Kalpa Publications in Computing
Volume 22, 2025, Pages 1070–1079
Proceedings of The Sixth International Conference on Civil and Building Engineering Informatics

SIMULATION OF RESPONSE TIME REDUCTION OF OHCA CONSIDERING DRONE BASE SELECTION FOR AED DELIVERY

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Abstract: Out-of-Hospital Cardiac Arrest (OHCA) is a critical medical emergency that requires immediate intervention. With technological advancements, integrating drones into the Emergency Medical Services (EMS) has emerged as a promising solution. This study examines OHCA cases in Taipei and New Taipei City, Taiwan, from September to December 2019. A two-phase optimization model was employed to identify the effective locations for drone bases. Among the scenarios tested, settings with a maximum flight time of 7 minutes, 90% OHCA case coverage, and 13 drone bases, demonstrated the best overall performance in terms of system-wide and area-specific usage rates, response time reduction, and cost-effectiveness. These findings provide valuable insights into the feasibility of drone deployment and offer practical reference for real-world emergency applications.

Keywords: OHCA, AED, EMS, Drones, Response time

1. INTRODUCTION

Out-of-Hospital Cardiact Arrest (OHCA) is a leading cause of global mortality (Myat et al., 2018), and the most important predictive factor for survival is response time (O'Keeffe et al., 2011). Rapid intervention is essential to the survival of OHCA patients.

As technological advancements progress and labor resources diminish, integrating technology into emergency medical response systems may offer significant advantages. During rush hours, there could be delays for ambulance arrival, while rural areas could be harder to reach. To address this, the use of drones as a supplement to traditional Emergency Medical Services (EMS) may provide a viable solution for improving response times and patient outcomes.

This study focuses on OHCA cases in Taipei and New Taipei City, Taiwan, from September to December 2019. It investigates the integration of a drone system into existing EMS. Spatial analysis will first be conducted to determine efficient drone base locations, followed by simulations of the integrated system. The performance of the combined drone-EMS system will be compared with that of the conventional EMS system without drone support, with service effectiveness analyzed across different area types.

The primary outcome of this study will be the difference in Automated External Defibrillator (AED) response time after integrating the drone system. Additionally, the study will assess the usage rate and response time differences across various area types, including urban, suburban, and rural regions. The findings of this research can be used to evaluate the feasibility of drone base deployment and its practical application in real-world emergency scenarios.

2. LITERATURE REVIEW

In this part, we will first explore the feasibility of drone applications, followed by an analysis of the methodologies for drone base selection. Finally, we will identify the research gaps that this study aims to address.

2.1 Drone Application in AED delivery

Previous work suggests that deploying drones for AED delivery in rural areas during OHCA events is both safe and feasible (Claesson et al., 2016a). The feasibility of AED delivery by drone during nighttime was also evaluated, showing no significant difference in performance between day and night operations (Scholz et al., 2023). Through a geographical model, assessment of the potential usage of drone systems in response time reduction for AEDs has been conducted. Numerical simulations in high-density urban areas indicated that 26% of OHCAs in Greater Paris could benefit from drone-delivered AEDs before the arrival of basic life support teams (Derkenne et al., 2021).

2.2 Optimal Drone Base Selection

The selection of drone bases should account for ambulance response time, incidences of OHCA cases, distance, and density of incidents. In their work, different weights were assigned to urban and rural areas, and a Geographic Information System (GIS) combined with the Multi-Criteria Evaluation (MCE) method were utilized to facilitate base selection (Claesson et al., 2016b). In a related approach, a mathematical optimization model was used to minimize the number of drone bases while ensuring that at least f% of OHCAs were covered. The model iteratively adjusted the coverage rate (f) and the maximum flight time (t) to achieve targeted reductions in response time (Boutilier et al., 2017). Another two-stage optimization model was employed for base selection: Phase 1 maximized the number of OHCAs reached within 5 minutes, and Phase 2 minimized the mean response time while maintaining the same coverage level (Starks et al., 2024).

2.3 Research Gap

Current studies primarily focus on single-city implementations, limiting the potential benefits of cross-regional integration. Furthermore, research that combines spatial analysis with simulation is relatively scarce. This study will address these gaps by applying spatial analysis to the Greater Taipei Area, covering both Taipei and New Taipei’s OHCA cases, to identify efficient drone base locations using an optimization model. Simulation analysis will then be conducted to evaluate response time reductions. The results will provide insights into how different base configurations affect response times across various geographical settings.

