A Data-Driven Simulator for the Strategic Positioning of Aerial Ambulance Drones Reaching Out-Of-Hospital Cardiac Arrests: A Genetic Algorithmic Approach

Abstract — **The Internet of Things provides solutions for many societal challenges including unmanned aerial vehicles assisting in emergency situations that are out of immediate reach for traditional emergency services. Out of hospital cardiac arrest (OHCA) outcome statistics are poor in Northern Ireland with less than 50% of victims receiving the necessary emergency care on time. The aim of this study is to use heterogenous datasets to build a simulator to determine the difference in response times when having aerial ambulance drones available compared to response times when depending solely on ambulance services and publicly accessible AEDs for OHCA victims. A Genetic Algorithm has been developed to determine a strategic number and positioning of drone bases to optimize OHCA emergency response times.**

Index Terms— **OHCA, AED, UAV, Ambulance Drone**

I. Introduction

The Internet of Things (IoT) is the connection of devices across a network, where each device is uniquely identified and can send and receive data. These devices predominantly consist of sensors, actuators, internet connectivity and artificial intelligence (AI). *Statista* forecast the market for IoT will go from 212 billion USD in 2019 up to 1.6 trillion USD by 2025 [1]. Smart cities use IoT technology to enhance their efficiency, sustainability, economic development and the quality of life for their citizens. There are a number of examples for smart cities worldwide, with Hong Kong, Toronto, New York, Stockholm and London being amongst the top smart cities in the world [2]. These smart cities can benefit from improvements in energy efficiency, infrastructure, transportation, public safety, water treatment, healthcare and multiple further areas.

Healthcare will see an improvement for patient care due to the ever-increasing amount of data on patients' health, along with smart devices specifically designed to aid vulnerable patients. Research and development into flying drones have seen a vast amount of use-cases being created in recent years. Ambulance drone prototypes are being manufactured to carry or include a built-in Automated External Defibrillator (AED) to target the problem of reaching out-of-hospital cardiac arrest patients as fast as possible. In some cases, these drones can reach out-of-hospital cardiac arrest (OHCA) patients faster than an ambulance or even a bystander utilizing a publicly accessible AED [3].

Research carried out by the University of Warwick highlighted how there are approximately 60,000 OCHAs annually in the United Kingdom. However, only around 28,000 receive a resuscitation attempt, which is less than 50% of the time [4]. The majority (83%) of OHCAs occur at home with only 55.2% of those reached by ambulance service staff receiving cardiopulmonary resuscitation (CPR), whilst publicly accessible AEDs were only used around 2.3% of the time [4]. A cardiac arrest is when the heart malfunctions and stops beating unexpectedly, mainly triggered by electrical malfunctions in the heart that can be caused by an irregular heartbeat (arrythmia). As a result, there can be an insufficient supply of oxygenated blood to the brain, lungs and other vital organs and eventually the patient will lose consciousness. Death will occur minutes later if the patient does not receive CPR (Cardiopulmonary Resuscitation) and the required treatment [5]. A heart attack is when the blood flow to the heart is blocked, preventing oxygen-rich blood reaching a section of the heart. This will lead to the affected section becoming malnourished and eventually dying. However, before a heart attack occurs, there may be symptoms for minutes, hours or days for which a patient can seek treatment. A heart attack does not always lead to a cardiac arrest but it is a very common cause [5]. Therefore, a patient can have a limited amount of time to contact the emergency services to request urgent treatment if they notice oncoming symptoms. Once the patient experiences a cardiac arrest, they have a 50-70% chance of survival if they receive defibrillation within the first 3-5 minutes. The chance of survival then drops by 10% with every minute that passes after 5 minutes [6].

The current protocol for someone who is in cardiac arrest is immediate basic life support (BLS) and CPR if there is a trained person nearby. The patient will then require urgent defibrillation which can be received in an ambulance or by a nearby public AED. Publicly accessible AEDs are situated in places where there are usually a lot of people, for example, supermarkets, tourist areas, schools, offices and sports centers.

