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Effective Distribution of Primary Relief Supplies in Post-Disaster Scenarios

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Abstract

The frequency, severity, and impact of natural disasters are increasing globally, posing significant risks to both human lives and economic systems. Rising population density and the expansion of high-risk areas have further exacerbated the destructive consequences of these events. Earthquakes, in particular, represent a critical threat to densely populated regions, requiring the development of effective disaster response strategies. In this study, an optimization model was developed to ensure the fastest and most efficient delivery of aid materials stored in AFAD warehouses to the affected regions of Bingöl. In order to better represent local aid demands, Bingöl province was divided into 52 regions based on neighborhood proximity and population density. To avoid logistical complexity, the model ensures that each region receives aid from a single warehouse. It optimizes the timely and accurate distribution of five aid types (tents, beds, bed sets, heaters, and kitchen sets) by considering warehouse capacities, locations, available resources, geographical accessibility, and road conditions. The model was tested under two different scenarios to determine optimal warehouse-to-region assignments and was solved using IBM ILOG CPLEX software. According to the results, a total of 470,271 aid items were delivered using 525 vehicles, with each vehicle serving an average of 377 people. In this context, the model aims to accelerate post-disaster response, prevent potential complexity in aid distribution, and minimize human losses.

Key words: Disaster management, AFAD warehouses, Emergency logistics, Humanitarian logistics, Optimization.

1. Introduction

Rapid and effective distribution of aid during disasters is crucial for meeting the basic needs of affected individuals. The success of post-disaster aid distribution depends not only on having sufficient resources but also on the swift delivery of these resources to the areas in need. In this context, the location, capacity, and logistics strategies of the warehouses used in the distribution process play a key role in managing the disaster effectively.

Delivering aid to victims is one of the fundamental response activities after a disaster. Alongside aid materials pre-stocked by governments and non-governmental organizations (NGOs) or procured after the disaster, individuals also provide in-kind donations to support those affected. However, only a portion of these donations is suitable for meeting urgent needs [1, 2].

When disasters occur—whether natural or industrial in nature—humanitarian aid operations are promptly initiated to remove the deceased, rescue the injured, distribute supplies, and provide shelter and medical assistance. Delays in the delivery of supplies or the provision of aid in such

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situations can result in loss of life. Thus, humanitarian logistics is vital for the effectiveness of a relief effort, as it ensures the flow of goods and services in the supply chain [3].

Aid distribution is a core task during the post-disaster response phase, addressing the needs of affected areas and mitigating the impact of disasters [4]. The efficiency of aid distribution is influenced by two main factors [5], the pre-positioning location and quantity of emergency supplies, and operational efficiency in establishing distribution centers and conducting sorting, collection, loading, and unloading activities. As the location and quantity of emergency supplies are predetermined, establishing temporary cross-docking centers to expedite sorting, collection, loading, and unloading processes is critical for enhancing the efficiency of aid distribution [6].

Additionally, disruptions in communication and transportation infrastructure will make accessing information more challenging; hence, decisions made post-disaster will be built upon uncertainties, such as the extent of emergency aid required and the time it will take for aid to reach the affected areas [7]. This highlights the increased importance of strategic planning under uncertain conditions for post-disaster aid distribution.

Infrastructure networks, including the affected areas, shelters, warehouses, centers, and distribution points, play a vital role in delivering humanitarian aid to demand points [8-10]. These networks facilitate the connection between government and non-governmental organizations, enabling the mobility of resources and access to critical facilities during times of need [11, 12].

Another significant concern in post-disaster humanitarian logistics is the ability to sustain operations under conditions of scarcity. Disasters can devastate materials and resources within affected communities, and the flow of critical supplies from external sources may be delayed. This leads to survivors being deprived of critical materials that would ordinarily be readily available [13]. Therefore, ensuring rapid and sufficient access to resources under scarcity conditions is a critical factor for the success of relief efforts.

This study focuses on matching the regions in need with provinces providing aid in the case of Bingöl Province. It aims to propose a planning model for directing post-earthquake aid to ensure the appropriate quantity of aid is delivered to the right locations at the right time. Through the proposed mathematical model, the study seeks to facilitate the delivery of post-disaster aid to the regions in need, minimizing the impacts of the emergencies brought by disasters. Comprehensive analyses are conducted to determine the affected regions, prioritize their needs, and match them with donor provinces. Key steps in this process include identifying the impacted areas, ensuring the accessibility of aid, determining the priority of needs, and considering geographical and logistical factors.

The rest of the paper is structured as follows: Section 2 reviews the literature on post-disaster humanitarian logistics, with a focus on emergency logistics and the methodological approaches commonly adopted in this field. Section 3 outlines the problem definition, the data required for the mathematical model and the model itself. Section 4 presents the implementation results of the proposed model. Finally, Section 5 provides conclusions, managerial implications for decision-makers and directions for future research.

2. Literature Review

To position this study and highlight its contribution, we review the literature on humanitarian aid logistics management, addressing logistical system design issues and related methodological approaches explicitly.