3. METHOD

In the methodology section, we will first describe the role of drones within the EMS system, followed by detailed assumptions related to drone operations. Next, we will outline the data preprocessing steps and the optimization model employed for selecting optimal drone base locations.

3.1 Overview of Approach

After OHCA occurs, the dispatch center will receive the report information and decide whether to dispatch a drone for the OHCA. For OHCA cases, it is essential that there are at least two people present to assist the victim, as one needs to perform CPR while the other prepares and uses the AED. Thus, if there is no bystander performing CPR, the drone will not be dispatched.

To validate the influence of integrating drones into the existing EMS, a simulation model will be used. The historical EMS response time, based on real-world data, will be compared to the drone simulation response time, which represents the time taken for a drone to transport an AED. The shorter of the two times will be selected as the system (EMS + Drone) response time.

3.2 Assumption

The flight distance of the drone will be calculated using the linear distance between the selected drone base and the OHCA location. Considering the practical limitations, it takes time to connect from the EMS center to dispatch the drone, and door-to-door drone delivery is not feasible in urban areas. Therefore, in the simulation, we need to account for the dispatch connection time $\boldsymbol{T}_{\mathrm{c}}$ and AED retrieval time at different accident locations $\boldsymbol{i}$, denoted as $\boldsymbol{T}_{\mathrm{a},i}$, in addition to the drone flight time. For high-rise buildings, higher floors require more time; thus, for every floor added, the time increases by $\boldsymbol{T}_{\mathrm{f}}$.

For the performance of the drone itself, we referred to the drone type 'Ceptor' from GlobeUAV, Germany, which has been used in both emergency delivery simulations and real-life situations in the past (Baumgarten et al., 2022; Scholz et al., 2023). Consequently, several time related parameters (in seconds) are set:

Table 1. Parameters

parameters	value	
T_c (s)	60	
$T_{a,\,i}$ (s)	30,	i ∈{workplace, street, nursing home, public building, school}
	60,	i ∈{residential area, unclear}
T_f (s)	10	
Ascend acceleration (m/s^2)	1.0	
Descend acceleration (m/s^2)	1.0	
Horizontal acceleration (m/s^2)	19.8	
Horizontal speed (km/h)	50	
Cruise height (m)	100	

3.3 Data Preprocess

To conduct the simulation, it is essential to preprocess the data by discarding entries with suspected misclassified or missing values. Additionally, certain geographical data is indispensable; however, some key information, such as latitude and longitude, may be absent from the raw dataset despite the presence of addresses. In such cases, geocoding will be performed using addresses and an API to obtain the corresponding latitude and longitude coordinates. Furthermore, the classification of areas into urban, suburban, and rural zones will be completed to support the analysis.

3.4 Optimization Model for Drone Base Selection

Given the practical constraints and associated costs, establishing drone stations across the entire city is not cost effective. Therefore, we decided to use a limited number of drones and identify optimal station locations to restrict cost expenditures. It is essential to determine both the number of drones to be deployed and their precise placement. This selection process will be carried out using a two-phase optimization model, using Python with the Gurobi solver employed to ensure efficient problem-solving.

(1) Phase 1: Optimizing the Number of Drone Station

To ensure that the drone service can reach OHCA cases within a specified time limit while maintaining sufficient coverage across the city, the model explores various combinations of maximum flight time *t* and OHCA case coverage rate *f*. This approach involves performing a grid search to identify the most feasible and optimal number of drone bases. In each combination of *t* and *f*, the following parameters are adjusted and pre-processed, and the model should be solved.

a. Set and Index
- $\mathbb{I}$: the set of drone base candidates, index by *i*
- $\mathbb{J}$: the set of OHCA cases, index by *j*

b. Parameters
- *f*: Indicates the percentage of covered OHCA.
- *t*: Indicates the maximum drone flying time.
- *R*: Defines the coverage radius
- a_{ij}: Binary parameters indicating whether OHCA case *j* is covered by drone base candidate *i*.
- *I*: The number of fire stations, representing the number of drone base candidates.
- *J*: The number of OHCA cases in the training set.

c. Decision variables
- z_{ij}: Binary variable indicating whether OHCA case *j* is covered by drone base *i*.
- y_i: Binary variable indicating whether a drone base is established at candidate location *i*.

