Air Taxis as Ambulance - New Zealand

Feasibility study

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Chapter 1

Introduction

Previous years has brought numerous advances in the fields of Artificial Intelligence (AI), drones, autonomous control of means of transport, electric engines and battery technology. Together, the previously mentioned created a very fertile ground for new types of transportation, including autonomous electric Vertical Take-off and Landing (eVTOL) vehicles. The new automated hybrids between helicopters, drones and airplanes are getting increased amount of traction and publicity in the news worldwide as numerous startups, big technology and transportation companies are joining the race. The main promising idea behind the cutting-edge eVTOLs technology is the added third dimension to the congested 2D transportation system in today's city-centred society.

The most notable advantages of the eVTOLs technology in general is the reduced transportation time, less pollution and added new segment in the transportation mix. On the other hand, as the public saw in recent years with adoption of e-scooters such as Bird or Lime, there are always two sides of the equation. Most commonly debated issues around the autonomous eV-

TOLs is safety [27], electric efficiency [28] and noise pollution in the cities [9]. With the current pace of the technological progress the biggest hurdles such as the noise pollution are being tackled with increased speed and the eVTOLs future looks promising and the first mock flights are happening all over the globe from Singapore to Dubai.

One of the most ambitious innovators in the sector, company called Wisk, signed a deal with government of New Zealand in early February 2020, that will allow the tech startup to start testing their eVTOL called Cora in practice. First test flight are said to take place in Canterbury and are going to be a part of Airspace Integration Trial led by the New Zealand government [32].

One of the exemplary usages of eVTOLs is the Emergency Medical Ambulance network, where the use of the new autonomous technology could save countless lives and provide rapid services. Just looking at U.S., the average reduction of 6 minutes in arrival times, when compared to ground ambulance, would make a difference between the survival and passing away of nearly 20,000 patients every year [17]. The same study also shows that theoretical cost of autonomous eVTOLs per trip to the patient would be one eighth of the ground ambulance due to under-utilization of ground ambulances and the relatively long time they spend servicing one patient (1-1.5hrs).

With the background being set, we now focus on the aim of this master thesis. The test flights of Wisk in New Zealand are a perfect base for a feasibility study and a proposal of a method of deployment eVTOLs as a part of the medical ambulance systems. Mountainous country such as New

Zealand with just a limited amount of mountain passes through some of the regions with higher altitude provides an ideal scenario of the deployment of such technology. The aim of this thesis is therefore to optimize the number of locations of the hypothetical Air Ambulances on the two islands through the deployment of a Set Covering optimization algorithm. Following the first task, a cost and lives saved analysis is run to asses the actual benefits before possible deployment of the technology.

The main focus of the drone-like aerial vehicles was so far focused on the various models of lightweight delivery and camera-mounted drones. This trend is also reflected in the literature about the topic. There is a very wide and thorough range of articles on the usage of the drones in medical sector that can serve as a starting point for this thesis. Combined with the optimization work that was performed for ground ambulance systems in the past, this thesis aims to build on top of the currently published work about eVTOLs.

The eVTOLs technology is still in its infancy and therefore the scientific articles are not paying enough attention to the trend. Even though similar optimization and statistical methods used in this work were used before for tasks e.g. drug delivery and, as already mentioned, ground ambulance, this work is aiming for applying the methods to this brand new industry to better understand its potential.

As a society, we have started gathering an enormous amounts of data points without making an actual use and utilizing the potential of the information source we have at hand. This master thesis is a zero-cost tool that makes use of freely available information to drive important country-wide decisions. If automated, the study could serve as a first tool to asses the feasibility of deployment of the Air Ambulance eVTOLs for any other region in the world with only the regional data needed as the new input. The master thesis is to this date the only assessment tool of this kind for the feasibility of the Air Ambulance use of eVTOLs and can hopefully push the adoption of the new technology by wider public.

The rest of the thesis is structured into following parts. In the first part, literature review is focusing on the work done on optimization of locations of ground ambulances and on various topics concerning eVTOL technology, as the aim of the first part of the thesis is to combine the two. The second part focuses on the development of the methodology for the Air Ambulance Set Covering optimization and the following simulation of the actual cost and fatalities reduction. The third part describes the collection of the data set of population density on New Zealand islands and the locations of medical centers. Also, the application of the developed optimization algorithm, implemented in Python, on the gathered data is outlined and the final outcomes are drawn. Furthermore, the simulation assessing the correctness of the optimization solution is set up and run as well as costs and benefits analysis. The fourth part describes results of the implementation with regards to other found literature on ground and possible air ambulance usage. The final part concludes all the taken steps and the obtained results and shows whether it makes sense to use this approach for the establishing of Air Ambulances in New Zealand.

