Operations Research, Spring 2023 (111-2)
Group P Final Project: Optimizing The Efficiency of Fire Rescue Operations

Mark Znidar	T11902137
Wei-Chien Kao	B07102052
Techi Teng	B08703045
Chia-Jen Hsu	B08704040
Edwin Lee	T11502303

June 10, 2023

1 Background and Motivation

In 2020, there were 22,248 fire accidents in Taiwan[1]. Despite the efforts of the authorities and the firefighters, there were 161 deaths and 363 injuries in 2020, with a 7.33% growth rate in deaths compared to the previous year[2]. Hence, in this study, we aim to address this issue using an Operations Research approach to enhance fire-fighting endeavors. Our model focuses on the Greater Taipei Area and Taoyuan City, also known as the Taipei–Keelung–Taoyuan metropolitan area, as it constitutes approximately 40% of the Taiwanese population[3].

Currently, rescue operations are organized based on location, specifically the municipal districts. For example, the fourth corps of the New Taipei City Fire Department handles fire incidents that occur in the blue area shown in Figure 1. In this study, our objective is to explore potential optimization opportunities within this existing framework.

There are two distinct goals in our optimization plan. Firstly, we aim to minimize the total time required for rescue operations, including sending the squad, ambulance, and first responders. It is well-established that there is a clear relationship between the arrival time of first responders and the rate of fatalities. Research has shown that the sooner first responders arrive at the scene of an emergency, the lower the likelihood of death and property damages[4]. Therefore, minimizing response time is crucial in our optimization plan.

Secondly, we aim to determine the total number of accidents that are within a distance of P meters from the nearest available fire station (i.e., the daily intervention limit

[1] National Fire Agency, R.O.C. (2021). *Fire Accidents Statistics.* Retrieved from `https://www.nfa.gov.tw/cht/index.php?code=list&ids=220`.

[2] Ibid.

[3] *Department of Household Registration, R.O.C. (2023). Population Statistics.* Retrieved from `https://gis.ris.gov.tw`.

[4] For instance, see Challands, Neil. (2010). *The Relationships Between Fire Service Response Time and Fire Outcomes.* Fire Technology, 46, 665-676. doi: 10.1007/s10694-009-0111-y.

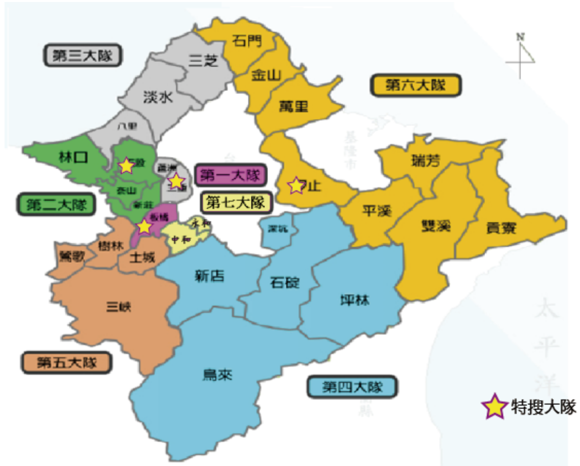


Figure 1: Fire Brigade Division of New Taipei City.
Source: New Taipei City Fire Department

is not reached). The distance between the fire station and the accident location has a direct correlation with the response time[5]. By identifying fire incident locations where the distance requirement is not satisfied, we can propose potential locations for constructing new fire stations.

Additionally, our analysis will explore the possibility of removing certain constraints, such as the division of the town, to provide insights for future policy-making considerations.

2 Data Processing

We first retrieved raw data needed from the following sources and performed some preprocessing to make it appropriate for our research. All the data was taken from the Taiwanese government database.

2.1 Sources of Raw Data

1. Fire Incident Case Data
   The data is obtained from the open database of the central government. It contains information about fire incidents that happened in Taiwan during a particular year. We retrieved data for 2018-2020.

2. Fire Station Locations
   The fire station data is gathered from the Fire Department of the City or the open database of the central government. We transform the address section into longitude and latitude format (WGS84) to calculate the distance between fire stations and incident sites.