Several studies have been conducted to solve models under uncertainty. For instance, [14] developed mathematical models for scheduling and routing land and air vehicles with a dual objective of efficiently providing telecommunications capabilities and emergency supplies. They found that the column generation (CG)-based computational approach outperformed exact methods in solving the MILP model proposed for the two-stage decision framework. [15] presented a comprehensive mixed-integer linear programming (MILP) model to integrate pre- and post-disaster decisions in humanitarian supply chain (HSC) design, considering quantitative flexibility contracts and equitable distribution of aid materials under uncertainty for potential disasters like floods and earthquakes. [16] addressed disaster relief logistics (DRL), providing adequate aid materials to disaster victims. They explicitly considered supplier selection and inventory, corresponding to static preparedness decisions and dynamic post-disaster purchasing and delivery, formulating a risk-averse two-stage distributional optimization (DO) model to tackle uncertain dynamic DRL with incomplete distribution data. [17] examined a highly integrated humanitarian aid network design problem under the adverse effects of disasters, where network reinforcement planning and inventory prepositioning arrangements are optimized collaboratively. Based on problem structure and decomposition optimization, they proposed both exact and heuristic approaches to solve bilinear subproblems. Taking into account hybrid uncertainties in demand and travel time, [6] developed two mathematical models to optimize post-disaster relief kit assembly and distribution, aiming to minimize total cost and maximize demand satisfaction.

Emergency management has always been a prominent topic for researchers, as it is a discipline that prepares for, responds to, and aids in the reconstruction of communities after disasters. For example, [18] developed a resilient aid supply plan by creating an integrated supply-storage model, specifically designed to determine the integrated aid supply-storage plan using a portfolio of supply sources. [19] evaluated aid centers for flexibility and efficiency in housing the injured and sick under disaster and pandemic conditions by applying Geographic Information Systems (GIS) and multi-criteria decision-making (MCDM) according to standard criteria. [20] developed an integrated decision-support framework containing a model-based data propagation component to coordinate damage assessment, road repair, and aid distribution in real time during the disaster response phase. [21] proposed a dynamic prepositioning strategy to efficiently meet the needs of victims under uncertain and dynamic demands within the humanitarian aid context. [22] contributed to a better understanding of disasters, disaster preparedness, post-disaster recovery, and production efficiency in Caribbean firms, examining the impact of a firm’s disaster preparedness and post-disaster recovery strategies on technical efficiency using Stochastic Frontier Analysis (SFA). [23] presented a technique for extracting information from primary social media sources to find and distribute critical aid needed in emergencies and disaster situations. [24] examined emergency resource allocation and vehicle routing in post-disaster emergency management, which are the fundamental and inseparable response actions. They proposed individual and joint chance-constrained programming DSO models for multi-period emergency resource allocation and vehicle routing under demand distribution uncertainty, uncovering managerial insights that could be valuable for disaster response operations. [25] focused on the three-dimensional objectives of efficiency, effectiveness, and equity in humanitarian logistics. They proposed an emergency material allocation model with multiple rescue sites, affected sites, and periods, meeting the requirement for timely emergency distribution and providing decision-makers with a rapid distribution plan.

Although the issues related to undesired materials or material convergence post-disaster and the challenges caused by useless donations are strongly emphasized in the literature, only a few studies address how to tackle these issues. For instance, [2] proposed a classification process as an intermediate step in the flow of donated aid, in addition to suggesting a greening strategy for needed materials to be sent to aid organization warehouses for later use in other disaster situations. In this context, they focused on the economic and environmental dimensions of sustainability among the three pillars of sustainability: economic, environmental, and social. [26] developed a two-stage stochastic programming model and solution method to assist decision-makers in preparing for and addressing the logistics of aid material distribution after a major earthquake. [27] focused on the design of a three-layered network to support short-term recovery under demand and capacity uncertainty, aiming for the distribution of critical materials to affected populations post-disaster. [28] presented disaster conditions where multilevel networks support aid mode strategies based on predicted demand, focusing on an analytical solution to determine if these strategies contribute to providing aid based on forecasted demand. [29] proposed a five-step procedure to generate and analyze earthquake disaster scenarios at the block level in urban areas, allowing for rapid response planning by estimating the amount and location of aid demand for each scenario. [30] introduced the socially costly vehicle routing problem: a mathematical optimization model that considers social costs to determine the right mix for transporting, routing, and delivering critical material. Due to the NP-hard nature of the problem, they developed a hybrid metaheuristic algorithm with a novel local search to solve it. [31] a distributionally robust optimization model (DROM) is developed to optimize relief distribution and facility locations while minimizing costs and addressing uncertainties.

Makes a significant contribution to the existing literature by introducing a novel model that optimizes post-disaster humanitarian logistics. While various optimization models for disaster aid distribution exist in the literature, the proposed model is uniquely developed based on AFAD warehouses, presenting an original application within the context of disaster management in Türkiye. Unlike most existing studies that focus on general humanitarian logistics, this model optimizes aid distribution processes for a specific region in detail, simplifying logistical coordination by ensuring that each region receives aid from only one warehouse, considering the worst-case scenario. Additionally, it integrates critical factors such as geographical accessibility, road conditions, and warehouse capacities directly into the modeling process, providing a realistic and practical solution. The most significant innovation of this study is its flexible structure, which is tested under different scenarios to adapt to varying disaster conditions. With these features, the model offers strategic insights for decision-makers in disaster management, contributing to the acceleration of post-disaster aid distribution, the minimization of victimization, and the more efficient management of logistical processes.

