ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

DYNAMIC RESOURCE ALLOCATION FOR HUMANITARIAN RELIEF CHAIN COORDINATION INTEGRATED WITH VOLUNTEERS

Ph.D. THESIS

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Department of Industrial Engineering

Industrial Engineering Programme

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

İNSANİ YARDIM ZİNCİRİ KOORDİNASYONUNDA GÖNÜLLÜLERLE ENTEGRE DİNAMİK KAYNAK TAHSİSİ MODELİ

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MAYIS 2025

Emine Nisa Kapukaya, a Ph.D. student of ITU Graduate School student ID 507172110, successfully defended the thesis/dissertation entitled "DYNAMIC RESOURCE ALLOCATION FOR HUMANITARIAN RELIEF CHAIN COORDINATION INTEGRATED WITH VOLUNTEERS", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 18 March 2025
Date of Defense : 14 May 2025

To my faith in myself,

FOREWORD

This thesis focuses on resource planning for search and rescue, as well as first aid activities, within the field of disaster management. In this context, a dynamic resource planning and allocation system is proposed, incorporating volunteers, rescue teams, and both renewable and non-renewable resource requirements.

This approach prioritizes saving human lives while addressing the urgency of the process. It also seeks to optimize the use of both available and additional resources to minimize unmet demand. The efficient allocation of resources is ensured by balancing the transfer of resources between regions and the employment of additional human workforce. Furthermore, the minimization of total unmet human resource demand, as well as renewable and non-renewable resource needs, is targeted. This study is expected to assist decision-makers during the disaster preparedness and response phases and contribute to the literature with a holistic approach.

I would like to express my gratitude to my valuable advisor Prof. Dr. Şule Itır SATOĞLU, who supported me at every stage of this study and contributed to all my studies throughout my graduate education. I am grateful to my professors and colleagues at Istanbul Technical University, Department of Industrial Engineering, for their help and contributions throughout the thesis process.

I would like to thank my colleagues Dr. Mehmet Kürşat ÖKSÜZ and Dr. Nadide ÇAĞLAYAN ÖZAYDIN for all their contributions and support throughout my PhD studies.

I am deeply grateful to my mother, my father, and my brother for their immense efforts and sacrifices in every aspect of my life. One of my greatest thanks goes to my son, Selim, for allowing me the time and space to complete this thesis. Finally, I would like to express my heartfelt gratitude to my dear husband, Dr. Furkan Kapukaya, for his unwavering moral support throughout this challenging period.

May 2025

Emine Nisa KAPUKAYA
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TABLE OF CONTENTS

Page

ABBREVIATIONS

AFAD	: Disaster and Emergency Management Presidency.
CRED	**:** Centre for Research on the Epidemiology of Disasters
DMC	: Disaster Management Center
EM-DAT	**:** Emergency Event Database
HL	**:** Humanitarian Logistics
NATO	**:** North Atlantic Treaty Organization
NGO	**:** Non-Governmental Organizations
NRR	**:** Non-renewable Resource
RR	**:** Renewable Resource
TLA	**:** Traditional Labor Assignment
VLA	**:** Volunteer Labor Assignment

LIST OF TABLES

Page

LIST OF FIGURES

Page

DYNAMIC RESOURCE ALLOCATION FOR HUMANITARIAN RELIEF CHAIN COORDINATION INTEGRATED WITH VOLUNTEERS

SUMMARY

Each disaster situation has its own specific resource requirements and structures. In the event of a disaster, the number of injuries and lives lost, financial needs, and aid requirements vary based on the type of the disaster. Furthermore, the scale of the disaster, its location, and the socio-economic level of the affected region affect required resources and the actors to participate in relief operations and coordination structure. Volunteers are usually the early responders to the disaster, and need to be employed, as mass casualty events cause a sudden demand surge, and the governmental resources are usually not enough to satisfy all human resource requirements.

In this study, a multi-objective dynamic resource allocation model is developed for search-and-rescue and first aid activities under uncertainty with a focus on saving human lives by prioritizing urgent tasks, where the volunteers are employed. A detailed framework covering these tasks and required resources is presented. We considered search-and-rescue units composed of team members from certain fields of expertise and volunteers as human resources. Moreover, the use of different types of renewable and nonrenewable resources required during these tasks and pre-positioning and distribution of these according to needs within the model were planned. In the model, it is aimed to minimize the total unmet human resource demand, the number of resources transferred between regions, and the total unmet renewable and non-renewable resource demand. Hence, a three- objective stochastic programming model is formulated. A real case study was conducted to address resource allocation after the expected major Marmara Earthquake for a district of Istanbul.

Demand assessment was made considering the number of buildings expected to be damaged or destroyed, the classification of victims according to the NATO triage system and the number of victims expected to suffer with minor or severe injuries. To meet this demand, officially appointed rescue units and trained volunteers expected to receive training at predetermined levels of classified volunteerism in different professions and spontaneous volunteers are planned to work together in coordination. As the volunteers are usually the first responders, their consideration of resource allocation is invaluable.

This is the first study that simultaneously places and dynamically allocates renewable and non-renewable resources and human resources, including the official rescue units and volunteers, for the search-and-rescue and first-aid tasks. Incorporating volunteers' assignments to the search-and-rescue and first-aid teams, considering their expertise levels and prior training, and quitting behavior are unique contributions to our study.

The Augmented Epsilon-Constraint-2 (AUGMECON2) Algorithm was employed where necessary iterations were performed in the IBM ILOG CPLEX software environment to obtain the Pareto optimal solutions.

Results were analyzed with sensitivity analyses. Besides, the model was solved based on the equity policy to minimize the maximum unmet demand among different regions. The outcomes of this research offer some administrative insights, in which ideas for resource allocation planning were suggested, considering both human and material resources.

Most of the unmet human resources demand occurred in the first period since additional resource deployment and interregional transfer of human resources could not be achieved. The population density and the high number of casualties in some regions cause the unmet demand in these regions to be higher than in others. Although targeting the equity policy in total unmet demand among regions in the model is expected to provide equitable results, the total unmet demand, in this case, was much higher than without aiming for equity.

As the model's results show, the lack of even one resource will prevent the completion of the task. In cases where some of the resources are used together, a communication system can be used to synchronize them. In the same way, a system that dynamically transmits the number of available resources in the regions to the center will be extremely beneficial in terms of ensuring the management of the process with optimum resources by preventing extra resources from coming to the regions. This requires pre-planning for healthy data flow from disaster areas to transmit the current situation in the region to the system.

Integrated decisions for pre- and post-disaster stages are crucial for potential disaster scenarios, as they help determine the expected resource requirements. Improper pre-disaster decision-making will affect post-earthquake decisions, leading to a shortfall in meeting demand.

İNSANİ YARDIM ZİNCİRİ KOORDİNASYONUNDA GÖNÜLLÜLERLE ENTEGRE DİNAMİK KAYNAK TAHSİSİ MODELİ

ÖZET

Her afet durumu yönetimi, kendi özel kaynak gereksinimlerine ve yapısına sahiptir. Can kaybı, mali ihtiyaçlar ve yardım gereksinimleri felaket türüne bağlı olarak değişir. Afetin büyüklüğü ve yeri, etkilenen bölgenin sosyo-ekonomik düzeyi, yardım operasyonlarındaki aktörlerin katılımını ve koordinasyon yapısını etkiler.

Buradan yola çıkarak, yapılan çalışmada afet yönetiminde kaynak tahsisi zorluğunu ele almak için bir model geliştirilmiştir. Model, insan hayatını kurtarma aciliyetine dayanarak görevleri önceliklendirmeye odaklanmıştır. Beklenen büyük Marmara Depremi için İstanbul'un bir ilçesi için gerçek bir vaka çalışması yapılmıştır. Talep, beklenen hasarlı veya yıkılmış binaların sayısı, NATO triyaj sistemine göre afetzedelerin sınıflandırılması ve hafif veya ciddi yaralanması beklenen afetzede sayısı göz önünde bulundurularak değerlendirilmiştir. Bu talebi karşılamak için, kurtarma birimleri, eğitimli gönüllüler ve spontane gönüllülerin koordinasyon içinde çalışması planlanmıştır. Model ayrıca gönüllülerin eğitim maliyetlerini, yol hasarı olasılığını ve kaynakların bölgeler arasında transferini de dikkate almaktadır.

JICA (2002) tarafından İstanbul için önerilen ve modelde farklı afet şiddet seviyelerini temsil eden dört olası deprem senaryosuna dayanarak, her ana senaryodan beş senaryo oluşturulmuş ve toplam yirmi senaryo elde edilmiştir. Senaryoların gerçekleşme olasılıklarının 0,01 ile 0,1 arasında değiştiği ve JICA'nın ana senaryolarının gerçekleşme olasılığı en yüksek senaryolar olduğu varsayılmıştır. Senaryolar oluşturulurken, S1'den itibaren her senaryoda durumun %10 kötüleştiği, yani beklenen can kaybı sayısının %10 arttığı varsayılmıştır. Bu çalışmada, yolların hasar oranlarına göre mesafe artışını dikkate alarak olasılıksal yol hasarı arıza yaklaşımı kullanılmıştır. Çalışmada resmi kurtarma birimleri ve gönüllüler insan kaynağı olarak ve yenilenebilir ve yenilenemez diğer kaynaklar da materyal kaynaklar olarak ele alınmıştır ve bunların senkronize şekilde çalışması hedeflenmiştir. Bu kaynakların ihtiyaçlara göre önceden pozisyonlandırılması ve afet sonrasında ihtiyaç durumuna göre dağıtımı planlanmıştır.

Modelin amacı, karşılanmayan talebi, bölgeler arasındaki toplam beklenen kaynak transferini ve karşılanmayan yenilenebilir ve yenilenemez kaynakları en aza indirmektir. Bunun için, üç amaçlı stokastik bir dinamik model oluşturulmuştur.

Çok amaçlı bu modeli çözmek için AUGMECON2 yöntemi uygulanmış ve sonuçlar analiz edilmiştir. Çalışma, afet yönetiminde hem insan hem de diğer kaynakların tahsisi ve yönetimi noktasında, idari bilgiler ve öngörüler sunmakta ve kaynak tahsisi planlama fikirleri önermektedir.

Ayrıca, bölgeler arası karşılanmamış talebin azami düzeye indirilmesi amacıyla model, eşitlik politikası esas alınarak yeniden oluşturulmuştur. İlk olarak, Politika 1 olarak bölgeler arasında eşitlik sağlanması amaçlanmadan sonuçlar elde edildi. Daha

sonra, aynı verilerle, model, Politika 2 olarak bölgeler arası eşitliğin hedeflendiği durum için çözüldü. Bir felaketten sonra kaynak dağıtımında eşitlik vurgulanırken, kurbanların enkazdan zamanında kurtarılmasına öncelik vermek, bölgeler arasında eşit dağıtım sağlamaktan daha önemlidir. Ayrıca, bölgeler arasında eşitlik sağlanması amaçlandığında, toplam karşılanmamış talep daha yüksektir ve kaynak tahsisi sorununu çözmek daha fazla zaman alır. Modelde bölgeler arasında toplam karşılanmamış talepte eşitlik politikasının hedeflenmesinin eşitlikçi sonuçlar sağlaması beklenmesine rağmen, bu durumda toplam karşılanmamış talebin eşitlik hedeflenmediği duruma göre çok daha yüksek olduğu bulunmuştur.

Model sonuçları parametrelere göre değişebileceğinden, ilk amaç fonksiyonundaki ceza değerlerine ve senaryo olasılıklarına dayalı duyarlılık analizi yapılmıştır. Ceza değerleri değiştikten sonra, değişmeyen veya hafifçe artan (16 değerden 12'si) karşılanmamış talep değerleri, en kötü senaryolar olan Senaryo 19 ve 20'ye aittir. Bunun nedeni insan kaynaklarının yetersiz olması ve daha iyi sonuçlara ulaşılamamasıdır. Ayrıca senaryo olasılıklarının etkisini anlamak için orijinal ceza değerleri korunarak senaryoların olasılıkları kötü senaryolara daha yüksek olasılıklar verilerek değiştirildi. Sonuç olarak modelin, karşılanmamış talepler için ceza değerleri ve senaryo olasılıkları değişimine karşı dayanıklı olduğu söylenebilir.

Bu tez, afet yönetimi alanında arama ve kurtarma ve ilk yardım faaliyetleri için kaynak planlamasına odaklanmaktadır. Bu bağlamda, gönüllüleri, kurtarma ekiplerini ve hem yenilenebilir hem de yenilenemeyen kaynak gereksinimlerini içeren dinamik bir kaynak planlama ve tahsis sistemi önerilmektedir. Önerilen yaklaşım, insan hayatlarını kurtarmayı önceliklendirir ve karşılanmamış talebi en aza indirmek için mevcut ve ek kaynakların kullanımını optimize etmeyi hedeflerken sürecin aciliyetini dikkate alır. Kaynakların verimli tahsisi, bölgeler arasında kaynak transferi ve ek insan işgücünün istihdamı arasında denge kurularak sağlanır. Ayrıca, toplam karşılanmamış insan kaynağı talebinin yanı sıra yenilenebilir ve yenilenemeyen kaynak ihtiyaçlarının en aza indirilmesi hedeflenmektedir. Bu çalışmanın, afetlere hazırlık ve müdahale aşamalarında karar vericilere yardımcı olması ve bütünsel bir yaklaşımla literatüre katkıda bulunması beklenmektedir.

Bu çalışma, resmi kurtarma personelinin yanı sıra afet müdahale ekiplerinde gönüllülerin eğitimini ve görevlendirilmesinin ele alındığı literatürdeki ilk çalışmadır. Tüm yenilenebilir, yenilenemez ve insan kaynaklarının afet öncesi ve sonrası tahsisini ve transferini planlar. Modelimiz, bir afetten sonra yardım için doğru ekipleri, gerekli malzemeleri ve araçları bulmakta zorlanan insanların sorununu ele almaya yardımcı olur ve nihayetinde yardım sağlamadaki gecikmeyi azaltır. Bu nedenle, metodolojimiz afet koordinasyon ajansları tarafından kaynakları etkili bir şekilde koordine etmek ve yönetmek, gönüllüleri harekete geçirmek de dahil olmak üzere kritik erken saatlerde kullanılabilir.

Bu çalışma deprem felaketine odaklanmıştır. Gelecekteki çalışmalar, toplumları etkileyen diğer afetler için kaynak tahsisine odaklanabilir. Ayrıca, kurbanlar için arama-kurtarma ve ilk yardım dışındaki görevler gelecekte yoğunlaştırılabilir. Modeli ilk 72 saat için uygulamış olsak da, kurtarma dönemi için kaynak tahsis sorununu yönetmek amacıyla daha uzun bir zaman aralığını kapsayan dönemler düşünülebilir.

Ayrıca, önerilen matematiksel model, kuruluşlar içinde ve arasında veri paylaşmayı sağlayan bir yazılım aracı olan bir API'ye (Uygulama Programlama Arayüzü) yerleştirilebilir. Modelin sonuçlarının gösterdiği gibi, tek bir kaynağın bile eksikliği görevin tamamlanmasını engelleyecektir. Bu nedenle, bölgelerdeki kullanılabilir kaynakların sayısını komuta merkezine dinamik olarak ileten bir bilgi sistemi, ihtiyaç duyulandan fazla kaynakların afet bölgelerine gelmesini önleyerek sürecin optimum kaynaklarla yönetilmesini kolaylaştırmak için oldukça faydalı olacaktır. Bu, afet bölgelerinden komuta merkezine doğru veri akışı için afet öncesi planlamayı gerektirir ve mevcut durum hakkında bilgi iletir. Afet yönetimi, hükümet ve sivil toplum kuruluşları da dahil olmak üzere birden fazla tarafın işbirliği yapmasını gerektirdiğinden, bu API aracılığıyla kararlarla ilgili girdi veri toplama, karar alma ve çıktı veri iletimi gelecekteki afetlerde kaynak tahsisi için faydalı olacaktır.

1. INTRODUCTION

A disaster is defined as “a sudden, calamitous event that seriously disrupts the functioning of a community or society and causes human, material, and economic or environmental losses that exceed the community’s or society’s ability to cope using its own resources.” by the International Federation of Red Cross and Red Crescent Societies (Url-1).

According to Mizutori (2020), head of the United Nations Office for Disaster Risk Reduction (UNDRR), while hazards may be natural and unavoidable, only become disasters when a community does not have the appropriate resources or is not organized to withstand the impact, and its population is vulnerable because of poverty, or it is somehow socially disadvantaged (Url-2).

A natural hazard becomes a disaster when it causes life and injury along with economic losses, so the effect of disasters can and should be avoided. It is crucial for communities to reduce risks and become more resilient, preventing natural events from causing disasters by being prepared. The recent pandemics crises experienced between 2020-2022 and 2023 Turkey Kahramanmaraş earthquake once again revealed the importance of resource planning in disaster management.

After the Marmara earthquake, which occurred on August 17, 1999 (Mw=7.6), resulted in the unfortunate loss of approximately 17,000 people and injured 50,000 people, there had never been such a devastating earthquake in Turkey or even in the world until 2023(AFAD). On February 6 in 2023, Turkey faced the harsh reality of an earthquake once again. The first earthquake struck Kahramanmaraş at 04:17 A.M. and it was announced with a magnitude of 7.7. The epicenter of which was determined as Pazarcık district, and the focal depth was 8.6 kilometers (Url-3).

Approximately nine hours following the initial earthquake, a second earthquake with 7.5 magnitude occurred in the region. Dozens of buildings damaged in the first earthquake collapsed in the second earthquake causing destruction not only in Kahramanmaraş but also in at least 10 provinces along the fault line including Syria.

The disaster area was home to about 14 million people which corresponds to 16.4% of the country's population and have been affected by the earthquake.

In addition to the roads that were destroyed by the devastating effect of the earthquake and making transportation impossible. The roads were closed because the heavy snowfall also made it impossible to reach the disaster area. Since the earthquake affected a very large region, the provinces in the nearby areas were insufficient in helping each other.

Turkey is in a seismic belt, and a 7.5 magnitude earthquake is expected to occur in the Marmara region, which encompasses Istanbul. This earthquake can devastate more than 60 percent of the region's production, industry, and trade, making it crucial to develop a humanitarian logistics network to mitigate the consequences.

With the conclusion to be drawn from this massive earthquake, resource planning in disaster areas should have been done in a way to plan the region's own resources in the most optimal way and requires the least external resources.

However, designing such a network is challenging as humanitarian supply chains are more complex and unpredictable than traditional ones and are affected by unreliable and incomplete information about delivery times, demand levels, and locations (Falasca *et al.*, 2012).

Although it is vital for first aid to be administered within the first 72 hours, it has been observed that in some cases it can take more than 10 days to reach all victims, with some individuals receiving assistance even after the fifteenth day.

