Optimizing resource allocation and coordination in case of natural disasters using a game theory

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Abstract. Natural disasters, such as earthquakes, floods, and hurricanes, cause immense damage to lives and infrastructure, with traditional resource allocation methods often failing to address the urgency and equity required in disaster response. This research proposes a game-theoretic model to optimize resource distribution among key stakeholders, including government representatives, NGOs, private sectors, and affected populations. The model treats resource allocation as a strategic interaction, aiming to minimize unmet needs and maximize fairness. Using a cooperative approach, it incorporates equilibrium analysis and coalition formation to improve coordination. The Analytical Hierarchy Process (AHP) prioritizes regions based on disaster severity, population density, and accessibility, while a linear programming model ensures optimal allocation under constraints. A case study involving three regions with varying resource needs demonstrated the model's effectiveness in addressing shortages for two regions, though challenges persist for the most severely affected area. Results show that government representatives play a pivotal role, contributing the majority of resources with the highest operational efficiency (utility score >0.8). The study underscores the utility of game theory in disaster management, highlighting its potential to ensure timely, equitable, and efficient resource distribution. Future research could enhance the model by incorporating real-time data, multi-modal logistics, and dynamic resilience factors to address the evolving complexities of disaster scenarios. This framework offers a practical and scalable solution for improving disaster response and reducing the suffering of affected populations.

Keywords: Game theory, Resource allocation, natural disaster

1 Introduction

Natural disasters, do it correctly: earthquakes, floods, and hurricanes are among the most catastrophic events known to humanity wreaking havoc on humans and infrastructure. Due to climate change, these events have been on the rise and the United Nations informs that

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more than 200 million people are affected by natural disasters every single year resulting in an economic loss of around $520 billion worldwide[1]. After such cataclysms, due to the need for survival and recovery, people expect a quick relief response containing the provision of crucial items – mainly food, clothes, and medicine. For instance, during the earthquake in Haiti, which occurred in 2010, there were about 1.5 million displaced persons necessitating speedy delivery of humanitarian assistance including food and medicines[2]. The problem is how to provide appropriate coverage in several devastated regions with available resources and provide the necessary assistance to those who need it the most.

All the existing practices regarding resource distribution in times of emergency or disaster are still based on one or several major sources of control where all logistics are planned and strategically matured. These strategies are mostly based on the supply chain which was structured once for a purpose and it takes a lot of time to unlearn this when cellular situations since it is disaster-prone. Some of these methods are associated with serious constraints like low effectiveness in distribution and the absence of real-time information. A case study for example illustrated how it was possible to increase the suffering of affected people by giving them a delay of up to 30% for the resource supply, using traditional techniques[3]. Furthermore, several currently developed approaches do not sufficiently consider the competition for the same resources amongst the different participants such as government agencies, non-governmental organizations, and local communities.

This research explores how to fill these gaps using the functional approach in which game theory is applied in the management of resources in conditions of natural calamities. Game theory offers a broad perspective as it has been designed to simulate players competing over a limited number of resources that they are trying to optimize. This research will treat resource distribution and acquisition as a game and see how different stakeholders will be able to work together or against one another in order to achieve more favorable outcomes. One of the research tasks will be to create a multi-event crisis management model in which emergency locations are treated as players competing with each other over resources to be drawn from limited supply stations. The goal is to find feasible and fair strategies that provide for an equal division of resources and eliminate as much as possible other costs of a non-monetary nature associated with the acquisition of resources.

The importance of this research does not end with the theorization of new concepts as it has a bearing on the practical operation of disaster management teams and the communities affected. In particular, using the principles of game theory, this research intends to improve decision-making procedures in situations of crisis to advance the timely and effective distribution of resources. The effectiveness of coordinating among the various stakeholders of humanitarian response undertaking can thus assure a great reduction in response times and improvement in the overall effectiveness of the humanitarian action. In the end, this study intends to enable communities through the development of relevant tools and strategies that will allow them to be in a position to prepare and withstand the impact of natural disasters.

2 Literature review

Wang et al.[4] presents two possible concepts that were analyzed on how to tackle the problem of interdependent electric power and natural gas distribution systems (IENDS) on the back of evidence collected. The studies were able to identify cascading failures in the interdependencies amongst systems, especially the reliability of fuel supply for generators in case of emergencies. The authors have pinpointed the deficiencies in the coordination of available emergency resources including fuel resources, demand responses and repair work.

