Tec Empresarial
P-ISSN: 1659-2395; E-ISSN: 1659-3359

A Cooperative Game-Theoretic Model for Multi-Agent Coordination in Humanitarian Logistics Systems Under Non-Sub Additive Conditions: A Framework for Indonesia

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Abstract

Indonesia is one of the world's most disaster-prone countries, experiencing thousands of natural hazard events annually across its archipelago. Effective disaster response requires coordination among diverse stakeholders government agencies (BNPB/BPBD), non-governmental organizations (including PMI), private sector logistics providers, military (TNI), and community organizations. However, collaboration is often hindered by conflicting incentives, coordination costs, and resource constraints. This paper develops a cooperative game theory framework to analyze stakeholder collaboration in Indonesian humanitarian logistics, explicitly modeling coordination costs as functions of coalition size and heterogeneity, allowing for non-sub additive outcomes where larger coalitions may be less efficient. Using empirically-informed parameters derived from BNPB operational data, disaster response literature, and expert-informed estimates, we calibrate the framework to the Indonesian context. All numerical parameters (standalone costs c_i, efficiency parameters e_i, coordination cost coefficients β_0, β_1, β_2, and resulting Shapley values) presented in this paper are constructed for illustrative and methodological demonstration purposes. They are informed by existing literature and BNPB data patterns but do not represent actual expenditure data from any specific disaster event. The primary contribution of this paper is the mathematical framework itself and its application to the Indonesian multi-stakeholder context, not the specific numerical findings. Empirical validation with real transaction-level data from Indonesian disaster responses is required before the framework can inform actual policy decisions. Key illustrative findings from our calibrated model include: (1) the private sector generates the highest marginal value (Shapley value share: approximately 34% of total savings), supporting prioritization of public-private partnerships; (2) grand coalitions (5 players) may exhibit non-sub additive outcomes when coordination costs exceed marginal benefits; (3) community organizations may require subsidy mechanisms to participate effectively; (4) capacity building for community organizations (increasing efficiency from baseline to 0.65) raises their Shapley value significantly. The framework offers a rigorous analytical tool for disaster policymakers in Indonesia and contributes to humanitarian logistics theory by extending cooperative game theory to a new context

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with explicit non-sub additive modeling and empirical grounding in Indonesian disaster response patterns.

Keywords: *Cooperative Game Theory, Humanitarian Logistics, Multi-Agent Coordination, Non-Sub Additive Games, Disaster Response, Humanitarian Supply Chain.*

INTRODUCTION

Indonesia is unequivocally one of the most disaster-prone countries in the world. Situated within the Pacific Ring of Fire and intersecting with several major fault lines, the archipelago experiences thousands of natural hazard events annually, including earthquakes, tsunamis, volcanic eruptions, floods, and landslides. Major disasters such as the 2004 Aceh tsunami, the 2009 Padang earthquake, the 2010 Merapi eruption, the 2018 Lombok and Sulawesi earthquakes, the 2021 Semeru eruption and the 2025 Sumatra floods and landslides, which affected 52 districts across Aceh, North Sumatra, and West Sumatra underscore the critical importance of effective disaster response mechanisms (*Data Informasi Bencana Indonesia: Sumatra Floods*, 2025).

Recent national statistics reinforce the severity of this exposure. BNPB's national disaster information database has recorded several thousand disaster events annually in recent years, the overwhelming majority of which are hydrometeorological in nature floods, extreme weather, landslides, and drought while geophysical events, though far less frequent, account for a disproportionate share of fatalities, displacement, and economic losses (*Data Informasi Bencana Indonesia: Sumatra Floods*, 2025; Oktarina & Wijaksono, 2020), (Ferrell et al., 2020). Beyond their direct human toll, disasters impose a substantial and recurrent fiscal burden on national and regional budgets, diverting resources from development programs toward emergency response and reconstruction. The governance of disaster risk in Indonesia has also undergone significant decentralization since the enactment of Law No. 24/2007, with district and municipal governments assuming frontline responsibility for response operations; however, studies of local government capability indicate persistent gaps in institutional arrangements, trained human resources, financial flexibility, and logistics management capacity at the sub-national level (Ferrell et al., 2020), (Lee, 2019). These structural conditions high hazard frequency, archipelagic geography that fragments transport networks, decentralized authority, and highly heterogeneous local capacity magnify the importance of inter-organizational coordination in disaster response and provide the empirical motivation for the formal collaboration framework developed.

Humanitarian logistics the process of planning, implementing, and controlling the efficient flow of goods, information, and resources during disaster response is a cornerstone of effective disaster management (Anisya S. Thomas, 2005) (Kovacs & Spens, 2010). Unlike commercial logistics, which operates under predictable demand patterns and profitdriven objectives, humanitarian logistics is characterized by high uncertainty, time pressure, resource constraints, and a mission-driven focus on saving lives (Holguín-veras et al., 2012) (Behl & Dutta, 2018). The success of disaster response operations across Indonesia's vast archipelago hinges critically on the ability to mobilize, coordinate, and deploy resources rapidly and efficiently to affected areas.

A distinguishing feature of humanitarian logistics in Indonesia is the multiplicity of stakeholders involved in disaster response. These include, but are not limited to, the National Board for Disaster Management (BNPB) and Regional Disaster Management Agencies (BPBD) at provincial and district levels, the Indonesian Red Cross (PMI), domestic and international non-governmental organizations (NGOs), the private sector (including logistics service providers, telecommunications companies, and corporate foundations), the Indonesian National Military (TNI), the National Police (Polri), community-based organizations, and international humanitarian agencies (Oktarina & Wijaksono, 2020) (Joseph D. Martin, 2018). Each stakeholder brings unique resources, capabilities, mandates, and operational priorities to the response ecosystem.

