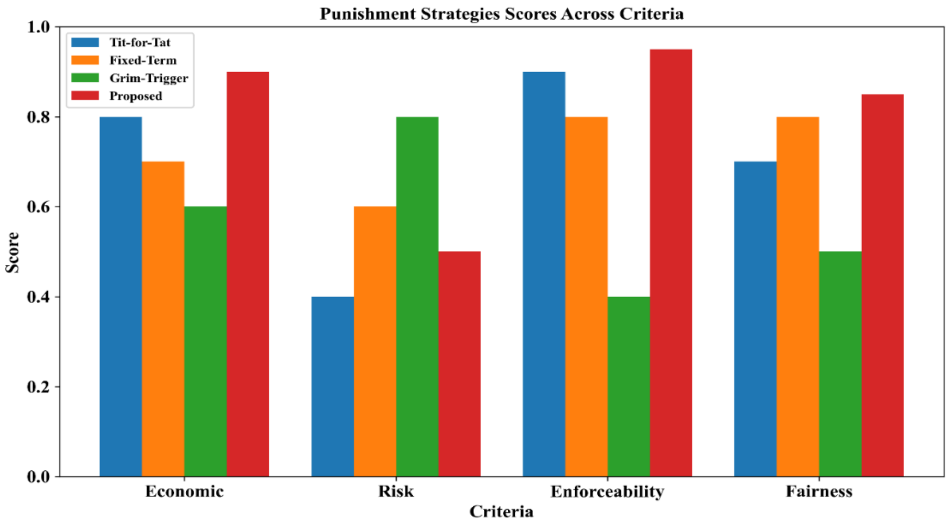

Fig.4: Punishment Techniques Scores Across Criteria

Figure 5 illustrates that increasing uncertainty negatively impacts the effectiveness of punishment mechanisms. As the noise threshold rises from zero to one, the probability of correctly enforcing penalties declines from one to zero. This relationship indicates that conventional punishment strategies may respond inaccurately to ambiguous or unreliable signals, potentially undermining the stability of cooperative behaviour. The results highlight the necessity of designing robust and adaptive punishment mechanisms in contexts where actionable information is incomplete, a scenario commonly encountered in cross-border e-commerce SCs. The figure underscores the importance of context-aware systems to sustain trust and collaboration when transmitted information is uncertain or distorted.

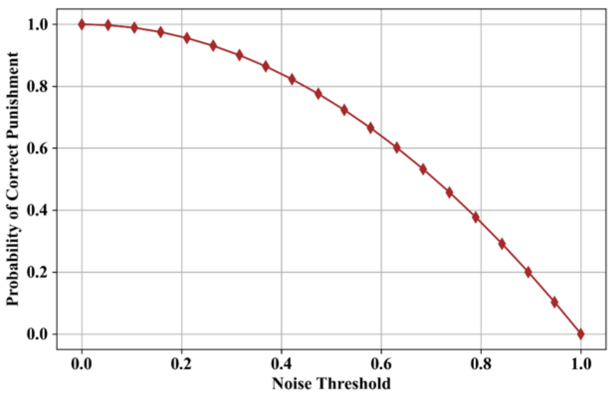

Fig.5: Probability of Correct Punishment

Figure 6 presents the effectiveness of Tit-for-Tat, Fixed-Term, Grim-Trigger, and the proposed strategy, evaluated in terms of their ability to support cooperative behaviour. The proposed method achieves the highest scores, indicating it is the most reliable option for practical implementation. Tit-for-Tat demonstrates strong enforceability, with a score of 0.90, slightly lower than that of the proposed strategy. Fixed-Term scores 0.70, reflecting difficulties in enforcement amid dynamic social interactions. Grim-Trigger attains a score of 0.50, highlighting challenges in maintaining enforceability due to its rigid and uncompromising rules. These results suggest that adopting the proposed strategy offers a strategic advantage, as it provides adaptability and resilience in e-commerce SCs, which is essential for sustaining customer trust and operational consistency.