These difficulties led us to present a simple “supply-demand-repair” strategy, which combines fuel supply, electricity and gas demand reserve and facility maintenance into a single model. This problem was formulated mathematically by applying mixed-integer second-order cone programming (MISOCP) model to obtain the best decisions and not only on the possible local optima. The methodology has been confirmed within case studies of test systems with regard to IENDS providing efficient coordination of resources in the course of the recovery period after the disaster. The numerical results were then able to demonstrate the practical relevance of the proposed strategy in managing cascading failures. On the other hand, the study recognized gaps such as limited investigation of generators operating problems related to fuel supply and less effort in dealing with interaction among emergency resources during disaster stages.

Ebrahimi et al.[5] have researched on how resource allocation is done within the scope of organizational challenges with reference to resilience and business survival during calamitous situations. Some of the issues seem to be pertinent such as resource existence that is on the verge of abundancy due to ‘too much’ outputs and services, poor allocation of available resources and the potential of operation breaks as a result of catastrophic occurrences. To counter these challenges, the researchers sought to formulate a mathematics based model with the aim of global resource allocation and at the same time minimize the resilience deficiencies and maximize continuity. By means of the -constraint approach, the model has an organized methodology on how to efficiently use the scanty resources available while staying within some restrictions. The textile industry served as a proof of concept for the model as it was put to work and the results were impressive. When a model was applied to this industry, for instance, there was always recovery from work processes above the critical tolerance limits. Employing this approach made it possible to prevent large losses and damages by ensuring the constancy of the basic activities and processes in the period of a crisis. In spite of the validity of the model, more work is needed to assess the comprehensive applicability of the model across sectors and also integrate the concept of dynamic and flexible resource deployment at a time of changeable levels of crisis.

Wang et al.[6] focused on overcoming major challenges that burden resource management in steps of emergencies caused by natural disasters. The demand and supply of resources during post-disaster scenarios is vastly uncertain and dynamic. The authors identify key problems relating to the huge number of secondary disasters triggered by a single disaster (such as floods and landslides) and the deficiencies with traditional practice that sets successful completion of a single objective (such as a time, responsiveness, efficiency, fairness, etc) rather than multiple objectives. In this regard, the authors developed a multiperiod and multi-echelon multi objective emergency allocation model where an enhanced star algorithm is applied to single out mobility barrier obstacle and later Applied Multiobjective Cellular Genetic Algorithm (MOCGA) for better logistics outcome. The outcomes indicated an increase by 22.2 percent in the rate of total supply provided which signified the model has ability to improve the time and other factors in the logistics of emergencies. Besides, MOCGA with anticipation of A* in logistics was found to be relevant for utilization in reality scenarios and that vigorous systems are vital in logistics of disaster response. Still the study can improve on such gaps, like dealing with the multi-dimensionality of the second order scenarios or more complex ones , introducing resilience parameters together with risk ones or consideration on multi transport modalities for better allocation of existing resources.

The problem of resource allocation during natural disasters was highlighted in the work of Majumder et al[7], with the specific aim of discussing the fair distribution among limited resources such as helicopters, that are distributed amongst numerous crisis locations active at the same time. There are crisis locations (players, in game-theory terms) that are interested in acquiring resources and the non-monetary costs incurred while resources are acquired are also costs that were highlighted in this study. In order to do this, the authors formulated a non-cooperative game-theoretic model which allowed them to investigate the competition between various locations for limited supply and its allocation between the sites. Once Pure Strategy Nash Equilibria (PSNE) were not accessible, Mixed Strategy Nash Equilibria (MSNE) were also included, which gave the players the chance to opt for the actions depending on the probable events under uncertain conditions. The results showed that this approach guaranteed equity on the resources so as to sustain the requirements of the various locations. Moreover, the guidance from the MSNE was beneficial in resolving the issues emanating from competing want satisfaction. There were some shortcomings of the study such as only looking at helicopters as the one resource inputs to be used, while there are other important inputs in a disaster such as food supplies, medical supplies and personnel. Additionally, the other issues were the documented issues in terms of how a game theoretic approach would be employed in real world situations.