The studies reviewed in the literature are summarized in Table 1, organized by disaster phase—pre-disaster (PreD) and post-disaster (PoD)—and types of aid provided.

Table 1. Summary of humanitarian aid logistics optimization models

Author(s)	Phase		Type of Aid											
	PreD	PoD	Water	Food	Aid Kit	Hygiene Kit	Shelter	Tent	Clothing	Blanket	Bed	Bed Set	Heater	Kitchen Set
Faiz et al. [14]		✓	✓	✓	✓									
Modarresi and Maleki [15]	✓	✓	✓	✓	✓			✓		✓				
Wang et al. [16]		✓	✓	✓	✓			✓		✓				
Zhang et al. [17]	✓	✓	✓	✓	✓			✓	✓					
Zhang et al. [6]		✓			✓									
Aghajani et al. [18]	✓	✓	✓	✓										
Choukolaei et al. [19]		✓		Location of Aid Centers										
Farzaneh et al. [20]		✓		✓	✓		✓							
Hu et al. [21]		✓	✓	✓	✓									
Mohan [22]	✓	✓		Unspecified										
Vishwanath et al. [23]		✓		Unspecified										
Wang et al. [24]		✓	✓	✓	✓	✓	✓	✓	✓	✓				
Wang and Sun [25]		✓	✓	✓				✓		✓				
Alegoz et al. [2]		✓		High-Priority Items										
Chang et al. [26]		✓	✓	✓						✓				
Daneshvar et al. [27]		✓		✓		✓	✓							
Kawase and Iryo [28]		✓		Unspecified										
Mota-Santiago et al. [29]		✓		Unspecified										
Sadeghi et al. [30]		✓	✓											
Wang et al. [31]		✓		Unspecified										
This paper		✓						✓		✓	✓	✓	✓	✓

3. Materials and Method

In this study, a mathematical optimization model has been developed to ensure the effective and timely distribution of relief materials stored in AFAD warehouses to the disaster-affected regions of Bingöl province. In the initial phase of the study, data on the locations, storage capacities, and types of relief supplies available in AFAD warehouses were collected. This data formed the foundation for constructing the optimization model. The primary objective of the model is to assign each region to a single AFAD warehouse, taking into account warehouse capacities, geographic proximity, and the diversity of aid materials (tent, bed, bed set, heater, kitchen set).

The problem was formulated as a deterministic linear optimization model with binary decision variables that indicate whether a region is assigned to a specific warehouse. The model was solved using IBM ILOG CPLEX Optimization Studio version 22.11.

Additionally, the study considers the possibility that some warehouses may become inoperable due to damage during a disaster, and an alternative scenario was developed to prevent potential disruptions in aid delivery and minimize victim impact.

3.1. Problem definition

This study was developed in response to the challenges encountered during the distribution of relief supplies following the most recent major earthquake in Türkiye, and it was applied specifically to Bingöl province, which is classified as a high-risk earthquake zone. In this context, a mathematical optimization model was developed to ensure the effective and timely distribution of relief materials stored in AFAD warehouses to the disaster-affected regions of Bingöl. The model was solved using IBM ILOG CPLEX Optimization Studio. IBM ILOG CPLEX is an optimization software designed to solve linear, integer, and quadratic programming problems.

The primary objective of the model is to assign each region to a single AFAD warehouse while determining the most appropriate distribution plan by considering various factors such as the diversity of aid types (tent, bed, bed set, heater, kitchen set), warehouse capacities, geographical distances, and transportation constraints. The model minimizes the total transportation distance while ensuring that the aid demands of all regions are fully met without exceeding the warehouse capacities.

During the modeling process, logistical constraints were also taken into account. These include the limited number of available vehicles, road distances calculated using GIS data, and the volume of each type of aid item. Each vehicle is assumed to have a maximum carrying capacity of 90 m^3. The volume of aid items was estimated based on average packaging dimensions used in previous earthquake relief operations.

To evaluate the robustness and practical applicability of the model, two different scenarios were analyzed:

Scenario 1: A scenario in which all 22 AFAD warehouses are actively involved in the distribution of aid.

Scenario 2: A scenario in which the warehouses located in provinces expected to be affected by the earthquake (Elazığ, Erzincan, Erzurum, and Muş), as identified in the AFAD Provincial Risk Reduction Plan (IRAP) [32], are excluded from the aid distribution process.

3.2. Data collection

In this study, data required to optimize aid distribution to Bingöl province were carefully selected and collected from various sources. These data enabled the accurate determination of the model's parameters and constraints. Below, the types of data used and the process of obtaining them are detailed:

Annexes 1 and 2 analyze the most affected provinces for Scenarios 1 and 2.

AFAD Warehouse Data: The data regarding the locations, capacities, and types of aid stored in AFAD warehouses, which will be used in aid distribution, were obtained from AFAD's official resources and sources identified through a literature review. These sources provide detailed information on the types of aid available at each warehouse and their respective capacities. The collected data were utilized in forming the model's "warehouse capacities" and "aid types" constraints.