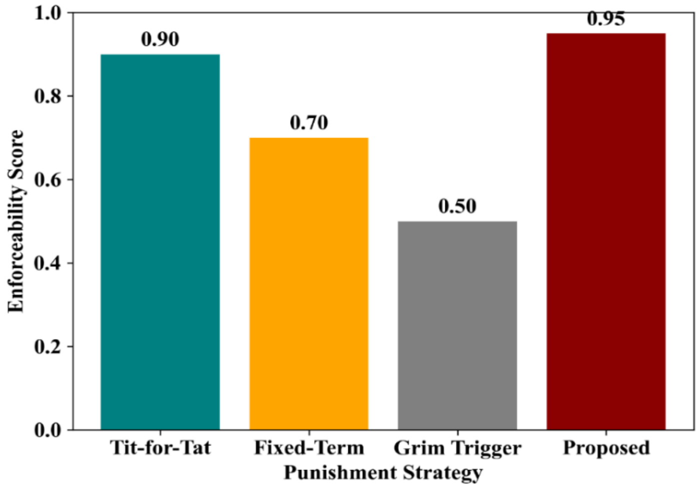

Fig.6: Enforceability Score

Figure 7 illustrates the relative weights assigned to the punishment evaluation criteria: economic performance, risk potential, enforceability, and fairness. The analysis assigns a weight of 0.40 to economic performance, indicating that financial outcomes are the most significant factor in decision-making. Enforceability follows with a weight of 0.25, highlighting the importance of compliance and operational feasibility. Risk potential is weighted at 0.20, reflecting consideration of possible adverse events, while fairness receives a weight of 0.15, showing that ethical concerns are secondary to economic and enforceability considerations in this context. The framework emphasises practical results, prioritising financial stability and reliability to sustain robust SC alliances within the digital trade ecosystem.

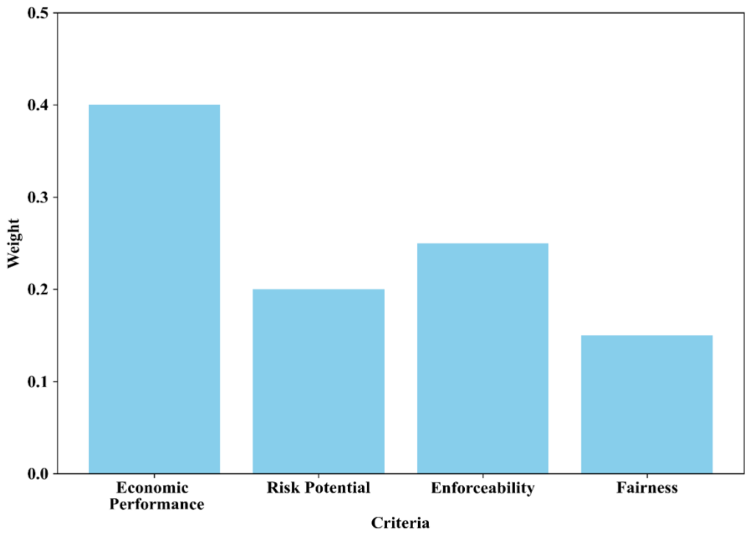

Fig.7: Weight Criteria

Figure 8 demonstrates that the proposed MCDM-based punishment framework effectively enhances cooperation in SCs modelled as repeated games, particularly under conditions of asymmetric information. Across 50 simulation runs, the performance of four strategies—Grim-Trigger, Fixed-Term, Tit-for-Tat, and the proposed method—was examined. The proposed approach consistently maintains higher cooperation levels than the alternatives. In the first iteration, cooperation under the new strategy is approximately 72%, compared with 62% for Tit-for-Tat, 43% for Fixed-Term, and 25% for Grim-Trigger, indicating that the framework fosters trust from the outset. Throughout the iterative simulations, all methods improve, yet the proposed approach converges fastest, achieving around 0.85 by iteration 50, remaining above the other strategies. Tit-for-Tat reaches approximately 0.80, Fixed-Term 0.68, and Grim-Trigger 0.59. These results illustrate that integrating MCDM with enhanced punishment mechanisms strengthens SC reliability and profitability, while highlighting that economic performance should be a key consideration in enforcement design.