Chen et al.[8] have approached the overcoming the challenges associated with resilience enhancement of distribution networks (DN) in a composite manner during natural disasters by considering resource management both before and after a disaster. The authors suggest that improving the system's defenses entails optimal purchases of resources and their allocation prior to overhauls while designing intelligent recovery mechanisms to restore damaged systems. Acknowledging the absence of integrated methods that combine the two phases, decisions of multiple phases were coordinated by means of a game structure proposed. The model accommodates a multi-stage optimization that explicitly incorporates the uncertainty of repair time and availability of resources, thereby enhancing planning. The outcome demonstrated the simulation model's potential in producing "as good as" resource allocation plans, facilitating the reduction of expected power loss while decision-making time is significantly shorter than when conventional approaches are employed. Nevertheless, there are further areas for investigation, such as the extent to which the strategies employed pre and post disaster within existing studies have been integrated, the shortcomings observed in the multi-level optimization approaches, and the models that fail to account for the uncertainties surrounding the distribution and timing of repairs.

Chang et al. [9] examined the barriers standing in the way of the optimization of resource allocation performance from the point of cross disciplinary research, and looking at the resource sharing understanding of the operators where some visual insights are more powerful than others thus arguing that such measures might lead to uneven distribution. The study employed a game-theory analysis in formulating and testing a mechanism that deals with distribution of resources by employing the axiomatic approach in social choice which has principles such as level completeness, synchrony, interaction, and pure excessive equal symmetry to define a generalized power index. By developing simulations, the authors created the Multi-Weighted Influence Index (MWII) which could be used to get either a balanced or optimal outcome by weighing the activity level of the operators and how much they stand to gain. Research findings provided evidence on the sufficiency of the constructed policy in the balancing of the equilibriums and most importantly the problem of resource allocation in the overall perspective of the relationship between the operators had been solved. However, the research made observations about some gaps such as the idea of conducting deeper comparisons of the work done so far with the existing ones including those by Hwang and Liao, and the missing concepts of pure excess equal symmetry and level of synchronization axioms in the previous works. These gaps highlight areas that need further enhancement and incorporation of new concepts to optimize resource allocation in the conditions of asymmetry and multi-operators.

Shi et al.[10] provide an overall framework for dealing with emergencies occurring in Chinese coal mines by looking for gaps in the existing literature that include lack of coordination, change of behavior of interest groups , and divergence of local government and coal mining companies' interests and structures. The effect of these game-playing mechanisms in coal mine accidents is examined through an evolutionary game theory’s framework that explains the interdependence logic among the actors and stresses a game approach to decision-making and uses numerical simulation to examine critical aspects of such a game, the simulation model. The data collection finds that a well-developed information-sharing system is necessary for the swift handling of the incidents while the level of reduction of the emergency response costs will determine the level of proactive actions, in this case, time and resources invested by the coal mining companies. It is also argued that the local authorities must set up reconciliatory repayments and reward compensation policies for effective coordination to prevail. However, the research identifies some weaknesses in the literature, especially insufficient analysis of questions on interaction mechanisms of coal mine emergencies and substantial scope for new studies in dynamic behavior evolution of the interested parties.

Ghasemi et al.[11] do focus on important aspects in their work especially in tackling logistical challenges of humanitarian aid after earthquakes that encompass cost minimization, issue of unmet demand of relief supplies and problem of evacuation. It seems they want to allow as many people as possible to evacuate and to reduce the total costs related to relief supply chain including logistics costs and costs associated with provision of services but definitely allow some members of the affected community to get their unmet needs attended to however minimize the likelihood that people will be evacuating without using routes which are probably traversable. The research adds a novel component by presenting a broad range of researches and perspectives, including a stochastic multi-objective location-allocation-routing model encompassing pre and post disaster period concerns. To address this issue, the researchers use a simulation method to fit relevant distribution functions for food, water, medicine, and other important relief items that the population has need of. The model applies the Epsilon-constraint technique for solving small and medium-scale problems while large-scale problems were solved using meta-heuristic algorithms (NSGA-II, PESA-II, and SPEA-II.). The results obtained show that the resources available were properly utilized since survivors were able to find shelters and distribution centers which were easily allocated to them along the most efficient routes even in situations which were uncertain.