d. Model

$$\text{Minimize} \quad \sum_{i=1}^{I} y_i \tag{1}$$

$$\text{Subject to} \quad \sum_{i=1}^{I} z_{ij} \leq 1 \qquad \forall\, j \in \mathbb{J} \tag{2}$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J} z_{ij} \geq \frac{f}{100} \times J \tag{3}$$

$$z_{ij} \leq a_{ij} y_i \qquad \forall\, i \in \mathbb{I}, \forall\, j \in \mathbb{J} \tag{4}$$

$$y_i, z_{ij} \in \{0,1\} \qquad \forall\, i \in \mathbb{I}, \forall\, j \in \mathbb{J} \tag{5}$$

(2) Phase 2: Optimizing the Location of Drone Station

Focusing solely on the coverage rate may result in multiple feasible solutions in some cases. Therefore, phase two considers both coverage and distance costs to provide a balanced solution that ensures adequate coverage while minimizing the total travel distance to reach OHCA cases.

a. Set and Index
- $\mathbb{I}$: the set of drone base candidates, index by *i*
- $\mathbb{J}$: the set of OHCA cases, index by *j*

b. Parameters
- *R*: The coverage radius of drone station.
- a_{ij}: Binary parameters indicating whether OHCA case *j* is covered by drone base candidate *i*.
- d_{ij}: The linear distance between drone base candidate *i* to OHCA case *j*.
- *n*: number of base selected
- α: the weight of coverage. $0 \leq \alpha \leq 1.0$.

c. Decision variables
- y_i: Binary variable indicating whether drone base candidate *i* is selected/established.
- x_j: Binary variable indicating whether OHCA case *j* is covered by at least one drone base's service area.
- z_{ij}: Binary variable indicating whether OHCA case *j* is covered by drone base *i*.

d. Model

$$\text{Maximize} \quad \alpha \sum_{j \in \mathbb{J}} x_j - (1-\alpha) \sum_{i \in \mathbb{I}, j \in \mathbb{J}} d_{ij} \, z_{ij} \tag{6}$$

$$\text{Subject to} \quad a_{ij} y_i \geq z_{ij} \qquad \forall i \in \mathbb{I}, j \in \mathbb{J} \tag{7}$$

$$\sum_{i \in \mathbb{I}} z_{ij} \geq x_j \qquad \forall j \in \mathbb{J} \tag{8}$$

$$\sum_{i \in \mathbb{I}} y_i \leq n \tag{9}$$

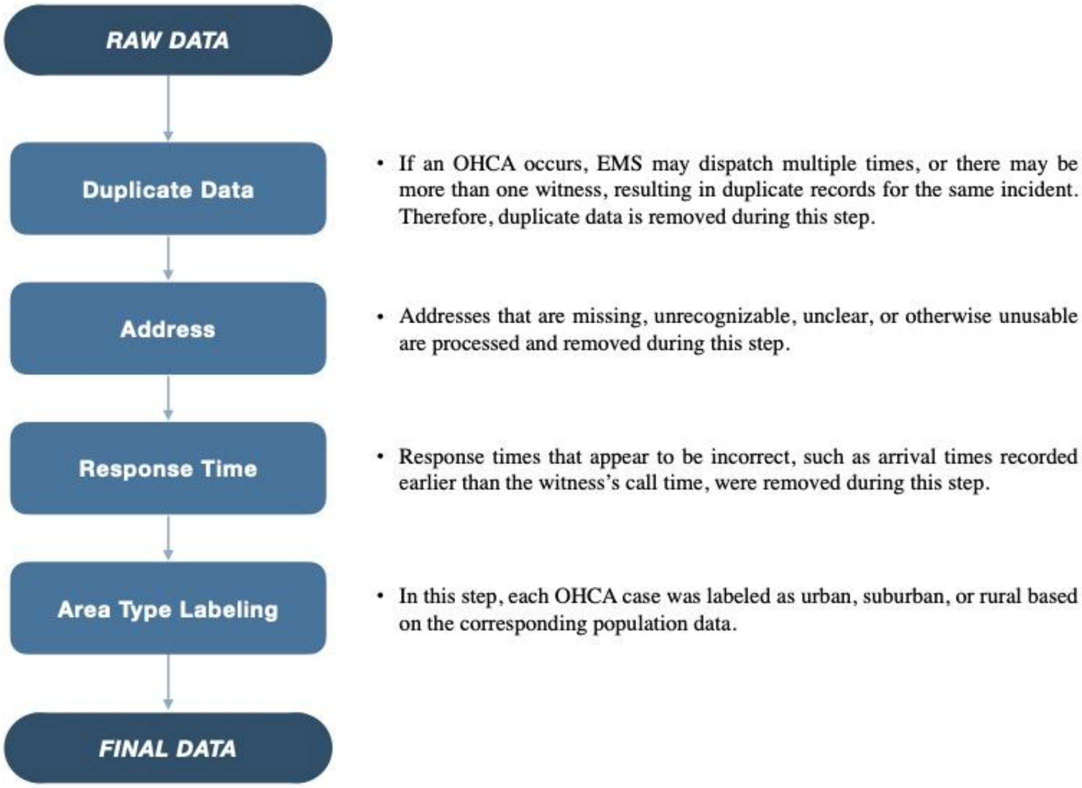
$$x_i, y_j, z_{ij} \in \{0,1\} \qquad \forall i \in \mathbb{I}, j \in \mathbb{J} \tag{10}$$