In Northern Ireland, Category A emergency calls are defined as life-threatening and should be responded to within 8 minutes. This category denotes the highest priority calls, including cardiac arrests. However, only 41.9% of Category A calls in Northern Ireland were responded to within the 8-minute target in 2018 [7]. This statistic is concerning considering OHCA incidents need a 3-5-minute response time. Ambulance drones which can carry an AED are being prototyped by Delft University of Technology in the Netherlands. These drones cost around $19,000 and can travel up to 100 km/h (62mph). They weigh 4 kg with a built-in defibrillator and can carry an additional payload of 4kg. The drone can fly autonomously when given GPS coordinates and has a built-in live camera and speaker to allow an emergency operator to communicate with the caller in real-time to provide CPR instructions or other medical advice [8].

The aim of this study is to provide a proof of concept for the use-case of drone-delivered AEDs using a data driven computer simulator program. The computer program will determine the optimum base locations and coverage for drone delivered AEDs across Northern Ireland to improve response times for OHCA emergency incidents. The program will compare the simulated drone response times with the response times from ambulance services and those from a human bystander accessing and retrieving a nearby publicly accessible AED.

The simulator uses several heterogenous datasets and a Genetic Algorithm to determine the strategic number and positioning of drone bases to optimize response times. The study specifically investigated the following research question:

- To what extent can drone-delivered AEDs reduce OHCA emergency response times according to simulator that uses real world data?

II. Research in the area

There are three drone options and their specifications described in *Table I* which are potentially suitable for the delivery of AEDs. The ambulance drone prototype developed by the *Delft University of Technology* is specifically designed for the transportation of a built-in AED to OHCA patients. There are other alternative drone prototypes being researched for emergency services capable of transporting a standalone AED. The Defikopter developed by a German non-profit group *Definetz* offers the transportation of an external AED which is delivered to a patient using GPS coordinates. This drone can reportedly travel at 70km/h (43mph) and costs around $26,000 [9]. Amazon have also developed a fully autonomous drone which can fly up to 15 miles with a given payload of under 2.2kg [10].

M.Fleck completed a case-study to understand the potential for manufacturers to include a defibrillator on a lightweight ambulance drone whilst maintaining quick and efficient treatment for an OHCA patient. This included a comparison of Schiller FRED EasyPort (600 grams) and the HeartSine Samaritan PAD 300p (1100 grams). The study carried out OHCA simulations to determine the usability of the AEDs for untrained users. The Schiller AED was lighter but less user-friendly than the HeartSine AED. It was concluded that clear verbal instructions were necessary to ensure correct defibrillation and reduced time-to-shock delays [11].

The combination of these lightweight AEDs with current aerial drone technology demonstrates the potential for future manufacturers. The lightweight HeartSine AED combined with the Amazon drone would enable the delivery of an AED to an OHCA patient within a 24km radius at 80km/h offering further delivery of an AED than the Tu Delft ambulance drone. Given the research undertaken in drone deliveries, it is apparent that the next upcoming years should produce fully capable drones for the prompt and safe delivery of AEDs to OHCA patients.

TABLE I.
DRONE SPECIFICATIONS

Manufacturer	Cost	Available AED	Max Speed	Payload	Range
Tu Delft	£19,000	Yes	100 km/h	4kg	12 km
Definetz	$26,000	Yes	70 km/h	-	10 km
Amazon	-	No	80 km/h	2.2kg	24 km

J.Lennartsson has carried out research into the strategic positioning of ambulance drones delivering defibrillators to OHCA patients in Stockholm County, Sweden [3]. Each of the drone bases had a radius of 10km and were decided based on where the most OHCAs occurred. The Stockholm county area is 6522 km^2 and 10 bases were selected. The results described in *Table II* indicate the extent to which response times were reduced. Within an 8.5-minute radius there were reductions of up to 22 minutes, in one case reducing from 31 to 9 minutes, with an average of 6.15 minutes reduction. In a 5-minute radius there were reductions up to 17 minutes, e.g. reducing from 22 minutes down to 5 minutes with an average of 5.4 minutes reduction. The drone locations within a 3-minute radius had reductions up to 19 minutes, reducing from 32 to 3 minutes and an average of an 8-minute reduction. This provides an indication that the drone networks have the potential to significantly reduce emergency response times.