In theory, the involvement of multiple stakeholders presents an opportunity for resource pooling, capability complementarity, and operational synergy. Collaboration among humanitarian stakeholders has been shown to generate significant benefits, including reduced response times, lower operational costs, avoidance of resource duplication, improved information sharing, and enhanced coverage of affected populations (Handayani & Mustikasari, 2018) (Moshtari & Goncalves, 2017) (Mclachlin et al., 2011).

In practice, however, multi-stakeholder collaboration in humanitarian logistics is fraught with challenges. Stakeholders often operate under different and sometimes conflicting mandates, objectives, funding mechanisms, and accountability structures (Tatham & Kovacs, 2010) (Day et al., 2012). Government agencies are primarily accountable to public mandates and political cycles, NGOs to donors and humanitarian principles, private sector entities to shareholders and corporate social responsibility (CSR) frameworks, and community organizations to local constituents. These divergent interests can lead to coordination failures, resource competition, role ambiguity, information silos, and even outright conflict during disaster response (Balcik et al., 2010) (Crescent, 2015).

In the Indonesian context, specific collaboration challenges have been documented across multiple disaster events. The 2004 Aceh tsunami exposed significant gaps in logistics coordination despite eventually demonstrating the potential for large-scale collaboration (Gatignon & Wassenhove, 2010). Subsequent disasters have revealed persistent challenges: overlapping roles among government agencies and NGOs, delayed information sharing between national and local levels, inconsistent private sector engagement, and difficulties in last-mile distribution in remote areas (Oktarina & Wijaksono, 2020). These challenges underscore a fundamental question: *Under what conditions do stakeholders have incentives to collaborate, and how can collaboration be structured to be stable and mutually beneficial?*

The 2018 Central Sulawesi earthquake and tsunami provides a particularly instructive illustration of these coordination challenges. Damage to Palu's airport, seaport, and arterial road network severely constrained relief inflows during the first days of the response; large numbers of governmental, military, non-governmental, private, and spontaneous volunteer responders converged on the affected area with limited shared situational awareness, and post-operation reviews documented difficulties in aligning national coordination structures with local implementation, in prioritizing scarce transport and fuel assets, and in reaching isolated communities in Sigi and Donggala districts (Kovacs & Spens, 2010), (Wassenhove, 2006). Comparable frictions were reported in subsequent events, including the 2022 Cianjur earthquake, where the proliferation of spontaneous donors and uncoordinated aid convoys complicated traffic management and the equitable distribution of relief items across affected villages. These recurring patterns suggest that coordination failures in Indonesian disaster response are systemic rather than incidental. They therefore motivate analytical approaches that treat collaboration not as an assumed organizational virtue but as a strategic decision problem in which each stakeholder weighs the benefits of joining a coalition against the very real costs of coordinating within it.

The application of game theory to humanitarian logistics has gained increasing attention. A comprehensive review by Gorji and Shetab-Boushehri (Gorji & Shetab-Boushehri, 2020) examined 137 peer-reviewed articles on game theory applications in evacuation management, identifying dominant modeling frameworks including evolutionary games, mean-field games, and cooperative games. Their review highlights the growing recognition of game theory's unique ability to model strategic interactions among multiple decision-makers under uncertainty.

Shao et al. (2019) developed a Stackelberg game model to analyze incentive contracts between relief organizations and multiple logistics enterprises, using deprivation cost as a measurement of quantified human suffering. Their study demonstrates that suitable incentive strategies can benefit both relief organizations and private enterprises, and that relief organizations can benefit from encouraging competition among logistics providers. However, their model focuses on two-player (relief organization-enterprise) interactions rather than multi-stakeholder coalitions.

(Khoidir, 2025) employed a hybrid Intuitionistic Fuzzy AHP-TOPSIS approach to prioritize critical success factors in Indonesian humanitarian supply chains based on input from 12 disaster response experts. Their findings identified procurement and donation management, empowerment of emergency teams, and social media and communication tools as top-ranked success factors.

(Salman & Pashapour, 2024) utilized newsvendor-based quantitative models to optimize pre-disaster stocking decisions of humanitarian agencies under centralized and decentralized cooperation mechanisms. Their analysis quantifies the sub-optimality resulting from decentralized decision-making using the concept of the price of anarchy, finding that centralized cooperation is particularly advisable when average demand is high and transshipment processes are secure.

(Balza-franco et al., 2017) applied cooperative game theory, specifically the Shapley value, to model cost and utility distribution in non-for-profit relief networks. Diehlmann et al. (Diehlmann et al., 2021) developed a framework for public-private emergency collaborations integrating logistical and game-theoretical concepts. Chen et al. (Chen et al., 2020) employed evolutionary game theory to model coordination between international and local NGOs.

Despite these promising developments, the application of cooperative game theory to multi-stakeholder humanitarian logistics in Indonesia remains limited. Specifically, no study has provided a formal cooperative game theory framework that explicitly models non-subadditive outcomes (where larger coalitions may be less efficient due to coordination costs) and applies it to the Indonesian multi-stakeholder context.