[5] National Fire Protection Association. (2023). *FIRE RESPONSE TIME.* Retrieved from `https://fems.dc.gov/page/fire-response-time`.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	city	district	street	id	notified_time	arrive_time	time_elaps	reason	death	injured	ambulance	fire_reqr	day_happe	cluster	wgs84aX	wgs84aY
2	新北市	八里區	文昌五街	H18A01A	2018/1/1 00:12	2018/1/1 00:16	4	其他-雜草、垃圾	0	0	0	1	1	3	121.4104	25.15427
3	新北市	淡水區	大同路	H18A01A	2018/1/1 00:34	2018/1/1 00:43	9	玩火-打火機	0	0	0	1	1	3	121.4637	25.14083
4	新北市	板橋區	中山路二	H18A01B	2018/1/1 01:09	2018/1/1 01:16	7	其他-雜草、垃圾	0	0	0	1	1	1	121.4789	25.01844
5	新北市	五股區	芳洲六路	H18A01E	2018/1/1 04:03	2018/1/1 04:11	8	其他-雜草、垃圾	0	0	0	1	1	2	121.4458	25.0871
6	新北市	瑞芳區	三爪子坑	H18A01M	2018/1/1 12:23	2018/1/1 12:30	7	電氣因素(不含車輛)-短路	0	0	0	1	1	6	121.8116	25.10736

Figure 2: Processed fire incident location data

3. Townships and Municipalities Map Data
   The data is from the open database of the central government. The Shapefile format data is capable of storing geographic features like the boundary of the districts and is used for data visualization.

2.2 Raw Data Processing

1. Processing fire incident case data

   After acquiring the fire incident data, our initial step is to address any missing or incorrect information. This involves dealing with instances where the district or street details are absent or when the recorded arrival time precedes the notified time. Once we have completed the city, district, and street information, we utilize Google GeoAPI to retrieve the longitude and latitude coordinates for each incident. Additionally, we augment the dataset by adding additional columns such as the requirement of ambulance (ambulance_reqr), fire (fire_reqr), date of the incident (day_happen), and municipal region (cluster).

   The ambulance_reqr and fire_reqr columns are derived by combining the data from the death and injured columns. The sum of these values is directly assigned to the ambulance_reqr column. For the fire_reqr column, its value is determined based on the sum obtained, ranging from 1 to 3, with different ranges indicating varying levels of urgency or severity.

   The day_happen column represents the time difference between the date of the notified_time and the first day of the year. Additionally, the cluster information is derived from the district information. For example, cluster 1 indicates that the incident occurred within the region covered by the first brigade of a specific city.

2. Processing fire station data

   The fire station location data includes the longitude, latitude, and cluster information, which is appended to the dataset. The process of obtaining this information is described in the previous section.

3 Formulation of the First Model

3.1 Formulation in Detail

Throughout the year, there are a total of J fire incidents. Each fire incident has specific requirements for fire rescue, denoted as R^F_j, and medical transportation, denoted as R^A_j.

	A	B	C	D	E
1	name	location	wgs84aX	wgs84aY	cluster
2	第一大隊部	基隆市信義區信二路299號	121.7445	25.13578	1
3	仁愛分隊	仁愛區成功一路86號	121.7379	25.1275	1
4	信二分隊	中正區信二路299號	121.7462	25.13109	1
5	中正分隊	中正區環港街100號	121.7933	25.14024	1

Figure 3: Processed station location data

Fire stations are assigned daily quotas for fire rescues, represented by Q^F, and medical transportation, represented by Q^A.

We categorize the severity of each fire incident into two levels based on the combined number of deaths and injuries. If the total exceeds a threshold value of T, the incident is classified as level-2 and requires a higher allocation of rescue resources compared to a level-1 incident. For this study, we set $T = 4$, where $R_j^F \in \{1, 2\}$ for level-1 incidents and $R_j^F = 3$ for level-2 incidents. If the fire rescue quota requirement is greater than 1, the rescue work needs to be divided among multiple responders within the brigade. Regarding medical transportation, each person rescued from the fire incident consumes a medical transportation quota of 1 for the brigade involved, and R_j^A equals to the number of dead and injured people combined in the accident.
For example, let's consider a scenario where $Q^F = 2$ and $Q^A = 5$, indicating that a fire station can handle 2 fire rescues and 5 incidents of ambulance transportation per day. Suppose a fire incident occurs with a requirement of $R_j^F = 2$ and $R_j^A = 3$, we would need to dispatch two fire stations (with firefighters) and three ambulances for the rescue operation.

In the first model, we aim to fully satisfy the requirements for each fire and medical transportation, simulating real-world rescue scenarios. The objective is to minimize the distance H_{ij} between fire stations and the incident locations to ensure efficient deployment of fire squads and ambulances. Further details regarding the model are provided below.