TABLE II.
STOCKHOLM OHCA RESPONSE IMPROVEMENTS USING AMBULANCE DRONES

Radius	Smallest Improvement	Largest Improvement	Average Improvement
8.5 min	-1 minutes	22 minutes	8 minutes
5 min	3 minutes	17 minutes	5.4 minutes
3 min	4 minutes	29 minutes	8 minutes

This research has involved the development of a data-driven simulator to estimate the potential improvement in OHCA response times by implementing a drone network in Northern Ireland. To find the most optimal positioning for each drone base in the network, a Genetic Algorithm has been developed using multiple datasets including publicly accessible AED locations and ambulance station locations.

III. Methodology

This study involved hosting an Ubuntu Linux server using Amazon's Elastic Compute Cloud (EC2) on Amazon Web Services and building a data-driven simulator using the Python programming language.
The simulator uses a number of datasets: 1) an open dataset from Northern Ireland Ambulance Service Health and Social Care Trust which specifies the geolocation of publicly accessible AEDs in Northern Ireland [12], 2) two open datasets from Northern Ireland Council and Voluntary Action (NICVA) which specifies the geolocation of local ambulance stations and General Practice (GP) clinics [13] [14], 3) a synthetic dataset generated by the author of probabilistic geolocations of 10,000 OHCA incidents, 4) two datasets from Northern Ireland Statistics and Research Agency (NISRA) which specify the geolocation of police and fire emergency stations that can be potential locations for operating AED drones. Given the law of diminishing returns we can determine the point at which the response time reduction from adding additional drones will begin to become smaller and therefore less cost effective. This enables us to select a subset of dataset 4 which is optimized using genetic programming to determine an optimal number of drones for reducing response times.

Drone Specifications

For this research we will be using the *Delft University of Technology's* drone specifications due to its specific design for immediate and optimal AED transportation. An image of the drone considered is shown in *Figure 1,* which can travel within a 12km radius on a single battery charge with an additional payload of 4kg. It has a built-in camera and can travel at 100km/h, and is stated to be fully autonomous which will be assumed throughout this study [15].

OHCA Incidents

To help simulate the most accurate distribution of incidents for the OHCAs, we have used the distribution of the days and time-of-days of OHCA incidents. This distribution was provided by HeartSine, a manufacturer of AED technology for public AEDs [16]. The probability density functions are shown in *Figure 2* and *Figure 3* and are used in the simulator to help distribute the OHCA incident simulations in this study.

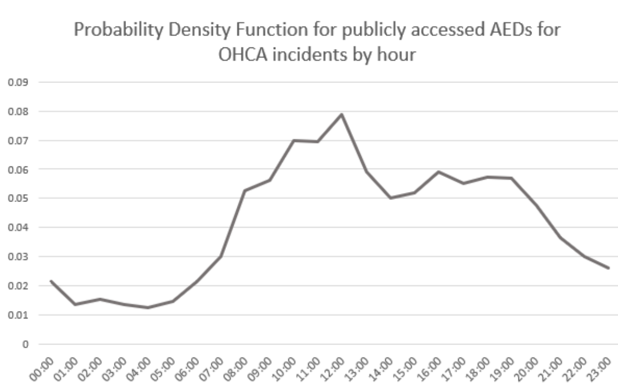

Figure 2: Probability Density Function for Publicly Accessed AEDs for OHCA incidents by hour.

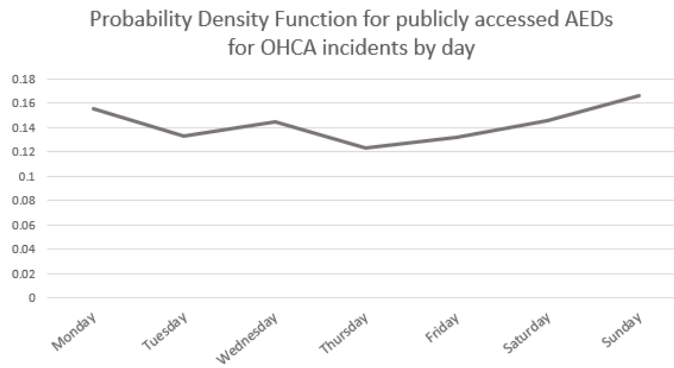

Figure 3: Probability Density Function for publicly accessed AEDs for OHCA incidents by day.

Northern Ireland Health and Social Care Trusts

We will be estimating the number of drone bases for each Health and Social Trust in Northern Ireland (HSCNI). There are five trusts, as shown in *Figure 4*: Northern, Western, South Eastern, Southern and Belfast trusts. The population density for each trust was publicly available from Northern Ireland Statistics and Research Agency [17]. The number of simulated OHCAs have been distributed evenly between the trusts depending on their population density.