The resource allocation problem is the problem of allocating and prioritizing a set of resources to a set of tasks. In a disaster, where many stakeholders will perform pre-determined tasks, the resource allocation objectives should be based on three pillars, according to Beamon and Balçık (2008). Both human resources and material supplies must be delivered to the affected individuals as soon as possible (effectiveness) by using optimum resources (efficiency) and without forgetting to consider fairness (equity). This is only possible if pre-disaster preparedness planning and response planning are carefully integrated (Pradhananga et al, 2016). Preparedness planning includes pre-locating resources, establishing a distribution network structure, and securing supplies. Response planning consists of delivering resources to the demand points, procuring extra supplies in case of unmet demand, and outlining the strategies for procuring these resources. Coordinating disaster relief poses various challenges, including the chaotic post-disaster environment, involvement of numerous actors, and limited resources (Beamon and Balçık, 2008). In post-disaster humanitarian logistics, various resource types must be effectively managed for efficient logistics operations, including goods delivery, casualty evacuation, and labor transfer (Al Theeb and Murray, 2017). These resources can be classified as human resources (including rescue or aid teams and volunteers), renewable (such as equipment), and non-renewable (consumable) material resources.

During the preparedness phase, various emergency supplies are pre-located in humanitarian supply chains, including renewable resources (RR) and non-renewable resources (NRR) like medical supplies (Ghaffari et al., 2020). Renewable resources are those whose supplies are abundant and can be easily replenished. Unlike nonrenewable resources, they are sustainable. A non-renewable resource refers to a natural substance that is not regenerated at the rate it is consumed (Url-4). In disaster management, RR, such as human resources and equipment, can be used repeatedly, while NRR cannot be reused.

Humanitarian logistics defined as "the process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information, from point of origin to point of consumption for the purpose of meeting the end beneficiary's requirements." by an advisory committee on humanitarian logistics by Fritz Institute (Thomas and Mizushia, 2005).

On average, natural disasters claim the lives of 45,000 individuals per year and are responsible for 0.1% of global deaths and affect close to 160 million people worldwide (Url-5). Figure 1.1- 1.4 shows number of disasters, number of deaths by disaster type, number of affected people and economic losses between 2003-2022 and in 2023, respectively. As can be seen, although earthquakes are small in number, they are the most dangerous natural disasters in terms of loss of life and economic loss.

In 2023, 399 natural disasters were reported by the Emergency Event Database (EM-DAT) which is considerably higher than the average of 369 annual catastrophic events between 2003 and 2022, killing 86473 people, affecting 93.1 million others, and costing 202.7 billion US$ in economic losses across the world in the Centre for Research on the Epidemiology of Disasters (CRED) (Url-6). In 2022, EM-DAT recorded 387 natural hazards and disasters worldwide, resulting in the loss of 30,704 lives and affecting 185 million individuals. Economic losses totaled around US$ 223.8 billion (Url-6).

Floods and storms also have the greatest value both in terms of numbers of occurrence and losses. When we look at disasters that have more human impact, such as drought, it is seen that their impact on people decreased in 2023 and the number of death people by drought value was only 247 (Url-6).

Here, it is clearly seen that a major disaster such as the earthquake that occurred in Türkiye can change the statistics and suddenly increase the number of deaths in disasters far above the previous years. As can be deduced from these values, the occurrence of natural disasters cannot be prevented, but its' losses can be prevented to a great extent with the required measures taken.

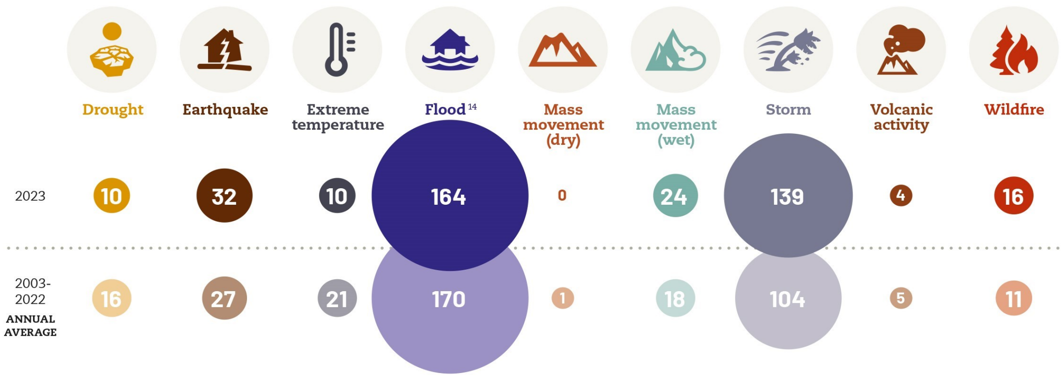

Figure 1.1 : Occurrence by disaster type: 2023 compared to 2003-2022 annual average (CRED).

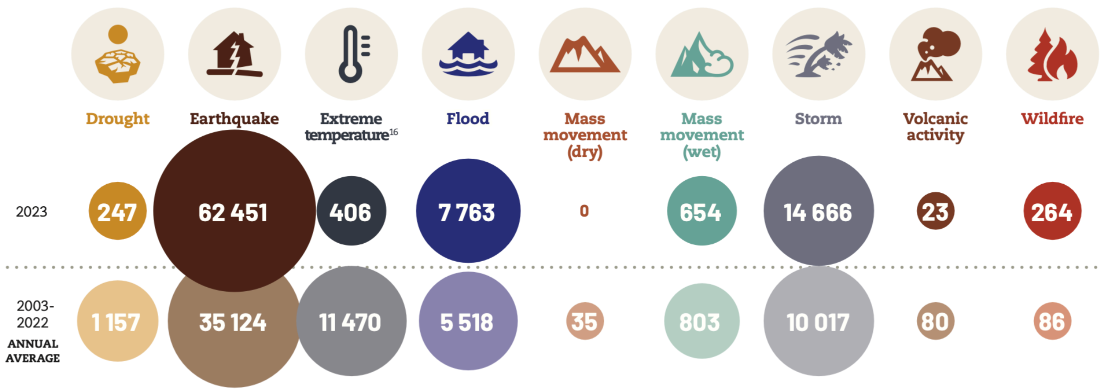

Figure 1.2 : Number of deaths by disaster type: 2023 compared to 2003-2022 annual average (CRED).

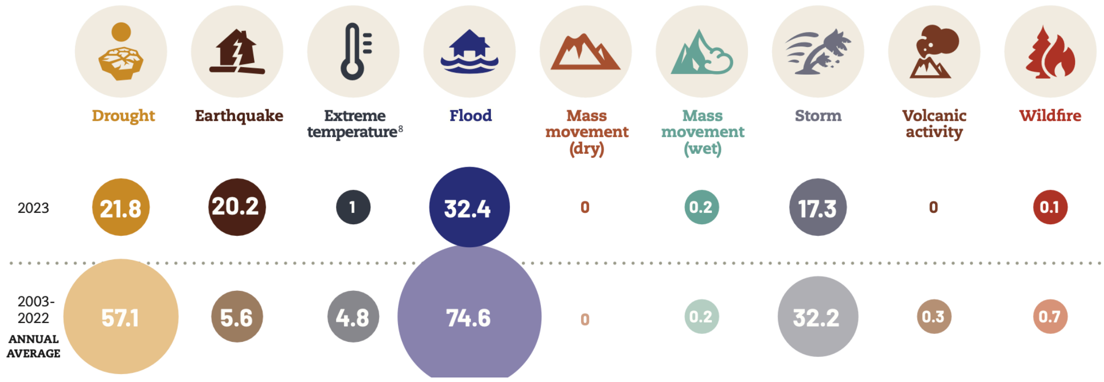

Figure 1.3 : Number of affected (million) by disaster type 2023 compared to 2003-2022 annual average (CRED).

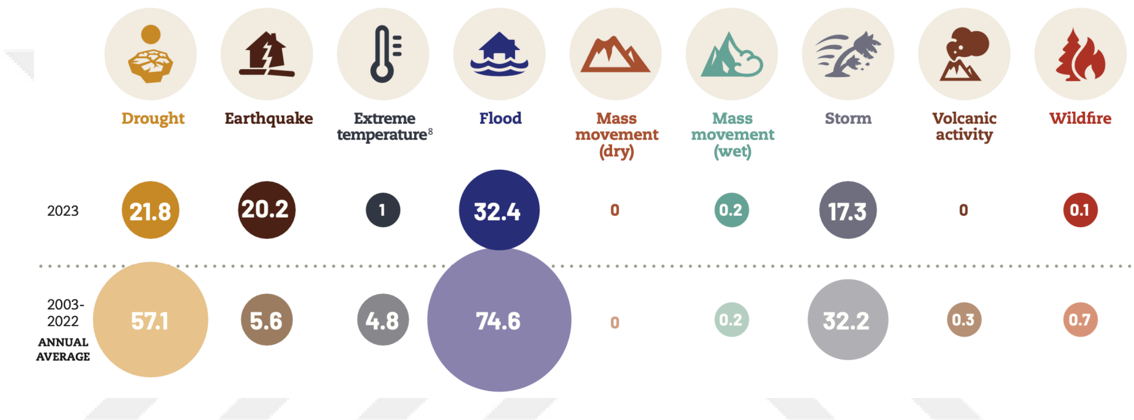

Figure 1.4 : Economic losses (billion US$) by disaster type 2023 compared to 2003-2022 annual average (CRED).

Disaster management plans must consider the interaction between government organizations and their collaboration with non-governmental organizations, civil organizations, private firms, and even foreign governments. According to the most recent study by Van Wassenhove (2022), collaboration and partnerships appear to be the only way to kill the beast. We must see the opportunities in convergence of the organization, sector, discipline, or technology, being aware of the difficulty in implementation. These tasks bring a diversity of both human and material resource requirements.

While it is commonly believed that having more personnel is better in disaster management, every person comes with his own needs. Sometimes the unconscious and uncoordinated crowd may hinder the rescue units and volunteers from completing their tasks. Improper interventions can affect the lives of disaster victims. It was stated that after the 1999 earthquake, volunteers who wanted to help enter the city, long queues of vehicles formed, and it was difficult to deliver the needs to the disaster area due to this traffic.

Achieving successful HL response is only possible if pre-disaster preparedness planning and response planning are carefully integrated (Pradhananga et al., 2016). Preparedness planning includes pre-locating resources, establishing a distribution network structure, and securing supplies. In response planning, it consists of actions that include the delivery of resources to demand points and the procurement of extra supplies in case of unmet demand, and how these resources will be procured.

Furthermore, ineffective demand planning has resulted in an imbalanced allocation of resources. It was observed that more than enough blankets were sent to the region, but the region did not receive sufficient drinking water. While some regions receive a lot of support, some regions may not receive enough help due to their location, proximity to the center, and damage to the roads.

Disasters that affect the functioning of society, whether there are sufficient resources to cope with it, whether there is a need for support other than the daily needs, determine whether this event is humanitarian or not.Emergency in Humanitarian Logistics is described as "Hazard impact causing adverse physical, social, psychological, economic or political effects that challenges the ability to rapidly and effectively respond" by Institute for Crisis Disaster and Risk Management in 2009.

Designing a humanitarian logistic network is crucial to mitigate the impact of disasters. A humanitarian logistics network is more complex and challenging to manage than a traditional supply network. Falasca et al. (2012) stated that demand movements are less stable and less predictable than commercial supply chains and that human supply chains are affected by unreliable, incomplete, or non-reliable information about delivery times, demand levels, and locations.

Differences between Commercial Supply Chain (CSC) and Humanitarian Supply Chain (HSC) summarized in Table 1.1. The main difference is objective, while CSC aims to maximize the profit and minimize labor cost, HSC chain generally aims to minimize shortage and task completion times (John et al, 2012). In CSC, tasks are main constraints and labors are assumed unconstrained, while in HSC committed labor are key constraints and pool size is determined by number of them. In CSC labor cost is predefined, however in HSC, volunteers are not paid most of the time. Labor working time and task preferences are also one of the key constraints in HSC.

Falasca et al. (2009) stated that “demand movements are less stable and less predictable in the humanitarian supply chain than in commercial supply chains, and that human supply chains are affected by unreliable, incomplete or unreliable information about delivery times, demand levels and locations”.

Table 1.1 : Comparison of Commercial Supply Chain and Humanitarian Supply Chain.

Model	Commercial Supply Chain	Humanitarian Supply Chain
Objective	Profit maximization	Task completion time minimization
	Labor cost minimization	Shortage minimization
Key constraints	Required task	Committed labor
Labor size constraints	Assumed unconstrained	Determined by committed labor
Labor cost	Non-trivial	Low-yet still non-trivial
Labor preferences	Time preferences (some models)	Volunteers time and task preferences
Labor shortages	Not an issue	Shortages need to be balanced

This study focuses on the development of a stochastic model for humanitarian disaster relief chain coordination integrated with official rescue units and volunteers considering multiple regions, and renewable and non-renewable resources. Two-stage stochastic programming model considering uncertainty in many parameters such as demand, resources, and transport durations is proposed.

It is aimed to ensure optimum human and material usage. For this purpose, we proposed a multi-objective stochastic model for the dynamic planning of resource allocation for disaster response. Objective functions of the model are

- Minimizing the total expected unmet human resource demand.
- Minimizing the total number of resources expected to be transferred between regions.
- Minimizing the expected unmet RRs and unmet NRRs in all disaster regions.

The requirement of rescue units and volunteers in different disaster scenarios and interregional labor & resource transfer planning is modeled in this study. Moreover, a real application of the model for a sub-district of Istanbul was made where the volunteers, rescue units, and renewable and non-renewable resources are dynamically assigned to respond to a major earthquake. Thus, the difference and requirements in volunteer & rescue units and renewable & non-renewable resource planning are clearly revealed in the model.

The scope of this work includes the immediate delivery of resources to the disaster area, conducting search and rescue operations, and providing first aid to disaster victims. These activities were chosen because they are essential and time-sensitive tasks crucial in a disaster's immediate aftermath.

To the best of our knowledge, it is the first study in which volunteers, official rescue units, and material resources are planned, dynamically assigned and resource transfers between regions are made. The dynamic assignment of these resources stands out as the most important difference of the model. In addition, a detailed study was conducted for search-and-rescue and first aid activities, sub-tasks these activities consisted of, workforce requirements of these tasks, and expected duration of these tasks. This application contributes to the literature as well as to the practitioners, for dynamic resource management in major disasters.

When planning disaster management, it is necessary to plan the pre-disaster (risk mitigation) and post-disaster (response) events together, because these are interrelated problems that mutually affect each other. In our study, we discussed the decisions to be taken before the disaster and the decisions to be taken after the disaster. The model will be valid for any situation where the scenarios cover the disaster situation that will occur.

In this study, allocation of human resources based on the skills of different professions is considered. Volunteers' employment in disasters is also a unique and essential aspect of this study since volunteers are usually a significant resource. Since the model established in this study addresses human needs with different skills and capabilities, it is flexible enough to be used in other post-earthquake activities.

Besides, the proposed stochastic programming model is novel since human resources, including volunteers and official teams for first aid and search-and-rescue tasks, as well as the equipment and consumable materials required for these tasks, are planned in an integrated way for pre-disaster and post-disaster stages, simultaneously, *for the* *first time in the literature*. This is important because the lack of any type of these resources may cause unmet demand. Training of the volunteers and pre-positioning of the material resources are decided before the disaster, and dynamic resource assignments and transfers are decided post-disaster.

Our study significantly contributes to volunteer human resources planning for disaster response. We have not observed any resource allocation and team assignment studies in the literature with a hybrid structure including the volunteers in the teams. This novel approach has never been studied before. In addition, we conducted a comprehensive study on search-and-rescue and first aid tasks, including the sub-tasks these activities consist of, the workforce requirements, and the expected duration. This application adds to the literature and provides a comprehensive guide for practitioners in dynamic resource management in major disasters.

Equity is one of the most popular discussion topics in humanitarian aid. It plays an important role in the effective distribution and equitable aid use. Policies were produced for situations where equity was targeted and where equity was not targeted in resource distribution between regions, and the results were compared in our study. Since the model results may vary based on the parameters, a sensitivity analysis is conducted separately, considering scenario probabilities and the penalty values in the first objective function.

The AUGMECON2 method was used to obtain Pareto-optimal solutions in the model. AUGMECON2 is a solution technique developed to efficiently generate Pareto-optimal solutions for multi-objective linear and integer optimization problems, such as the one presented in this study. It was preferred in this context because it is well-suited to the size and structure of our model and was designed to overcome the limitations of earlier approaches, particularly the traditional ε-constraint method.

Furthermore, AUGMECON2 can be easily implemented using standard single-objective MILP solvers such as CPLEX, which makes it both practical and computationally efficient for the problem at hand.

This study considers disaster scenarios involving different numbers of victims used to estimate the resources needed during rescue from debris, the transfer of the victims to a safe area, first aid treatments according to triage, and their transfer. Hence, the requirement for rescue units and volunteers in different disaster scenarios and interregional labor and resource transfer planning is modeled in this study. In the model, RRs and NRRs were pre-positioned before the earthquake, and volunteers were decided to be trained in advance. After the earthquake, volunteers, rescue units, RRs, and NRRS were dynamically assigned to respond to a significant earthquake.

The structure of this paper is as follows: All aspects of resource allocation in humanitarian logistics are discussed in the next section. A comprehensive literature review is provided in Section 3. In Section 4, the problem is defined with a framework for better understanding, and the proposed stochastic mathematical model is explained. Section 5 presents the application of the model, including a computational study based on a real case in Istanbul, along with data collection. The results of the case study are then discussed in detail, and managerial implications are provided. Finally, Section 6 concludes the paper and outlines directions for future research.

2. RESOURCE ALLOCATION IN HUMANITARIAN LOGISTICS

In the event of a disaster, the most important reason for people to suffer is the inability to access the required resources on time and as much as needed. As the number of individuals in need increases, the time taken to deliver necessary supplies may also be prolonged. While some basic needed materials are over-distributed, some of the needed materials are not accessible at all. In this case, the most accurate action is to be aware of identifying, procuring, and distributing needs and avoiding both oversupply and scarcity. To solve these problems, resource allocation should be handled carefully. It is necessary to create a multi-stage network that differs from the traditional supply chain, which is difficult to manage.

Current studies designed emergency logistics as if there is only one organization owning all the required resources. It is unlikely that every organization will have all sorts of resources. Different stakeholders should be assigned to meet different needs, and, in some cases, there is insufficient resources, and existing resources need to allocate fairly and quickly.

Resource allocation in case of disaster, where a large number of stakeholders will perform pre-determined tasks; the objectives should be based on three pillars according to Beamon and Balçık (2008):

- Effectiveness: The extent to which disaster victim needs are met or victims are served in a timely manner.
- Efficiency: The measure of how economically resources is utilized while providing a certain level of service.
- Equity: fairness in the distribution of goods and services and ensuring that no affected area is systematically disadvantaged.

Rodríguez-Espíndola et al, (2018) divide Humanitarian Logistics Response Phase activities into; healthcare, distribution, facility management, searching victims, setting up temporary settlement sites, escorting the critically injured victims, psychological counseling and health education for the victims. Not just the relief products, equipment, vehicles and people are also considered as implied as essential resources.

2.1 Humanitarian Logistics

Tasks in Humanitarian Logistics classified into four main phases: mitigation, preparedness, response, and recovery. These stages represent the relevant phases experienced during disaster management and required activities and priorities, which changes in time (Rodríguez-Espíndola et al, 2018).

Mitigation tasks include activities for reducing the long-term risk of a disaster (Sperling and Schryen, 2021). Preparedness phase includes all activities performed before a disaster that aims reduce the effects when disaster strikes. Disaster preparedness involves the activities undertaken to prepare a community to react when a disaster takes place (Altay and Green, 2006). While mitigation and preparedness refer to the time before a disaster, response phase activities take place in the immediate aftermath of a disaster. The main objective of response phase is the deployment of the required resources to the affected people (Rauchecker and Schryen, 2019). The recovery stage includes tasks to return to the normal course of life and restore the functioning of the community.