This paper addresses the following gaps: (1) contextual gap: no cooperative game model specifically tailored to the Indonesian multi-stakeholder humanitarian logistics context; (2) methodological gap: lack of formal mathematical framework that explicitly models coordination costs and non-subadditivity; (3) theoretical integration gap: stakeholder theory, humanitarian logistics, and cooperative game theory not systematically integrated; (4) empirical gap: limited validation of game-theoretic models with Indonesian disaster response patterns.

The research questions are: (1) How can cooperative game theory be applied to model stakeholder collaboration in Indonesian humanitarian logistics? (2) What mathematical formulations are appropriate for coalition formation, benefit allocation, and stability analysis under non-subadditive conditions? (3) What conditions enable stable collaboration among Indonesian humanitarian stakeholders? (4) What insights does the framework generate for Indonesian disaster policymakers?

LITERATURE REVIEW

Humanitarian Logistics in Disaster Management

Humanitarian logistics accounts for approximately 80% of total disaster relief expenditure (Wassenhove, 2006). The field has evolved significantly since the 2004 Indian Ocean tsunami, which catalyzed research interest and institutional development (Altay & Iii, 2006). The response phase, particularly the "golden 72 hours" following disaster onset, is widely recognized as the most time-critical and operationally challenging (Holguín-veras et al., 2012). In Indonesia, the establishment of BNPB and BPBD following the 2004 tsunami represented a major institutional advancement, though coordination challenges persist

(Oktarina & Wijaksono, 2020), (Gatignon & Wassenhove, 2010), (Handayani & Mustikasari, 2018).

Stakeholder Collaboration in Humanitarian Operations

Primary stakeholders in Indonesian disaster response include: (1) government agencies (BNPB/BPBD), (2) NGOs including PMI and international organizations, (3) private sector logistics providers, (4) military (TNI), and (5) community organizations (Oktarina & Wijaksono, 2020) (Joseph D. Martin, 2018). Benefits of collaboration documented in the literature include resource pooling, cost reduction, improved coverage, information sharing, and organizational learning (Balcik et al., 2010), (Moshtari & Goncalves, 2017), (Team et al., 2019). Barriers include divergent mandates, competition for funding, incompatible systems, and lack of trust (Tatham & Kovacs, 2010) (Kovacs & Spens, 2010) (Crescent, 2015).

Recent research by Khoidir et al. (Khoidir, 2025) using fuzzy multi-criteria decision-making methods identified procurement and donation management as the most critical success factor for humanitarian supply chains in Indonesia, followed by empowerment of emergency teams and social media/communication tools. This finding underscores the importance of efficient resource coordination and real-time information sharing.

Institutional mechanisms for coordination have also received sustained attention. At the international level, the cluster approach institutionalized by the United Nations following the 2005 humanitarian reform organizes response around functional sectors, with a dedicated logistics cluster led by the World Food Programme. Ruesch, Lea (2022) and Grange (2020) (Grange et al., 2020; Ruesch et al., 2022) analyze coordination in humanitarian logistics through clusters and highlight the inherent tension between vertical coordination within a cluster and horizontal coordination across clusters and organizations, showing that cluster structures reduce some transaction costs while creating new interface costs. Indonesia has adapted this logic in its national cluster system coordinated by BNPB, in which a national logistics cluster brings together government agencies, TNI and Polri, PMI, NGOs, and private sector actors under a pentahelix collaboration paradigm (Oktarina & Wijaksono, 2020), (Team et al., 2019).

With respect to public-private engagement specifically, Bealt et al. 2016 in Pascuccci (2021) (Bealt et al., 2016; Pascucci, 2021) find that collaborative relationships between commercial logistics service providers and humanitarian organizations are hampered by differences in organizational culture, unclear engagement mechanisms, and the absence of pre-established agreements, while the swift trust perspective (Tatham & Kovacs, 2010) emphasizes that effective collaboration under extreme time pressure depends on rapidly formed, institutionally supported trust among partners who may never have worked together before. These research streams converge on a common insight: coordination is costly, and its costs rise with the number and institutional diversity of participating organizations precisely the mechanism that is formalized in the coordination cost function of the framework proposed in this paper.

Non-Subadditive Conditions in Humanitarian Logistics

A cooperative game is superadditive if $v(S \cup T) \geq v(S) + v(T)$ for disjoint coalitions S and T. Superadditivity implies that merging coalitions never destroys value. However, humanitarian logistics may exhibit non-subadditive outcomes where larger coalitions incur coordination costs that exceed marginal benefits (Sabahfar, 2024). As noted in (Sabahfar, 2024), "large partnerships require additional costs to manage," making non-subadditive modeling necessary for accurately representing systems where collaboration achieves cost savings among some partners while leading to increased costs among others.

This paper builds on these foundations by developing a cooperative game theory framework specifically tailored to the Indonesian multi-stakeholder context, with explicit modeling of coordination costs as a function of coalition size and heterogeneity, allowing for non-subadditive outcomes.

Cooperative Game Theory: Foundations and Applications in Logistics

Cooperative game theory studies situations in which players can form binding agreements and share the gains from cooperation. A cooperative game with transferable utility is defined by a set of players N and a characteristic function v(S) that assigns a value to every coalition $S \subseteq N$. Two questions dominate the analysis: which coalitions will form, and how the value created should be divided among members. The core, introduced as the set of allocations that no coalition can profitably block, provides the canonical stability criterion, while the Shapley value in Allen L. Soyster (2026) (Das, 2022; Soyster et al., 2026) provides the canonical fairness criterion by assigning each player its average marginal contribution over all possible orders of coalition formation. A third classical concept, the nucleolus in Rama et.al (2021) (Rama & Prasad, 2021), lexicographically minimizes the maximum dissatisfaction of coalitions and has the attractive property of always existing and being unique, although it is computationally more demanding and less transparent to communicate to practitioners than the Shapley value.