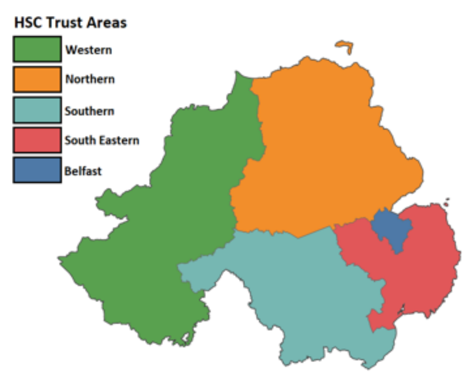

Figure 4: Health and Social Care Trust Areas Northern Ireland OHCA incident simulations in this study.

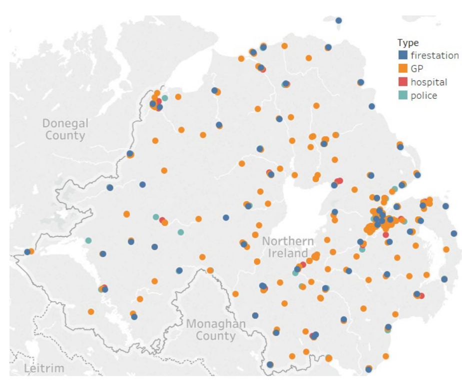

Figure 5: Candidate Drone Bases in Northern Ireland.

Candidate Drone Bases

For this study, all police stations, fire stations, hospitals and general practice (GP) clinics are included as potential AED drone bases. These have been selected as they are in a secure location with a professional capable of maintaining and operating drones. This included a total of 242 potential locations for the AED drone bases shown in *Figure 5*.

No-Fly Zones

There are five drone flight restriction areas in Northern Ireland which make it illegal to fly a drone within a 5km radius unless the user of the drone has the required permissions [18]. These restricted zones as shown in *Figure 6* are taken into consideration for the data-driven simulator when calculating response times after the ambulance drone bases are included.

Figure 6: No-Fly Zones for Drones in Northern Ireland.

Generating Geolocation Points

There are no publicly available OHCA incidents for Northern Ireland. Therefore, demonstrative data was generated using randomly selected coordinates to represent OHCA incidents in each trust. These selected points are only in residential roads or addresses, and excluding places such as within lakes, mountains and other extreme locations. The distribution of 10,000 generated points is shown in *Figure 7* and *Table III* across all health trusts, and was determined through the use of the Geocoding API from the Google Maps Platform [19]. Using the Haversine formula (equation 1):

$$d = 2r\arcsin\left(\sqrt{\left(\frac{\varphi_2 - \varphi_1}{2}\right) + \cos(\varphi_1)\cos(\varphi_2)\,sin^2\left(\frac{\lambda_2 - \lambda_1}{2}\right)}\right) \quad (1)$$

where d is the distance between two points on a sphere, r is the radius of the sphere (earth's radius = 6356km), φ_1 and φ_2 are the origin and destination latitude points in radians and λ_1 and λ_1 are origin and destination longitude points in radians we can determine the distance between two points on earth given their longitude and latitude [20]. This formula was used to find the distance from the generated point and the nearest ambulance station and publicly accessible AED. Using the time and date data for OHCA incidents, a day and hour was generated for each point based on the probability for an OHCA incident occurring. These generated points are saved as a CSV file to ensure consistent results throughout the research. The flow chart for this algorithm to generate geolocations are shown in *Figure 8*.

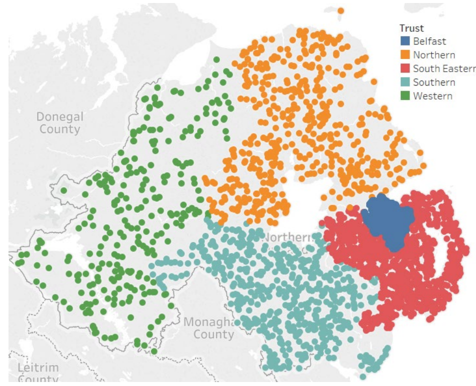

Figure 7: OHCA incident distribution for health trusts.