During the preparedness phase, various emergency supplies such as tents, blankets, medical kits, mosquito nets, hygiene kits, etc. are supposed to be pre-located in humanitarian supply chains. Renewable resources include first aid social workers or paramedics (doctors and nurses) and non-renewable medical supplies (i.e., surgical blades, vaccines, antibiotic bandages, syringes, latex gloves, etc. (Ghaffari et al., 2020). In some studies, the terms 'medical team' and 'renewable resources', can be used interchangeably.

2.2 Human Resource Allocation

Human resources can be classified as professional paid aid workers and volunteers.

2.2.1 Professional rescue units and paid aid workers

Aid workers (also known as development workers, humanitarian aid workers, aid workers) are people who, for a wage or salary, help people in countries affected by man-made and natural disasters such as wars, epidemics and earthquakes, and manage projects in those regions (Url-7).

An aid worker is responsible for assessing emergencies, distributing supplies, building relationships with local communities and staff, monitoring project progress, coordinating volunteers, conducting workshops, managing budgets, producing reports, liaising with international agencies and government officials, recruiting and training staff, ensuring safety protocols are followed, and communicating with donors and local authorities.

In times of emergencies, teams must quickly assess the situation and provide necessary interventions. This requires them to act swiftly despite facing physically and mentally challenging conditions. Additionally, aid workers encounter unfamiliar demographics, cultures, political environments, and climates during their efforts (Tint et al, 2015).

Every country has an official institution or agency authorized to deal with natural disasters and emergencies. These institutions usually coordinate disaster response teams, prepare emergency plans, and conduct public awareness activities. Disaster management organizations may differ structurally from country to country. These differences depend on the country's management system, geographical conditions, disaster risks and legal framework. In Turkey, this organization is AFAD (Disaster and Emergency Management Presidency).

To summarize the mission of AFAD briefly, it is to carry out intervention studies to eliminate the effects of disaster or emergency by evaluating all kinds of resources belonging to public, private sector and non-governmental organizations, foreign persons and organizations during disasters and emergencies (Url-8).

Duties of AFAD;

• Taking the necessary measures for the effective implementation of disaster and emergency situations and civil defense services at the country level.

• Ensuring coordination between institutions and organizations that carry out preparation and risk reduction before the occurrence of the incidents, the intervention to be made during the incident and the improvement to be carried out after the incident.

• Conducting and coordinating humanitarian aid operations at home and abroad.

270 thousand people have joined AFAD's "Volunteer System" since 3 January 2019.

INSARAG is a network of more than 90 countries and organizations that aims to establish international standards for USAR teams and methodology for international coordination in earthquake response. AFAD is working to improve the capacity of search-and-rescue units established in 11 provinces and to raise them to INSARAG (International Search and Rescue Advisory Group) standards (Url-9). In this context, first Istanbul AFAD, then Ankara AFAD, received the title of Heavy Search and Rescue Team.

2.2.2 Volunteers

In the aftermath of a disaster, even if the system is planned properly, volunteers reach the disaster area first. Moreover, survivors are the ones that become volunteers after and become more active and cooperative than outsiders (Dubey et al., 2018).

Shin and Kleiner (2003), define a volunteer as "an individual who offers him/herself to a service without an expectation of monetary compensation." According to the IFRC's definition, "A volunteer is someone who works for a more humane and peaceful world by delivering services directly to vulnerable people and seeking to prevent and reduce vulnerability and exclusion. Volunteering is carried out by people acting of their own free will – not through any external social, economic or political pressure – with no desire for material or financial gain.".

The Red Cross website shows that 90 percent of the humanitarian work is carried out by volunteers and 95 percent of disaster relief workers are volunteers (Garcia et al., 2018). According to the Corporation for National and Community Service (CNCS), in 2017 volunteers reportedly contributed 7.7 billion hours to the community in 2014, an estimated $ 173 billion (Url-10).

Despite the invaluable contributions of volunteers in all aspects of post-disaster relief and recovery efforts, one of the biggest problems is still considered the mismanagement of volunteers. Sometimes the unconscious and uncoordinated crowd may hinder the rescue units and volunteers from completing their tasks. Improper interventions can affect the lives of disaster victims. It was stated that after the 1999 earthquake, volunteers who wanted to help enter the city, long queues of vehicles formed, and it was difficult to deliver the needs to the disaster area due to this traffic.

From a planning standpoint, volunteers are considered renewable resources that need to be allocated alongside other essentials like equipment and food. Since volunteers possess varying skill sets, they are classified as different resource types. However, some individuals may have multiple skills, allowing them to fit into more than one resource category (Garcia et al, 2018).

The most important point in volunteer management is to assign the volunteers to the tasks appropriate for their preferences and skill levels. Assigning too many volunteers to certain tasks while other tasks are also likely to cause serious problems, such as swelling in some regions in the long run is one of the irreversible consequences of bad management (Lassiter, 2015). To mitigate these issues, procedures should be developed to systematically integrate these volunteers into the system and emerge them after a disaster. Therefore, volunteers are an important part of the human resources in disaster response.

Volunteers may have received specific training, or they may be spontaneous volunteers who come to help after a disaster. Spontaneous volunteers are also called unaffiliated, informal, emergent, episodic, or disaster volunteers. They are people living in or near the affected areas, or even disaster survivors, and often uneducated. Spontaneous volunteers account for 75% of search and rescue efforts (Abualkhair et al, 2019). Even in goodwill, sometimes it can have bad effects; these unmanaged spontaneous volunteers are called "Secondary disasters within the disaster". So, volunteer management is becoming important since crowdsourcing is one of the challenging factors in a disaster.

Volunteers can be more difficult to manage because of the non-compulsory nature of the work and rapidly changing conditions. Although volunteers play a crucial role in disaster response, they bring unique management challenges to organizations that find themselves amid a complex workforce optimization problem when a crisis occurs. Government and nonprofit emergency response agencies often respond to these crises with not only their employees but also with hundreds or thousands of volunteers that provide their services. (Garcia et al, 2018).

Volunteering levels can be very broad in humanitarian aid and job descriptions. However, in the case of sudden disasters, it is important to use the job definitions and to determine the volunteering levels according to the trainings, especially in the first 72 hours, which is considered critical.

Volunteers should be assigned tasks based not just on their abilities but also according to their preferences since they are not paid workers and desired to be sustainable (Falasca and Zobel, 2012). Procedures should be developed to process and integrate these volunteers.

While Traditional Labor Assignment (TLA) strives to produce programs that minimize labor costs, Volunteer Labor Assignment (VLA) primarily based on voluntary choices. Labor costs of voluntary assignments are generally insignificant and sometimes ignored, compared to traditional labor assignment.

- Volunteer preferences: Variations between the tasks that volunteers want to be assigned and the tasks they are assigned to are important for determining the volunteer satisfaction. This volunteer satisfaction and working time of the volunteers are critical to ensure the continuity of the volunteer and therefore to consider volunteers as renewable resources.
- Volunteers cannot be forced to perform regular shifts.
- Traditional labors are accessible where organizations need, however when volunteers are not satisfied, they can stop working, which can be very costly for organizations.
- Volunteers' abilities and capacities are uncertain.
- Short planning time remains for VLA.
- Volunteers need for shelter and food too (Garcia et al, 2018).
- Lack of resources on the ground (Mayorga et al., 2017; Balcik and Beamon, 2008).
- Sudden and irregular volunteer arrival makes planning more complex.

Volunteers at various educational and skill levels are trained to meet some needs even when there are not enough officials. Especially in large scale disasters where transportation is negatively affected, those who conduct search-and-rescue operations after an earthquake are 35 to 50 percent of the residents living in that area. Especially shortly after the disaster, some of these works are completed with the rescues from the wreckage surface. Later, officials and experts who have been trained in this area reach the region, and with the help of spontaneous volunteers, they begin to rescue victims deep inside the wreckage.

Volunteers can take part in a variety of roles in almost any field in disaster management. 90% of the Red Cross workforce are volunteers. A specially trained Red Cross team supported search-and-rescue teams, checks buildings for people who might be trapped. The main duties of the volunteers are as follows;

- Conduct search-and-rescue efforts

- Provide medical care
- Serve food and water
- Distribute relief supplies
- Build emergency shelter
- Restore communications
- Restore water supplies
- Teach disaster preparedness
- Rebuild communities

Some volunteering organizations such as Redcross, also offer first aid certification classes that volunteers learn how to respond to specific situations and gain the ability to help those in need as they wait for medical professionals to arrive.

According to IFRC "Organizations must maintain a volunteer database and volunteers must be adequately trained. There is a basic minimum, especially on the front line," says Red Cross director. It is also stated that poorly trained volunteers who had received the correct training has risk of losing their life.

The capability of first responders can make the difference between lives saved and lives lost. "When a disaster happens, the first response is going to be through local people," says Pablo Medina, IFRC's global operations coordinator. Local populations can enhance their capacity to respond by studying general first-aid training and basic disaster response skills in advance."

2.3 Material Resource Allocation

Renewable resources are those whose supplies are abundant and can be easily replenished. Unlike nonrenewable resources, they are sustainable. A non-renewable resource refers to a natural substance that is not regenerated at the rate it is consumed (Url-4). When we consider these resources within the scope of disaster management, it is seen that there is a slight change in the definitions. Renewable resources can be considered as resources that can be used repeatedly, such as human resources, ambulances, and excavators, while nonrenewable resources can be considered as resources that cannot be reused.

During the preparedness phase, various emergency supplies such as tents, blankets, medical kits, mosquito nets, hygiene kits, etc. are supposed to be pre-located in humanitarian supply chains. Renewable resources include first aid social workers or paramedics (doctors and nurses) and non-renewable medical supplies (i.e., surgical blades, vaccines, antibiotic bandages, syringes, latex gloves, etc. (Ghaffari et al, 2020). In some studies, the terms 'medical team' and 'renewable resources', can be used interchangeably.

Because regions have different infrastructure and geographic characteristics, they damaged at different levels/types, so both common-purpose (i.e., standard) rescue kits and site-specific(customized) rescue kits are needed (Ghaffari et al, 2020). In some cases, several emergency supplies (such as tents, blankets, kitchenware) are packaged in standard kits/pallets and considered as a single item (Balçık et al, 2016).

Despite the timely arrival of medical kits, patients did not receive proper treatment due to the absence of first aid teams, emphasizing the need to synchronize renewable and nonrenewable resources, as highlighted by lessons from Hurricane Katrina (Wang, 2014).

The World Health Organization (WHO) has developed standardized health kits containing medicines and medical supplies to address various health needs during humanitarian crises and disasters. These kits are prepositioned in key locations to enable quick mobilization during emergency situations. Additionally, long-term agreements with suppliers are established to ensure the swift delivery of kits when needed (Url-11). However, the prepositioned resources were significantly fewer than the actual demand and were stored too far from the affected areas (U.S. House of Representatives, 2006). Similarly, the Federal Emergency Management Agency (FEMA) prepositioned water and food supplies for Hurricane Rita, which occurred in September 2005, showed effective prepositioning can significantly improve disaster response efforts (Pradhananga et al, 2016).

2.4 Coordination and Collaboration of the Resources

Gillespie defines coordination as "the cooperation of independent units for the purpose of eliminating fragmentation, gaps" in service delivery, and unnecessary (as opposed to strategic) duplication of services" in 1991.

When a disaster occurs, various government agencies, such as the armed forces and firefighters, are always present where necessary to combat the worst incidents. One of the biggest challenges of this problem is the fact that multiple stakeholders work at the same time and that there is a very short time for these decisions to be made, apart from the selection and implementation of the appropriate conflicting decisions (Shin et al, 2019).

Coordination has continued to the fundamental weakness of the humanitarian action and relief agencies often fail to make efforts or find it difficult to cooperate (Balçık et al, 2010).

Humanitarian logistics, inter-agency communication, job description and authorization should be planned in pre-disaster stages. Commitment and organizations' involvements are the key factors for coordination.

Plans should be made to take into account the interaction between government agencies and their cooperation with other organizations, such as non-governmental organizations, civil organizations, private firms and even foreign governments (Rodríguez-Espíndola et al, 2018) (Tatham and Kovacks, 2010). Poor coordination and demand-supply mismatches lead to unnecessary suffering and must be avoided to prevent duplication of efforts. "A lack of coordination generally due to conflict among human actors" according to Dubey et al. (2018). In addition, coordination helps to reduce costs when institutions act jointly. In addition, long-term agreements can reduce storage costs as well.

The involvement of numbers and diversification actors in the relief effects makes the system complex and challenging (Balçık et al, 2010). Balancing human and material resources is not a simple matter and is complicated by the involvement of many actors in multiple periods (Rodríguez-Espíndola et al, 2018).

In some cases, there may be hierarchical flow between these stakeholders, as well as situations where all stakeholders interact with each other.

The biggest result to drawn from the two major earthquakes in Turkey, 1999, was that there was no authorization, and the institutions were not properly coordinated, some regions received much support, while some did not.

Factors that affect Coordination in Humanitarian Relief Supply Chains:

1. Number and diversity of actors
2. Donor and Funding
3. Competition
4. Media
5. Unpredictability
6. Resource scarcity/oversupply
7. Cost of coordination (Balçık et al,2010)

Depending on the type and size of the disaster and the number of actors involved in the relief operation, coordination structure varies. In addition, the geographical characteristics of the region where the disaster occurs are also important. Each institution may have its own capacity, application area and level of expertise. As the number and diversity of actors increases, it is difficult to manage these actors, especially in a chaotic environment.

2.5 Search-and-Rescue and First Aid Activities

Search-and-rescue (SAR) activities are part of a complex emergency system that emerges to respond to disasters, what has been termed "helpful behavior in emergencies" (Poteyeva,2007). The initial SAR activity is accomplished by volunteers and emergent groups. Volunteers are most effective in surface rescues where no expertise is required, such as when victims are visible and easily reachable. They are also valuable in low-risk tasks like basic first aid and food distribution.

Bad results that may occur in debris studies require serious attention and knowledge due to factors such as the building is still unstable. Therefore, such deep search-and-rescue efforts should not be carried out before an official rescue unit or expert volunteer team arrives, but spontaneous and novice volunteers can support and assist them in line with the orders of these officials.

Intermediate search-and-rescue training includes topics such as team formation and duty distribution, search methods for injured individuals (physical search, device-assisted, and dog search), debris recognition, identification of basic rescue equipment, patient/injured transport techniques, and the use of recovery materials according to INSARAG Guidelines.

For better understanding, we have created a framework that explains search-and-rescue and first aid activities. These activities are divided into tasks to define workforce requirements, and the required task after an earthquake is presented in detail in Table 2.1. There are eight tasks that need to be completed after an earthquake for search-and-rescue and first-aid purposes, as shown in the figure. These are rescuing from the surface (S1), rescuing from debris (S2), dispatching to a safe zone (S3), dead victim removal (S4), and triage of the victims (S5) that pertains to the search-and-rescue group. Besides, first aid tasks for minimal casualties (T1), delayed casualties (T2), and immediate casualties (T3) must be provided. These tasks are also shown in Figure 2. All these tasks need different amounts of human and material resources that vary according to the nature of the task.

Table 2.1 : Search-and-Rescue and First Aid Tasks Requirements after an Eartquake.

Search-and-Rescue Tasks	**Explanation and Task Requirements**
S1-Rescue from Surface	Providing the rescue of the injured on the surface with wooden or light metal elements, masonry or adobe structures.
S2-Rescue from Debris	Perform technical search and rescue operations in collapsed or compromised structures made of heavy wood or reinforced masonry, including those strengthened with structural steel. Additionally, they must carry out rigging and lifting procedures.
S3- Dispatch to safe zone	Transferring of the survivors of unharmed but whose home heavily damaged to a safe zone.
S4- Death Removal	Removing the bodies of deceased victims from the rubble
S5- Triage	Process of assigning priority to patients' treatments when the immediate demand for medical resources exceeds availability.

First Aid Tasks	Explanation and Task Requirements
T1- Minimal Casualties	First aid activities of injuried victims that requires outpatient treatment.
T2- Delayed Casualties	First aid and transfer activities of victims that require short-term hospital treatment.
T3- Immediate Casualties	First aid and transfer activities of victims with serious injuries requiring long-term hospital treatment.

First aid is the life-saving intervention that everyone who has trained on this subject makes using the materials that can be found at the place of the event.It is done using all kinds of advanced techniques and medicines made by the experts of the work. Figure 2.1 shows these tasks, the order in which they should be performed, and the types of resources required for these tasks.

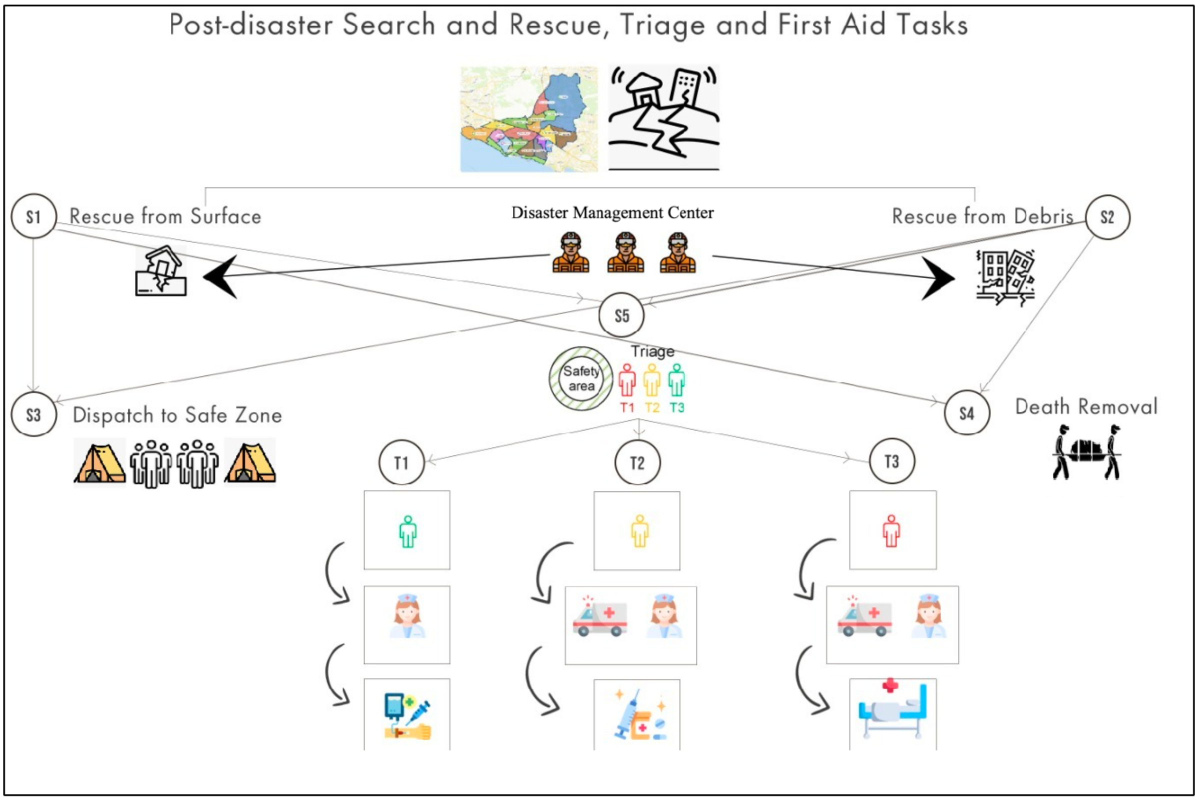

Figure 2.1 : Search-and-Rescue and First-Aid Task Resource Requirements After an Earthquake

3. LITERATURE REVIEW

Humanitarian aid logistics has garnered significant interest, particularly in recent years. Although the terms Humanitarian Logistics and Disaster Management are often used interchangeably in the literature, there are slight differences; while Humanitarian Logistics covers all activities, disaster management is a situation where local resources are insufficient to cope with the disaster. Facility location, network flow, and inventory management are key focus areas in humanitarian logistics, as noted by Altay and Green (2006). For a more detailed literature review, refer to Galindo and Batta (2013), Behl and Dutta (2019), and Chiappetta Jabbour et al. (2019).