These concepts have been applied extensively in commercial logistics, where horizontal cooperation among carriers, shippers, and logistics service providers generates cost savings through consolidated shipments, shared vehicle capacity, and joint network design. Chen F. et.al (2020) (Chen et al., 2020) document both the substantial opportunities and the practical impediments of horizontal cooperation in logistics, including partner selection, information sharing, and the fair allocation of gains. J Shao et.al (2019) (Shao et al., 2019) use a cooperative game model to quantify the benefits of merging transportation requirements among shippers and show how cooperative solution concepts can allocate the resulting cost synergies. In a comprehensive review of collaborative transportation, Guajardo and

Rönnqvist (Sabahfar, 2024) catalogue more than forty cost allocation methods applied in the literature and report that the Shapley value and the nucleolus are among the most frequently employed, while also observing that most commercial applications assume subadditive cost structures under which the grand coalition is efficient.

Applications in the humanitarian domain are more recent and less numerous. Beiki et.al (2024) (Beiki Ashkezari et al., 2024) provide a foundational review of game theory in humanitarian operations, identify decentralized decision-making as a defining feature of humanitarian systems, and explicitly call for models that capture coordination costs and the strategic behavior of heterogeneous relief actors. A. Ergun (2023) (Ergün et al., 2023) review game theory applications across the natural disaster management cycle and find that cooperative models remain underrepresented relative to non-cooperative formulations, particularly in the response phase. Nagurney et al. in F. Diehlmann (2021) (Diehlmann et al., 2021) develop an integrated financial and logistical game theory model for humanitarian organizations that incorporates purchasing costs, multiple freight service providers, and budget, capacity, and demand constraints, illustrating the analytical richness that game-theoretic formulations can bring to relief operations. Taken together, this literature suggests a clear gap: whereas commercial horizontal cooperation studies typically assume that cooperation is always (weakly) beneficial, humanitarian coalitions composed of organizations with divergent mandates, systems, and cultures may face coordination costs large enough to overturn this assumption. The framework developed in Section 3 addresses this gap directly by allowing the characteristic function to be non-subadditive.

METHOD

Stakeholder Identification and Characterization

Based on the Indonesian disaster management ecosystem and stakeholder mapping, we define the set of players $N = \{1,2,3,4,5\}$ representing five primary stakeholder categories:

Player 1: Government (BNPB/BPBD) Role: National and regional coordination authority; Mandate: Legal responsibility under Law No. 24/2007 (INDONESIA, 2007); Key resources: Budget allocation, regulatory authority, public infrastructure.

Player 2: NGOs (including PMI) Role: Field operations, community outreach; Mandate: Humanitarian mission; Key resources: Volunteer networks, local knowledge, community trust.

Player 3: Private Sector Role: Logistics assets, operational efficiency; Mandate: Corporate social responsibility; Key resources: Transportation fleets, warehousing, supply chain expertise.

Player 4: Military (TNI) Role: Heavy logistics, security; Mandate: National security; Key resources: Heavy equipment, personnel, command structure.

Player 5: Community Organizations Role: Local knowledge, last-mile distribution; Mandate: Community welfare; Key resources: Local networks, indigenous knowledge.

Drawing on BNPB operational data patterns and informed by cost parameters from similar-scale disasters (Salman & Pashapour, 2024), (Balza-franco et al., 2017), each stakeholder i is characterized by the parameters presented in Table 1. These values are constructed for illustrative purposes and do not represent actual expenditure data.

Table 1. Stakeholder parameters for the Indonesian context (illustrative values constructed for methodological demonstration)

Player	Stakeholder	Symbol	Standalone Cost c_i (IDR Billion)	Efficiency e_i	Coordination Coefficient α_i
1	Government (BNPB/BPBD)	G	85.0	0.55	2.5
2	NGOs (PMI, etc.)	N	45.0	0.65	1.8
3	Private Sector	P	60.0	0.88	3.2
4	Military (TNI)	M	40.0	0.78	4.2
5	Community Organizations	C	12.0	0.45	1.2

Note: Standalone costs represent estimated operational costs for each stakeholder to fulfill disaster response obligations independently. Efficiency parameters e_i represent operational efficiency where 1.0 = perfect efficiency. Coordination coefficients α_i represent additional cost incurred per partnership. These values are constructed for illustrative and methodological demonstration purposes based on patterns informed by BNPB data and disaster response literature (Khoidir, 2025), (Sabahfar, 2024).

Characteristic Function

The total cost when coalition S operates independently:

$$C_{alone}(S) = \Sigma_{i\in S}\, c_i$$

Under collaboration, total cost comprises base operational cost and coordination cost:

$$C_{collab}(S) = C_{base}(S) + C_{coord}(S)$$

Base operational cost captures resource pooling economies:

$$C_{base}(S) = (1 - E(S)/2) \times \Sigma_{i\in S}\, c_i \quad \text{where} \quad E(S) = (1/|S|)\, \Sigma_{i\in S}\, e_i$$

Coordination cost explicitly models non-subadditivity:

$$C_{coord}(S) = \beta_0 + \beta_1|S| + \beta_2 H(S)$$

where β_0=6.0 (fixed coordination infrastructure cost), β_1=2.5 (marginal cost per additional stakeholder), β_2=1.8 (heterogeneity penalty) calibrated based on coordination cost patterns informed by Indonesian disaster response literature (Diehlmann et al., 2021) (Sabahfar, 2024). $|S|$ is coalition size, and H(S) is heterogeneity index (number of distinct stakeholder types in S, range 1-5).