3.2 Parameters

I : the set of fire stations

J : the set of accident locations

Q^F : fire rescue quota per day

Q^A : ambulance quota per day

H_{ij} : distance between fire station i and accident location j for $i \in I, j \in J$

R_j^F : requirement of fire quota for accident j for $j \in J$

R_j^A : requirement of ambulance quota for accident j for $j \in J$

B_{ij} : whether fire station i can go to rescue accident j for $i \in I, j \in J$

A_{jd} : whether accident j happens on day d for $j \in J, d \in D$

3.3 Decision Variables

a_{ij} : whether to send squad in fire station i to accident j for $i \in I$ and $j \in J$
x_{ij} : amount of ambulance for fire station i to send to accident j for $i \in I$ and $j \in J$

3.4 Objective Function

The objective is to minimize the following function:

$$\min \sum_{i \in I} \sum_{j \in J} a_{ij} H_{ij} + \sum_{i \in I} \sum_{j \in J} x_{ij} H_{ij}$$

subject to the following constraints:

$$\sum_{j \in J} a_{ij} A_{jd} \leq Q^F \quad \forall i \in I, d \in D \tag{1}$$

$$\sum_{j \in J} x_{ij} A_{jd} \leq Q^A \quad \forall i \in I, d \in D \tag{2}$$

$$\sum_{i} a_{ij} \geq R_j^F \quad \forall j \in J \tag{3}$$

$$\sum_{i} x_{ij} \geq R_j^A \quad \forall j \in J \tag{4}$$

$$a_{ij} \leq B_{ij} \quad \forall i \in I, j \in J \tag{5}$$

$$x_{ij} \leq R_j^A B_{ij} \quad \forall i \in I, j \in J \tag{6}$$

$$a_{ij} \in \{0, 1\} \tag{7}$$

$$x_{ij} \in \mathbb{Z}^+ \cup \{0\}. \tag{8}$$

Constraint (1) ensures that the number of fires saved by each station does not exceed its daily quota, while constraint (2) ensures that the number of ambulances dispatched by each station remains within its daily quota. To meet the fire rescue and ambulance requirements for each incident, constraints (3) and (4) are included.

To maintain the operational boundaries of the fire stations, constraints (5) and (6) stipulate that each fire station can only respond to incidents within its designated brigade region. Additionally, constraints (7) and (8) impose restrictions on the variables involved in the model, ensuring that they remain within appropriate ranges and adhere to the problem's constraints.

This model will be solved twice to simulate two different scenarios. In the first scenario, fire stations can only rescue accidents within their designated brigade regions, adhering to constraints (5) and (6). In the second scenario, an accident can be saved by the nearest fire station regardless of the brigade, and constraints (5) and (6) will be removed. By comparing the results of these two simulations, we can evaluate the impact of brigade restrictions on the effectiveness of the fire station placements.

4 Formulation of the Second Model

4.1 Formulation in Detail

In the second model, we build upon the notations and concepts introduced in the first model. However, our focus now shifts towards maximizing the number of rescues within a limited time frame, aiming to enhance the effectiveness of rescue operations and improve the survival rate of victims. In this section, we introduce two additional decision variables while maintaining consistency with the notation used in the previous section.

The objective of this model is to maximize the number of accidents that can be rescued within a distance of P meters from the nearest fire station. Considering that the fire truck operates at a speed of 1100 m/min (approximately 65 km/h), which exceeds the legally regulated limit, we set a time limit of 5 minutes for the fire station to reach the accident scene. As a result, we define the value of P to be 5500 meters, ensuring that the accidents considered for rescue operations are within a reasonable proximity to the fire station.

By utilizing this second model, we are able to identify the locations where the current arrangement of fire stations fails to meet the timely rescue requirements for accidents. Based on these findings, we can provide informed recommendations regarding potential locations for constructing new fire stations. This proactive approach aims to optimize emergency response times and enhance overall rescue capabilities within the region.