Until the end of October 2023, merely 142 of the Humanitarian Logistics studies include “Resource Allocation”, 312 of them include “Coordination” and 47 of them include “Volunteer” keywords, separately. We can conclude that a very limited number of studies (only 11) include “Coordination” and “Volunteer” keywords. For the disaster situation, there are only 4 studies that deal with volunteer management and resource allocation at the same time (Garcia et al, 2018; Abualkhair et al, 2020**;** Sperling and Schryen, 2022; Diaz et al, 2022). We can analyze the resource allocation literature in two parts human resources and material resources.

This section will discuss the studies associated with the resource allocation problem in disasters, including material, equipment, and human resources. Studies dealing with the volunteers are especially examined as well.

3.1 Human Resource Management Literature

One humanitarian logistic challenge that has not received sufficient attention is the difficulty in coordinating numerous human resources effectively. Only 6% of previous studies are allocation problems, while other humanitarian logistics studies are location and routing problems (Garcia et al, 2018). Although studies on resource allocation exist, their scope is primarily related to equipment and tools, and except for a few articles, the issue of human resource allocation is rarely touched upon.

Human resource management literature has been examined under two headings: rescue units and volunteers.

3.1.1 Rescue unit management literature

While there have been relatively few studies explicitly focusing on aid workers, some studies address the topics of rescue units and Urban Search and Rescue (USAR) teams.

Chen and Miller-Hooks (2012) proposed a multi-stage stochastic optimization model that aims to maximize the expected total number of people rescued while dynamically deploying USAR (Urban Search and Rescue) teams to disaster areas partially or fully due to need and shortage. Column generation approach used to solve the problem. Rawls and Turnquist (2012), built a model for planning of shelters aftermath of a disaster, for the evacuees' arrivals. S shaped curve is proposed for the number of people responding to an evacuation over time in a disaster considering different policies for arrivals.

Nayeri et al, (2018) built a decision support model to allocate and schedule the rescue units as an unrelated parallel machine scheduling problem considering time windows for incidents. A modified USAR model deployed by the international humanitarian logistics community is provided in the model. In this research first three-day rescue period is divided into several equal length time periods.

Chen et al,2021, it gives new perspective to human resource allocation problems by introducing two-sided decision-making model that consider rescue tasks but also volunteers individual choices. Through the three main subjects, the demander, supplier, and intermediary, tasks and preference information are shared, and matching is done accordingly. They worked on a case study, a storm surge disaster relief in China. Volunteers come from diversified origins with complicated motivations, random behaviors and different expectations from tasks. Before dispatching, volunteers grouped based on gender, professional skills, physical ability, practical experience to form different volunteer teams (Chen et al, 2021).

While there are many studies on dispatching officials, there are few studies on task distribution in disaster management.

Rodríguez-Espíndola (2018b) proposed first dynamic model that takes into account optimization of the number of organizations involved for resource allocation and aid distribution. Two major floods in Mexico selected as application disaster area, model aims to balance the cost and level of service, and this bi-objective model is solved with both Pareto optimal with weighted sum and epsilon constraint methods to get Pareto Frontier.

Li et al., (2019) model consider multiple disaster areas and departure places to best reflect rescuers' effects, preferences, and competence degrees. Satisfaction degrees are calculated depending on the intention (preference list) competence degrees, professional skills of rescuers, and requirements of tasks.

Rauchecker and Schryen (2019) proposed a model for scheduling rescue units for disaster incidents minimizing the (weighted) sum of completion times. An exact branch-and-price algorithm is used to solve the NP-hard problem.

Shin et al. proposed repair crew problem-minimizes the last transportation time of the entire demand nodes (2019). When a disaster occurs, various government agencies, such as the armed forces and firefighters, are always present where necessary to combat the worst incidents. One of the biggest challenges of this problem is the fact that multiple stakeholders work at the same time and that there is a very short time for these decisions to be made, apart from the selection and implementation of the appropriate conflicting decisions.

In Sarma et al (2019)'s study, model aims to minimize total cost and total time of the relief logistics operation with collaboration of resource collection by the NGO's.

Zhang et al. (2017) developed a multi-stage programming model for the dynamic allocation of rescue teams in NDM. To solve this model, they introduced the C-metric method and the nondominated sorting genetic algorithm (NSGA-II), along with disaster-specific scheduling strategies. More recently, the ASRT (Algorithm for the Scheduling of Relief Teams) problem has been addressed in a manner like routing and scheduling problems (Wex et al., 2014; Nayeri et al., 2022).

The recent study of Nayeri (2022) addresses the problem of the major challenges in the relief operations in the management problem under uncertainty and proposes a scenario-based mathematical model to minimize total relief times of incidents.

3.1.2 Volunteer management literature

The literature on volunteer management is relatively scarce. Most of the existing studies had minor problems that assumes number of volunteers and task demands known in advance, therefore focused on exposing them to various constraints. Volunteers can be more difficult to manage because of the non-compulsory nature of the work and rapidly changing conditions.

Although volunteers play a crucial role in disaster response, they bring unique management challenges to organizations that find themselves in the midst of a complex workforce optimization problem when a crisis occurs.

The first study considering volunteer management is the annual music festival volunteer problem, which was handled by Gordon and Erkut in 2004. Studies have been carried out to include volunteers in the emergency management system.

Falasca et al. (2009) study is one of the first multi-objective models on volunteer management in humanitarian aid, and they developed a multi-criteria optimization model to assign volunteers to tasks. Falasca and Zobel (2012) provided a new approach to voluntary management, using decision-makers preferences and information in the voluntary assignment process, allowing them to examine tradeoffs between conflicting objectives. Lassiter et al.'s study (2015) minimizes the total unfulfilled task demands for different task groups, considering the uncertainty of the demand and voluntary task matching, which aligns the skill levels of tasks and the volunteers.

In Whittaker et al's study (2015), informal volunteerism is divided into emergent and extending volunteers. In Mayorga *et al.'s (2017)* study, human resources planning was addressed, considering the uncertainty in voluntary arrivals and departures to represent voluntary behaviors. Ludwig et al. (2017) propose a public display application to connect volunteers with victims in disaster scenarios, considering potential internet and phone outages.

Garcia *et al*. (2018)'s MIP model addresses the problem of distribution of tasks to volunteers and other RR and NRR, especially in severe situations. The research highlights notable distinctions between available voluntary resources and requests due to frequent fluctuations in requirements. Abualkhair et al. (2019) optimized help center performance based on beneficiary, donor, and voluntary idle times measurements. The system is analyzed in an agent-based simulation environment to evaluate the effectiveness of spontaneous volunteers in the queues of various volunteer policies.

Chen et al. (2021) gave a new perspective on human resource allocation problems by introducing two-sided decision-making models that consider rescue tasks but also volunteer individual choices. Through the three main subjects, the demander, supplier, and intermediary, tasks and preference information are shared, and matching is done accordingly. They worked on a case study, a storm surge disaster relief in China. Volunteers come from diversified origins with complicated motivations, random behaviors, and different expectations from tasks. Before dispatching, volunteers grouped based on gender, professional skills, physical ability, and practical experience to form different volunteer teams.

Although the models vary in volunteer management problems, there are a few shared features in general. One of them is the proportion of permanent volunteers and event-based volunteers. Another is to make the planning periods for two or three days and accept them as 12-hour shifts. In addition to these characteristics, volunteers are prevented from shifting consecutively (Garcia et al, 2018).

3.2 Material Resource Management

Relief material management is receiving increased attention in the field of relief supply chain. Various research studies have proposed models and strategies to effectively distribute essential relief supplies in times of emergencies such as hurricanes. Some scholars have even explored the use of option contracts in relief material management, finding it to be a superior approach compared to instant purchasing. The optimal inventory strategies for relief commodities vary depending on their characteristics, such as perishable rates. Additionally, in certain situations, outsourcing can improve the efficiency of the relief supply chain and benefit all members involved (Yao et al 2018).

The most suitable inventory and management strategies for relief commodities differ based on the commodities' specific attributes (Ghaffari et al, 2020). Sometimes, several emergency supplies (such as tents, blankets, and kitchenware) are packaged in standard kits/pallets and considered a single item (Balçık et al, 2016). These kits are prepositioned in critical locations for quick mobilization during emergencies.

The prepositioned resources for Hurricane Rita in 2005 were insufficient or conveniently located, leading to a shortage of supplies in the affected areas. With the lesson learned, it has been noted that appropriate prepositioning for various disasters helps significantly improve disaster response (Pradhananga et al., 2016). On the other hand, even if medical kits are delivered on time, patients may not be treated appropriately because no first-aid teams are available to use these kits to treat the affected people. Learning from past experiences and focusing on synchronizing RR and NRR for effective disaster management is essential to address these challenges.

Scholars have suggested different models and approaches to organize and distribute crucial relief supplies during emergencies efficiently. Tzeng *et al.* (2007) developed a fuzzy multi-objective programming model for emergency relief distribution to decrease expenses, minimize travel duration, and maximize satisfaction to improve the effectiveness and fairness of delivering relief supplies to needy areas. Rawls and Turnquist (2011) built a model for planning shelters after a disaster. The study highlights the complexity of decision-making in preparing for natural disasters, including determining the locations and capacities of emergency distribution centers and allocating inventories of relief supplies. Rezaei-Malek et al. (2016) proposed a model that combines location allocation and distribution planning by identifying the most suitable location for storing and distributing perishable commodities in the pre-disaster phase. Pradhananga (2016) proposed scenario-based, two-stage stochastic programming to deliver supplies to disaster victims in a timely and cost-effective manner while minimizing social costs.

Pradhananga 2016 proposed a scenario-based two-stage stochastic programming for deliver supplies to the disaster victims in a timely and cost-effective manner by minimizing the social cost.

Rodríguez-Espíndola et al. (2018) suggested a dynamic model to support disaster response involving the use of human and material resources for multiple organizations aiming to investigate the tradeoff between the usage of resources and levels of service provided. The purpose of this research is to design a dynamic optimization model to support relief distribution and resource allocation, which includes resources from many organizations considering the difficulty of resource allocation by examining scarcity and redundancy. Bi objective model was solved with weighted sum and epsilon constraint methods to get the Pareto optimal solution.

Yu et al. (2018) proposed a model that aims to minimize accessibility costs, initial state-based deprivations, and terminal penalty costs to enhance the efficiency, effectiveness, and equity of resource allocation simultaneously. In this study, resources such as water, food, clothing, medicine, tents, and machinery are generally categorized into two types: daily consumable relief items, including water, food, and medicine, and essential daily-use equipment for survivors.

Sabouhi *et al*. (2019) propose a mixed-integer linear programming model for the evacuation and distribution process during emergencies by simultaneously planning vehicle routes and schedules to minimize the total arrival time of vehicles at affected areas, shelters, and distribution centers. Ghasemi *et al*. (2019) developed a mathematical framework incorporating various factors, including resources, periods, and uncertainties, to minimize costs associated with facility selection, distribution, and inadequate relief materials in earthquake response. Shao *et al.* (2020) analyzed the supply and demand of relief materials for various types and severities of disasters, offering detailed lists of comprehensive relief requirements. To improve equity in disaster distribution, Wan *et al.* (2023) propose a new model that aims to improve the allocation of emergency materials after a disaster by considering the uncertainty in demand and severity of the disaster utilizing fuzzy numbers to minimize unsatisfied demand, distribution costs, and transportation route risks.

Besides, some studies recommend pre-positioning inventory and service outsourcing as well as delivery option contracting in relief material supply chain management to ensure the availability and flexibility of the optimal quantity of relief commodities to be ordered before and after a disaster (Yao et al., 2018).

3.3 Coordination Literature

In the event of a disaster, each institution should know its own pre-determined actions and act accordingly. There are hardly any articles consider the importance of employment only the necessary organizations (Rodríguez-Espíndola et al, 2018). Besides, there is a limited number of coordination studies.

Jahre and Jensen (2010) compared their proposed system to existing systems and made contributions via cluster systems to coordination theory. Charles and Lauras (2011) built a model that minimizes cost and improves the efficiency of disaster response while considering humanitarian constraints. John et al (2012) review major issues affecting the management of a humanitarian supply chain in the pre-disaster post-disaster response phase. Kaynak and Tuğer (2014) proposed a model based on defining all the stakeholders of a system and assessing their consciousness level about a natural disaster, focusing on the clusters for disaster coordination operations.

Krejci (2015) proposed an agent-based simulation study and discrete event hybrid model, which includes three different types of agents: donors, international NGOs (INGOs), and local NGOs (INGOs). Relief chain actors developed using NetLogo. The aim of this model is to examine the humanitarian logistic actors' decisions and interactions during the (pre-disaster) stage. Specifically, this model is used to determine how relief chain performance (as the amount of demand per dollar spent on transport costs) affects donor resource allocation decisions and NGO coordination decisions.

Several studies focus on Big Data and building trust in coordination. Papadopoulos et al. (2017) conducted the first study on Big Data in resilience, establishing a theoretical framework using Big Data. Here, 'resilience' refers to flexibility and recovery capacity. Data was collected from Twitter, news sources, Facebook, WordPress, and Instagram to determine whether useful information could be extracted to locate people in need after an earthquake.

Dubey et al. (2017) contribute to the literature by examining the relationship between information sharing, swift trust, and commitment in the Humanitarian Supply Chain (HSC) through an empirical study that develops a theoretical framework. While swift trust typically takes time to form, the urgency in HSCs limits this process, making it less effective compared to commercial supply chains. Hastily formed networks in relief operations have been studied, and Tatham and Kovács (2010) emphasized that speed is not the only constraint in disaster relief-stabilized communication and transport infrastructure are also critical challenges.

3.4 Stochastic Optimization Literature in Humanitarian Logistics

Optimization under uncertainty has long been a topic of greatest interest to researchers in the field of operations research (Lassiter et al, 2015). Stochastic optimization, stochastic programming, and robust optimization are the three methods to handle uncertainty.

Stochastic programming is most common method to model uncertainties in Humanitarian Logistics Literature. Since nature of the humanitarian logistic is uncertain, stochastic programming and robust optimization analysis are most popular techniques for all stages and all areas. Stochastic optimization is also considered to use to tackle the uncertainties in coordination and volunteer management.

Two-stage stochastic linear programs with recourse consist of two main components: a fixed structural stage and a flexible control stage. The first stage involves decisions made under fixed constraints, independent of uncertainty, as they must be determined before uncertain parameters are known. Once uncertainty is realized, the second-stage control variables allow for recourse actions to adapt accordingly (Barbarosoglu & Arda, 2004).

Mete and Zabinsky (2010) introduced a two-stage stochastic programming model for determining medical warehouse locations and supply distribution. In the first stage, decisions are made regarding warehouse placement, operations, and the required quantities of various medical supplies. The second stage focuses on planning the distribution of these supplies to hospitals. Pradhananga et al 2016, proposed a scenario-based two-stage stochastic programming for deliver supplies to the disaster victims in a timely and cost-effective manner by minimizing the social cost.

Çağlayan and Satoğlu proposed a multi-objective two-stage stochastic programming model for casualty transportation system in large-scale disasters, taking into consideration the deterioration of the casualties' condition (2021). They developed a data-driven decision support tool for the management of ambulances and hospitals.

Öksüz and Satoğlu (2023) proposed a post-disaster emergency medical response system that addresses the deterioration of the conditions of disaster victims. This multi-objective stochastic model includes location planning of medical centers, casualty allocation, and medical staff assignment.

The summary of the pioneering studies about resource allocation in disasters, selected from the literature review is also presented in Table 1, sorted by publishing year. The table also shows where our study is distinguished from other studies. The studies considering the volunteers are rare, and none of them consider both volunteers and official rescue units in disaster response teams, simultaneously. This also shows the contribution of our study. Besides, usage of the two-stage stochastic programming method is also a strong aspect of our study, as several past studies merely consider resource allocation in disasters in a deterministic setting.

Table 3.1 : Literature Review Summary.

Author	Year	Model Type	Resource Type			Objective function				Time horizon		Uncertainty		Disaster Type	
			Volunteer	Rescue Unit	Material Resource	Relief time	Coverage (Demand)	Cost	Distance	Single period	Multi-period	Deterministic	Stochastic	Earthquake	Other or Undefined
Tzeng et al.	2007	Fuzzy multi-objective model			*	*	*	*			*	*		*	
Falasca & Zobel	2012	Multi-objective model	*				*	*			*	*			*
Lassiter et al.	2015	Robust optimization model	*				*				*		*		*
Pradhananga et al.	2016	Two-stage stochastic model			*			*			*		*		*
Shin et al.	2019	MILP model		*	*		*				*	*			*
Rodríguez-Espíndola et al.	2018	Multi objective MIP model		*	*		*	*			*	*			*
Abualkhair et al.	2019	Queuing system	*			*					*		*		*
Rauchecker & Schryen	2019	Binary linear programming model		*		*				*		*			*
Sarma et al.	2019	Multi-objective MIP model			*		*	*		*		*			*
Çağlayan and Satoğlu	2021	Two-stage stochastic multi-objective model		*			*		*		*		*	*	
Nayeri et al.	2018 2022	Parallel machine scheduling problem		*		*					*	*			*
Oksuz and Satoglu	2023	Two-stage stochastic multi-objective model		*		*	*		*		*		*	*	
Wan *et al.*	2023	Dynamic multi-objective model			*	*		*	*		*		*		*
This paper	2024	Two-stage stochastic,multi-objective model	*	*	*	*	*	*	*		*		*	*	

4. PROPOSED STOCHASTIC MODEL

This section includes the following titles, respectively: problem description, model assumptions, proposed multi-objective stochastic programming model, solution methodology.

4.1 Problem Description

For the first 72 hours after an earthquake for a neighborhood in Istanbul, Kartal, a dynamic resource allocation study is proposed for search-rescue and first aid activities with a focus on saving human life in order of importance. Each activity is divided into tasks to better define labor requirements.

Before the disaster, resources are planned according to the expected value estimated based on the scenarios. After the disaster, according to the actual scenario, the demands in the disaster zones are realized, and additional resources and transfers are decided.

The determination of demands for pre-disaster and post-disaster resource assignments made accordingly is explained in the flow chart in Figure 4.1. As figure implies, in the pre-disaster stage, the expected demand for human resources (including rescue and first-aid teams and volunteers) and renewable and non-renewable resources is estimated based on all scenarios. According to these, the materials are pre-positioned, and the volunteers' training plans are made. In the post-disaster stage, according to the actual demand, dynamic assignments and transfers of human and material resources and additional resource allocations from outside the disaster zones are made periodically. Regional disaster management centers, responsible for disaster preparedness and response, make these decisions. The bold arcs represent the actual or realized demand.