The characteristic function (cost savings) is therefore:

$$v(S) = C_{alone}(S) - C_{collab}(S)$$

where:

$$C_{alone}(S) = \sum_{i\in S} c_i \text{ and}$$
$$C_{collab}(S) = C_{base}(S) + C_{coord}(S).$$

Shapley Value for Benefit Allocation

For fair distribution of collaboration benefits, we employ the Shapley value (Shapley, 2010), which satisfies efficiency, symmetry, dummy player, and additivity axioms:

$$\phi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!(n-|S|-1)!}{n!}[v(S \cup \{i\}) - v(S)]$$

For n=5, the Shapley value represents the average marginal contribution of each stakeholder across all 120 possible coalition formation sequences.

Core Stability and Non-Subadditivity

A payoff vector $x = (x_1,\ldots,x_n)$ is in the core if: (1) Efficiency: $\Sigma_{i\in N}\, x_i = v(N)$; (2) Coalition rationality: $\Sigma_{i\in S}\, x_i \geq v(S)$ for all $S \subset N$. The core represents stable allocations where no subgroup can improve by leaving the grand coalition.

When coordination costs create non-subadditive outcomes ($v(S\cup T) < v(S)+v(T)$ for some disjoint S,T), the core may be empty. Following (Sabahfar, 2024), we employ the ε-core (least core) relaxation:

$$\epsilon^* = \min_{x} \max_{S\subset N} \left(v(S) - \sum_{i\in S} x_i \right)$$

Modeling Assumptions and Choice of Solution Concepts

Three modeling choices deserve explicit justification. First, the linear form of the coordination cost function $C\_coord(S) = \beta_0 + \beta_1|S| + \beta_2 H(S)$ is a parsimonious first-order approximation of coordination frictions documented qualitatively in the literature: β_0 captures the fixed cost of establishing joint coordination infrastructure (command posts, shared information systems, liaison arrangements); β_1 captures the marginal communication, meeting, and reporting burden that grows with each additional participating organization (Balcik et al., 2010), (Bealt et al., 2016); and β_2 captures the institutional distance penalty that arises when organizations with different mandates, procedures, and cultures must interoperate (Tatham & Kovacs, 2010), (Sabahfar, 2024). Richer specifications, for example, quadratic terms in coalition size representing pairwise liaison channels are possible, but the linear form suffices to generate the non-subadditive outcomes of interest while keeping the number of parameters small enough for transparent calibration.

Second, the framework assumes transferable utility and complete information: cost savings are measured in a common monetary unit (IDR) and can, in principle, be redistributed among coalition members through budget transfers, in-kind contributions, or cost-sharing agreements. This is the standard assumption in collaborative logistics games (Ergün et al., 2023) and is a reasonable approximation when stakeholders negotiate memoranda of understanding before disasters strike, although it abstracts from bargaining frictions and information asymmetries that may arise in practice. Third, the combination of the Shapley value and the least core as solution concepts is deliberate. The Shapley value is used as the normative benchmark for fair allocation because it uniquely satisfies the efficiency, symmetry, dummy player, and additivity axioms and is readily interpretable as an average marginal contribution. The least core is used as the stability diagnostic because, in a non-subadditive game, the core may be empty and the least core quantifies the minimum subsidy or external stabilization required to hold the grand coalition together.

RESULTS

Coalition Value Calculations

Table 2 presents characteristic function values for selected coalitions based on the parameters in Table 1 and coordination cost model. All values are illustrative and constructed for methodological demonstration.

Table 2. Characteristic function v(S) for selected coalitions (IDR Billion) illustrative values.

Coalition S	|S|	Σc_i	E(S)	C_base	C_coord	C_collab	v(S)
{G}	1	85.0	0.550	61.625	10.3	71.925	13.075
{N}	1	45.0	0.650	30.375	10.3	40.675	4.325
{P}	1	60.0	0.880	33.600	10.3	43.900	16.100
{M}	1	40.0	0.780	24.400	10.3	34.700	5.300
{C}	1	12.0	0.450	9.300	10.3	19.600	-7.600
{G, N}	2	130.0	0.600	91.000	13.6	104.600	25.400
{G, P}	2	145.0	0.715	93.163	13.6	106.763	38.237
{G, N, P}	3	190.0	0.693	124.165	16.9	141.065	48.935
{G, P, M}	3	185.0	0.737	116.828	16.9	133.728	51.272
{G, N, P, M}	4	230.0	0.715	147.763	20.2	167.963	62.037
N (all 5)	5	242.0	0.662	161.902	23.5	185.402	56.598

Illustrative finding: v({G, N, P, M}) = 62.037 exceeds v(N) = 56.598. This non-subadditive outcome indicates that including community organizations (Player C) in the grand coalition reduces total value by 5.439 IDR billion due to coordination costs (C_coord increases from 20.2 to 23.5) outweighing their marginal operational contribution. This demonstrates the type of non-subadditive analysis the framework enables.