4. RESULTS

The Results section will be divided into three parts: the data preprocessing; the outcomes of drone station selection, including a sensitivity analysis of multiple combinations of *f* and *t* as well as the top eight configurations for the number and locations of drone bases; and the performance evaluation of the drone-enhanced system across different area types and the overall system.

4.1 Data

The data used in this study comprise OHCA cases from Taipei, New Taipei City, and Taiwan, collected between September and December 2019. Before conducting the simulations, several data preprocessing steps were completed, as outlined in Figure 1. The area classification method proposed by Claesson et al. (2016) was adopted, where urban areas are defined as having ≥6,000 inhabitants/km², and rural areas as having <250 inhabitants/km². Population data from the Taiwan's Ministry of the Interior's Socioeconomic Data Platform were combined with these criteria to categorize the areas as urban, suburban, or rural. The final dataset included 2,724 urban cases, 481 suburban cases, and 62 rural cases, totaling 3,267 OHCA incidents. The average AED response time for Taipei City is 357.76 seconds, for New Taipei City 339.17 seconds, and for both cities combined, 345.62 seconds.



- If an OHCA occurs, EMS may dispatch multiple times, or there may be more than one witness, resulting in duplicate records for the same incident. Therefore, duplicate data is removed during this step.
- Addresses that are missing, unrecognizable, unclear, or otherwise unusable are processed and removed during this step.
- Response times that appear to be incorrect, such as arrival times recorded earlier than the witness's call time, were removed during this step.
- In this step, each OHCA case was labeled as urban, suburban, or rural based on the corresponding population data.

Figure 1. Data Preprocessing

4.2 Drone Bases

To select drone base locations that optimize both rescue efficiency and cost-effectiveness, various combinations of maximum flight time t and coverage rate f were evaluated using the Phase 1 model. The maximum flight time of the Ceptor drone is 60 minutes. Therefore, we set the parameter t to 30 minutes and down to 5 minutes. Since a higher coverage rate is always preferred, we evaluated the coverage rate f from 100% to 50% and did not continue further below 50%. The output N, which represents the minimum number of necessary drones (equivalent to the number of drone bases, as each base supports one drone), is presented in Table 2.

Table 2. Sensitivity Analysis of Different (*t*, *f*)

Test	*t*	*f*	N	Test	*t*	*f*	N	Test	*t*	*f*	N	Test	*t*	*f*	N	Test	*t*	*f*	N
1	30	100%	3	8	15	100%	-	15	10	100%	-	22	7	100%	-	29	5	100%	-
2	30	95%	1	9	15	95%	3	16	10	95%	6	23	7	95%	18	30	5	95%	-
3	30	90%	1	10	15	90%	2	17	10	90%	5	24	7	90%	13	31	5	90%	-
4	30	80%	1	11	15	80%	1	18	10	80%	3	25	7	80%	8	32	5	80%	41
5	30	70%	1	12	15	70%	1	19	10	70%	2	26	7	70%	6	33	5	70%	26
6	30	60%	1	13	15	60%	1	20	10	60%	2	27	7	60%	4	34	5	60%	18
7	30	50%	1	14	15	50%	1	21	10	50%	1	28	7	50%	3	35	5	50%	13

The options that provide sufficient coverage with a limited number of drone bases are highlighted in blue. Eight combinations of *t* and *f* were used as parameters for the Phase 2 optimization. The corresponding geographical plot, which illustrates the OHCA density distribution, the selected drone bases, and their coverage areas, is presented in Figure 2.