In the event of a disaster, it is not always necessary to divide time into equal-length periods. The dynamics of each period vary, and the elapsed time is especially critical in the initial moments. Periodization may differ based on the type of disaster, considering the expected number of casualties over time. Our model covers a 72-hour time window, divided into four periods: 0-12 hours, 12-24 hours, 24-48 hours, and 48-72 hours.

Tasks can be sorted in order of importance, just as search and rescue activities take priority over food delivery right after the disaster. (Lassiter, 2015). Considering this situation, if a task cannot be completed, the value of the loss experienced will change according to the order of importance as penalty cost of unmet demands. Teams consisting of volunteers and rescue units will take part in addressing these tasks. Rescue units consist of government-appointed employees with a variety of roles and professions. On the other hand, volunteers can either spontaneously come forward or have acquired specific skills through training.

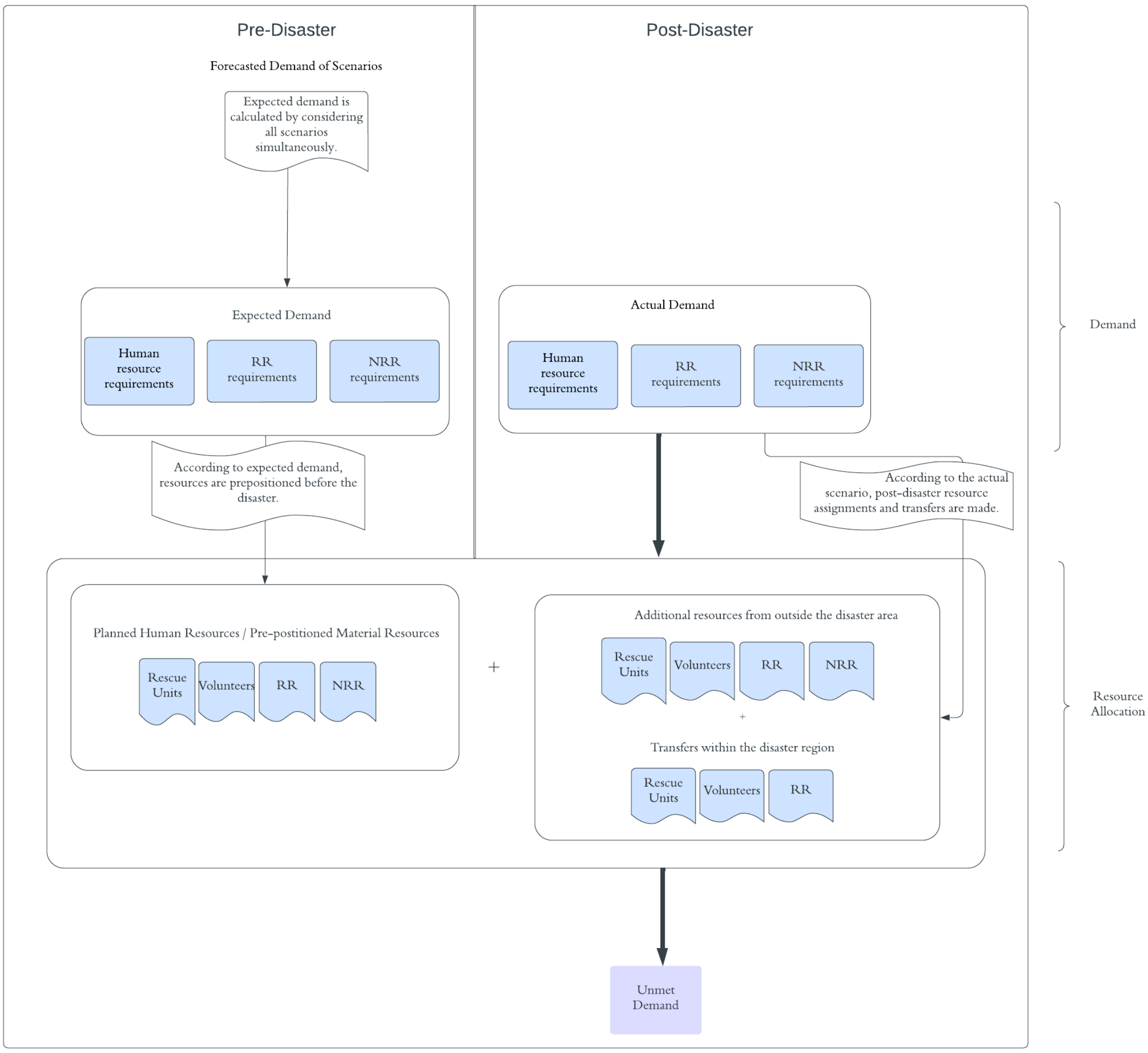

Figure 4.1 : Pre-disaster and Post-disaster Demands and Resource Requirements.

4.2 Model Assumptions

Following assumptions are made in the model.

- All the resource requirements of each region are located in the center of the neighborhood and the transfer of resources is made from this point.
- For each region, casualties rescued from the surface in that area originate from slightly and moderately damaged buildings, and the casualties that need to be rescued from the debris are from heavily damaged buildings.
- There are three types of casualties, which are classified based on the triage rule of NATO.
- Treatment of patients whose condition is minimal and who can be treated on an outpatient basis is carried out by a health worker in a place close to the triage area, without being transferred to the hospital. Other injured people are transferred to the hospitals.
- Volunteers can work on predetermined tasks.
- Skilled volunteers, who received volunteer training from certain occupational groups, will be able to immediately start working at the scene in case of disaster and fulfill some tasks, but rescue units are sent to the disaster areas from the DMC.
- Team, which consists of the people required for a task, will not disperse until the task is completed.
- It is assumed that there is no vehicle resource constraint for the transfer between regions.

4.3 Proposed Multi-Objective Stochastic Programming Model

A multi-objective, two-stage stochastic programming model was developed for resource allocation of humanitarian relief chain coordination integrated with volunteers and official rescue units considering multiple regions, RRs, and NRRs.

The indices, parameters, decision variables, and model formulation are explained below.

<u>Index and sets:</u>

t : Tasks ($t \in T$)

w : Professions ($w \in W$)

s : Possible scenarios ($s \in S$)

p : Periods ($p \in P$)

b : Regions/disaster areas ($b \in B$)

r : Renewable resource types ($r \in R$)

n : Non-renewable resource types (n∈N)

T : set of Tasks

W1 : set of professions that only volunteers operate (*W1∈W*)

W2 : set of professions that only rescue units operate (*W2∈W*)

W : set of Professions

S : set of Scenarios

P : set of Periods

R : set of Resources

N : set of Non-renewable resources

<u>Parameters:</u>

Pr^s : Occurrence probability of scenario s.

${Cas_{tpb}}^s$: Casualty number, requiring task-t in disaster region-b in period-p according to scenario-s.

Vp_{wpb} : Volunteer with profession-w number already trained to perform to be deployed in disaster region-b in period-p.

RU_{wp} : Rescue unit with profession-w number to be deployed in period-p.

TC_w : Training cost of volunteers to perform profession-w.

Pen_{tp} : Penalty cost for unmet demand of task-t in period-p.

$dura_{ts}$: Duration of task-t according to scenario-s.

$ttime_{bb'}$: Traveling time from region-b to region-b'.

Req_{tw} : Human resource requirement from profession-w to accomplish task-t.

$RReq_{tr}$: The number of renewable resources-r required to accomplish task-t.

$NRReq_{tn}$: The number of non-renewable resources-n required to accomplish task-t.

$dfreq_p$: The frequency of distribution for non-renewable resources in period p.

PL_p : Length (duration) of period-p.

$Vmax_p$: Allowed working hours for volunteers in period-p.

$RUmax_p$: Allowed working hours for rescue units in period-p.

${lf_{bb'}}^s$: Traveling time increase ratio of the road-b to b' according to scenario-s due to road failures.

Nr_r: The existing total number of renewable resource-r in the disaster area at the beginning

Nnr_nThe existing total number of non-renewable resource-n in the disaster area at the beginning

usg_n: The ratio of the usage time of non-renewable resource-n to the total duration of the task in which it is used.

${D_{wpb}}^s$: Demand for profession-w in the disaster region-b in period-p according to scenario-s (man*hours).

$${D_{wpb}}^s = \sum_{t \in T} {Cas_{tpb}}^s * Req_{tw} * \mathrm{dura}_{ts} \quad ; \ (w \in W), (\forall \mathrm{p} \in \mathrm{P}), (\forall \mathrm{b} \in \mathrm{B}), (\forall \mathrm{s} \in \mathrm{S})$$

${RD_{rpb}}^s$: Demand of renewable resource-r in period-p in region-b according to scenario-s.

$${RD_{rpb}}^s = \frac{\sum_{t \in T} {Cas_{tpb}}^s * RReq_{tr} * \mathrm{dura}_{ts}}{PL_p} \ ; \ (\forall r \in R), (\forall p \in P), (\forall b \in B), (\forall s \in S)$$

${NRD_{npb}}^s$: Demand of non-renewable resource-n in period-p in region-b according to scenario-s.

$${NRD_{npb}}^s = \sum_{t \in T} {Cas_{tpb}}^s * NRReq_{tn} * \mathrm{dfreq}_p; (n \in NR)(p \in P)(\forall b \in B)(\forall s \in S)$$

<u>Scalars:</u>

Pc3 : The penalty cost ratio for unmet demand of Renewable Resource relative to the unmet demand of Non-Renewable Resource.

Vq : Volunteer quitting rate.

RUq: Rescue unit quitting rate.

Ratv: Ratio of the number of additional volunteers to be accepted to the disaster area to the current number of volunteers.

Ratr: Ratio of the number of additional rescue units to be accepted to the disaster area to the current number of rescue units.

<u>Decision variables:</u>

First Stage Decision Variables:

$VExp_{wb}$: Additional volunteer number to be trained before the disaster to meet the demand in profession-w to be deployed in the disaster region-b.

MR_{rb}: Amount of renewable resource-r prepositioned to meet the demand in disaster region b.

MNR_{nb}: Amount of non-renewable resource-n prepositioned to meet the demand in disaster region-b.

Second Stage Decision Variables:

${UD_{wpb}}^s$: Unmet demand of human workforce with profession-w in region-b in period-p according to scenario-s (man*hour).

$VA_{wpb}{}^{s}$: Volunteer with profession-w that is assigned to region-b in period-p according to scenario-s (man*hour).

$RUA_{wpb}{}^{s}$: Rescue unit with profession-w that is assigned to region-b in period-p according to scenario-s (man*hour).

$Vadd_{wpb}{}^{s}$: Additional volunteer number with profession-w to region-b from outside of the disaster area in period-p according to scenario-s (man).

$RUadd_{wpb}{}^{s}$: Additional rescue unit number with profession-w to region-b from outside of the disaster area in period-p according to scenario-s (man).

$VTr_{wpbb'}{}^{s}$: Transferred volunteer number with profession-w in period-p from region-b to region-b' according to scenario-s (man).

$RUTr_{wpbb'}{}^{s}$: Transferred rescue unit number with profession-w in period-p from region-b to region-b' according to scenario-s (man).

ARR_{rpbs}: Additional renewable resource-r number required to meet the demand in disaster region-b in period- p according to scenario-s (unit).

$ANRR_{npbs}$: Additional non-renewable resource-n number required to meet the demand in disaster region-b in period-p according to scenario-s (unit).

$RTr_{rpbb'}{}^{s}$: Transferred renewable resource-r number in period-p from region-b to region-b' according to scenario-s (unit).

$RUD_{rpb}{}^{s}$: Unmet demand of renewable resource-r in period-p of region-b according to scenario-s (unit).

$RA_{rpb}{}^{s}$: Assigned renewable resource-r number in period-p to region-b according to scenario-s (unit).

$NRUD_{npb}{}^{s}$: Unmet demand of non-renewable resource-n in period-p of region-b according to scenario-s (unit).

$NRAva_{npb}{}^{s}$: Available non-renewable resource-n in period-p in region-b according to scenario-s (unit).

$NRAs_{npb}{}^{s}$: Assigned non-renewable resource-n number in period-p to region-b according to scenario-s (unit).

Objective-1

$$Minimize \sum_{s\in S} Pr^s \left[\sum_{w\in W}\sum_{t\in T}\sum_{b\in B}\sum_{p=1} (\mathrm{D}_{wpb}{}^s - \left(VExp_{wb} + Vp_{wpb}\right) * \mathrm{Vmax}_p - RU_{wp} \right.$$

$$\left. * RUmax_{p}) * Pen_{tp} + \sum_{w\in W}\sum_{t\in T}\sum_{b\in B}\sum_{p\in 2..P} \mathrm{UD}_{wpb}{}^s * Pen_{tp} \right] \tag{1.1}$$

Objective-2

$$Minimize \sum_{s\in S} Pr^s \left[\sum_{w\in W}\sum_{p\in P}\sum_{b\prime\in B}\sum_{b\prime\in \mathrm{B}} \left(\mathrm{VTr}_{wpbb'}{}^s + \mathrm{RUTr}_{wpbb'}{}^s\right) \right.$$

$$\left. + \sum_{r\in R}\sum_{p\in P}\sum_{b\in b}\sum_{b\prime\in B} \left(RTr_{rpbb\prime}{}^s\right) \right] \tag{1.2}$$

Objective-3

$$Minimize \sum_{s\in S} Pr^s \left[\sum_{r\in R}\sum_{p=1}\sum_{b\in B} (\mathrm{RD}_{rpb}{}^s - MR_{rb}) * Pc3 \right.$$

$$+ \sum_{n\in N}\sum_{p=1}\sum_{b\in B} \mathrm{NRD}_{npb}{}^s - (MNR_{nb} - \mathrm{NRAva}_{npb}{}^s) \tag{1.3}$$

$$\left. + \sum_{r\in R}\sum_{p\in P}\sum_{b\in B} \mathrm{RUD}_{rpb}{}^s * Pc3 + \sum_{n\in N}\sum_{p\in P}\sum_{b\in B} \mathrm{NRUD}_{npb}{}^s \right]$$

Subject to

Demand Constraints:

$$\mathrm{UD}_{wpb}{}^s = \mathrm{D}_{wpb}{}^s - \left(VExp_{wb} + Vp_{wpb}\right) * \mathrm{Vmax}_p - RU_{wp} * RUmax_{p};$$

$$(\forall w \in W), (p = 1), (\forall b \in B), (\forall s \in S) \tag{2}$$

$$\mathrm{UD}_{wpb}{}^s = \mathrm{D}_{wpb}{}^s + \mathrm{UD}_{w(p-1)b}{}^s - \mathrm{VA}_{wpb}{}^s - \mathrm{RUA}_{wpb}{}^s;$$

$$(\forall w \in W), (p = 2..P), (\forall b \in B), (\forall s \in S) \tag{3}$$

$$\left(VExp_{wb} + Vp_{wpb}\right) * \mathrm{Vmax}_p = VA_{wpb}{}^s \; ; \; (\forall w \in W), (p = 1), (\forall b \in B), (\forall s \in S) \tag{4}$$

$$RU_{wp} * RUmax_{p} = RUA_{wpb}{}^{s}; \quad (\forall w \in W), (p = 1), (\forall b \in B), (\forall s \in S) \tag{5}$$

$$VA_{wpb}{}^{s} = VA_{w(p-1)b}{}^{s} * (1 - Vq) + \left(\mathrm{Vadd}_{wpb}{}^{s} + Vp_{wpb} + \sum_{b' \in B} VTr_{wpb'b}{}^{s} - \sum_{b' \in B} VTr_{wpbb'}{}^{s} \right) * \mathrm{Vmax}_{p} - \sum_{b' \in B} VTr_{wpb'b}{}^{s} * ttime_{b'b}(1 + \mathrm{f}_{b'b}{}^{s}) \tag{6}$$

$$(\forall w \in W1), (p = 2..P), (\forall t \in T), (\forall b \in B), (\forall s \in S)$$

$$RUA_{wpb}{}^{s} = RUA_{w(p-1)b}{}^{s} * (1 - RUq) + \left(RU_{wp} + \mathrm{Radd}_{wpb}{}^{s} + \sum_{b' \in B} RUTr_{wpb'b}{}^{s} - \sum_{b' \in B} RUTr_{wpbb'}{}^{s} \right) * RUmax_{p} - \sum_{b' \in B} RUTr_{wpb'b}{}^{s} * ttime_{b'b}(1 + \mathrm{f}_{b'b}{}^{s}) \tag{7}$$

$$(\forall w \in W2), (p = 2..P), (\forall t \in T), (\forall b \in B), (\forall s \in S)$$

<u>*Renewable Resource Constraint:*</u>

$$\sum_{b \in B} MR_{rb} \leq Nr_{r} \; ; \; (\forall r \in R) \tag{8}$$

$$RA_{rpb}{}^{s} \leq MR_{rb} \; ; \qquad (\forall r \in R)(p = 1)(\forall b \in B)(\forall s \in S) \tag{9}$$

$$RA_{rpb}{}^{s} \leq RA_{r(p-1)b}{}^{s} + ARR_{rpb}{}^{s} + \textstyle\sum_{b' \in B} \mathrm{RTr}_{rpb'b}{}^{s} - \sum_{b' \in B} \mathrm{RTr}_{rpbb'}{}^{s}; \quad (\forall r \in R)(p = 2..P)(\forall b \in B)(\forall s \in S) \tag{10}$$

$$RUA_{wpb}{}^{s} + VA_{wpb}{}^{s} \geq \sum_{t \in T} (RReq_{tr} * Req_{tw} * \mathrm{dura}_{ts}) * RA_{rpb}{}^{s}; \tag{11}$$

$$(\forall w \in W)\ (r \in R)\ (\forall p \in P)(\forall b \in B)(\forall s \in S)$$

$$RUD_{rpb}{}^{s} = \mathrm{RD}_{rpb}{}^{s} - RA_{rpb}{}^{s}; (r \in R)(\forall p \in P)(\forall b \in B)(\forall s \in S) \tag{12}$$

<u>*Non-Renewable Resource Constraint:*</u>

$$\sum_{b \in B} MNR_{nb} \leq Nnr_{n}; \quad (n \in NR) \tag{13}$$

$$\mathrm{NRAva}_{npb}{}^{s} = MNR_{nb} - \mathrm{NRAs}_{npb}{}^{s}; \quad (n \in NR)(p = 1)(\forall b \in B)(\forall s \in S) \tag{14}$$

$$\mathrm{NRAva}_{npb}{}^{s} = \mathrm{NRAva}_{n(p-1)b}{}^{s} - \mathrm{NRAs}_{npb}{}^{s} + \mathrm{ANRR}_{npb}{}^{s}; (n \in NR)(p = 2..4)(\forall b \in B)(\forall s \in S) \tag{15}$$

$$NRUD_{npb}{}^{s} = \mathrm{NRD}_{npb}{}^{s} - NRAs_{npb}{}^{s};\ (n \in NR)(\forall p \in P)(\forall b \in B)(\forall s \in S) \tag{16}$$

$$RUA_{wpb}{}^{s} + VA_{wpb}{}^{\ s} \geq \sum_{t \in T} NRReq_{tn} * Req_{tw} * \mathrm{dura}_{ts} * NRAs_{npb}{}^{s} * usg_{n}; \tag{17}$$
$$(\forall w \in W)(n \in NR)(\forall p \in P)(\forall b \in B)(\forall s \in S)$$

Other Constraints:

$$\mathrm{Ratv} * \mathrm{Vadd}_{wpb}{}^{s} * \mathrm{Vmax}_{p} \ \leq \mathrm{VA}_{w(p-1)b}{}^{\ s};\ (\forall w \in ov)(p = 2..4)(\forall b \in B)(\forall s \in S) \tag{18}$$

$$\mathrm{Ratr} * \mathrm{Radd}_{wpb}{}^{s} * RUmax_{\ p} \leq \mathrm{RUA}_{w(p-1)b}{}^{\ s};\ (\forall w \in or)(p = 2..4)(\forall b \in B)(\forall s \in S) \tag{19}$$

$$\sum_{w \in W} \sum_{\forall b \in B} VExp_{wb} * \mathrm{TC}_{w} \leq Budget \tag{20}$$

$$VTr_{wpbb}{}^{\ s} = 0 \quad (\forall w \in W), (\forall p \in P), (\forall b \in B), (\forall s \in S) \tag{21}$$

$$RUTr_{wpbb}{}^{s} = 0 \quad (\forall w \in W)(\forall p \in P), (\forall b \in B), (\forall s \in S) \tag{22}$$

$$VTr_{wpb'b}{}^{\ s} = 0 \ \ (\forall w \in W), (p = 1), (\forall b, b' \in B)(\forall s \in S) \tag{23}$$

Binary and positive variables:

$$VExp_{wb}, RUTr_{wpbb'}{}^{\ s}, \mathrm{Vadd}_{wpb}{}^{s}, \mathrm{Radd}_{wpb}{}^{s}, MR_{rb}\ , MNR_{nb}, RA_{rpb}{}^{s},$$
$$ARR_{rpb}{}^{s}, \mathrm{ANRR}_{npb}{}^{s}, NRAs_{npb}{}^{s}, NRAv_{npb}{}^{s}, \mathrm{RUD}_{rpb}{}^{s}, \mathrm{NRUD}_{npb}{}^{s} \geq 0 \ \ and\ integer \tag{24}$$

$$\mathrm{UD}_{wpb}{}^{s},\ RUA_{wpb}{}^{s}, VA_{wpb}{}^{s},\ \ VTr_{wpbb'}{}^{\ s}, \mathrm{RTr}_{rpb'b}{}^{s} \geq 0 \tag{25}$$

As a first-stage decision, regardless of the scenarios, the number of expected volunteers that need training and the number of resources that should be pre-positioned in the regions to meet RR and NRR demand for the first period of the disaster are decided. As a second stage decision, after the disaster occurs, the amount of interregional resource transfer and additional resource allocation to the regions are decided according to the needs of the regions.