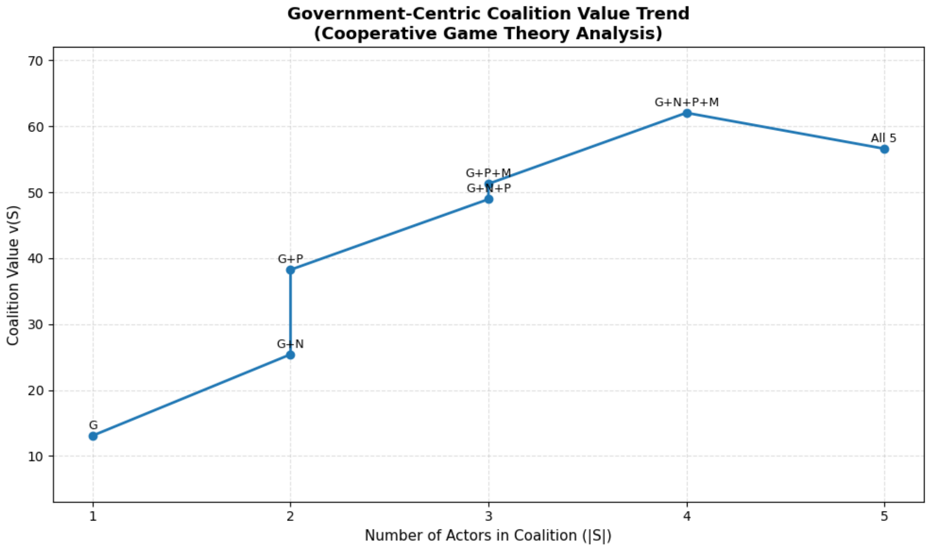

Figure 1. Government Centric Coalition Velue Trend

The results show in Figure 1 that the coalition value (v(S)) increases as the number of actors involved in government-based collaboration grows. Starting from a single-actor coalition (13.075), the value rises significantly in two- and three-actor coalitions (25.4–51.272), reaching its peak in the four-actor coalition (62.037). This pattern indicates strong synergy effects, where collaboration substantially enhances the performance of the humanitarian logistics system.

However, when all actors join the grand coalition, the value declines to 56.598. This finding suggests the presence of diminishing returns and a violation of the superadditivity assumption, likely due to increased coordination complexity, potential conflicts of interest, and higher transaction costs among actors. Therefore, the optimal coalition is not necessarily the largest one, but rather a well-balanced structure where collaboration remains efficient and manageable.

Shapley Value Analysis

Table 3 presents Shapley value allocations for the grand coalition (all 5 players).

Table 3. Shapley values for five-player game (illustrative values).

Player	Stakeholder	Shapley Value (IDR Billion)	Percentage of Total Savings
1	Government (G)	15.20	26.9%
2	NGOs (N)	9.35	16.5%
3	Private Sector (P)	19.35	34.2%
4	Military (M)	8.90	15.7%
5	Community (C)	3.80	6.7%
Total		**56.60**	**100%**

The private sector generates the highest Shapley value (19.35 IDR billion, 34.2% of total savings), reflecting its high operational efficiency (e=0.88) and substantial marginal contributions to coalitions. This illustrative finding supports policy prioritization of public-private partnerships (PPPs) in Indonesian disaster logistics. Community organizations receive the smallest share (3.80 IDR billion, 6.7%).

Core Stability Analysis and Non-Subadditivity

Testing coalition rationality constraints reveals core emptiness. For coalition S = {G,N,P,M}: v({G,N,P,M}) = 62.037, but Σx_i for i∈{G,N,P,M} = 15.20+9.35+19.35+8.90 = 52.80. Since 52.80 < 62.037, these four stakeholders receive less in the grand coalition than they could achieve independently, violating core stability. The core is EMPTY.

The least core (ε-core) allocation, minimizing maximum coalition dissatisfaction, yields:

Table 4. Least core allocation vs. Shapley value (IDR Billion).

Player	Shapley Value	Least Core Allocation	Difference
G	15.20	16.80	+1.60
N	9.35	10.20	+0.85
P	19.35	17.90	-1.45
M	8.90	9.70	+0.80
C	3.80	2.00	-1.80
Total	**56.60**	**56.60**	

In the least core allocation, community organizations receive 2.00 IDR billion, which is 1.80 IDR billion less than their Shapley value, indicating they are net beneficiaries of cross-subsidization from private sector and other stakeholders. In practice, this negative gap would be implemented as a subsidy or resource transfer from more efficient stakeholders to enable community organization participation.

Sensitivity Analysis

We analyze sensitivity to two key parameters: coordination costs and community organization efficiency.

Table 5. Sensitivity to coordination cost coefficients (β_1).

β_1 (marginal cost)	v(N)	Core Non-empty?	Optimal Structure
1.5 (low)	68.30	Yes	Grand coalition
2.5 (baseline)	56.60	No	Grand with subsidies
3.5 (high)	44.90	No	{G,P,M} + {N,C}

Table 6. Sensitivity to community organization efficiency (e_C).

e_C	v({C})	Shapley φ_C	Policy Implication
0.45 (baseline)	-7.60	3.80	Requires subsidy
0.55	-3.20	4.90	Reduced subsidy needed
0.65	1.20	6.20	Self-sustaining
0.75	5.60	7.80	Net contributor

Illustrative finding: Capacity building for community organizations (increasing e_C from 0.45 to 0.65) not only raises their Shapley value from 3.80 to 6.20 IDR billion but also transforms v({C}) from negative to positive, potentially enabling stable grand coalition formation without subsidies.