AFAD has established 27 logistics warehouses across Türkiye. Table 2 shows the quantities of disaster relief aid materials stored in warehouses located in 22 provinces [33, 34].

Table 2. AFAD Warehouse capacity information [33, 34]

Province	Number of Container	Tent	Bed	Bed Set	Heater	Kitchen Set
Adana	96	48000	115200	192000	69120	138240
Adıyaman	48	24000	57600	96000	34560	69120
Afyonkarahisar	96	48000	115200	192000	69120	138240
Balıkesir	48	24000	57600	96000	34560	69120
Bursa	48	24000	57600	96000	34560	69120
Denizli	96	48000	115200	192000	69120	138240
Diyarbakır	48	24000	57600	96000	34560	69120
Elazığ	48	24000	57600	96000	34560	69120
Erzincan	48	24000	57600	96000	34560	69120
Erzurum	96	48000	115200	192000	69120	138240
Kastamonu	48	24000	57600	96000	34560	69120
Manisa	96	48000	115200	192000	69120	138240
Kahramanmaraş	96	48000	115200	192000	69120	138240
Muğla	48	24000	57600	96000	34560	69120
Muş	96	48000	115200	192000	69120	138240
Samsun	96	48000	115200	192000	69120	138240
Sivas	48	24000	57600	96000	34560	69120
Tekirdağ	96	48000	115200	192000	69120	138240
Aksaray	48	24000	57600	96000	34560	69120
Kırıkkale	48	24000	57600	96000	34560	69120
Yalova	48	24000	57600	96000	34560	69120
Düzce	48	24000	57600	96000	34560	69120

Regional Aid Needs: The population density, demographic characteristics, and potential post-disaster aid needs of Bingöl's districts were extracted from official reports provided by the Turkish Statistical Institute (TÜİK) and local administrations. The needs for different types of aid for each region (B) were analyzed and used as the "regional needs" parameter in the model. The demand quantities required by the regions were determined based on the per-household aid distribution rates announced by AFAD during the last major earthquake, which were then scaled according to the demographic structure of Bingöl province. Additionally, considering the possibility of extraordinary situations, estimated demand values were calculated with a safety margin. Warehouse capacities were planned to meet demand even in worst-case scenarios and were modeled with a capacity exceeding normal demand levels. Furthermore, regional demand calculations were proportioned to the population and set at approximately twice the estimated need, creating an additional safety margin to accommodate sudden increases. As a result, the dataset was structured to ensure that aid is delivered in a timely and sufficient manner. Table 3 presents the needs of the regions.

Table 3. Need capacity of the regions

	Tent	Bed	Bed set	Heater	Kitchen set		Tent	Bed	Bed set	Heater	Kitchen set
B1	458	3666	3666	458	458	**B27**	630	5040	5040	630	630
B2	424	3390	3390	424	424	**B28**	536	4286	4286	536	536
B3	623	4980	4980	623	623	**B29**	536	4286	4286	536	536
B4	623	4980	4980	623	623	**B30**	536	4287	4287	536	536
B5	438	3501	3501	438	438	**B31**	536	4287	4287	536	536
B6	438	3501	3501	438	438	**B32**	536	4287	4287	536	536
B7	454	3634	3634	454	454	**B33**	507	4055	4055	507	507
B8	471	3766	3766	471	471	**B34**	507	4055	4055	507	507
B9	356	2844	2844	356	356	**B35**	507	4055	4055	507	507
B10	465	3720	3720	465	465	**B36**	507	4055	4055	507	507
B11	465	3720	3720	465	465	**B37**	404	3230	3230	404	404
B12	483	3863	3863	483	483	**B38**	404	3230	3230	404	404

Table 3. Need capacity of the regions (continued)

B13	460	3678	3678	460	460	**B39**	382	3052	3052	382	382
B14	460	3678	3678	460	460	**B40**	382	3052	3052	382	382
B15	460	3678	3678	460	460	**B41**	523	4182	4182	523	523
B16	690	5521	5521	690	690	**B42**	523	4182	4182	523	523
B17	509	4075	4075	509	509	**B43**	408	3262	3262	408	408
B18	528	4223	4223	528	528	**B44**	331	2648	2648	331	331
B19	528	4223	4223	528	528	**B45**	335	2683	2683	335	335
B20	528	4223	4223	528	528	**B46**	332	2654	2654	332	332
B21	528	4223	4223	528	528	**B47**	401	3207	3207	401	401
B22	528	4223	4223	528	528	**B48**	665	5317	5317	665	665
B23	552	4419	4419	552	552	**B49**	665	5317	5317	665	665
B24	478	3826	3826	478	478	**B50**	463	3704	3704	463	463
B25	478	3826	3826	478	478	**B51**	124	991	991	124	124
B26	478	3826	3826	478	478	**B52**	174	1389	1389	174	174

Geographical and Distance Data: The road distances between AFAD warehouses and regions in Bingöl were calculated using GIS and mapping services. Due to unpredictable traffic conditions following a disaster, it is not possible to determine exact travel times. In the dataset, the preferred routes are main roads, while roads with a higher risk of damage, such as mountain roads and single-lane roads, have been excluded from consideration. These data were used to develop the "distance" parameters in the model by accounting for actual road distances. The distances between regions (B) and warehouses (D) play a critical role in determining which warehouse should supply aid to a specific region.