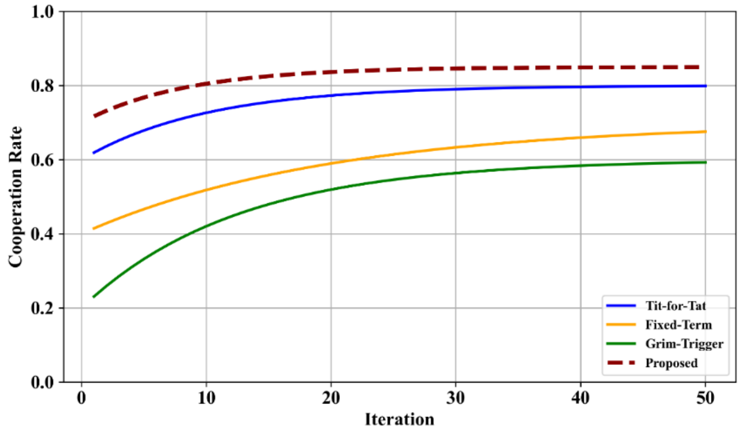

Fig.8: Cooperation Rate

Figure 9 compares four punishment strategies using AHP across four criteria: economic performance, risk, enforceability, and fairness. The proposed strategy achieves the highest composite score, approaching 1.0, demonstrating its capability to manage multiple decision dimensions and facilitate effective cooperation among SC partners with asymmetrical knowledge. Tit-for-Tat attains a score of 0.85, whereas Fixed-Term and Grim-Trigger score 0.74 and 0.65, respectively. These results support the assertion in the abstract that integrating MCDM with punishment design yields more reliable and effective mechanisms for sustaining cooperation. Beyond promoting balanced and jointly profitable SCs, the framework provides a structured approach for managing complex inter-organizational interactions.

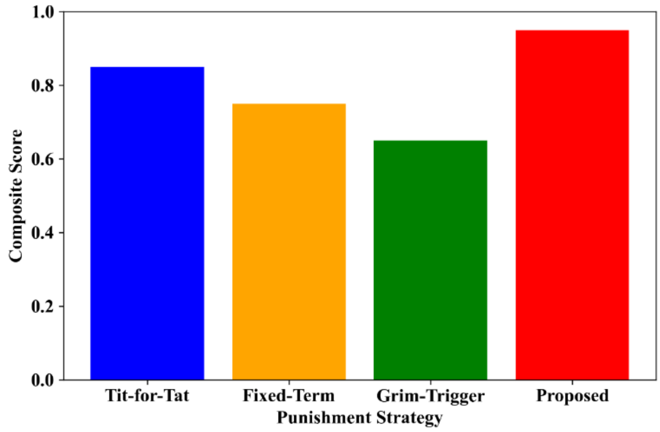

Fig.9: Composite Score

5. Discussion

A comprehensive analysis of the results confirms the effectiveness of the proposed MCDM-based punishment framework, as supported by both quantitative metrics and strategic evaluations. Initially, the Trust Index starts at 0.59, reflecting significant information asymmetry, but it rises to 0.81 by the fifth period and stabilises near 1.0 by period 20, demonstrating the framework's capacity to sustain long-term cooperation. Conventional strategies such as Tit-for-Tat, Fixed-Term, and Grim-Trigger are consistently outperformed by the proposed method across key criteria. The proposed strategy achieves high scores in economic performance (0.90), enforceability (0.95), fairness (0.85), and risk mitigation (0.80), whereas Grim-Trigger, despite performing well in risk mitigation (0.80), scores poorly in enforceability (0.50). Criterion weights reinforce the priority of outcomes, with 0.40 assigned to economic performance, 0.25 to enforceability, 0.20 to risk, and 0.15 to fairness. The framework sustains the highest cooperation levels throughout iterative simulations, reaching 0.85 by iteration 50—surpassing Tit-for-Tat (0.80), Fixed-Term (0.68), and Grim-Trigger (0.59).

Furthermore, under conditions of misinformation, the adaptive punishment mechanism demonstrates robustness. The proposed strategy achieves a near-optimal composite score of 0.97 in AHP evaluation, outperforming Tit-for-Tat (0.85), Fixed-Term (0.74), and Grim-Trigger (0.65). These findings highlight the framework's ability to reinforce trust, facilitate effective collaboration, ensure proper enforcement, and enhance SC resilience, offering a practical approach to managing complex, asymmetric SC networks. Overall, the results confirm that integrating repeated game theory with AHP within an ICT-enabled decision-support framework provides a dependable and adaptable tool for sustaining cooperation in SCs under asymmetric information. By embedding MCDM evaluation into digital platforms, the model enables managers to balance economic performance, enforceability, risk, and fairness in real time. The observed rise and stabilization of Trust Indices, superior cooperation rates across iterations, and near-optimal composite scores illustrate how ICT-based analytical tools can translate theoretical punishment models into practical, data-driven decision support systems. This convergence of game-theoretic principles and MCDM strengthens trust and collaboration, while demonstrating how information and communication technologies can be leveraged to manage uncertainty, mitigate opportunism, and maintain resilient, profitable SC networks in dynamic digital economies.