Wang et al,[12] emphasise on the key aspects of the emergency relief chains during the natural disasters focusing on the factors such as the uniform structure of relief stakeholders, absence of a viable coordinating mechanism and the use of geometric depictions of the disaster suffering areas in the decision-making processes. The paper notes the deployment of saving units on a systematic basis coupled with organizations of reserves to be detrimental to effective and efficient response regime, and that scant attention has been directed at the coordination-based pa’management parameters that are crucial in fostering effective response systems. The authors’ construct a two-level, multiphase emergency plan model which integrates a Multi-Objective Cellular Genetic Algorithm (MOCGA) to determine the best distribution of resources across different states during an emergency.

The model is confirmed to be true through numerical simulations which are particularly applied to flood relief in Hunan province of China. The findings of the study are that government-enterprise coordination is able to increase the efficiency and the economic effects of the use of the resources thus easing up the pressures on the supply. The optimal performance of the system in the ideal situation is achieved when the level of government coordination reaches the transitional middle level which greatly shortens the distance from which the resources are to be redistributed during the response.

Nguyen et al.[13] focus on the intricate variables that impede effective disaster management, resource allocation, data constraints, and complex assignment of time. The paper exposes the challenge of controlling resources during disaster events due to the fast changing and unpredictable conditions in which resources are located, where even geographical barriers render traditional ways of resource allocation useless and ineffective. It also points out the lack of enough data in the beginning of a disaster making any decision-making without sufficient data nearly impossible. In addition, the disaster management scheduling problem does not have a clear objective function which makes optimization even more difficult. The researcher shows how the heuristic multi-agent reinforcement learning algorithm, ResQ, recognizes victims and potential helpers on Twitter and successfully coordinates rescue operations using advanced learning. The findings also confirm that ResQ provides a higher rate of recovery of the volunteers' assets and reduced attached response time compared to the search strategies that were relied on in the past. Validation with real data emphasizes the practical applications of the algorithm in disaster events.

Choksi et al.[14] consider several issues regarding resource management in post-disaster situations such as efficient allocation of resources, particularly over demand and under demand of resources, and task scheduling. The paper underscores the necessity of having adequate resources in the right places in advance in order to avoid deaths and injuries as well as loss of property in the event of a disaster while addressing issues like resource balance. The effective performance of task scheduling is also considered important in normal operational situations. The approach employed contains a multiobjective allocation resource allocator that sets some requirements as priorities, including those offered in the resource and a priority scheduling mechanism for dealing with over demand cases. The proposed algorithms are evaluated with the help of simulation, the outcome showing that this new approach is more effective than the traditional ones, as all resources are effectively used, and tasks are completed in least time possible. The study also indicates that the algorithm meets the requirements of demand over the various equipment locations in the system and solves the most relevant requirements. In the meantime, the paper does point out some gaps in the research, such as the ability to broaden the scope of the algorithm by adding more parameters suitable for various developing events, as well as the ability to further test the method in terms of a wider scope of developing situations in order to strengthen the evidence for its robustness.

Wang et al.[15] disorders similar challenges concerning the specific allocation of emergency resources. These include efficiency as opposed to equity, the issue of increasing the number of stages of the resource allocation process, and the issue of resource availability. Existing models always use efficiency or fairness as the encompassing rationing principle which is especially the case for implementing large scale disasters. Some researchers also propose multiobjective optimization models and allocate resources according to their scarcity and resources only after ensuring equity in decision making. The authors applied the Particle Swarm Optimization method to solve the model and verified it with several case examples including that of the Ya'an earthquake in China. The results of the analysis suggested that the fair distribution of available resources is ensured regardless of the intervention constraint. Also, the model addresses a number of the development challenges in the region. However, the transportation cost may pose a problem to fairness and supply conditions. It should be noted that this article provides the reasons for the gap in the literature such as shortage of research on the issues of fairness in resource allocation, few studies on multilevel allocation issues informed us about the fairness and especially, the insufficient analysis of transport costs on the fairness of allocation.

Resources management in disaster situations has been identified by Wang et al.[16] as an acute problem with a set of tasks that include: cross-regional allocation models, equity-emphasis, and resource allocation that is long-term. Views that balance optimization and equity are rare, because they are general, and the existing approaches are unable to manage cross-regional emergency needs and response on earthquakes and therefore do not make economic sense. This situation arises when it paves the way for interactively choosing between competition for efficiency and cooperation for distributing resources appropriately; it is easy to see that both cannot be satisfied within the constraints of a static framework, particularly inter-temporal interactions. To solve these conflicts the authors developed a 'multiperiod and multiobjective' model that allows for both self-rescue and inter-rescue. At the end, their goal under this new optimization paradigm was to minimize delivery time, keep costs low and at the same time, raise coverage rates. The algorithm OWFA-TDED deals with such optimization problems in which the preferences of decision-makers are taken into account. The model is tested using data from actual disaster situations, including during the Wenchuan Earthquake. The authors also analyze the issues of practicality. The model developed enabled the optimization of cross-regional multiperiod allocation, under which the range of equity bias was lowered, dissatisfaction on the supply side was reduced, and overall improvements in terms of losses were observed.