Number of Vehicles: Based on research in the literature, the capacity of a single vehicle is assumed to be 90 m³. Additionally, the model determines the number of vehicles required when a warehouse dispatches aid to a region.

The dimensions of the relief materials were calculated based on the data from [35]. The volume of each type of relief material is as follows:

$\alpha_1 = 0.464 \qquad \alpha_2 = 0.137 \qquad \alpha_3 = 0.020 \qquad \alpha_4 = 0.048 \qquad \alpha_5 = 0.029$

The collected data were preprocessed for use in the model and optimized using IBM ILOG CPLEX 22.11 software. The reliability and currency of the data were meticulously assessed to enhance the model's accuracy. This ensured that the theoretical foundation of the model was grounded in realistic conditions, thereby contributing to the effective planning of aid distribution for Bingöl province.

3.3. Mathematical model

The goal is to optimally distribute aid from AFAD warehouses to the regions of Bingöl province. The constraints and variables used in the model aim to ensure that each region is assigned only one warehouse, while optimizing the capacities of the warehouses and the needs of the regions. The mathematical model in this study is developed based on the vehicle routing problem for humanitarian logistics, as considered in the work of [36].

Notation:

Indices	
i	Set of demand regions.
j	Set of AFAD warehouses.
t	Set of aid types. (1 = Tent, 2 = Bed, 3 = Bed Set, 4 = Heater, 5 = Kitchen Set)
Parameters	
d_{ij}	Road distance between region i and warehouse j.
c_{jt}	Capacity of warehouse j for aid type t.
r_{it}	Need of region i for aid type t.
M	A sufficiently large positive number (e.g., $M = 10^6$).
h	Set of warehouses to be excluded (h = {2, 3, 4, 5}).
α_t	Unit volume for aid type t (m^3)
V_{max}	Maximum transport capacity per vehicle (90 units)

Decision Variables	
x_{ij}	Binary variable 1, if aid is sent to region i from warehouse j, and otherwise, 0
y_{ijt}	Quantity of aid type t sent from warehouse j to region i.
z_{ij}	Number of transport vehicles between region i and warehouse j.

Objective function (1) minimizes the distance required to deliver relief supplies between the region and the warehouse.

$$\min Z = \sum_{i\epsilon I}\sum_{j\epsilon J} d_{ij}z_{ij} \tag{1}$$

Constraints:

$$\sum_{j\epsilon J} y_{ijt} = r_{it} \qquad \forall i \in I,\ \forall t \in T \tag{2}$$

$$\sum_{i\epsilon I} y_{ijt} \leq c_{jt} \qquad \forall j \in J,\ \forall t \in T \tag{3}$$

$$y_{ijt} = 0 \qquad \forall i \in I,\ \forall j \in h, \forall t \in T \tag{4}$$

$$y_{ijt} \leq M.x_{ij} \qquad \forall i \in I, \forall j \in J, \forall t \in T \tag{5}$$

$$\sum_{j\epsilon J} x_{ij} = 1 \qquad \forall i \in I \tag{6}$$

$$\sum_{t\epsilon T} \alpha_t y_{ijt} \leq V_{max} z_{ij} \qquad \forall i \in I, \forall j \in J \tag{7}$$

$$x_{ij} \epsilon \{0,1\} \qquad \forall i \in I, \forall j \in J \qquad (8)$$

$$y_{ijt} \geq 0 \qquad \forall i \in I, \forall j \in J, \forall t \in T$$
$$z_{ij} \geq 0 \qquad \forall i \in I, \forall j \in J \text{ and } z_{ij} \in \mathbb{Z}^{+} \qquad (9)$$

If aid types are available in varying amounts in the warehouses, separate capacity and demand constraints are applied for each aid type, as shown in Constraint (2). The model ensures that the quantity of each aid type dispatched from each warehouse does not exceed its capacity Constraint (3). Warehouses that are most likely to be affected during a disaster are prohibited from sending aid to any region Constraint (4). To ensures logical consistency, the quantity y_{ijt} is positive if aid type t is sent from warehouse j to region i, otherwise it must be zero Constraint (5). For a specific region and aid type, assistance must be supplied from only one warehouse Constraint (6). The total volume of relief materials delivered to each region must not exceed the capacity of the transportation vehicles Constraint (7). A binary decision variable constraint is implemented to ensure that x_{ij} is binary (0 or 1) Constraint (8). Finally, the quantity of relief materials delivered to each region and the capacity of transportation vehicles cannot be negative Constraint (9).

4. Discussion

This section presents the results of the model analysis conducted under two different scenarios. In the first scenario, all warehouses participate in the aid distribution process, providing a broader range of resources and access. In the second scenario, the effects of excluding the warehouses from the regions predicted to be affected by the earthquake are analyzed. The results of both scenarios are compared, particularly in terms of resource capacity, distribution speed, and aid accessibility rates.

The model was formulated and solved using IBM ILOG CPLEX Optimization Studio version 22.11 on a MacBook equipped with an Apple M2 chip and 8 GB of RAM. It consists of 8,008 decision variables, including 1,144 binary and 6,864 integer variables, and 7,286 constraints. The scenarios were solved in 00:00:47 (47 seconds), demonstrating that the model is computationally tractable.