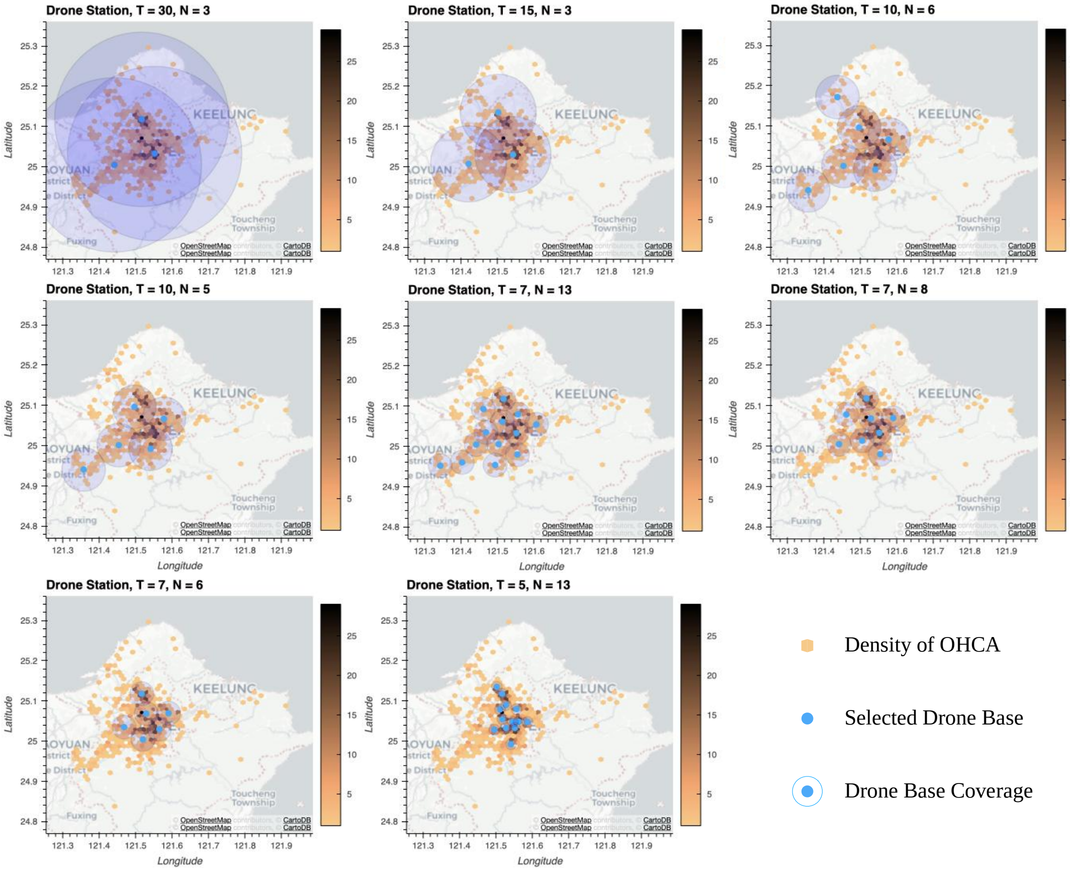


Figure 2. OHCA Density Distribution with Selected Drone Bases and Coverage Areas

4.3 System Performance

The primary outputs of the simulation will be the response time differences and the usage rates of the drones. The secondary outcomes include the response time differences and usage rates across different area types. The indices referenced in the analysis of system and area type comparisons are detailed in Table 3 and Table 4, respectively. The system performance outputs are presented in Table 5, while a comparison of different areas is provided in Table 6. The top three performances for each index will be highlighted in red.

Table 3. System Performance Index Description

Index	**Description**
System U.R.	Total system drone utilization rate.
RT > 5min U.R.	Drone utilization rate for OHCA cases with response times longer than 5 minutes.
# Drone served	Number of OHCA cases served by drones.
System RT Diff	The difference between historical EMS response time and simulated system response time for the total system.
Drone served RT Diff	The difference between historical EMS response time and simulated system response time for OHCA cases utilizing drones.

Table 4. Area Type Comparison Index Description

Index	**Description**
Urban U.R.	Urban OHCA drone utilization rate
Urban RT Diff	The difference between historical EMS response time and simulated response time for urban OHCA cases utilizing drones.
Suburban U.R.	Suburban OHCA drone utilization rate
Suburban RT Diff	The difference between historical EMS response time and simulated response time for suburban OHCA cases utilizing drones.
Rural U.R.	Rural OHCA drone utilization rate
Rural RT Diff	The difference between historical EMS response time and simulated response time for rural OHCA cases utilizing drones.
Rural-Urban Diff	The simulated response time difference between rural and urban regions.