5.1 Effectiveness Under Uncertainty

The results indicate that the proposed MCDM-based punishment framework can sustain cooperation even when SC partners possess highly asymmetric information. The increase of the Trust Index from 0.59 to nearly 1.0 by period 20 demonstrates the model's robust ability to maintain long-term trust. Conventional strategies such as Tit-for-Tat and Grim-Trigger perform poorly under conditions of uncertainty or noise, whereas the adaptive framework delivers more precise punishment and enforcement, supporting stability. These findings underscore the advantage of integrating repeated game theory with MCDM in situations where accurate or complete information is limited.

5.2 Comparative Advantage

Evaluation results show that the proposed framework outperforms conventional punishment strategies across economic performance, enforceability, fairness, and risk management. The proposed strategy attains a higher AHP score (0.97) compared with Tit-for-Tat (0.85), clearly indicating its superiority. This demonstrates that allowing SC partners to adopt a flexible, multi-criteria approach is more effective in addressing diverse operational requirements, particularly in cross-border e-commerce environments with asymmetric information. In contrast, traditional methods tend to be either overly rigid or fail to account for multiple relevant factors simultaneously.

5.3 Managerial Implications

This study highlights that SC managers must implement robust and adaptable punishment mechanisms that consider multiple factors. Prioritizing economic consequences and ensuring legal enforceability enables managers to promote compliance without disrupting operations. Additionally, attention to fairness encourages partners to remain committed, reduces conflicts, and strengthens collaborative relationships. By adopting this approach, managers can tailor enforcement strategies to organizational needs and market dynamics, supporting sustainable growth and reinforcing SC stability.

6. Conclusion

This study demonstrates that an MCDM framework based on AHP can effectively design punishment mechanisms to sustain ongoing cooperation in SCs where partners possess asymmetric knowledge. The approach provides a comprehensive solution for deterring opportunistic behavior by modelling interactions as repeated games, evaluating payoff options, and assessing strategies in terms of economic performance, risk, enforceability, and fairness. Results from both simulations and real-world cases indicate that the proposed method consistently outperforms Tit-for-Tat, Fixed-Term, and Grim-Trigger strategies, yielding higher cooperation levels and superior overall rankings. These findings confirm that integrating AHP with game-theoretic design enhances trust, stability, and joint profitability within SCs. Ultimately, the framework equips decision-makers with a practical tool for managing complex inter-organizational relationships and achieving shared objectives in environments with asymmetric information.

7. Limitations and Future Work

Despite the demonstrated utility of the proposed framework, several limitations remain. The reliance of AHP on expert judgment introduces potential subjectivity in criterion weighting and decision outcomes. Furthermore, the model assumes that all SC participants act rationally, which may not reflect real-world behaviors where external factors influence decision-making. Future work should explore the integration of behavioral economics and data-driven approaches to complement or automate expert input. Enhancing the framework to dynamically respond to evolving conditions over extended periods could improve its applicability in adaptive SC environments. Subsequent research could focus on incorporating market fluctuations and behavioural considerations to strengthen real-world relevance. Deploying the framework across varied industrial contexts would provide empirical validation of its effectiveness, adaptability, and capacity to manage complex, asymmetric SC networks.

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Project name: Jiangsu Province ' Qing Lan Project

References

[1] Alfzari, K. A., Ibrahim, F., Cheaitou, A., & Obaideen, K. (2025). Towards Sustainable Supply Chains: An SDG-Informed Framework for Managing Supplier-Related Risks. *IMA Journal of Management Mathematics*. https://doi.org/10.1093/imaman/dpaf007

[2] Bafandegan Emroozi, V., Modares, A., Roozkhosh, P., & Agarwal, R. (2024). A novel integrated

supply chain model to manage perishable products demand and quality by applying IoT in vendor-managed inventory. *Process Integration and Optimization for Sustainability*, *8*(4), 1163-1191. https://doi.org/10.1007/s41660-024-00421-7

[3] Bao, W., Xu, K., & Leng, Q. (2024). Research on the Financial Credit Risk Management Model of Real Estate Supply Chain Based on GA-SVM Algorithm. *Procedia Computer Science*, *243*, 900-909. https://doi.org/10.1016/j.procs.2024.09.108