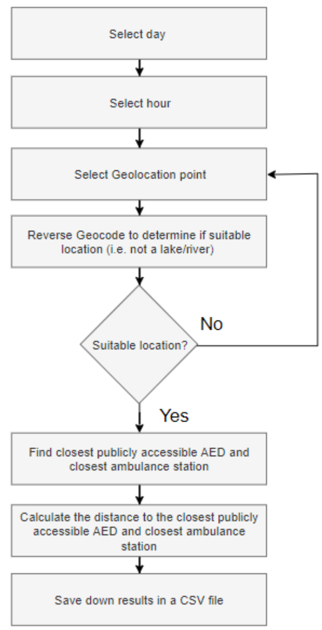

Figure 8: Generating Points Flow Chart.

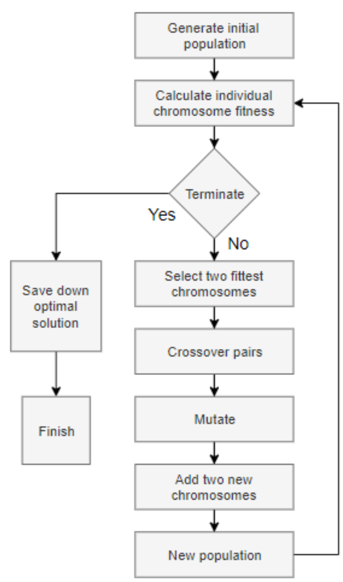

Figure 9: Genetic Algorithm flow chart.

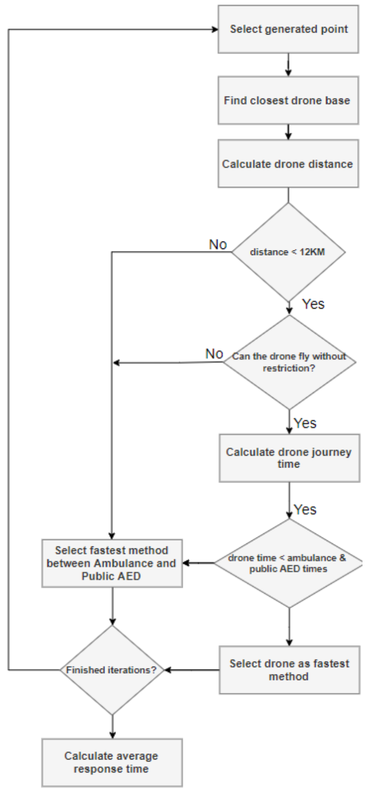

Figure 10: Fitness test simulations.

TABLE III.
DISTRIBUTION OF SIMULATIONS BASED ON POPULATION DENSITY IN NORTHERN IRELAND

HSCT	Population Density in Northern Ireland	No. of Simulations
Belfast	77.30%	7730
Northern	4.91%	491
South Eastern	9.82%	982
Southern	5.24%	524
Western	2.73%	273

SIMULATIONS

These probabilistic OHCA geolocation points were used to create simulations for the travel response times for: 1) a nearby ambulance to arrive at the scene, 2) a bystander to obtain a publicly accessible AED and 3) for the ambulance drone to arrive at the scene (once the drone bases have been strategically selected using a data-driven approach). The Google Maps Platform with the Distance Matrix API [19] was also implemented to run the simulations for ambulance response times. The consideration of distance and time travelled whilst incorporating vehicle traffic was also calculated to generate more accurate results. To represent a response time from a blue light ambulance dispatch, the time travelled was reduced by 25%. Simulating the journey to reach a publicly accessible AED, the Distance Matrix API was used again but for driving to and from the public AED location. To simulate the drone journey, the Haversine formula was used again to calculate the distance to travel in order to determine estimated travel times.