The first objective function (1.1) aims to minimize the unmet demand(man*hour), which is a non-negative variable that describes the demand that cannot be met by the total working hours of volunteers (volunteer pool and additional required volunteers) and rescue units. For a better understanding of the equation, the unmet demand calculation for the first period and the following periods are expressed separately.

In Equation (1.1.), Vp_{wpb} parameter represents the number of volunteers with profession-w already trained to be deployed in disaster region-b in period-p., and the VExpwb is the decision variable for the number of volunteers to be trained before the disaster. So, the total number of available and to be trained volunteers is multiplied with the maximum number of work hours of a volunteer in period-p (Vmaxp) to find the total volunteer workforce capacity. Besides, $RUmax_p$ representing the allowed working hours for rescue units in period-p is multiplied with the RU_{wp} namely the rescue unit (people) with profession-w to be deployed in period-p, that yields the total available official rescue units' hourly capacity. The total volunteer and rescue units' available capacity is subtracted from the total workforce demand (Dwpbs) to find the unmet workforce demand (in hours) in the first period, according to the scenario-s, in the first term. The second term in this objective is the unmet demand in the following periods according to each scenario, which is computed in Constraint (2). Both terms are multiplied with a penalty value for each period.

The second objective function (1.2) minimizes the number of human resources and RR transfers between regions. As for the third objective function (1.3), the total unmet demand for material resources (RRs and NRRs) is minimized.

Constraint 2 demonstrates that the total unmet demand equals the required demand minus the volunteer and rescue units assigned for the first period. Constraint 3 states that the total unmet demand after the first period can be determined by subtracting the human resource assigned in that period from the sum of the total demand for that period and the unmet demand from the previous period. Constraint 4 demonstrates that the total as-signable workforce for volunteers in the first period is equal to the total volunteer number in the volunteer pool (volunteers that are already trained) and expected volunteers (first-stage decision variable), multiplied by the time allowed for volunteers to work in the first period. Constraint 5, likewise, shows an assignable workforce for rescue units for the first period. Here, only the rescue units available before the disaster can be assigned.

Constraint 6 states that, starting from the second period, the total assignable work-force (in hours) for volunteers is determined by computing the workforce assigned to that region in the previous period multiplied by one minus the quitting ratio, plus the additional volunteers assigned to the region, plus the workforce transferred to that region from other regions, and minus the workforce transferred from that region. The time spent on the road from that region to other regions is also considered. This constraint also considers volunteers' quitting behavior and maximum working hours. Similarly, constraint 7 shows the total assignable workforce provided for rescue units, following a similar calculation approach as constraint 6.

Constraint 8 ensures that the total number of RRs prepositioned to the regions is less than the initial number of RRs. Assigned RR numbers for the first period are calculated in constraint 9, while those from the second period are shown in constraint 10. Constraint 10 ensures that the RR number assigned in any period in a region (b) is smaller than the resources allocated in the previous period, plus any additional resources transferred to the region minus the resources transferred from that region.

Constraint 11 stipulates that the rescue teams and volunteers assigned to a disaster region must be at least as much as that needed by the renewable resources allocated to a region in a certain period. In other words, renewable resources are not assigned if no human workforce, including rescue units and volunteers, is assigned to a region in a period. Hence, simultaneous human and renewable resource (RR) assignment is attained. The utility of simultaneous assignment is that valuable human resources can exploit renewable resources (equipment, vehicles, etc.) to perform the tasks. The unmet RRs are calculated by subtracting the assigned number from the demand of the RRs in constraint 12.

The constraints used for NRRs are constraints 13–17. Constraint 13 ensures that the total number of NRRs prepositioned to the regions is less than the initial available number. Constraint 14 calculates the remaining available NRRs from the first period by subtracting the assigned ones from the total. In contrast, in constraint 15, the available number of NRRs after the first period is calculated by including additional assignments. The level of unmet NRR demand is shown in constraint 16, such that the assigned NRR number in each region is subtracted from that region's demand.

By constraint 17, no more NRRs than the assigned human workforce can use for each period can be assigned because NRRs are used by human resources during tasks. In other words, if no human resource is assigned to a disaster region in a period, no NRRs are assigned there. Hence, the simultaneous NRR and human resource assignments are attained. The reason for simultaneous assignment is that valuable human resources can only exploit non-renewable resources, and the associated tasks can be performed. Therefore, this constraint stipulates the simultaneous assignment of human and NRR resources. For volunteers in constraint 18 and rescue units in constraint 19, the additional human workforce from outside the disaster area was ensured to be no more than the predetermined percentage of the workforce assigned in the previous period. This is due to security reasons and the intension to prevent the crowd in the disaster regions.

Constraint 20 aims to allow for the training of volunteers as much as the budget allows. It was stated that, in constraint 21 for volunteers and constraint 22 for rescue units, there was no labor transfer within the district in all periods. Constraint 23 prevents volunteer transfers in the first period since this resource is already assigned to that district. Constraints 24 and 25 are non-negativity and integer constraints.

4.4 Solution Methodology

4.4.1 Multi-Objective Mathematical Programming

In most cases, multiple alternative solutions exist rather than a single optimal solution, as some objectives may conflict with each other. Since not all objective functions can be improved simultaneously, alternative solutions are generated, and these potential solutions are referred to as efficient (Pareto optimal) solutions (Torabi et al., 2010). The epsilon-constraint method, first introduced by Haimes et al. in 1971 (Zhang and Reimann, 2014), involves selecting one objective function for optimization while restricting the others to predefined values that meet minimum requirements. The traditional epsilon-constraint method iteratively increases the constraint bound by a fixed δ constant (Laumanns et al., 2006).

Mavrotas (2009) proposed the AUGMECON method to avoid this shortcoming of the traditional constraint method. This modification performs lexicographic optimization on the rest of the objective functions if there is an alternative optimum. Mavrotas (2009) proposed transforming objective function constraints into equalities by introducing slack or surplus variables. These slack or surplus variables force the model to produce only efficient solutions where epsilon is a small number (usually between 10^{-3} and 10^{-6}).

Mavrotas and Florios (2013) improved the method to AUGMECON2. The difference between the AUGMECON and AUGMECON 2 methods is that they perform a kind of lexicographical optimization to ensure the order of importance among the objectives with a slight change in the objective function.

The objective function values from the payoff table are segmented into predefined equal intervals for each objective function, and the methodology is executed iteratively. A more detailed description of AUGMECON2 and the algorithm steps can be found in Mavratos and Florios's article (2013). For studies using the Augmecon2 method in humanitarian aid, the readers can refer to (Çağlayan and Satoğlu, 2021; Öksüz and Satoğlu, 2023).

The general formulation of AUGMECON2 is as follows:

$$\min \quad \left(f_1(x) + eps \times \left(\frac{s_2}{fmax_2 - fmin_2} + 10^{-1} \times \frac{s_3}{fmax_3 - fmin_3} + \cdots + 10^{-(p-2)} \times \frac{s_p}{fmax_p - fmin_p}\right)\right) \tag{3.8}$$

subject to

$$f_2(x) + s_2 = fmin_2 + t \times (fmax_2 - fmin_2\,)/q_2 \tag{3.9}$$

$$f_3(x) + s_3 = fmin_3 + t \times (fmax_3 - fmin_3\,)/q_3 \tag{3.10}$$

$$\dots$$

$$f_p(x) + s_p = fmin_p + t \times (fmax_p - fmin_p\,)/q_p \tag{3.11}$$

$$x \in S \; and \; s_i \in R^{+}. \tag{3.12}$$

where $S_2, S_3, \dots, S_p$ are the surplus variables of the respective constraints for objective functions 2, 3, … , p, and eps ∈ [10^{-6}, 10^{-3}]. Firstly, the objective function range was calculated for each objective function 2, 3, … , p. Then, the range of the k-th objective function was divided to q_k equal intervals (q_k - 1) using intermediate equidistant grid points for the t-th iteration. The details of this method have been presented in Mavrotas and Florios (2013).

4.4.2 Two-Stage Stochastic Models

Researchers in operations research have long focused on optimization under uncertainty. The three primary approaches to addressing uncertainty are stochastic optimization, stochastic programming, and robust optimization.

Stochastic programming is most common method to model uncertainties in Humanitarian Logistics Literature. Since nature of the humanitarian logistic is uncertain, stochastic programming considered to use to tackle the uncertainties in coordination and volunteer management.

Two methods are used, either cluster-based or scenario-based for solving stochastic optimization problems or dealing with uncertainty in decision-making models. In scenario-based models; It is aimed to minimize expected cost and deviations from the best cost. While cluster-based models are generally used in cases where the data set is large, and the parameters are continuous; Scenario-based models are generally used when the parameters are discrete.”

Table 4.1 : Single-Stage Stochastic Problems vs Multi-Stage Stochastic Problems.

Feature	Single-Stage Stochastic Problems	Multi-Stage Stochastic Problems
Decision Timing	All decisions made upfront	Decisions made in multiple stages
Recourse	No recourse, decision is fixed	Recourse available, adjust decisions over time
Flexibility	No flexibility after decision	Flexibility to adjust based on new information
Uncertainty	Fixed set of possible scenarios	Uncertainty evolves over stages
Complexity	Easier to solve	More complex, requires dynamic programming
Objective	Optimize expected value across all scenarios	Optimize across multiple stages

In Single-Stage Stochastic Problems, all decisions are made at the beginning of the problem before any uncertainty is revealed, whereas in Multi-Stage Stochastic Problems, decisions are made in stages, with some uncertainty being resolved between stages (Table 4.1). In single-stage stochastic problems, once a decision is made, it is fixed with no opportunity for adjustment, and the objective is typically to optimize the expected value across all scenarios. In multi-stage stochastic problems, decisions are made in stages, allowing the decision-maker to adjust based on newly revealed information, with each stage's decisions affecting future outcomes.

Two-stage stochastic linear programs with recourse consist of two main components: a fixed structural stage and a flexible control stage. The first stage involves decisions made under fixed constraints, independent of uncertainty, as they must be determined before uncertain parameters are known. Once uncertainty is realized, the second-stage control variables allow for recourse actions to adapt accordingly (Barbarosoglu and Arda, 2004).

The general formulation of a two-stage stochastic programming model is as follows

$$Min\ \ c^T x + E_\xi Q(x, \xi) \tag{3.1}$$

$$s.t.\ Ax = b\ , \tag{3.2}$$

$$x \geq 0\ , \tag{3.3}$$

where, $c^T x$ denotes the optimal value of the first-stage decision, E_ξ denotes the mathematical expectation with respect to random vector ξ and, $Q(x, \xi)$ is the optimal value of the second-stage problem, which is defined as follows:

$$Min\ \ q^T y \tag{3.4}$$

$$s.t.\ \ W_y = h - T_x\ , \tag{3.5}$$

$$x, y \geq 0\ , \tag{3.6}$$

The second-stage problem depends on the data ξ(ω) ≡ (q(ω), h(ω), T(ω)), elements of which can be random, while the matrix W is assumed to be known beforehand. The matrices T(ω) and W are called the technology and recourse matrices, respectively (Kleywegt and Shapiro, 2001).

5. APPLICATIONS OF THE MODEL

This section covers the case study, data collection, results, managerial implications and insights, as well as sensitivity analysis.

5.1 Case Study

We proposed a stochastic model and conducted a case study for the Kartal district of Istanbul. It is one of the most crowded districts of Istanbul, with nearly 470.000 inhabitants, 20 sub-districts (demand points), and one Disaster Management Center.

In the event of a disaster, the number of the loss of life and injured victims, financial needs and aid requirements differ according to the type of disaster. In this direction, statistical reports are prepared by various institutions dealing with the studies carried out on the location where the disaster is expected to occur. In Turkey, there are earthquake reports prepared by different institutions, including the number of injured and dead, varying according to the scenarios created by taking into account the location, day-night situation and time factors.

The Earthquake Hazard and Risk Analysis report in Istanbul was created based on the Japan International Cooperation Agency (JICA) report, Directorate of Earthquake and Geotechnical Investigation (DEZIM) reports, and the “Possible Earthquake Loss Estimates Booklet” prepared by Istanbul Metropolitan Municipality and Kandilli Observatory (IBB-KRDAE, 2020) for district-specific analyzes and mappings. We utilized these reports to estimate the expected casualty numbers in different scenarios.

The JICA report on the anticipated Istanbul earthquake predicts 73,000 fatalities, 120,000 severe injuries, and 252,000 damaged buildings, with 51,000 of them being heavily affected.

Approximately 1,939,000 occupants or unprotected people in lightly damaged buildings will suffer minor injuries or be trapped under overturned furniture/or fixed door and window. These people can be rescued by local disaster service groups (JICA).

"Possible Earthquake Loss Estimate Booklets" was prepared by Istanbul Metropolitan Municipality (IBB) with Kandilli Observatory and Earthquake Research Institute (KRDAE) to renew the possible earthquake damage and loss estimates of the city by using the current population, building and infrastructure inventories of Istanbul. In 2020, using this data, these estimates were recompiled for districts on a neighborhood basis, and district-specific analyzes and mappings were made.

It is estimated that an average of 57% of the buildings in Istanbul will not be damaged in the scenario earthquake with a magnitude of Mw=7.5. On average, 13% of buildings are moderately damaged, 3% are severely damaged, and 1% are very severely damaged, totaling approximately 194,000 buildings.

For each building class, the number of people at the relevant injury level is estimated by multiplying the number of buildings at each damage level by the average population in those buildings and the injury rate of the relevant building occupants. These rates are based on observational data and expert interpretation in the absence of data (DEZİM).

Factors that will affect the number of injured and dead in a disaster include the number of building floors and the materials used in construction, as these influence the building's ability to withstand the impact. Additionally, the time and season of the earthquake are significant, as they can determine the number of people present in buildings and their ability to evacuate or respond to the disaster.

Rescue units consist of government-appointed employees with a variety of roles and professions. On the other hand, volunteers can either spontaneously come forward or have acquired specific skills through training. Rescue units come together at the Disaster Management Center (DMC) immediately after the disaster and are transferred to the required region in line with the needs. Additional human resources are also sent to disaster areas through DMCs in the following periods. In the first period, volunteers start working in the predetermined disaster areas. Then, they are transferred to the required areas in subsequent periods, just like rescue units

Multiple scenarios representing different disaster severity levels are considered in the model. The JICA (2002) proposed four possible earthquake scenarios for Istanbul (Model A, B, C, and D). We generated five scenarios from each of the main scenarios of JICA and obtained twenty scenarios (Öksuz and Satoglu, 2020), as seen in Table 4.2. The occurrence probabilities of the scenarios are assumed to change between 0.01 and 0.1, and scenarios that are most likely to occur in the main scenarios of JICA. While creating the scenarios, it was assumed that the situation worsened by 10% in each scenario starting from S1; that is, the expected number of casualties increased by 10%. In this study, we used the probabilistic link failure approach, considering the distance increase according to the damage rates of the roads. Table 5.1 provides the probabilistic travel time increase ratios for each scenario, uniformly distributed UNIF (0,0.38).

Table 5.1 : The magnitudes, probabilities, damage/casualties' multiplier ratios, and travel time increase ratios associated with each disaster scenario.

Scenarios	Magnitude of Earthquake	Occurrence Probability	Disaster Damage Increase Rate	Travel Time Increase Ratio (%)
S1	6.9	0.1	1	0.27
S2	6.9	0.08	1.1	0.18
S3	6.9	0.07	1.2	0.25
S4	6.9	0.09	1.3	0.2
S5	6.9	0.05	1.5	0.09
S6	7.4	0.07	1.6	0.21
S7	7.4	0.04	1.8	0.21
S8	7.4	0.06	1.9	0.21
S9	7.4	0.03	2.1	0.24
S10	7.4	0.02	2.4	0.14
S11	7.5	0.05	2.6	0.19
S12	7.5	0.04	2.9	0.1
S13	7.5	0.06	3.1	0.3
S14	7.5	0.03	3.5	0.11
S15	7.5	0.04	3.8	0.16
S16	7.9	0.05	4.2	0.13
S17	7.9	0.06	4.6	0.26
S18	7.9	0.02	5.1	0.11
S19	7.9	0.03	5.6	0.23
S20	7.9	0.01	6.1	0.13

The distance between disaster regions was found using Google Maps by taking the shortest path. The traveling time model is formed based on the Ambulance Travel Times (Budge et al., 2010). For routes shorter than 4.13 km, the travel time is calculated by multiplying $2.42\sqrt{d}$, where d is the distance, and m(d) is the ambulance's traveling time. Interregional transfers (for volunteers and rescue units) are made at the beginning of each period.

$$m(d)=\{2.42\ \sqrt{d} \quad \text{if } d\leq 4.13 \text{ km} ; \quad 2.46+0.596d \quad \text{if } d>4.13 \text{ km} \}$$

Population in demand points is obtained from the Turkish Statistical Institute. Casualty numbers were obtained from JICA (2002) and DEZIM (IBB-KRDAE, 2020) reports, which state many factors, such as the neighborhood's infrastructure. Moreover, the strength of the houses affects the expected number of casualties. Casualty numbers are distributed to periods according to rates given in the study by Rawls and Turnquist (2012). in which demand occurrence rates for the first 72 hours. 0-12. 12-24. 24-48. and 48-72h are 0.6. 0.25. 0.10. and 0.05, respectively. This means that 60% of this region's disaster victims can be reached in the first 12 hours. These are presented in Table 5.2. In the stage of creating scenarios, it was determined that the most optimistic situation, namely scenario-1, was the number of injured and missing persons stated in the reports. From Scenario 2 onwards, it has been assumed that the situation worsened, and the numbers increased by 10% in each scenario.

