Simulation Modeling of Multi-Agent Coordination in Maritime Emergency Response Systems

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***Abstract*—This research creates a multi-agent simulation model for the maritime emergency response system, integrating agent-based modeling with evolutionary game theory. The model captures strategic interactions among four key stakeholders, such as Maritime Administration, Ship Operators, Crew Members, and Insurance Companies—who adaptively adjust strategies under bounded rationality. Through replicator dynamics and stability analysis, we identify equilibrium conditions and optimal coordination mechanisms. Numerical simulations reveal critical thresholds for safety compliance and effective incentive structures. The framework bears the potential for action in maritime safety policy over the bottom-up modeling approaches to emergent complex system dynamics toward regulatory design applicable for safety-critical system domains.**

Keywords-Maritime emergency response; agent-based modeling; evolutionary game theory.

I. Introduction

Maritime emergency response faces critical coordination challenges, with inadequate stakeholder collaboration identified as a primary factor in accident escalation and delayed responses [1]. This real-world problem motivates our investigation into strategic interactions among regulatory authorities, ship operators, crew members, and insurance companies in emergency scenarios.

Traditional analytical methods struggle to capture the complex adaptive nature of maritime emergency systems, where multiple heterogeneous agents interact dynamically. Simulation modeling offers unique advantages in revealing emergent properties — how individual-level decisions generate system-level behaviors [2]. This study integrates agent-based modeling with evolutionary game theory to develop a multi-agent coordination model for maritime emergency response. Unlike conventional approaches, our model explicitly characterizes bounded rational agents who adaptively adjust strategies through environmental feedback and mutual observations.

Our contributions include: (1) developing a four-agent evolutionary game model tailored for maritime emergency scenarios; (2) systematically analyzing parameter impacts on system evolution through simulation experiments; (3) proposing validated mechanism design frameworks for enhanced coordination. These advances provide quantitative tools for maritime safety policy formulation.

This paper is organized as follows. Section II presents the model formulation, including agent definitions and game-theoretic framework. Section III provides the simulation experiments and analysis.

II. Model Formulation

This section presents the mathematical foundation of our multi-agent coordination model, establishing the game-theoretic framework and defining stakeholder interactions within the maritime emergency response system.

A. Game-Theoretic Distributed Auction with Spatial-Temporal Dynamics

Assumption 1: The evolutionary game involves four stakeholders, such as Maritime Administration (M), Ship Operators (O), Crew Members (C), and Insurance Companies (I)—all of whom are assumed to exhibit bounded rationality.

Assumption 2: Each stakeholder has two pure strategy choices [3][4]:

Maritime Administration (M) chooses between Strict Regulation (MS) and Lenient Regulation (ML);

Ship Operators (O) choose between High Safety Investment (OH) and Low Safety Investment (OL);

Crew Members (C) choose between Active Emergency Response (CA) and Passive Emergency Response (CP);

Insurance Companies (I) choose between Strict Review (IS) and Lenient Review (IL).

Assumption 3: The strategy choices of stakeholders are interdependent, and the probability of strategy adjustment is determined by payoff differences.

Table I presents the definitions of the relevant parameters.

B. Model Construction

One of the principal innovations of this model lies in its formulation of accident probability as a function of collective stakeholder actions. This mechanism can be intuitively conceptualized through a multi-layered risk mitigation framework.

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TABLE I. PART OF FACTORS

Descriptions of Factors	Symbol	Description
Maritime Administration	C_M^S, C_M^L	Cost of strict or lenient regulation
	L_M	Social loss and liability cost in the event of an accident
	R_M	Social benefit from a good safety record
Ship Operators	C_O^H, C_O^L	Cost of high or low safety investment
	F_S, F_L	Fine for violation under strict or lenient regulation
	L_O	Direct economic loss from an accident
	R_O	Normal operational revenue
Crew Members	C_C^A, C_C^P	Cost of active or passive response
	B_C	Bonus for successful emergency response
	W_C	Base wage
Insurance Companies	C_I^S, C_I^L	Cost of strict or lenient review
	P_I	Insurance payout in case of accident
	R_I	Insurance premium revenue
Risk Parameters	P_B	The basic risk reflects the inherent risks of offshore operations
	$\alpha_M, \alpha_O, \alpha_C, \alpha_I$	Individually representing the risk reduction coefficient of safety measures for M, O, C, and I

Consider the safety measures adopted by each stakeholder as constituting an independent protective layer. The baseline risk, denoted as P_B, represents the intrinsic accident probability in the absence of any interventions. Each protective layer attenuates a portion of the aggregate risk:

$$P_{accident} = P_B \cdot (1-\delta_M \cdot \alpha_M) \cdot (1-\delta_O \cdot \alpha_O) \cdot (1-\delta_C \cdot \alpha_C) \cdot (1-\delta_I \cdot \alpha_I) \quad (1)$$

Where:

δ_M=1 if M chooses Strict (MS), 0 if Lenient (ML);

δ_O=1 if O chooses High Safety Investment (OH), 0 if Low Safety Investment;

δ_C=1 if C chooses Active Emergency Response (CA), 0 if Passive Emergency Response (CP);

δ_I=1 if C chooses Strict (IS), 0 if Lenient (IL).

In the model, the maritime management administration, the ship operators, the crew members, and the insurance companies make their strategy choices based on their own will. According to the above assumptions, the partial payoff functions of the four-party game is shown in Table 2.

III. SIMULATION EXPERIMENTS AND ANALYSIS

We are implementing a three-phase experimental design using agent-based Monte Carlo simulations. Phase one establishes baseline dynamics with neutral parameters to observe natural system evolution without intervention. Phase two employs Latin Hypercube Sampling across 10,000 parameter combinations, systematically varying penalty ratios and risk reduction coefficients to identify critical control variables. Phase three tests policy interventions—pure economic incentives, combined strategies, and three temporal adjustment patterns—under crisis (high initial accident rate), stable, and chaotic initial conditions, ensuring robust policy recommendations across diverse real-world scenarios.

TABLE II. PART OF THE GAME PAYOFF FUNCTIONS

Stakeholder	Payoff Matrix
Maritime Administration	$R_M - C_M(\text{strategy}) - P_{accident} \cdot L_M$
Ship Operators	$R_O - C_O(\text{strategy}) - F(\text{regulation}) - P_{accident} \cdot L_O$
Crew Members	$W_C - C_C(\text{strategy}) + (1 - P_{accident}) \cdot B_C \cdot \delta_C$
Insurance Companies	$R_I - C_I(\text{strategy}) - P_{accident} \cdot P_I$

IV. CONCLUSION

Looking forward, we are developing what we call an "adaptive policy framework" that learns from system feedback and adjusts parameters automatically. The ultimate vision is a living system that continuously optimizes itself, making maritime transport progressively safer while maintaining economic viability.

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