Xiao-Bing et al.[17] focus on the problem of distribution of resources within limits, the use of competing interests of various stakeholders, and optimization problem complexities. The authors state that limited resources and differences in interests such as that of local government, farmers, and insurance companies add to the intricacy of the system. However, most existing approaches are able to achieve certain slices of the Pareto optimal surface, but not the entire area which includes all the solutions needed for the competition. To cope with these drawbacks, a new approach based on multiobjective optimization problems MOOP is proposed where ripple-spreading algorithm models with the aim to evaluate the entire pareto front. This novel framework provides complete access to all optimal solutions instead of approximations as on most-available approaches. The case study results on agriculture risk governance ARG demonstrate the efficiency of the developed methodology and its better performance. The findings indicate that the proposed scheme improves decisions by providing a better fit of the solutions to stakeholder needs thereby enhancing the resource allocation process.

Sutter et al.[18] examine primary failures in disaster relief with emphasis on the government and private sector, looking at which gets the job done better. Most of such claims tend to be fraudulent, as disaster relief agencies insist on imposingly precious resources. Moreover, local facts are sometimes not paid enough usage such that assistance is required too late. Then the paper looks into these problems by analyzing cases such as FEMA, the Coast Guard and and the literature by exposing differences in the incentives and the operations between public and private sectors. The study notes some critical implications of prior local knowledge on the effectiveness of response to disasters. The evidence suggests that government agencies and other private sector actors such as non-profit organizations provide services that can be termed as community-based and tend to be more effective than the government. The research also notes that price gouging laws have unintended consequences that add more complexities to the management of resources in the course of a disaster. With these conclusions in mind, however, some gaps in the research are underlined, such as too little effort devoted to a comparative analysis of the role of incentives and knowledge, and more work required in applying local knowledge when developing policies [19, 20].

Based on the literature review it was evident that the approach of the game theory to solve the issue of the resource location at the time of natural disaster was used by many researchers. However, the researcher hasn't forced much on the stakeholders and their dynamic behavior while considering the resource allocation and their overall allocation in terms of quantity. This research will focus on the stakeholder's consideration while preparing the game theory as well as the model solution in terms of the stakeholder limitations for the resource allocations. To do this next section gives the game theory model.

3 Methodology

Step 1:- Problem Formulation

In the first step, a problem of the natural disaster was defined with the stakeholders who can supply the resources in case of natural catastrophic damages.

A. The stakeholders are (Players of the Game):
-Government representative (GR): The authority from the government who are resource providers in case of natural disasters.
- Non-Government Organizations (NGOs): This is the team who comes forward in case of emergency.
- Private Sector (PS): Contributing logistics and funds.
- Affected Population (AP): The end user of the resources.

B. Objective Function:
The main objective of this theory is to minimize the suffering of the people by providing the resources that they need with minimum time and optimizing allocation. The mathematical expression of the same is given in the equation 1. The main assumption of the equation is available resources are always equal to or more than they need to allocate.

$$\min S = \sum_{i=1}^{n} (N_i - R_i)^2 \tag{1}$$

$$\text{provided } R_i \leq A_i \tag{2}$$

Where:
N_i : Resource needs of region i.
R_i : Resource allocated to region i.
A_i : Availability of resources for region i.

Step 2:- Modeling the game
Initially The game was considered as the non-cooperative strategy with m players. The action space for the player is explained below.

A. Action space for players: Each player p selects an allocation strategy a_p from their feasible set A_p^ , the mathematical relationship between the above two parameters is shown in equation 3.

$$a_p \in A_p \tag{3}$$

B. The function of the player in case of the Payoff: The utility U_p for player p depends on their operational efficiency and satisfaction with resource distribution. Equation 4 shows the relationship between the utility and the parameter which depends on the utility of the player.

$$U_p = \sum_{i=1}^{n} f_p(R_i) - \rho C_p(a_p) \tag{4}$$

Where:

- f_p (R_i) : Satisfaction function of resources allocated to regions i.
- p : Weighting factors representing player p's priorities.
- C_p (a_p) : Cost of strategy a_p.