Table 5. System with Drone's Performance

Test	*t*	*f*	**N**	System U.R.	RT > 5min U.R.	# Drone served	System RT Diff	Drone served RT Diff
1'	30	100%	3	9.09%	16.94%	222	22.235	245.770
9'	15	95%	3	8.59%	16.00%	205	21.023	246.044
16'	10	95%	6	11.35%	21.16%	271	29.609	261.741
17'	10	90%	5	10.64%	19.83%	254	28.511	268.945
24'	7	90%	13	18.77%	34.97%	448	53.397	285.078
25'	7	80%	8	15.25%	28.42%	364	39.760	261.439
26'	7	70%	6	14.08%	26.23%	336	35.733	254.618
35'	5	50%	13	20.78%	38.72%	496	53.042	255.782

Table 6. Area Type Comparison

Test	*t*	*f*	**N**	Urban U. R.	Urban RT Diff	Suburban U. R.	Suburban RT Diff	Rural U. R.	Rural RT Diff	Rural-Urban Diff
1’	30	100%	3	8.85%	223.633	10.76%	372.186	10.53%	322.906	99.273
9’	15	95%	3	8.41%	226.716	10.07%	353.051	5.26%	525.370	298.654
16’	10	95%	6	10.29%	240.594	19.10%	306.018	10.53%	1306.764	1066.170
17’	10	90%	5	9.86%	246.661	16.32%	321.982	10.53%	1306.764	1060.103
24’	7	90%	13	17.74%	262.941	25.35%	371.484	31.58%	595.254	332.313
25’	7	80%	8	15.00%	248.770	17.01%	342.993	15.79%	246.955	-1.816
26’	7	70%	6	13.94%	238.853	15.28%	354.550	10.53%	341.979	103.126
35’	5	50%	13	20.91%	242.070	20.49%	353.231	10.53%	363.445	121.375

5. DISCUSSION

In the drone base location selection process, it can be observed that as the maximum flight time *t* decreases, the number of required drone bases increases, as shown in Table 2. Due to population density, which is strongly correlated with OHCA density, a smaller *t* ensures shorter response times but causes the drones to cluster in the central urban areas, making it difficult to cover all OHCA cases. However, dense areas usually have more ambulance bases. As a result, the drone bases are not that beneficial to the system if placed in dense urban areas.

According to the simulation results, Test 24’ in Table 5 and Table 6, with a maximum flight time of 7 minutes, 90% OHCA case coverage, and 13 drone bases, achieved the best overall performance. In this scenario, the drones could serve 448 cases, representing 18.77% of all OHCA cases and 34.97% of cases with a historical response time longer than 5 minutes. The system response time difference is 53.397 seconds, indicating that the addition of drones can reduce the response time by an average of 53.397 seconds per case. For the cases served by drones, the response time was reduced by 285.078 seconds per case.

Focusing on the area-type comparison, Test 24’ achieved the best performance across urban, suburban, and rural areas, serving 31.58% of rural OHCA cases and reducing the response time by an average of 595.254 seconds for these cases. Since most fire stations are located in relatively urban areas, if the primary goal is to improve efficiency in rural areas with minimal cost, Test 17’ would be a good choice, as it can reduce the rural response time by up to 1306.764 seconds per case. On the other hand, if the objective is to maximize the number of cases covered regardless of location, Test 35’ would be a viable option.

6. CONCLUSION AND FUTURE WORK

This work has demonstrated the assessment of adding drone into an EMS for AED delivery in a cross city geospatial area. Through the analysis of data collected from Taipei City and New Taipei City, the drones improve OHCA response time. The results demonstrate that the maximum flight time and coverage rate influence the selection of drone base locations, which in turn impacts the response time difference. Among the tested scenarios, Test 24 provides the most balanced performance both system-wide and across all area types, improving rural OHCA coverage while maintaining a reasonable number of drone bases.

The data used in this research covers only three months. Using a larger dataset or data from other cities could provide more robust insights. Additionally, in urban areas, the presence of tall buildings may affect the flight paths of drones, making it essential to account for these factors to better reflect real-world conditions. Furthermore, the selection of drone base locations should not be limited to fire stations; instead, potential locations could be optimized based on the distribution of OHCA cases.

ACKNOWLEDGMENTS

We sincerely thank the Taipei and New Taipei City Fire Department for their invaluable assistance in collecting the data essential to this study, which formed the foundation of our research. We are also grateful to the the support from the National Science and Technology Council of Taiwan for grant NSTC 113-2628-E-002-026-MY3, which made this study possible. This support was crucial to the success of our work, and we deeply appreciate it.

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