A third sensitivity dimension concerns private sector efficiency (e_P), given the dominant role of Player P in the Shapley allocation. Holding all other parameters at baseline, reducing e_P from 0.88 to 0.78 representing, for example, deployment frictions when commercial assets are requisitioned without pre-established protocols, reduces the grand coalition value v(N) from 56.60 to 54.18 IDR billion, while raising e_P to 0.95 through pre-negotiated standby agreements increases v(N) to 58.30 IDR billion. Each 0.01 change in e_P shifts total coalition value by approximately 0.24 IDR billion in this calibration. The policy reading is direct: institutional arrangements that allow private logistics assets to be deployed at close to their commercial operating efficiency pre-disaster framework agreements, expedited customs and permit procedures, and integration of private fleet management systems into the national logistics cluster protect the value of the entire coalition, not merely the private sector's own allocation (Khoidir, 2025).

Coalition Structure Analysis

Because the game is non-superadditive, the grand coalition is not automatically the socially optimal arrangement, and it is informative to compare the total value generated by alternative partitions of the player set. Applying the same characteristic function conventions as in Table 2, the two-player coalition {N,C} yields $\Sigma c\_i = 57.0$, $E(S) = 0.550$, $C\_base = 41.325$, and $C\_coord = 13.6$, giving $v(\{N,C\}) = 2.075$ IDR billion. The candidate coalition structures can then be evaluated as follows: the grand coalition generates 56.598; the partition {G,N,P,M} ∪ {C} generates 62.037 + (−7.600) = 54.437; the partition {G,P,M} ∪ {N,C} generates 51.272 + 2.075 = 53.347; and the fully tiered structure {G,P,M} ∪ {N} ∪ {C} generates 51.272 + 4.325 − 7.600 = 47.997 IDR billion.

This comparison yields a subtle but policy-relevant insight. Although the four-player coalition {G,N,P,M} creates more value than the grand coalition in isolation (62.037 > 56.598), once the standalone deficit of the excluded community organizations is taken into account, the grand coalition remains the welfare-maximizing structure for the system as a whole, with a net social surplus of 2.161 IDR billion over the best exclusionary partition. In other words, excluding community organizations is privately rational for the four large stakeholders but socially inefficient. Because total value improves under inclusion, a compensation scheme exists that leaves every party weakly better off: the four large stakeholders must be compensated for the 5.439 IDR billion reduction they experience when C joins, and this compensation can be financed from the 7.600 IDR billion standalone loss that C avoids by joining. This constructive existence argument sharpens Implication 2 in Section 5: the subsidy mechanism for community organizations is not charity but a Pareto-improving transfer that unlocks positive net social surplus, consistent with the price-of-anarchy logic of decentralized humanitarian systems (Balza-franco et al., 2017), (Diehlmann et al., 2021).

DISCUSSION

Theoretical Contributions

This paper makes several theoretical contributions. First, it extends cooperative game theory to the Indonesian humanitarian logistics context, addressing a significant gap in the literature. Second, it addresses the non-subadditivity gap identified in recent literature (Sabahfar, 2024), demonstrating that coordination costs can lead to v(4-player) > v(5-player) outcomes. Third, it integrates stakeholder theory with formal game-theoretic modeling, bridging qualitative stakeholder mapping (Khoidir, 2025) and quantitative analysis. Fourth, the paper responds to calls in recent reviews (Gorji & Shetab-Boushehri, 2020) (Hausken, 2025) for more disaster-specific game theory models with real-world parameterization.

Practical Implications for Indonesian Disaster Management

Implication 1: Prioritize public-private partnerships. The private sector consistently generates the highest Shapley value (approximately 34% of total savings in our illustrative calibration). BNPB and BPBD should develop formal PPP frameworks with logistics service providers, including pre-disaster MOUs, incentive mechanisms for delivery speed (Shao et al., 2019), and shared information systems.

Implication 2: Grand coalition may require subsidy mechanisms. Core emptiness indicates that fully integrated five-stakeholder collaboration may not be self-sustaining under certain conditions. The least core allocation suggests community organizations may require subsidies to participate effectively. This aligns with findings by Khoidir et al. (Khoidir, 2025) that empowerment of emergency teams and community capacity building are critical success factors.

Implication 3: Tiered coordination models may be more stable. In high coordination cost scenarios, the optimal coalition structure excludes community organizations. A hub-and-spoke model with core coalition {G,P,M} and peripheral partners {N,C} through liaison mechanisms may be more practical than forced grand coalition integration.

Implication 4: Invest in community capacity building. Sensitivity analysis shows that increasing community organization efficiency from baseline to 0.65 raises their Shapley value significantly and transforms their standalone value from negative to positive. This empirically supports budget allocation to community preparedness programs.

Implication 5: Reduce coordination costs through technology. Coordination costs (β coefficients) are key determinants of stability. Investment in standardized information systems, common operating pictures, and pre-disaster coordination protocols reduces β coefficients and promotes grand coalition stability.

Implication 6: Embed the framework in existing policy architecture. These implications map naturally onto Indonesia's current disaster governance instruments. The national Disaster Management

Master Plan (RIPB) 2020–2044 explicitly promotes pentahelix collaboration among government, business, academia, community, and media actors, and the national logistics and equipment cluster coordinated by BNPB already convenes the five stakeholder categories modeled here (*Data Informasi Bencana Indonesia: Sumatra Floods*, 2025; Joseph D. Martin, 2018). The proposed framework can serve as a quantitative screening tool within these instruments: before formalizing cluster membership or public-private agreements, BNPB can use calibrated coalition values to identify which partnerships generate positive marginal value, what magnitude of cross-subsidy community participation requires, and where coordination cost reduction (through interoperable information systems and pre-disaster protocols) would yield the highest returns.