4.1. First scenario: situation with all warehouses participating

With the participation of all warehouses, the available aid materials had a wide resource capacity. This resulted in greater flexibility and inclusiveness in the types of aid provided to the regions. The geographical spread of the resources shortened the distances to the regions, enabling a faster distribution process. This is particularly advantageous in situations requiring quick intervention immediately after the disaster. With the participation of all warehouses, distance were reduced, and the distribution process became more efficient, as the broader distribution of resources lowered transportation distance. When the model was solved using IBM ILOG CPLEX 22.11, the objective value obtained was 71,762 and the quantities of aid types sent are shown in Table 4.

4.2. Second scenario: situation with the exclusion of provinces affected by the earthquake

In the second scenario, a situation was examined where the provinces predicted to be affected by the earthquake did not participate in the aid distribution process. In this case:

The reduction in the number of warehouses limited the resource capacity. This, particularly in the distribution of aid over large areas, led to longer access times for some regions. The decrease in the number of warehouses resulted in increased transportation times to specific regions. For geographically distant regions, the aid process had to be spread over a longer time frame. When the model was solved using IBM ILOG CPLEX 22.11, the objective value obtained was 130,572 and the quantities of aid types sent are shown in Table 5.

This notation is used in Table 4 and Table 5: W denotes warehouses, A represents aid types, R refers to regions, V indicates the number of vehicles used for transportation, and To stands for the total amount of aid delivered.

Table 4. Region-warehouse matching according to Scenario 1

W	2					4					5					12					
A	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	V
R																					
1											458	3666	3666	458	458						10
2																424	3390	3390	424	424	9
3																623	4980	4980	623	623	13
4																623	4980	4980	623	623	13
5																438	3501	3501	438	438	9
6																438	3501	3501	438	438	9
7						454	3634	3634	454	454											10
8						471	3766	3766	471	471											10
9											356	2844	2844	356	356						8
10	465	3720	3720	465	465																10
11	465	3720	3720	465	465																10
12																483	3863	3863	483	483	10
13											460	3678	3678	460	460						10
14											460	3678	3678	460	460						10
15	460	3678	3678	460	460																10
16																690	5521	5521	690	690	14
17	509	4075	4075	509	509																11
18																528	4223	4223	528	528	11
19	528	4223	4223	528	528																11
20	528	4223	4223	528	528																11
21	528	4223	4223	528	528																11
22	528	4223	4223	528	528																11
23											552	4419	4419	552	552						12
24																478	3826	3826	478	478	10
25																478	3826	3826	478	478	10
26	478	3826	3826	478	478																10
27																630	5040	5040	630	630	13
28																536	4286	4286	536	536	11
29																536	4286	4286	536	536	11
30																536	4287	4287	536	536	11
31																536	4287	4287	536	536	11
32																536	4287	4287	536	536	11
33	507	4055	4055	507	507																11
34	507	4055	4055	507	507																11
35											507	4055	4055	507	507						11
36	507	4055	4055	507	507																11
37											404	3230	3230	404	404						9
38											404	3230	3230	404	404						9
39																382	3052	3052	382	382	8
40																382	3052	3052	382	382	8
41	523	4182	4182	523	523																11
42	523	4182	4182	523	523																11
43											408	3262	3262	408	408						9
44											331	2648	2648	331	331						7
45											335	2683	2683	335	335						7
46											332	2654	2654	332	332						7
47											401	3207	3207	401	401						9
48											665	5317	5317	665	665						14
49											665	5317	5317	665	665						14
50											463	3704	3704	463	463						10
51	124	991	991	124	124																3
52						174	1389	1389	174	174											4
To	7180	57431	57431	7180	7180	1099	8789	8789	1099	1099	7201	57592	57592	7201	7201	9277	74188	74188	9277	9277	525

Table 5. Region-warehouse matching according to Scenario 2

W	6					7					12					
A	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5	V
R																
1											458	3666	3666	458	458	10
2											424	3390	3390	424	424	9
3											623	4980	4980	623	623	13
4											623	4980	4980	623	623	13
5						438	3501	3501	438	438						9
6											438	3501	3501	438	438	9
7											454	3634	3634	454	454	10
8	471	3766	3766	471	471											10
9	356	2844	2844	356	356											8
10											465	3720	3720	465	465	10
11											465	3720	3720	465	465	10
12	483	3863	3863	483	483											10
13											460	3678	3678	460	460	10
14											460	3678	3678	460	460	10
15											460	3678	3678	460	460	10
16						690	5521	5521	690	690						14
17											509	4075	4075	509	509	11
18						528	4223	4223	528	528						11
19						528	4223	4223	528	528						11
20						528	4223	4223	528	528						11
21						528	4223	4223	528	528						11
22						528	4223	4223	528	528						11
23											552	4419	4419	552	552	12
24						478	3826	3826	478	478						10
25						478	3826	3826	478	478						10
26											478	3826	3826	478	478	10
27	630	5040	5040	630	630											13
28	536	4286	4286	536	536											11
29						536	4286	4286	536	536						11
30						536	4287	4287	536	536						11
31						536	4287	4287	536	536						11
32						536	4287	4287	536	536						11
33											507	4055	4055	507	507	11
34											507	4055	4055	507	507	11
35											507	4055	4055	507	507	11
36											507	4055	4055	507	507	11
37											404	3230	3230	404	404	9
38											404	3230	3230	404	404	9
39											382	3052	3052	382	382	8
40	382	3052	3052	382	382											8
41											523	4182	4182	523	523	11
42											523	4182	4182	523	523	11
43											408	3262	3262	408	408	9
44						331	2648	2648	331	331						7
45											335	2683	2683	335	335	7
46											332	2654	2654	332	332	7
47											401	3207	3207	401	401	9
48											665	5317	5317	665	665	14
49											665	5317	5317	665	665	14
50											463	3704	3704	463	463	10
51	124	991	991	124	124											3
52	174	1389	1389	174	174											4
To	3156	25231	25231	3156	3156	7199	57584	57584	7199	7199	14402	115185	115185	14402	14402	525