GENETIC ALGORITHM FOR POSITIONING DRONES

The Genetic Algorithm (GA) is used to optimize solutions by replicating the biological evolution process based on the concept of natural selection. The algorithm runs through a specified number of iterations (generations) whilst retaining the fittest solutions each time, eventually reaching an optimum solution. The main components of the algorithm are:

1) *Genes:* The genes are individual components from which a chromosome is made up of. The optimum solution after the GA finishes should retain the best suited genes for the problem. In the case for this study the genes will consist of individual drone bases.
2) *Chromosome:* A chromosome is a collection of genes and at the end of the GA iterations the most optimum set of genes (a chromosome) should be retained.
3) *Population:* The population is the collection of chromosomes for each generation, the chromosomes will change every generation except for the two fittest which remain each time until the final generation which will only keep the fittest chromosome.
4) *Crossover:* The crossover operation happens each generation by joining pairs of chromosomes (parents) in a certain order. This could be achieved by taking half of each parent chromosome to make a new child chromosome.
5) *Mutation:* To ensure genetic diversity from one generation to the next random mutations are added to chromosomes based on a set probability of occurrence. Selected genes are replaced with a new randomly generated gene.
6) *Fitness-Test:* The fitness test determines how well each chromosome performs. The fittest chromosome will remain at the end of the algorithm giving the optimum generated solution.

The Genetic Algorithm is described by the flow chart in *Figure 9*. The initial population is generated with random drone bases selected as genes to make up a set number of chromosomes. After the initial population is generated, the two fittest chromosomes are retained and then crossed over to create a new chromosome. This same crossover process occurs with the rest of the pairs in descending order of fitness. Mutation happens 10% of the time after a crossover to ensure genetic diversity. Additional randomly generated chromosomes are also added within each generation to ensure the population size remains the same each time, and then the individual chromosome fitness is calculated. This same process will happen for a set number of generations which will leave the remaining fittest chromosome with the optimum drone base network from all generated chromosomes based on the fitness of travel times to OHCA incident locations.

FITNESS TEST

To determine the fitness of each chromosome the average response time for the emergency services was calculated with the selected drone bases included to reach the simulated OHCA incidents. In *Figure 10* the flow chart describes the algorithm iterating through generated points (OHCA incidents) and finding the fastest method of emergency response. Given the drone cannot travel further than 12km distance, if the closest drone base that is over that limit will be excluded and the next fastest method will be accepted. Once all iterations for OHCA incidents are complete the average response time is calculated, and this is then the fitness indicator for the chromosome.

IV. Results

The following results demonstrate the difference in emergency response times for OHCA incidents throughout Northern Ireland's health and social care trusts. The results depict the response times before a drone network is implemented including only ambulances and public AEDs and after a drone network is implemented including ambulances, public AEDs and ambulance UAVs responding to incidents.

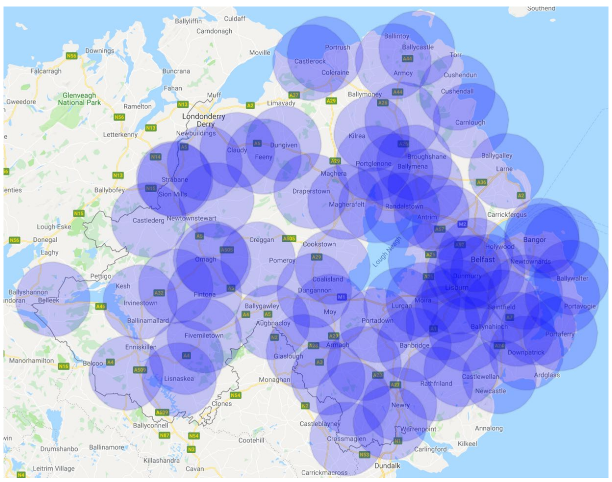

Figure 11: Final drone base locations across Northern Ireland.

Final Drone Bases (N=78) selected for Northern Ireland

Figure 11 is the final distribution of drone bases determined using the Genetic Algorithmic approach. There is a total of 78 drone bases, which would cost approximately £1.17million to implement if each drone costs £15,000. There are further annual costs to be considered associated with training and maintenance of the drones.

Time Group reductions After Drone Network Implemented

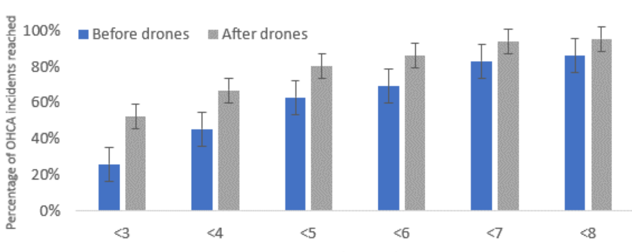

Figure 12: OHCA response time groups after drone network implemented.