Table 5.2 : Expected Casualty Number for Base Case Scenario (Scenario-1).

Period	Period1	Period2	Period3	Period4	Total
Hours	0-12 h	12-24 h	24-48 h	48-72 h	72 h
	Casualty Emergence Rate				
	60%	25%	10%	5%	100%
Tasks	**Expected Casualty Number**				
S1- Casualties rescued from surface	605	252	101	50	1008
S2- Casualties rescued from debris	468	195	78	39	780
S3- Casualties dispatched to safe zone	1500	625	250	125	2500
S4- Death casualties	106	44	18	9	176
S5- Triaged casualties	1073	447	179	89	1788
T1- Minimal casualties	689	287	115	57	1148
T2- casualties	332	138	55	28	553
T3- Immediate casualties	52	22	9	4	87

Table 5.5 provides the requirements for volunteers, rescue units, and RRs and NRRs based on the task types. The table shows that some professions planned to take part in the study can only be operated by volunteers or rescue units, and both workforce types can operate some. For the people planning to participate in the teams formed for the model, the task profession requirement table was created based on the USAR medium-level and hard-level rescue teams from the INSARAG Guidelines (2020). To complete these tasks, a specified number of people from each profession must be present in the disaster area to form a team. Volunteers and rescue teams must work actively for several hours each period. Since the period lengths differ, active working times allowed for the human resources also differ.

It is known that there are pre-determined volunteers in the disaster areas who are planned to work in a certain period and region at the time of the disaster. Since the training time required for each volunteer level is different, the training costs of volunteers also vary according to their level of expertise. It is planned to transfer these volunteers between regions if necessary or to accept additional volunteer support from outside the disaster area.

Similar task assignment planning is adopted for rescue units. Unlike volunteers, the region to which rescue teams will be assigned is not determined in advance and will be assigned to the regions upon request. In the same way as volunteers, it is agreed that optimal numbers of inter-regional transfers and additional rescue unit support will be assigned.

Within the available budget, the aim is to increase the number of volunteers (expected volunteers) by providing pre-disaster training at the expense of a cost. The arrival times of rescue units and volunteers may vary for various reasons (such as road failures and psychological and physical problems). At the end of each period, quitting behavior may occur due to various reasons for both the volunteer and rescue units also considered. This quitting rate is expected to be higher for volunteers as they work voluntarily. In line with the needs, interregional transfers are planned to start from the beginning of the second period.

Task durations for scenario1 are provided in Table 5.3. In each scenario starting from Scenario 1, it is assumed that the duration increases by 5%.

If a task cannot be completed, the value of the loss experienced will change according to the order of importance as penalty cost of unmet demands. The penalty cost values expected to arise for each task whose demand cannot be met are shown in Table 5.4.

Table 5.3 : Duration of the Tasks for Scenario1(minutes).

Task	**S1**	**S2**	**S3**	**S4**	**S5**	**T1**	**T2**	**T3**
Duration	120	200	20	200	40	30	60	60

Table 5.4 : Penalty Cost for Unmet Demand for Tasks.

Tasks	Period1	Period2	Period3	Period4
S1	1	2	3	4
S2	3	3	3	3
S3	1	1	1	1
S4	1	2	3	4
S5	2	2	1	1
T1	1	1	1	1
T2	2	2	2	2
T3	3	3	3	3

Table 5.5 : Task/Profession Requirement Table.

	Human Resource Requirements of Tasks								Material Resource Requirements of Tasks	
Profession	1	2	3	4	5	6	7	8	Renewable Resources	Non- Renewable Resources
Rescue Unit	Team Commander	Search and Rescue Officer	Communication Officer	Equipment Manager	Doctor	Paramedics	Ambulance Driver			
Volunteer		Search & Rescue Volunteer			Professional Healthcare Volunteer	First Aid Volunteer		Spontaneous Volunteer (Support staff)		
S1-Rescue from Surface	1	2	1	1	0	0	0	1	0	0
S2-Rescue from Debris	1	3	1	1	0	0	0	1	0	0
S3- Dispatch to Safe Zone	0	0	0	0	0	0	0	1	0	0
S4- Death Removal	1	2	0	1	0	0	0	1	0	0
S5- Triage	0	0	0	0	0	1	0	0	0	0
T1- Minimal Casualties First Aid	0	0	0	0	0	1	0	1	0	1
T2- Delayed Casualties First Aid	0	0	0	0	1	1	1	1	1	1
T3- Immediate Casualties First Aid	0	0	0	0	1	1	1	0	1	1

Regarding material resources, Table 4.4 also presents the tasks that require RRs and NRRs. In the study, an ambulance, one of the resources that can be used repeatedly, was chosen as an RR. For the ambulance and driver to work simultaneously, they must be in the disaster area simultaneously. As NRR, medical kits used by the medical staff in the treatment of T1-T2-T3 victims after triage were considered. These kits are known to be consumed once used. Due to capacity and economic constraints, unlimited resource storage will not be possible.

5.2 Results for the Case Study without Targeting Equity (Policy1)

The model has been solved in IBM CPLEX Optimization Studio 22.1.0. All computational work was performed on a 64-bit operating system, Intel Cor™ i7-6500U 2.50 GHz CPU, and 8.00 GB RAM personal computer. Pareto optimal solutions of the proposed multi-objective model were obtained for the case study. CPU times for solutions range from 330 seconds to 1510 seconds. First, the model was solved for all three objectives separately, and the payoff table was constructed as shown in Table 5.

First, the model was solved for all three objectives separately, and the payoff table was constructed as shown in Table 5.6. Table 5.6 shows that if unmet demand (z1) is minimized, its value will be 114367. It indicates that 114367 man*hour unmet demand will arise even if minimized. Resource transfer (z2) will be 17128.2, and unmet material resource (z3) will be 24181.

Table 5.6 : Payoff table.

Minimized Objective Function	z1	z2	z3
Min Z1 (Unmet human resource, man*hour)	114367.0	17128.2	24181.0
Min Z2 (Resource transfer, unit)	2058460.3	0.0	24181.0
Min Z3 (Unmet material resource, unit)	1825928.6	13650.0	9526.5
Range (Max-Min)		17128.2	14654.5

On the other hand, if the z2 is minimized, z1 will be 2058460.3, z2 will be 0, and z3 will be 24181. If the z3 is minimized, z1 will be 1825928.6, z2 will be 13650, and z3 will be 9526.5. Based on the payoff table, the ranges of the second and third objective functions are R2=

17128.2 and R3=14654.5, respectively. Ranges are divided into 100 equal intervals (q). The AUGMECON2 process for all grid points is as follows:

For i = 0–100

e3 = 9526.5+ i x 146.5

for j = 0–100

e2 = 0 + j x 171.3

Solve model

Next j

Next i

Subsequently, constraints for the second and third objectives were added to the model, with the right-hand sides of these constraints (e2, e3) changing at each iteration. This approach yielded pareto optimal solutions across 100 grid points. The decision maker selects one of these solutions (trade-offs) based on priorities and makes decisions accordingly. In our pareto optimal solutions, after a point, any worsening of other objective functions will not improve objective 1. We evaluated the pareto optimal solutions and choose Experiment 3 where z1 = 114,842.5, z2 = 514, and z3 = 9966, since the primary purpose of disaster management is to save as many people as possible and respond to the victims' needs as quickly as possible. Since it was observed that the objective function did not change with the improvements made in (z2), the model was run again assuming z2 = 100, z1 = 114,840.7, and z3 = 9966. According to the results obtained for Experiment 3, the number of transferred resources (z2) slightly affects the number of unmet material resources (z3). The unmet demand in each region is very high, and resource transfers (z2) have little effect on the total unmet human (z1) and material resources (z3) demand. According to the findings, most unmet demand occurs in the first period. While unmet human demand originates mainly from the first, second, and fourth professions, namely team commander, search and rescue officer, and equipment manager, it is naturally high in all resources in the worst-case scenarios S20 and S19. Although resources are abundant in some occupations, task groups still need to be completed, and demand needs to be met due to these deficiencies. After the first period, unmet demand decreases with interregional transfers and additional resources. Table 5.7 shows the results of unmet demands for the first period, which

Table 5.7 : Unmet Demand in the first period for Scenario 20 (a) and Scenario 19 (b).

	20				19			
Region	Profession	Human Resource Unmet Demand (man*hour)	NRR Unmet Demand (unit)	RR Unmet Dema (unit)	Profession	Human Resource Unmet Demand (man*hour)	NRR Unmet Demand (unit)	RRUnmet Demand (unit)
1	2	583	269	15	4	477		
					1	477		
2	2	716	367	21	4	612	375	18
	4	716			1	612		
	1	716			2	564		
					3	500		
3	4	615	354	17	4	532	288	15
	1	615			1	532		
4			257	14			231	12
5			232	13			205	11
6			147	10			130	8
7			255	15			228	13
8	1	650	366		4	561	346	16
					1	561		
					3	448		
					2	489		
9			154	7			138	6
10			221	13			196	11
11	4	687	326	17	4	591	335	1
	1	687			1	591		
	2	562			2	610		
					3	464		
12			239	13			213	11
13	2	702	249	144	4	437	223	12
14	4	935	513	29	4	430	458	24
	1	935			1	430		
	3	775						
	2	719						
	8	601						
15	2	946	353	19	4	606	313	18
	4	706			1	606		
	3	58			2	542		
					3	481		
16	4	547	347	17	4	472	315	16
	1	547			1	472		
17	1	715	466	25	2	541	499	24
	4	886			3	606		
	2	828						
	3	709						
18			187	10			167	8
19	2	1157	561	30	4	950	500	26
	4	1098			1	950		
	1	1098			3	798		
	3	921			2	699		
20			3302	17			270	15

constitutes most of the unmet demands, and for the 20th and 19th scenarios, which represent the most pessimistic values, on a regional basis.

The results reveal that, despite minor variations, unmet demands exhibit significant parallels across regions. This highlights the necessity for synchronized resource utilization and indicates that, in some instances, an abundance of specific resources may still be ineffective if there are shortages in others. For example, in region-1, in the first period, the human resources with professions 1,2 and 4, renewable resources (ambulances), and non-renewable resources are insufficient in both scenarios. In region 2, human resources for professions 1, 2, 3, and 4 are inadequate, and renewable and non-renewable resources are lacking. The similar situation is also valid for the regions 11, 14, 15, 17 and 19. Human resources with the required professions are available in the rest of the regions in the first period, but renewable or non-renewable resources are lacking. However, after the first period, unmet demand decreases with interregional transfers and additional resources

Table 5.8 : Prepositioned Renewable and Non-Renewable Resources before Disaster.

Region	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Prepositioned Renewable Resource Amount (Ambulances)	3	3	3	3	2	2	3	3	2	2	3	2	3	5	3	3	5	2	5	3
Prepositioned Non-Renewable Resource Amount (Medical kits)	193	213	196	167	157	107	164	214	90	143	214	172	162	341	209	194	338	119	410	197

Table 5.8 shows how resource assignments for RRs and NRRs will be pre-positioned in each region at the beginning of the first period. It has been observed that there is no direct relationship between material resource distribution and neighborhood population, but there is a relationship with the casualty numbers. Moreover, it can be deduced that as-signments are parallel with allocating the human resources needed to utilize them.

Table 5.9 shows the number of volunteers expected to be trained from each profession before the earthquake, in addition to the existing volunteers, based on the budget allocated for volunteer training. Volunteers are expected to be trained in various numbers in different regions, mainly from the 2nd (search rescue officer) profession and 8th (support staff). Red

Cross and Red Crescent Societies also suggested that public media campaigns must be held before the disasters to encourage people to become volunteers, and to train them in advance. The guideline of the organizations stipulate that a limit must be set for the volunteering hours considering the disaster conditions and legislations, psychosocial support must be provided to the volunteers in emergencies, spontaneous volunteers must be applied orientation and training, and these must be registered and screened. These measures must be taken to better manage the volunteers in disaster environments.

Table 5.9 : Required Number of Trained Volunteers Before the Disaster.

	Regions																			
Professions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Search & Rescue Officer (Search & Rescue Volunteer)	47	66	54	25	26	10	35	58	2	18	56	28	9	64	23	42	79	0	90	12
Doctor (Professional Healthcare Volunteer)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Paramedics (First Aid Volunteer)	7	0	2	6	0	0	5	8	0	2	8	0	3	12	9	6	3	0	0	0
Support Staff (Spontaneous Volunteer)	42	66	51	33	33	5	34	58	3	22	61	33	36	85	65	32	95	3	127	41

The most significant additional resource requirements for the scenarios are reported in Table 5.10. As seen in table additional supports are spread over different regions and periods for each resource type. For example, extra human resources for the search and rescue officer, profession-2, is 22 people for the second region in the second period. Besides, 55 additional search and rescue volunteer are required for the second period of the 19th region. Additional ambulance and medical kits required are also denoted in this table. According to this table, the command center may request additional resources from governmental or non-governmental organizations.

Table A1 in the Appendix presents the transfers of the volunteers, rescue units and renewable resources starting from the second period. At each row, the number of resources transferred from a region to another region according to each scenario in a certain period are reported. For instance, 94 man-hours of spontaneous volunteer (profession 8) should be transferred from region 1 to 16 in the second period, according to Scenario 16.

Considering the concentrated demand in the first period, the model is sensitive to the emerging casualty number parameter. The model is also susceptible to task requirements and working time parameters, which impact determining human and other resource demands. Penalty cost for not meeting the RR was chosen considering that the ambulance in our case study has priority over the NRR medical kit.

Table 5.10 : Additional Resources Needed Out of the Disaster Regions.

Additional Rescue Units					Additional Volunteers					Additional RR (Ambulance)				Additional NRR (Medical Kit)			
Profession	**Period**	**Scenario**	**Region**	**Value**	**Profession**	**Period**	**Scenario**	**Region**	**Value**	**Period**	**Scenario**	**Region**	**Value**	**Period**	**Scenario**	**Region**	**Value**
4	2	20	4	18	2	2	20	19	42	3	20	7	25	2	20	19	410
3	2	20	17	16	2	2	19	19	42	3	19	14	25	2	19	19	410
2	2	20	17	14	2	2	18	19	42	4	19	6	25	2	18	19	410
2	2	18	15	13	2	3	20	3	30	4	17	20	25	2	17	19	410
2	2	17	15	13	2	2	20	14	30	4	16	10	25	2	16	19	410
3	2	18	17	12	2	2	19	14	30	2	13	14	21	2	19	14	341
2	3	20	15	12	2	2	18	14	30	2	14	7	16	2	18	14	341
2	2	19	15	11	2	2	17	14	30	2	20	19	9	2	17	14	341
6	2	20	19	9	2	2	20	11	27	2	15	14	8	2	16	14	341
2	2	19	17	9	2	2	20	2	27	2	19	19	7	2	15	14	341

In our case, since an ambulance is required to use the medical kit, the penalty cost was decided to give priority to meeting the ambulance need first. With the changes that can be made to the parameter, the priorities of the resources relative to each other can be determined.

Since our model covers only one district of Istanbul and the routes to be traveled are short, it has been observed that the time spent on the road during transfers and the damages that may occur do not significantly impact the model regarding assignable resources. However, as the transportation times will be stochastic in a disaster envi-ronment, variability in this parameter may significantly affect the results, in different disaster settings.

The model consists of 18 decision variables and 22 constraints. When the decision variables $VTr_{wpbb'}{}^{s}$ and $\mathrm{RTr}_{rpb'b}{}^{s}$ were defined as integers, the model could not be solved computationally. Therefore, these variables were treated as continuous within the scope of linear programming (LP). However, especially in cases involving multiple regions and parameters with high levels of uncertainty, the classical LP approach becomes insufficient due to the complexity of the problem. In such cases, stochastic programming models are required to incorporate these uncertainties effectively. Moreover, the development of exact solution methods capable of yielding optimal solutions for such models is essential to enhance the model's accuracy and decision-support capability.

Although Kartal district was selected as the region in this study, the proposed model is applicable for other crowded districts and even all of Istanbul. Therefore, it is scalable. However, when large data sets such as all districts of Istanbul are considered, the mathematical model may not be solved by using a standard solver in a reasonable computational time, as it is a mixed-integer stochastic programming model. In larger cases, multi-objective meta-heuristic algorithms, such as Non-Deterministic Sorting Genetic Algorithm (NSGA-II) or a Reference Vector Guided Multi-Objective Evolutionary Algorithm should be employed (Deb et al, 2002).

Besides, when the type of disaster changes, the tasks may also change and the types and amount of resources needed may change accordingly. For example, search and rescue tasks in the case of a flood and an earthquake probably require different resources, but even if the type and amounts of the required resources change, our mathematical model is still applicable, as it is flexible to be adapted to different disasters and associated tasks.

5.3 Results for the Case Study with Targeting Population Ratio-based Equity (Policy2)

First, we change the first objective (1.1) function as shown in (1.4) to ensure equity between regions in case of disaster. In this new objective function (1.4), we intend to minimize the maximum expected unmet demand for all disaster regions.

Objective-1

$$\begin{aligned} z1 \geq \sum_{s\in S} P_s\Big(\sum_{w\in W}\sum_{t\in T}\sum_{p=1}\big(\mathrm{Demand}_{wpb}{}^{s} - \left(VExp_{wb} + VPool_{wpb}\right) * \mathrm{Vmax}_p \\ - RU_{wp} * RUmax_{\,p}\big) * Pen_{tp} \\ + \sum_{w\in W}\sum_{t\in T}\sum_{p\in 2..P} \mathrm{UD}_{wpb}{}^{s} * Pen_{tp}\Big)\ ;\ (\forall \mathrm{b} \in \mathrm{B}) \end{aligned} \tag{1.4}$$

While trying to minimize the maximum unmet demand, we may ignore some low unmet demand regions since it does not improve the objective function. In the event of a disaster, this contradicts the principle of reaching and saving the casualty as much as possible. To avoid the obstacle created by the population density differences between the regions in terms of providing equity, the objective function has been updated by proportioning the district populations, as shown in (1.5).