4.2 Additional Paramters

M : a large enough number as the upper bound for $a_{ij}H_{ij}$ for $i \in I, j \in J$

F : $\dfrac{1}{|I|\,|J|\,H}$ where H $= \max\limits_{(i,j)\,\in\, I\times J} H_{ij}$ for $i \in I, j \in J$

P : distance threshold for incident location to be saved

4.3 Addtional Decision Variables

s_j : whether the accident j is rescued within P km for $j \in J$

y_{ij} : whether $a_{ij}H_{ij} \leq P$ for a given pair (i, j) for $i \in I, j \in J$

4.4 Objective Function

$$\max \sum_{j\in J} s_j - F \sum_{i\in I} \sum_{j\in J} a_{ij}H_{ij}$$

subject to the following constraints:

$$a_{ij}H_{ij} \leq P + M(1 - y_{ij}) \quad \forall i \in I, j \in J \tag{9}$$

$$s_j \leq \sum_{i \in I} y_{ij} \quad \forall j \in J \tag{10}$$

$$\sum_{j \in J} a_{ij} A_{jd} \leq Q^F \quad \forall i \in I, d \in D \tag{11}$$

$$\sum_{i \in I} a_{ij} \geq R_j^F \quad \forall j \in J \tag{12}$$

$$a_{ij} \leq B_{ij} \quad \forall i \in I, j \in J \tag{13}$$

$$a_{ij} \in \{0, 1\} \quad \forall i \in I, j \in J \tag{14}$$

$$y_{ij} \in \{0, 1\} \quad \forall i \in I, j \in J \tag{15}$$

$$s_j \in \{0, 1\} \quad \forall j \in J. \tag{16}$$

Constraint (9) means that the distance to the area of the rescue must be less or equal to the limited distance P. Constraint (10) says that for each fire station that rescues the incident site if one pair meets the distance constraint, the incident will contribute to the objective function Constraint (11) Daily saved fires should not exceed their respective quota for each station. Constraint (12) The fire rescue requirement must be satisfied. Constraint (13) is the brigade rescue constraint for the squad.

5 Results & Performance Analysis

5.1 First Model

With our first optimization model, we can provide the following results regarding the model's performance on the data of the Tapei-Keelung-Taoyuan metropolitan area from 2018 to 2020:

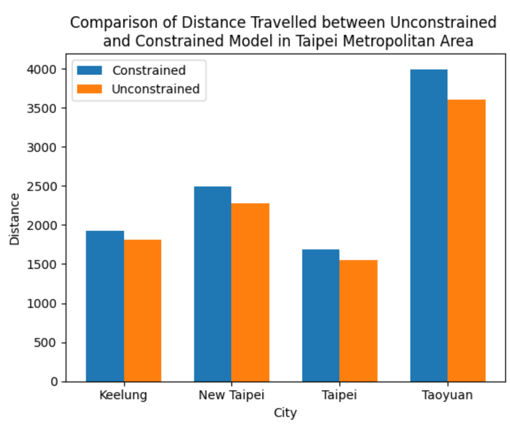


Figure 4: Result of model 1

With the constrained model, we have first successfully optimized the current situation with the model while following the brigade rescue constraint. Furthermore, by removing the brigade rescue constraint, we can minimize the average total distance needed to arrive at the accident location by around 11%. This shows that an operations research model can not only give us the best (according to our model) plan of actions under the current rescue strategy but estimate the benefit we gain by modifying the rescue strategy.

5.2 Second Model

With our second optimization model, we identify locations that are not satisfied within a distance limit, aiming to optimize rescue work within the golden window.

In addition, according to our budget assumption[6], we can assign 5 new fire stations to locations to satisfy as many accidents as possible. The candidate fire station locations are chosen based on the street data provided by the Taiwan government[7]. We convert the street names into longitude and latitude information to use in the Gurobi solver and re-run the LP to find the optimal assignment.

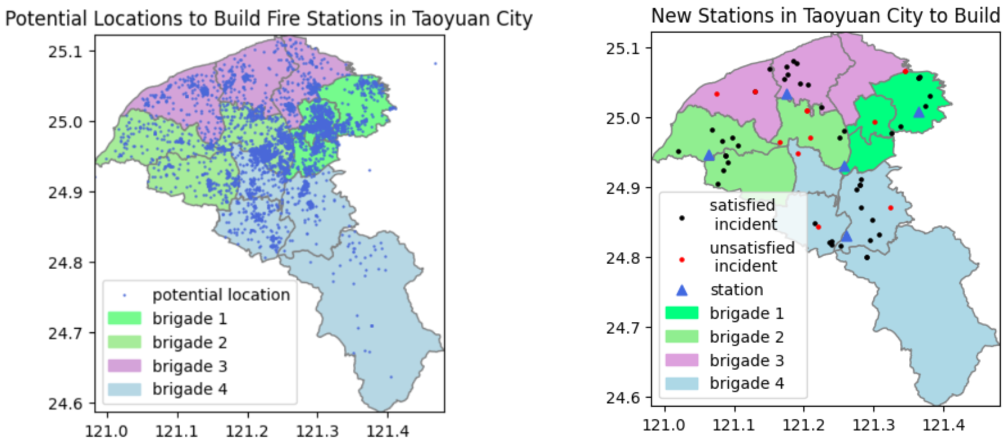
In analyzing the results for the Taipei-Keelung-Taoyuan metropolitan area, we observed varying outcomes across the cities. Keelung City and Taipei City demonstrated a high rate of successful reachability within the designated time limit, with only a few cases falling outside the limit. However, Taoyuan and New Taipei City exhibited several instances that presented opportunities for optimization after visualizing the data (see Figure 5 and 6). Upon modifying and rerunning the second model, we identified the potential locations to build new stations to satisfy more accidents in time.