Figure 12 describes the total percentage of OHCA incidents reached at each time interval from less than 3 minutes up to less than 8 minutes. Noticeably, there is an improvement at each interval with the greatest improvement for those incidents that can be reached in under 3 minutes. There are over double the number of incidents reached in under 3 minutes after the drone network in implemented.

Response Time Improvements Across Each Health And Social Care Trust

Figure 13 shows the improvement in the average response times for each social care trust in Northern Ireland ($p<0.05$). The average time is only reduced below the 3-minute mark in Belfast, but this is due to a larger population density in a smaller area with a greater number of emergency resources already available. The other trusts have more rural areas with a greater distance from an ambulance station or publicly accessible AED. These trusts have seen around a 50% improvement in response times after implementing a drone network. This may significantly increase the chance of survival for people living in more rural areas.

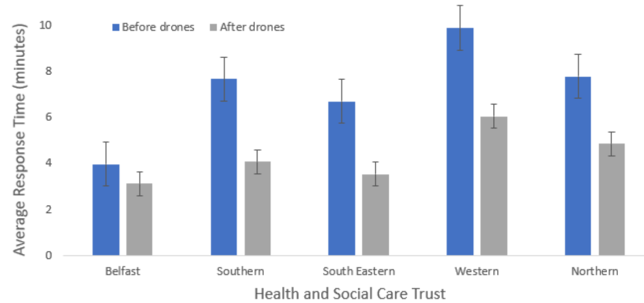

Figure 13: Comparison of average response times before and after ambulance drone network for Health and Social Care Trusts.

Response Time Boxplots Before and After Drone Networks Included

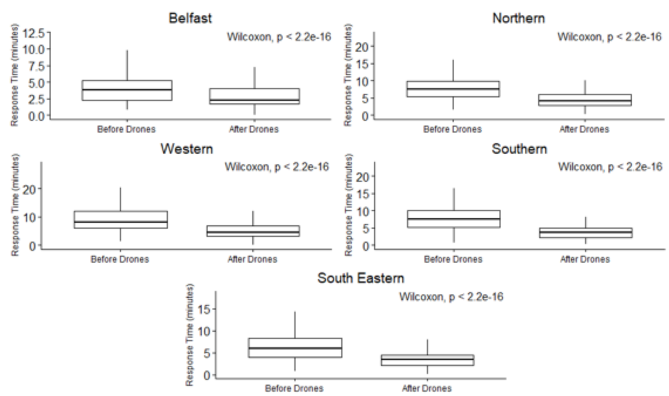

Figure 14: Boxplot for response times for OCHA in Northern Ireland before an ambulance drone network is implemented

Figure 14 boxplots shows the minimum, first quartile, median, third quartile and the maximum response times for each social care trust before and after the ambulance drone network has been implemented. These boxplot results will change accordingly to the number of drone bases selected in the ambulance drone network. The Wilcoxon test highlights that there is a significant difference in the response times before and after the drone network is included with the median being significantly reduced in each trust area.

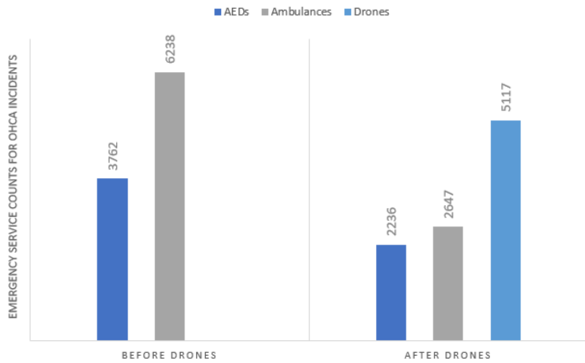

Figure 15: Emergency service count for OHCA incidents before and after drone network is implemented

Figure 15 displays the total count for each type of emergency service (publicly accessible AED, ambulance and drone) before and after a drone network is implemented. After the drone network was implemented publicly accessible AEDs made up 19.74% of responses, ambulances made up 25.66% and drones made up 54.6% of total responses. Drones make up a significant number of total faster responses for OHCA incidents.