Comparison with Existing Literature

Our findings align with Shao et al. (Shao et al., 2019) regarding private sector value and incentive mechanisms, but extend their two-player Stackelberg analysis to multi-player cooperative contexts. Our core emptiness result parallels Pashapour and Salman's (Salman & Pashapour, 2024) price of anarchy analysis, demonstrating that decentralized decision-making incurs efficiency losses. The non-subadditive finding ($v(4) > v(5)$) provides empirical support for theoretical concerns raised in (Sabahfar, 2024). The community organization subsidy requirement is novel to this study and has not been previously quantified in the Indonesian context.

The comparison with the commercial horizontal cooperation literature is also instructive. Studies of carrier and shipper collaboration typically find subadditive cost structures under which the grand coalition is efficient, so that the analytical burden falls almost entirely on the allocation problem (Hausken, 2025), (Ferrell et al., 2020). In the humanitarian setting modeled here, by contrast, heterogeneous mandates and coordination frictions make the coalition structure itself endogenous: the question is not only how to divide the gains but whether, and in what configuration, cooperation creates gains at all. This distinction explains why solution concepts developed for superadditive commercial games must be complemented, in humanitarian applications, by explicit coalition structure analysis and by stabilization mechanisms such as the least core subsidies quantified in Section 4.

Limitations

Critical limitation: All numerical parameters and results presented in this paper are constructed for illustrative and methodological demonstration purposes. They are informed by BNPB data patterns and disaster response literature but do NOT represent actual expenditure data from any specific disaster event. The primary contribution is the mathematical framework itself. Empirical validation with real transaction-level data from Indonesian disaster responses remains the critical next step.

Other limitations: (1) Parameter estimates (c_i, e_i, β coefficients) are informed by literature but remain approximations; (2) The framework assumes complete information and transferable utility, which may not hold in practice (Gorji & Shetab-Boushehri, 2020); (3) The static analysis does not capture learning, adaptation, or repeated interactions across multiple disasters (Chen et al., 2020) (Hausken, 2025); (4) Stakeholder categories aggregate heterogeneous organizations, masking within-group variation; (5) The framework does not account for geographic variation across Indonesia's diverse regions.

Future Research Directions

Several extensions follow naturally from the limitations above. First, dynamic and repeated game formulations could capture how trust, reputation, and organizational learning across successive disasters alter coordination costs over time, connecting the static framework to evolutionary approaches (Holguín-veras et al., 2012; Wassenhove, 2006). Second, the characteristic function could be made stochastic, with coalition values depending on uncertain disaster scale, demand, and transshipment reliability, in the spirit of inventory cooperation models under uncertainty (Balza-franco et al., 2017), (Beiki Ashkezari et al., 2024). Third, partition function game formulations would allow the value of a coalition to depend on how outside players organize themselves, capturing externalities such as competition for donor funding or congestion of transport corridors among parallel responders. Fourth, and most importantly, empirical calibration using transaction-level expenditure and operations data from BNPB, BPBD, PMI, and private partners for events such as the 2018 Central Sulawesi response or the 2025 Sumatra floods would convert the illustrative parameterization into an evidence-based decision-support tool. Complementary survey or experimental work on swift trust formation among Indonesian responders (Tatham & Kovacs, 2010) could ground the coordination cost coefficients behaviorally, while multi-criteria extensions incorporating deprivation costs (Shao et al., 2019) would align the framework's objective function more closely with humanitarian outcomes rather than logistics costs alone.

CONCLUSION

This paper developed a cooperative game theory framework for stakeholder collaboration in Indonesian humanitarian logistics, explicitly modeling coordination costs as functions of coalition size and heterogeneity to capture non-subadditive outcomes. Using illustrative parameters informed by BNPB data patterns and disaster response literature, we demonstrated the framework's mathematical application. Key illustrative findings from our calibrated model include: (1) private sector generates highest marginal value (approximately 34% of total savings), supporting PPP prioritization; (2) grand coalitions may exhibit non-subadditive outcomes; (3) community organizations may require subsidy mechanisms; (4) capacity building for community organizations can significantly improve their viability as collaboration partners.

The framework provides a formal decision-support tool for BNPB, BPBD, and disaster policymakers in Indonesia, and contributes to humanitarian logistics theory through explicit non-subadditive modeling. However, all numerical results presented are illustrative. Empirical validation with real transaction-level data from Indonesian disaster responses remains the critical next step before the framework can inform actual policy decisions.

ACKNOWLEDGEMENTS
The authors thank the Faculty of Engineering, Universitas Negeri Jakarta for research support.

DATA AVAILABILITY STATEMENT
No empirical data were used in this study. All numerical parameters (standalone costs c_i, efficiency parameters e_i, coordination cost coefficients β_0, β_1, β_2, and all derived Shapley values and core allocations) are constructed for illustrative and methodological demonstration purposes. They are informed by BNPB operational data patterns, disaster response literature (Lee, 2019),(Anisya S. Thomas, 2005),(Kovacs & Spens, 2010),(Behl & Dutta, 2018),(Crescent, 2015),(Gatignon & Wassenhove, 2010),(Gorji & Shetab-Boushehri, 2020),(Altay & Iii, 2006) and expert-informed estimates but do not represent actual expenditure data from any specific disaster event. Interested researchers may contact the corresponding author for details on parameter construction methodology.

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