Step 3:- Equilibrium Analysis

This step of the method talks about a point in the game where changing the strategy of the player doesn't give any incentive. Hence the Nesh equilibrium can be given in the form of equation 5. Where each player's strategy a_p^* satisfies:

$$U_p(a_p^*, a_{-p}^*) \geq U_p(a_p, a_{-p}^*) \quad \forall a_p \in A_p \tag{5}$$

Where,
a_p* represents the strategies of all other players.

However, equation 5 can't be quantified with the exact value of the allocation due to the few constants required in the equation. Hence step 4 gives the cooperative game approach for optimal coordination.

Step 4:- Cooperative Game Approach for the optimum condition

A. Coalition formation: In this step, a coalition between the stakeholder and resource allocation will be analyzed using equation 6.

$$\phi_p = \frac{C!(N - C - 1)!}{N!} [v(C \cup \{p\}) - v(C)] \tag{6}$$

Where, ν(C) is the value of the coalition and C = {GR, NGO's and PS}.

Step 5:- Linear programming Formulation: Optimize resource allocation ⟦R_i⟧_ under constraints:

$$\max \sum_{i=1}^{n} U(R_i) \quad \text{provided } R_i \leq A_i \quad \text{and } \sum_{i=1}^{n} R_i \leq T \tag{7}$$

Further, the weightage for each of the parameters will be assigned using the AHP method (Analytical Hierarchy Process)

- Severity of the disaster s_i
- Population density P_i
-Accessibility A_i

Equation 7 shows that resource allocation depends on the available resources with all the stakeholders, which are always more than needed. Where T is the total available resources.

Further, the dynamic payoff adjustment can be written by equation 8.

$$U_p^{t+1} = U_p^t + \eta U_p \tag{8}$$

Where, γ is the learning rate. Which shows the continuous additional resources based on the number of additional stakeholders. Further, to test the efficiency of the model a case study has been formed, and the results of the same are written in the next section of the research.

4 Results and discussion

To test the efficiency of the model a case study has been created and the data of the same is presented in this section.

Regions and resources needs:

- Regions A: Needs 100 units of the resources
- Regions B: Needs 150 units of the resources
- Regions C: Needs 200 units of the resources

Available Resources:
- Total Resources: 350 units.

Players (Stakeholders):
- Government Representative: 200 units available
- NGO’S: 100 units available
- private sector (PS): 50 units available

Priority Factors (via AHP):
- Region A: 0.3
- Region B: 0.4
- Region C: 0.4

This show that the region B and C are more important then the region A.

Further the model Formulation:
Objective function:

$$\min S = \sum_{i=1}^{3}(N_i - R_i)^2 \tag{9}$$

Equation 9 shows the function to minimize the unmet need and maximize the equitable distribution. Whereas the constraint equation 10 shows the need is always equal to or less than the available resources.

$$R_A + R_B + R_C \leq 350 \quad \text{and } R_i \leq N_i, \quad \forall i \in \{A, B, C\} \tag{10}$$

Now based on the model the results are plotted in terms of the graph shown in the figure 1 below.