On average, we found that approximately 40 cases over the course of three years could be optimized with the implementation of the newly built fire stations. Considering the average number of deaths or injuries observed from the time series data, this has the potential to save approximately 23 lives annually in Taoyuan and New Taipei City[8].

[6] We have allocated a budget of 250 million TWD, which represents approximately 0.001% of the Taiwanese GDP in 2022, or 3% of our annual military budgets. Based on official estimations, the construction cost for each fire station in Taoyuan City amounts to 50 million TWD. As a result, we are constrained to building or assigning a total of five new fire stations.

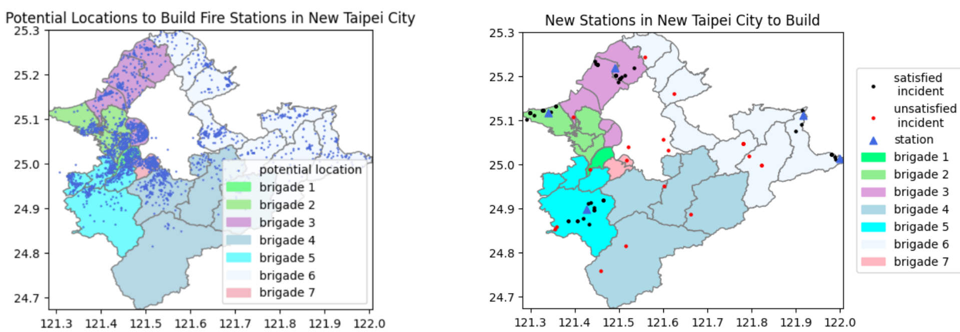
[7] Given the absence of more suitable candidates, we consider streets to be a reasonable approximation in addressing this problem. Streets, as they span across the region in question, offer some feasibility in terms of station construction. Moreover, considering that streets are crucial factors in selecting new locations for government buildings, they provide a practical basis for our approach.

[8] The calculation is based on the data and the collection period, so it could be subject to changes. Nevertheless, assuming homogeneity of fire accidents across three years and an average of 1.7 fatalities per accident, we can estimate the impact. By optimizing approximately 40 cases over this period, we project that it would result in saving approximately 23 lives ($40/3 \times 1.7 \approx 23$).



(a) (b)

Figure 5: Results of the Second Model (Taoyuan)



(a) (b)

Figure 6: Results of the Second Model (New Taipei)

5.3 Possible Drawbacks & Considerations of the Models

During the process of assigning new fire stations, our primary objective was to optimize their positions to effectively respond to the given accidents. However, it is important to note that we did not take into account the potential impact of regulations and other constraints that may pose challenges for construction of new stations. To ensure accurate and suitable placements, further research is necessary.

Our analysis was based on the assumption of homogeneity of fire accidents, relying on average fatality rates per accident. Nevertheless, it is crucial to consider the varying severity of incidents, response times, and community-specific risks when making placement decisions. By incorporating these factors, we can ensure that the fire stations are strategically situated to cater to the unique needs of each area.

The engagement of stakeholders, including local authorities, fire departments, and community members, is also vital in this process. Their valuable insights and expertise can provide a comprehensive understanding of localized challenges, identify high-risk areas, and contribute to the overall effectiveness of the fire station placement strategy.

Regular reviews and monitoring are also imperative in optimizing resource allocation, taking into consideration evolving incident patterns and the changing needs of the community. By conducting periodic evaluations, we can make necessary adjustments and ensure the most efficient utilization of resources in the long term.