Ambulance and Public AED Resource consideration

Further to consider are the limitations of ambulance resources across emergency incidents. According to the Northern Ireland Statistics Research Agency, there is a response time of 12+ minutes across the whole of Northern Ireland [21]. It is also important to note that some rural residential areas could take 25+ minutes to receive an ambulance from the closest ambulance service station. Category Response calls are not always OHCA incidents, but ambulance drones are specifically designed for OHCA incidents. This ensures a high chance of availability for an OHCA patient to receive rapid response for a drone even at busier times.

The simulator results show publicly accessible AEDs being used 37% of the time in OHCA cases before drones were introduced and just over 19% after the drone network was implemented. However, the Out-Of-Hospital Cardiac Arrest Outcomes (OHCAO) Registry claim publicly accessible AEDs are used only 2.3% of the time [4]. This is likely caused by having no available person to assist, no transport option to reach the nearest publicly accessible AED or being unaware of one nearby.

Limitations

Drones are currently a developing technology with many restrictions limiting their commercial capabilities. One major restriction is their battery capacity limiting their travel times and reducing their available uptime. This will likely improve significantly in the next few years of development with upcoming wireless charging hotspot technology currently being researched and prototyped [22]. The next biggest limitation are the flight restrictions in Northern Ireland including 5 registered no-fly zones around airports. There are also strict rules on drones always remaining within line of sight for the user and at least 50 meters from buildings, vehicles or large crowds and never above private residential areas. This will slow down the progress of implementing an emergency services autonomous drone network. However, as this is a relatively new technology, with increased research and development it is likely that necessary licenses will be introduced to tackle these problems for emergency unmanned aerial vehicles (UAV).

The weather is another factor to consider for drone capabilities. It may be difficult to successfully implement a drone network with the unpredictable weather conditions present in Northern Ireland. However, there are drones which have weather resistant technology such as the HexH20 Pro from QuadH20 drones [23] but this will likely raise the cost of the drone significantly.

Ethical and Societal Challenges

There are several social and ethical challenges surrounding the use of emergency UAVs. Safety and security are a concern for the technology used, the user in control and the public. *Montgomery et al.* discuss the vulnerabilities of drones being captured and controlled vis GPS spoofing or signal jamming [24]. These vulnerabilities can result in a drone crashing, risking public safety and damage to the drone. The drone is also at risk of not reaching its destination causing further delay to an OHCA patient. Privacy is another major concern for the use of drones. Ambulance drones would be required to fly over public and private areas with a built-in camera capturing video data for the entirety of its flight and once it is with the OCHA patient. This will result in sensitive information being vulnerable to hackers intercepting the data mid-flight or from the drone base. *Tarun Rana et al.* describe stronger encryption methods using Blockchain technology with Private and Public key cryptography [25]. These methods or similar will be necessary to provide optimal protection against these types of security risks. Noise pollution is another issue to be considered, although ambulance drones will not be as common an occurrence as delivery drones may be. Whilst implementing a network of emergency UAVs could potentially avoid a multitude of fatal OHCA incidents, there will be a trade-off between budget and availability. Extending the drone network will be expensive until UAV technology becomes widely produced and benefits from economies of scale.

V. Discussion and Conclusion

The results show significant improvements in response times for OHCA incidents when implementing a drone network. The drones also offer a dedicated response to these incidents and a shorter response time for rural incidents which is likely to improve the chances of survival for many cases. To implement a drone network throughout Northern Ireland with similar results would cost a significant amount. However, the drone network described in this paper is an example of an efficient solution, which can be altered depending on budget and success of trials with a smaller number of drones.

The Genetic Algorithmic approach is helpful in determining strategic positioning of drone bases, but it comes at a cost of computation time and potentially stochastic results. The data-driven simulator is useful for estimating the potential benefit of implementing the drone network, but its accuracy is limited without trial emergency drone flights.

This paper took the unique approach of using a data-driven simulator with a Genetic Algorithm to optimally select drone base locations throughout Northern Ireland and a data-driven simulator to estimate the potential reduction in response times for OHCA incidents.

Further Research

When finding an optimal drone network, it would be necessary to obtain previous OHCA cases which are not currently publicly available. This would help indicate high risk areas and provide more accurate information to assist the simulator in finding the most strategic positioning for drones throughout Northern Ireland. It would also be recommended to undertake further tests for the usability of emergency drones considering weather conditions and the ability of untrained bystanders to deliver successful defibrillation with accompanying human instructions.

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