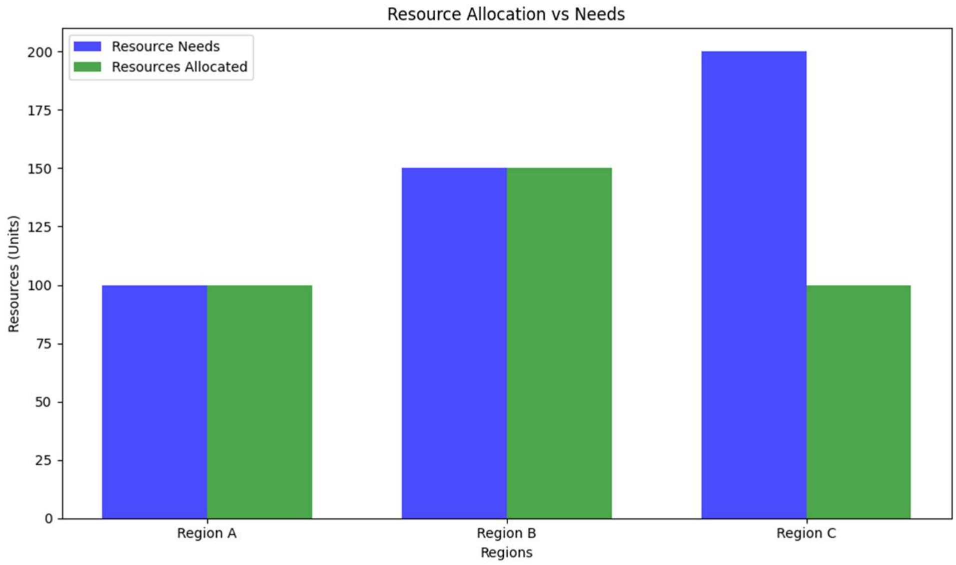

Fig. 1. Resources allocation Vs needs

Figure 1 shows that resource allocation using the model suggested by this research can mitigate the needs of regions A and B but is not able to fill the needs of region c due to undefined reasons. Whereas figure 2 shows the utility of the resources from all stakeholders. Based on figure 2 it says that government representatives are providing maximum utility which is more than 0.8.

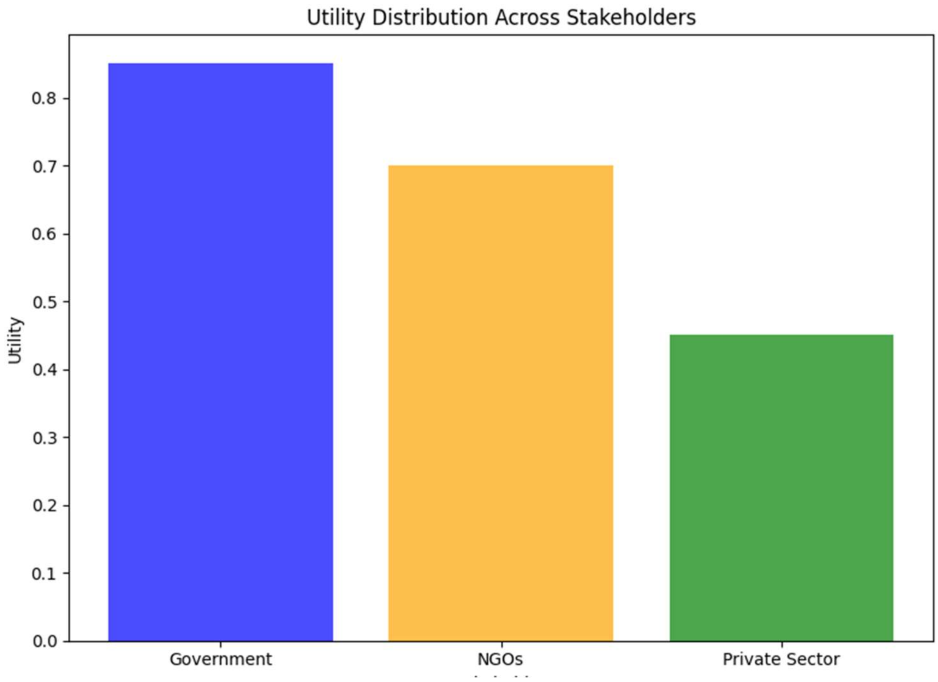

Fig. 2. Distribution of the resources among the stakeholders.

5 Conclusion

This study demonstrates the potential of a game-theoretic approach for optimizing resource allocation during natural disasters. By modeling stakeholders—government representatives, NGOs, and private entities—as players with defined action spaces, the proposed framework achieves a balance between efficiency and equity. The results from the case study, involving regions A, B, and C with respective needs of 100, 150, and 200 units against an available resource pool of 350 units, validate the model's efficacy. The allocation strategy effectively mitigates the resource demands of regions A and B but highlights challenges in fulfilling the needs of Region C. Stakeholders such as government representatives achieved the highest utility (0.8), underscoring their critical role in resource distribution. The cooperative game approach, complemented by linear programming and AHP weighting, ensures dynamic adjustments and equitable distribution based on severity, population density, and accessibility.

Future research should explore integrating real-time data from IoT and machine learning to enhance decision-making accuracy and address dynamic crisis scenarios. Additionally, incorporating multi-modal transportation logistics and resilience factors would further strengthen the model's adaptability to complex disasters.

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