6 Conclusion

By implementing our two optimization models, we have achieved the following objectives:

1. We have optimized the assignment of firefighting resources, improving the overall efficiency and effectiveness of emergency response operations.
2. By disregarding the constraints of the brigades, we have developed an improved strategy for the years 2018-2020. Implementing this strategy has the potential to enhance the safety of the people in the area.
3. We have identified locations where a significant number of accidents were not handled within the designated time limit. This information highlights the areas that require immediate attention and intervention to improve rescue operations.
4. Within the constraints of a limited budget, we have proposed suitable locations for constructing new fire stations. These locations have been selected strategically to maximize the number of unresolved accidents that can be addressed, thus increasing the overall effectiveness of the fire and rescue services.

7 Potential Areas for Further Research

Please note that the formulation presented in this study is not complete and should serve as a framework and demonstration of ideas for future research.

To extend the analysis, it would be beneficial to explore whether reassigning individual districts to different brigades (namely the recoloring of the map) in a more optimal way would yield favorable results. The obtained outcome could be compared with the solution obtained from Model 1, revealing the gap between the optimal solution (obtained with relaxation in Model 1). If the gap is small, it may be sufficient to reassign the districts to appropriate brigades rather than investing in the construction of new fire stations.

It is important to note that the current formulation only focuses on recoloring without any constraints and solely considers the optimization from the perspective of fire trucks. In future studies, it would be valuable to incorporate ambulances into the analysis and introduce additional constraints to align with Model 1. This comprehensive approach would provide a more holistic and realistic optimization solution.

For reference, please consult Figure 1.

7.1 Parameters

$$
\begin{aligned}
I &: \text{the set of fire stations} \\
J &: \text{the set of accident locations} \\
B &: \text{the set of brigades} \\
D &: \text{the set of districts} \\
H_{ji} &: \text{distance from accident } j \text{ to fire station } i \text{ for } i \in I, j \in J \\
F_{id} &: \text{station } i \text{ is in district } d \text{ for } i \in I, d \in D \\
K_{jd} &: \text{accident } j \text{ is in district } d \text{ for } j \in J, d \in D
\end{aligned}
$$

7.2 Decision Variables

$$
\begin{aligned}
z_{ji} &: \text{accident } j \text{ satisfied by fire station } i \text{ for } i \in I, j \in J \\
a_{jb} &: \text{accident } j \text{ falls under brigade } b \text{ for } j \in J, b \in B \\
s_{ib} &: \text{station } i \text{ falls under brigade } b \text{ for } i \in I, b \in B \\
d_{db} &: \text{district } d \text{ falls under brigade } b \text{ for } d \in D, b \in B
\end{aligned}
$$

7.3 Formulation

The objective is to minimize the following function:

$$\min \sum_{i \in I} \sum_{j \in J} z_{ji} H_{ji}$$

subject to the following constraints:

$$\sum_{b \in B} \sum_{i \in I} a_{jb} s_{ib} z_{ji} \geq 1 \quad \forall j \in J \tag{17}$$

$$\sum_{b \in B} d_{db} = 1 \quad \forall d \in D \tag{18}$$

$$\sum_{b \in B} \sum_{d \in D} F_{id} d_{db} s_{ib} = 1 \quad \forall i \in I \tag{19}$$

$$\sum_{b \in B} \sum_{d \in D} K_{jd} d_{db} a_{jb} = 1 \quad \forall j \in J \tag{20}$$

$$\sum_{b \in B} s_{ib} = 1 \quad \forall i \in I \tag{21}$$

$$\sum_{b \in B} a_{jb} = 1 \quad \forall j \in J \tag{22}$$

$$z_{ji} \in \{0,1\} \quad \forall j \in J, \quad \forall i \in I \tag{23}$$

$$a_{jb} \in \{0,1\} \quad \forall j \in J, \quad \forall b \in B \tag{24}$$

$$s_{ib} \in \{0,1\} \quad \forall i \in I, \quad \forall b \in B \tag{25}$$

$$d_{db} \in \{0,1\} \quad \forall d \in D, \quad \forall b \in B. \tag{26}$$

Constraint (17) ensures that each accident must be serviced by a fire station located within the same brigade. Constraint (18) states that each district can be assigned to only one brigade.

To facilitate the reassignment of fire stations to the appropriate brigades, we introduce constraint (19). Similarly, constraint (20) facilitates the reassignment of accidents to the appropriate brigades.

To ensure that each fire station is matched with only one brigade, we have constraint (21). Likewise, constraint (22) ensures that each accident is matched with only one brigade.

Constraints (23) to (26) impose necessary restrictions on the variables involved in the model, ensuring that they remain within appropriate ranges and adhere to the problem's constraints.