4.3. Numerical results

As a result of the implementation of our model, a plan was obtained that optimizes the distribution of aid materials from warehouses to 52 regions. This plan ensures that all five different types of aid (tents, beds, bed sets, heaters, and kitchen sets) required by each region are fully met while minimizing the total transportation distance.

When comparing the two scenarios, notable differences emerge:

In the first scenario, the participation of all warehouses facilitated rapid and widespread access to aid, while in the second scenario, the limited number of warehouses decreased the speed of access. The first scenario offers an advantage in terms of logistical distances, whereas in the second scenario, a significant increase in distances was observed. The reduction in the number of warehouses increased the operational burden on the remaining ones, leading to longer travel distances and less efficient distribution.

A total of 525 vehicles were used to deliver 470.271 aid items to the affected regions. Within this distribution plan, each vehicle was assigned to deliver aid to an average of 377 people. These results demonstrate the operational feasibility of the system and its ability to reach a large number of individuals effectively during post-disaster relief operations.

5. Conclusion

Effective planning of aid distribution is of vital importance in disaster situations. In this study, the aid distribution process for Bingöl province was examined through two different scenarios.

In the first scenario, all 22 AFAD warehouses were included in the distribution process. According to the model results, a total of 470.271 relief items would be delivered to Bingöl from the warehouses located in Elazığ, Erzurum, Muş, and Diyarbakır. This scenario offered advantages in terms of accessibility and logistical efficiency; since the total transportation distance was reduced, aid was delivered more quickly and warehouse workloads were balanced.

In the second scenario, warehouses in high-risk provinces expected to be affected by the disaster—namely Elazığ, Erzincan, Erzurum, and Muş—were excluded from the distribution process. In this case, aid to Bingöl was supplied from warehouses in Sivas, Adıyaman, and Diyarbakır, and again a total of 470.271 relief items were delivered. However, this scenario led to increased operational burden on the remaining warehouses and longer transportation distances.

A total of 525 vehicles were used to deliver aid to the disaster-affected areas, with each vehicle serving an average of 377 people.

Accordingly, this study assumes a worst-case scenario and develops a model based on data specific to Bingöl, a province with a high risk of earthquakes. To represent local aid needs more accurately and in greater detail, Bingöl was divided into 52 regions based on neighborhood proximity and population density. This regional division allows the model to balance geographical accessibility and population demand more precisely in the aid distribution process. As a result, the model is able to produce more accurate assignment decisions by taking into account the varying logistical conditions of each region. Official and up-to-date data from AFAD warehouses—such as aid types and storage capacities—were directly incorporated into the model. In addition, the scenarios consider the possibility that certain warehouses may become inoperable during a disaster. By ensuring that each region receives aid from a single warehouse, the model prevents logistical complexity in the distribution process. All components were formulated as an optimization model and solved to demonstrate its operational feasibility.

In future studies, aid distribution models can be further improved by addressing different regional conditions, alternative warehouse strategies, and transportation options through more detailed analyses.

Authorship Contributions

T. D. and H. M. A. collected the data, designed the models, contributed to the research's design, implementation, analysis, and evaluation of the results, and wrote the manuscript.

Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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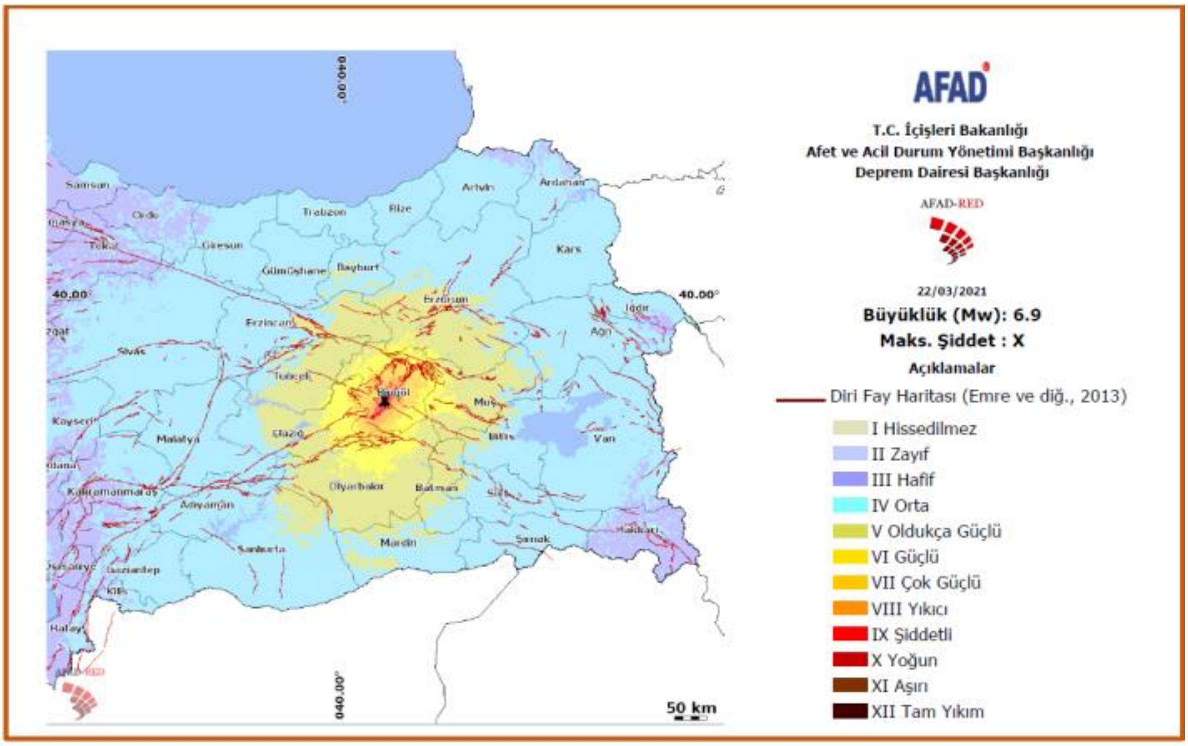
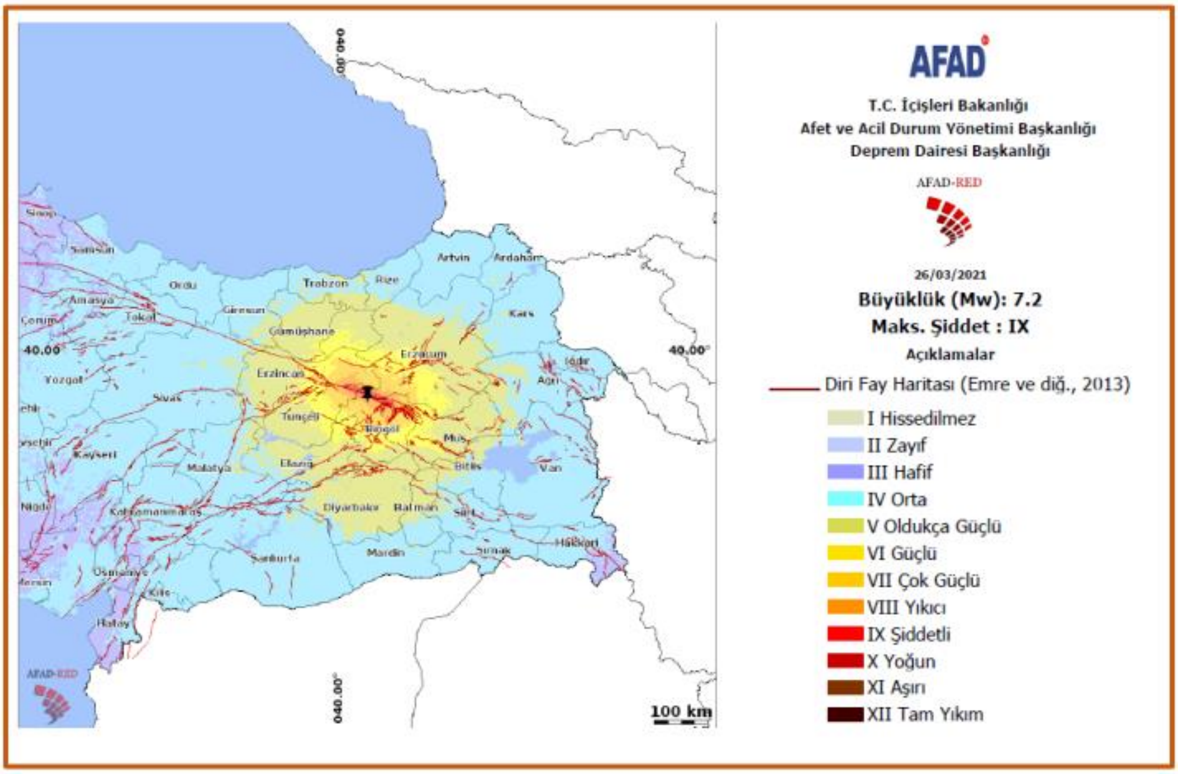
Appendix



Annex 1. The intensity distribution map generated by AFAD's RED analysis for a magnitude 6.9 earthquake [32]



Annex 2. The intensity distribution map generated by AFAD's RED analysis for a magnitude 7.2 earthquake [32]