Objective-1

$$z1 \geq \sum_{s \in S} P_s (\sum_{w \in W} \sum_{t \in T} \sum_{p=1} (\text{Demand}_{wpb}{}^{s} - (VExp_{wb} + VPool_{wpb}) * \text{Vmax}_p - RU_{wp} * RUmax_{\ p}) * Pen_{tp} + \sum_{w \in W} \sum_{t \in T} \sum_{p \in 2..P} \text{UD}_{wpb}{}^{s} * Pen_{tp}) / \boldsymbol{Pop_b} \ ; (\forall \text{b} \in \text{B}) \tag{1.5}$$

When the model is solved with the objective function z1 (1.5), the solution time of the model has increased noticeably. In this version of the model, as in the other version (1.3), it can be said that the bottleneck of the model is the unmet human resource in the first period. This is because 65% of casualties appeared in the first period. Still, this demand could not be met since there was no additional and interregional transfer of human resources in the first period. The population density and the high number of casualties in some regions cause the unmet demand in these regions to be higher than in others.

Policy 1 does not explicitly target equity in regional demands, so transfers only affect the demand in the region where they occur and do not impact total unmet demand. On the other hand, Policy 2 considers equity and allows for resources to be transferred between regions to address disparities in demand.

According to Policy 2, although the resources are transferred, the objective function z1 (minimization of maximum unmet demand) does not improve after a certain level. Similarly, additional resources (z3) do not enhance z1 after a certain level. These results can be observed from Figure 3.

The unmet demands of the regions according to the worst-case scenarios are shown on the population density map for Policy 1 and Policy 2 in Figure 5.1. Unmet demand is evenly distributed across regions with similar values when equity is not a priority. However, when Policy 2 is targeted, there is unmet demand spanning all periods. When we try to provide equity by minimizing the maximum unmet demand regionally, there are more significant differences in the number of unmet demands across regions. This highlights how equity is defined and addressed in regional planning. In both cases, the unmet demand in the periphery is less than in the inner regions.

Table A1 in the Appendix shows the resource transfers according to both policies. Both human resources and material resource transfer are made between regions generally in the 3rd and fourth periods. While no ambulance transfers were made in Policy 1, a maximum of 14 transfers were made in Policy 2, according to the worst-case scenario. When we look at the human resource transfers, it has been observed that the most transfers in all policies are second profession, additional support. As expected, more homogeneously distributed human resource transfers are observed in Policy2. Apart from the second profession, inter-regional transfers are mainly made for the sixth and eighth professions in volunteers and the fourth and sixth professions in rescue units in Policy1 and Policy2. When the selected solutions' results for both Policies are compared (as shown in Table 5.11), Policy 1's total unmet human demand is less, as it does not target equity.

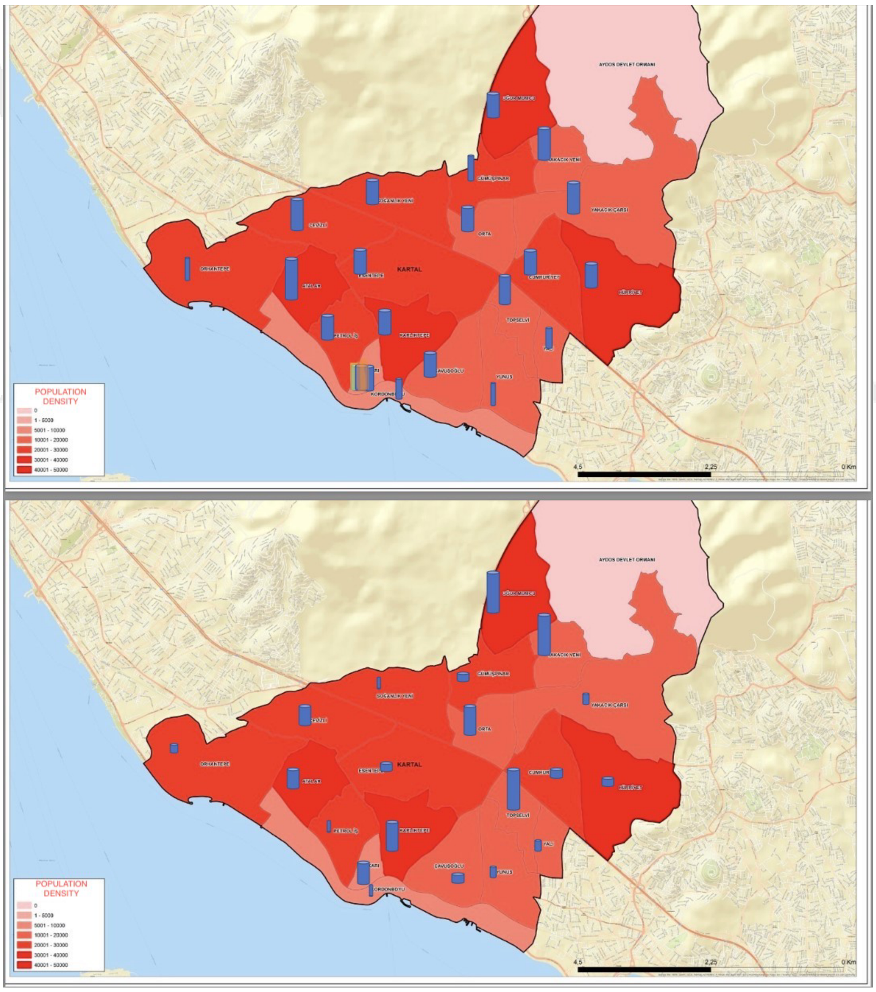

Figure 5.1 : Human Resource Unmet Demand without considering Equity-Policy1 (upper) considering Equity-Policy2 (lower).

Table 5.11 : Human Unmet Demand(hour) Comparison for Policy1 and Policy2.

		Unmet Demand Policy1			Unmet Demand Policy2		
Region	**Population**	**Profession**	**Period**	**Value**	**Profession**	**Period**	**Value**
1	32760				2	2	1265,8
					2	1	865,089
2	26687	2	1	734,309	4	1	723,803
		4	1	711,358	3	1	593,244
		1	1	711,358			
		3	1	580,798			
3	23290	1	1	608,827			
4	15216						
5	30321				2	2	1035,3
					2	1	699,153
6	26631						
7	50179				2	2	988,657
					8	2	947,501
					8	3	909,669
					2	3	790,788
					1	2	687,499
8	33945	1	1	645,173	2	2	1202,59
		2	1	643,12			
9	13052						
10	25608				2	4	640,084
11	18769	1	1	683,919	4	1	673,243
		2	2	509,419			
12	29558	1	1	494,103	2	2	1130,44
					2	1	766,117
13	28445				2	2	1118,02
		2	2	644,886	2	1	756,431
14	12659	4	1	950,765	3	1	755,474
		3	1	790,725	2	2	1573,5
		8	1	601,708			
15	41937	2	1	892,092	2	1	1084,09
		2	2	829,628	3	1	570,248
16	17299	1	1	547,043			
17	18757	1	1	880,347	1	1	866,954
		4	1	874,7	3	1	690,068
		2	1	590,831			
18	12335						
19	7739	4	1	1091,6			
		2	1	980,72			
		3	1	915,809			
		2	2	590,053			
20	1551						

5.4 Sensitivity Analysis

Especially considering the concentrated demand in the first period, the model is sensitive to the emerging casualty number parameter. The model is also susceptible to task requirements and working time parameters, which impact determining human and other resource demands.

Since our model covers only one district of Istanbul and the routes to be traveled are short, it has been observed that the time spent on the road during transfers and the damages that may occur do not significantly impact the model regarding assignable resources.

As the model results may change according to the parameters, a sensitivity analysis based on the scenario probabilities and the penalty values in the first objective function is made, separately. In the sensitivity analysis, the penalty values in the first objective function were all assumed to equal to one. Hence, differences among the weights of different decision variables are neutralized. Besides, to understand the impact of the scenario probabilities, by retaining the original penalty values, the probabilities of the scenarios were changed as shown in Table 5.12. Here, the bad scenarios were given higher probabilities, to see the impact of this parameter on the results.

Table 5.12 : Scenario Probabilities in the Original Model and Sensitivity Analysis Model.

Scenario	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Original	0.1	0.08	0.07	0.09	0.05	0.07	0.04	0.06	0.03	0.02	0.05	0.04	0.06	0.03	0.04	0.05	0.06	0.02	0.03	0.01
Sensitivity Analysis	0	0.02	0.02	0.03	0.03	0.03	0.04	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.06	0.07	0.07	0.08	0.09	0.1

The objective function results obtained for the two cases of the Sensitivity Analysis are presented in Table 5.13. The results imply that change of the penalty values affected the values of the first objective, as these parameters are the multipliers in the objective. For the sensitivity analysis based on the scenario probabilities, we may conclude that the total expected unmet human resource demand increased. However, as the scenario probabilities are the multipliers of the objective function-1, to better understand this change, the decision variables of unmet human resource demand should be further analyzed. The results of the decision variable of unmet human resources demand in the original model and those results obtained by equalizing all penalties into one are presented in Table 5.14, below.

Table 5.13 : Objective Functions of the Original Model, Penalty Values and Scenario Probabilities Sensitivity Analysis Models**.**

	Objective-1	Objective-2	Objective-3
Original Model	114840.7	100	9966
Penalty Values Sensitivity Model	65512.7	100	9966
Scenario Probabilities Sensitivity Model	279913.1	100	18813.1

Here, the highest 16 values among all results of the unmet human resource demand for all regions, scenarios and periods are reported, and the rest of the less significant values were not presented. When the values in the columns named "Original" and "Penalty Sensitivity" are compared, out of 16 values, seven values did not change, six of them decreased, and five of them slightly increased. The unmet demand values that did not change or slightly increased (12 values out of 16) after penalty values change belong to the Scenarios 19 and 20 that are the worst scenarios. This is because the human resources are insufficient, and better results could not be achieved. Besides, some of the variable values decreased only around 20%. In terms of the second and third objectives, penalty values did not cause any change, as seen in Table 4.14. Consequently, the model is not sensitive to the penalty values' change.

Table 5.14 : Sensitivity Analysis Results for the Unmet Human Resource Demand.

Profession	Period	Scenario	Region	Unmet Human Resource Demand (man-hours)		
				Original	Penalty sensitivity	Scenario Probability Sensitivity
2	1	20	19	1157	786	947
4	1	20	19	1098	1098	1098
1	1	20	19	1098	1098	1098
4	1	19	19	950	735	950
1	1	19	19	950	950	950
2	1	20	15	946	556	796
4	1	20	14	935	935	936
1	1	20	14	935	935	936
3	1	20	19	921	921	922
4	1	20	17	886	740	886
2	1	20	17	828	665	882
2	1	20	14	719	983	917
1	1	20	17	715	883	886
2	1	20	14	719	983	917
2	1	20	11	562	778	574
3	1	20	14	775	775	775

Besides, as seen in Table 5.14, the probabilities of medium to bad scenarios numbered 14-20 increased from 24% to 53%, and this caused the total unmet human resource demand (Objective -1) increase, as shown in Table 10. When we analyze the impact of change of the scenario probabilities on the unmet human resource demand, it may be concluded that increase in the scenario probabilities of the bad scenarios resulted in no change or very little increase of the decision variables. However, due to the scenario probabilities' increase, the first objective function value increased from 114840 to 279913. In terms of the second objective, the penalty values change had no impact. However, the third objective (expected material resource unmet demand) doubled. This is because of the increase of the bad scenarios' probability increases, as explained above. Since in bad scenarios the unmet material demand is higher than the other scenarios values, giving higher probability to them caused a higher expected total unmet material demand. The non-renewable resource demand did not change at all, but the renewable resources demand changed slightly. The highest renewable resources unmet demand values in all regions, scenarios and periods for the Sensitivity Analysis are presented in the Appendix in Table A2. One can see that the unmet demand values did not have any significant change, in cases of penalty values change or scenario probabilities change. Consequently, the model is also robust to the change of the scenario probabilities.

5.5 Managerial Implications and Insights

These findings provide valuable information to the Disaster and Emergency Management Presidencies responsible for human resources planning and coordination in disasters. These will also give regional authorities ideas about storing the necessary resources in advance and delivering them to the regions in need after the disaster.

This study can help organizations better allocate resources and plan volunteer recruitment efforts to address service gaps. By identifying trends in volunteer qualification requirements, NGOs can ensure they have the right skills and expertise to meet post-disaster needs.

Some academic and managerial implications arising from this study are as follows:

- Volunteers play an important role in meeting workforce needs in disaster management. Therefore, government and non-governmental organizations should encourage training of volunteers. The aim should be to increase the number of qualified volunteers by increasing awareness. In addition, considering that volunteers can also be disaster victims, the tendency of volunteers to quit their jobs can be prevented by providing psychological support to volunteers.

- While the first 72 hours are generally considered critical in disaster response, according to the model results, most of the unmet demand is in the first 12 hours. Since these hours are the most vital in access to resources during a disaster and the rate of deterioration in the condition of the injured is high, more preliminary preparation is required for pre-disaster resource planning.

- As the model's results show, the lack of even one resource will prevent the completion of the task. Therefore, an information system that dynamically transmits the number of available resources in the regions to the command center will be highly beneficial for facilitating the management of the process with optimum resources by preventing excess resources from coming into the disaster regions. This requires pre-disaster planning for accurate data flow from disaster areas to the command center to convey information about the current situation.

- To ensure coordination, especially in the material resources, working places of these resources should be planned on a regional basis. This plan must be communicated to local authorities in advance.

- It is important to consider the populations of disaster areas, the destruction rates that are expected to occur in the buildings, and the expected values for injured victims that may occur, considering all scenarios, both optimistic and pessimistic. Accurate and realistic data collection is necessary for effective resource planning based on potential disaster scenarios.

- Although it is not clear in the literature whether emergency groups positively or negatively affect a disaster response, it is necessary to form an ad-hoc team (immediate response) to enable official rescue units and volunteers from many different organizations and different professions to work together, especially in large-scale disasters.

- When existing resources cannot meet the demand, decisions must be made regarding support within disaster regions or resources from outside the affected area. Determining which of these options to choose is one of the decisions that must be made before the disaster.

- Developing a dynamic resource allocation software that uses our model would be beneficial to disaster management agencies and policy makers. The proposed mathematical model can be embedded into an API (Application Programming Interface) which is a software intermediary that allows to extract and share data within and across organizations.

6. CONCLUSIONS AND RECOMMENDATIONS

Each disaster situation has its specific resource requirements and structure. The number of casualties, injuries, financial needs, and aid requirements vary depending on the magnitude and type of disaster. In all disasters, pre-disaster resource planning, including material resource prepositioning, volunteer people’s training, and post-disaster resource assignment and transfers, are vital coordination activities for disaster preparedness. Without any of the required resources, the tasks cannot be fulfilled. Volunteers are usually the initial responders to disasters; their contribution is imperative.

This study proposed a multi-objective, two-stage stochastic programming model for dynamic resource planning and allocation, including volunteers, rescue units, and renewable and non-renewable resource requirements, especially for the search and rescue and first aid activities. Its first objective aims to minimize the unmet human resource demand using existing government rescue units, volunteers, and additional human resources. As a second objective, the resources were intended to be utilized efficiently by considering trade-offs between transferring the resources between regions and employing an additional human workforce. Besides, as the third objective, the total unmet demand for renewable and non-renewable resources is minimized. The decisions pertain to pre-disaster volunteers' training, prepositioned renewable and non-renewable resources, disaster response, assignment of the volunteers, rescue units, renewable and non-renewable resources, and their transfers between the regions. Here, the assignment of all human and material resources is simultaneously planned, as the lack of any resources disrupts the tasks.

Integrated decisions for pre- and post-disaster stages are crucial for potential disaster scenarios, as they help determine the expected resource requirements. Improper pre-disaster decision-making will affect post-earthquake decisions, leading to a shortfall in meeting demand. The necessity of using various resources synchronously to ensure disaster coordination brings about multi-purpose decisions. Therefore, it is not possible to constantly increase the number of each resource. Given crowdsourcing and the confusion it brings, the resulting administrative challenges can even be detrimental.

To reveal the utility of the proposed model, a real case study was conducted to decide and assess resource allocation after the expected significant earthquake in the Kartal district of Istanbul. Demand assessment was made based on the official reports considering the number of buildings expected to be damaged or destroyed and the number of victims expected to suffer minor or severe injuries. The multi-objective model was solved for the Case Study with the AUGMECON2 algorithm, Pareto optimal solutions were obtained, and the results were analyzed. As a result, some managerial insights for resource allocation planning for human and material resources are presented.

Our model helps address the issue of people struggling to find the right teams for help after a disaster, ultimately reducing the delay in providing aid. By effectively coordinating and managing resources, including mobilizing volunteers, we can meet the immediate demand for assistance in the crucial early hours, before outside resources can reach the affected areas.

This study is the first in the literature to consider volunteers' training and assignment in disaster response teams besides the official rescue staff. It plans all required renewable, non-renewable, and human resources' pre- and post-disaster allocation and transfers. The real case study also revealed its rigor. Our model helps address the issue of people struggling to find the right teams, necessary materials, and vehicles for help after a disaster, ultimately reducing the delay in providing aid. Therefore, our methodology can be utilized by disaster coordination agencies to effectively coordinate and manage resources, including mobilizing volunteers, in the crucial early hours.

In this study, only the earthquake disaster was discussed, and future studies can focus on resource allocation for other types of disasters affecting societies. Besides, tasks other than search-and-rescue and first aid for the victims can be concentrated in the future. Although we have applied the model for the first 72 hours, periods covering a more extended time interval can be considered to manage the resource allocation problem for the recovery period.

Moreover, the proposed mathematical model can be embedded into an API (Application Programming Interface) which is a software intermediary that allows to extract and share data within and across organizations. As the disaster management requires multiple parties to collaborate, including governmental and non-governmental organizations, input data collection, decision making and output data transmission related to the decisions by means of this API will be beneficial for resource allocation in future disasters.

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APPENDICES

APPENDIX A: Resource Transfers.

APPENDIX B: Unmet Renewable Resources Demand Values in the Sensitivity Analysis.

APPENDIX A : Resource Transfers.

Table A.1 : Volunteers, Rescue Units and Renewable Resource Transfers.

Volunteer Transfer						**Rescue Unit Transfer**						**Renewable Resource Transfer**				
Profession	Period	Scenario	Region	Region	Value	Profession	Period	Scenario	Region	Region	Value	Period	Scenario	Region	Region	Value
8	2	20	1	16	94	4	2	20	4	8	71	0	0	0	0	0
8	2	20	12	16	78.4	2	3	20	20	13	19	0	0	0	0	0
8	2	20	5	1	78	2	2	20	21	5	15	0	0	0	0	0
2	3	20	3	1	57.6	2	2	19	21	5	15	0	0	0	0	0
2	3	20	5	14	36.4	6	2	19	21	15	15	0	0	0	0	0
6	3	20	4	2	18.1	6	2	20	21	5	14	0	0	0	0	0
2	3	14	3	20	27.5	2	3	20	10	14	13	0	0	0	0	0
2	4	20	18	7	1	4	2	20	15	3	11	0	0	0	0	0

APPENDIX B : Unmet Renewable Resources Demand Values in the Sensitivity Analysis.

Table B.1 : Unmet Renewable Resources Demand Values in the Sensitivity Analysis

Period	Scenario	Region	Original	Penalty Values Sensitivity	Scenario Probabilities Sensitivity
1	20	19	30	30	32
1	20	14	29	30	29
1	19	19	26	26	28
1	20	17	25	25	25
1	19	14	24	25	24
1	19	17	22	22	22
1	18	19	22	22	24
1	20	2	21	21	20
1	18	14	21	22	21
1	20	15	19	19	19
1	18	17	19	19	19

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