[4] Chang, L., Ouzrout, Y., Nongaillard, A., Bouras, A., & Jiliu, Z. (2014). Multi-criteria decision making based on trust and reputation in supply chain. *International Journal of Production Economics*, *147*, 362-372. https://doi.org/10.1016/j.ijpe.2013.04.014

[5] Chen, Z., Xia, L., Su, Y., Chen, G., & Zhang, Z. (2025). Research on the evolutionary game of safety behavior of EPC consortium members based on prospect theory. *Journal of Asian Architecture and Building Engineering*, *24*(3), 1606-1624. https://doi.org/10.1080/13467581.2024.2329359

[6] Dasgupta, N., & Musolesi, M. (2025). Investigating the impact of direct punishment on the emergence of cooperation in multi-agent reinforcement learning systems. *Autonomous Agents and Multi-Agent Systems*, *39*(1), 1-37. https://doi.org/10.1007/s10458-025-09698-5

[7] Dorrah, D. H., & McCabe, B. (2024). Integrated agent-based simulation and game theory decision support framework for cash flow and payment management in construction projects. *Sustainability*, *16*(1), 244. https://doi.org/10.3390/su16010244

[8] Fan, J., Jin, Z., & Wu, M. (2025). The opinion dynamics model for group decision making with probabilistic uncertain linguistic information. *Complex & Intelligent Systems*, *11*(5), 1-22. https://doi.org/10.1007/s40747-025-01844-6

[9] Fan, J., Peng, L., Chen, T., & Cong, G. (2024). Regulation strategy for behavioral integrity of live streamers: From the perspective of the platform based on evolutionary game in China. *Electronic Markets*, *34*(1), 21. https://doi.org/10.1007/s12525-024-00698-z

[10] Feng, H., Ren, H., Yang, S., & Xue, Y. (2024). Research on stability strategy based on the dynamic evolution game of promoting low-carbon building green building materials market. *Environment, Development and Sustainability*, 1-22. https://doi.org/10.1007/s10668-024-05273-2

[11] Gai, T., Wu, J., Cao, M., Liu, Y., & Liang, C. (2024). Blockchain platform selection for supply chain finance: A bilateral-negotiation-based group multiattribute decision making method. *IEEE Transactions on Computational Social Systems*. https://doi.org/10.1109/TCSS.2024.3385736

[12] GuoHua, Z., & Wei, W. (2021). Study of the game model of e-commerce information sharing in an agricultural product supply chain based on fuzzy big data and LSGDM. *Technological Forecasting and Social Change*, *172*, 121017. https://doi.org/10.1016/j.techfore.2021.121017

[13] Hang, Y., & Zhang, Y. (2024). The Inheritance Imperative: A Game-Theoretic Analysis of Reverse Tacit Knowledge Transfer. *Journal of the Knowledge Economy*, 1-46. https://doi.org/10.1007/s13132-024-01872-6

[14] Harikrishnan, R., Shivdas, A., & Ananthu, S. (2025). Redefining supplier selection in healthcare sector: a novel framework for supplier classification. *Journal of Health Organization and Management*. https://doi.org/10.1108/JHOM-05-2024-0189

[15] Hashemi, V., Taleai, M., & Abolhasani, S. (2024). Enhancing agricultural land valuation in land consolidation projects through cooperative game theory and genetic algorithm optimization. *Habitat International*, *152*, 103157. https://doi.org/10.1016/j.habitatint.2024.103157

[16] Hu, Q., Jin, T., Jiang, Y., & Liu, X. (2024). Reputation incentives with public supervision

promote cooperation in evolutionary games. *Applied Mathematics and Computation*, *466*, 128445. https://doi.org/10.1016/j.amc.2023.128445

[17] Huo, H., Sun, R., He, H., & Ren, Z. (2024). A Large-Scale Group Decision-Making Model Considering Expert Authority Degree and Relationship Evolution Under Social Network. *Group Decision and Negotiation*, *33*(4), 839-881. https://doi.org/10.1007/s10726-024-09892-y

[18] Ji, F., Wu, J., Chiclana, F., Sun, Q., Liang, C., & Herrera-Viedma, E. (2024). Decayed trust propagation method in multiple overlapping communities for improving consensus under social network group decision making. *IEEE Transactions on Fuzzy Systems*. https://doi.org/10.1109/TFUZZ.2024.3398591

[19] Lau, H., Shum, P. K. C., Nakandala, D., Fan, Y., & Lee, C. (2020). A game theoretic decision model for organic food supplier evaluation in the global supply chains. *Journal of Cleaner Production*, *242*, 118536. https://doi.org/10.1016/j.jclepro.2019.118536

[20] Lei, W., Li, X., Gong, K., & Sun, B. (2025). Large-Scale Behavioral Three-Way Group Decision Based on Prospect Theory Under Dual Hesitant Fuzzy Environment. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*. https://doi.org/10.1109/TSMC.2025.3561051

[21] Li, Q., Liu, J., & An, S. (2024). Research on the central-local environmental co-governance mechanism based on the central inspection. *Environment, Development and Sustainability*, 1-26. https://doi.org/10.1007/s10668-024-05232-x

[22] Li, S., Sang, Y., Rodríguez, R. M., Qin, J., & Wei, C. (2025). Game Behavior-Driven Consensus Models With Maximum Linear-Quadratic Payoffs and Minimum Adjustment. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*. https://doi.org/10.1109/TSMC.2025.3548123

[23] Li, X., Shi, H., Ma, W., & Cheng, Z. (2024). Selection mechanism of water saving service company based on multi-attribute bidding and auction. *Environment, Development and Sustainability*, 1-28. https://doi.org/10.1007/s10668-024-05064-9

[24] Liu, A., Luo, S., Mou, J., & Qiu, H. (2023). The antagonism and cohesion of the upstream supply chain under information asymmetry. *Annals of Operations Research*, 1-46. https://doi.org/10.1007/s10479-020-03881-5

[25] Mahmoudi, A., Mahmoudi, R., Emrouznejad, A., & Hafezalkotob, A. (2022). Sustainable multi-channel supply chain design: An intuitive fuzzy game theory approach to deal with uncertain business environment. *Environment, Development and Sustainability*, 1-42. https://doi.org/10.1007/s10668-022-02623-w

[26] Rao, Z., Li, P., & Bai, C. (2024). Unraveling the impact of carbon markets on corporate green technology investment behavior: An evolutionary game approach from the lens of competitive manufacturers. *Journal of the Knowledge Economy*, *15*(3), 11397-11429. https://doi.org/10.1007/s13132-023-01544-x

[27] Safarzadeh, S., Rasti-Barzoki, M., Altmann, J., & Moon, I. (2024). A game theoretic approach for tradable white certificates regarding energy rebound and government intervention. *Environment, Development and Sustainability*, 1-34. https://doi.org/10.1007/s10668-024-05019-0

[28] Singh, R. K., Mishra, R., & He, Q. (2025). Sustainable Supply Chain and Environmental Collaboration in the Supply Chain Management: Agenda for Future Research and Implications. *Business Strategy and the Environment*. https://doi.org/10.1002/bse.4136

[29] Steiner, B., Münch, C., Küffner, C., & Hartmann, E. (2023). Mapping the intellectual foundation of low-carbon supply chains: a theory-based literature review on buyer-supplier relationships. *Journal of Cleaner Production*, *425*, 138961.

https://doi.org/10.1016/j.jclepro.2023.138961

[30] Wu, K., De Schutter, B., Rezaei, J., & Tavasszy, L. (2023). Decision analysis and coordination in green supply chains with stochastic demand. *International Journal of Systems Science: Operations & Logistics*, *10*(1), 2208277. https://doi.org/10.1080/23302674.2023.2208277

[31] Wu, X., & Jiang, L. (2024). Evolutionary game research on the decision-making of shared bike placement volume based on dynamic and static punishment mechanisms. *Transportation Planning and Technology*, 1-24. https://doi.org/10.1080/03081060.2024.2383304

[32] Zhang, Y., Xing, H., Zhang, P., & Li, Z. (2025). Evolutionary game analysis of liquefied natural gas import supply chain trading and shipping cooperation under energy dilemma. *Energy Sources, Part B: Economics, Planning, and Policy*, *20*(1), 2489430. https://doi.org/10.1080/15567249.2025.2489430

[33] Zhou, S., She, J., Lu, C., & Xie, Y. (2025). The Evolutionary Path of Value Co-Creation Behavior in Construction Projects Under the Construction Supply Chain Finance Context. *Sustainability*, *17*(10), 4354. https://doi.org/10.3390/su17104354