Chapter 2

Literature review

This part of the thesis is divided according to the different topics that need to be covered in order to understand the overall situation. The main parts of the review are focused on Ground Ambulance Location optimization, status of the Ambulance networks, eVTOLs prospects and also, work that has been done on assessing the costs and benefits of the studied technology as all the mentioned topics serve well as a starting point from with we can extend the techniques to Air Ambulances.

2.1 Ambulance status

Before we progress further into the topic, it is essential to state a little motivation of why we are looking into the usage of the eVTOLs as ambulances and why should it be of interest to upgrade this public service. If we focus on an example taken from the United States of America, the usual arrival time of the ground ambulance is around around 11 minutes for the metropolitan areas and almost 30 minutes in the rural areas [1]. If that waiting time was reduced only by as few as 6 minutes, in the U.S. only, we would be able to safe approximately 20,000 lives more yearly [17] [18]. One of the biggest issues is the under-utilization of the ground ambulances due to small territory coverage and slower speed [12]. Exactly those problems on the other hand, could be addressed exactly by eVTOLs, that are faster, can cover fast spaces thanks to the flight unrestricted by ground traffic and a fast departure right after the emergency call. Another comparison that should be made is the one with the currently used helicopter rescue system. Even though it would seem reasonable to make such a comparison, the initial cost of the helicopter for ambulance purposes, around $6 million, causes its fixed costs too high for every-day purposes [22]. With the estimated initial costs almost 20 times lower [17], the eVTOLs can pose more than a significant challenge not only to the helicopter usage but also, to the use of the ground ambulance. In case of New Zealand, the system is facing financing issues [34] while being partially funded by the government, partially by donations and partially by patients paying a share of the price when being transported.

2.2 Ground Ambulance Location

The optimization problem of ground ambulance locations has been studied since the early 70s [19] when the first Location Set Covering Problem (LSCP) [33] and Maximal Covering Location Problems (MCLP) were solved [5]. Those two solutions faced a strong shortcoming as once one of the locations was called and the ambulance dispatched the service was unavailable for the time of the mission. The problem of unavailability was solved by Double Standard Model (DSM) [10] introducing multiple coverings of one place. All of the previously mentioned methods are still rather rigid and therefore this thesis is based on DSM with added focus on uneven workload and unmet coverage requirements [7] is better for real life systems. For the purpose of this thesis, a DSM model with a relaxation of the rigid conditions on number of citizens covered with each ambulance site is used and is thoroughly explained in the next sections. The DSM is a Constrain Optimization problem with formulated function to maximize and constrains to follow, both are thoroughly described in the Method section.

All the described models are so-called strategic models that tackle the layout of ambulance stations and the number of ambulances within each of the stations. The following type of planning, called operational planning, which is used mainly when more stop of the vehicles are needed per trip are not in the scope of the thesis as they are not relevant for the problem at hand.

2.3 Air Taxi Usage of eVTOLs

The aim of this section is to study and reuse or adjust different aspects of the optimization problems used for the same technology although used for different purposes. Also, look at the other potential use cases can help to understand the biggest upsides of the technology and how to leverage them in the case of Air Ambulances. The eVTOLs technology can find its purpose in overcrowded cities and urban areas where its usage simplifies the further development of commuting while the technology still can stay competitive in terms of travel time [35]. The highest improvement would the technology offer for distances too long and congested for a car and too short for high speed trains or international flights [20]. Therefore, the usage of Air Ambulances seems very adequate as the need for fast movement through short to mid range distanced potentially congested areas is so far only covered by expensive helicopter travel. [35] suggests using a simulation for the demand setup after the optimization of the travelling routes which is also, as mentioned earlier, used in this thesis.

2.4 Medical Materials Drone Delivery

As eVTOLs are still in the development and are not yet fully commercialized, suitable proxy for the thesis are the drone delivery systems where small drones, up to few kilograms of weight, are delivering medical material to remote areas. This new unmanned approach was shown to produce effects alleviating the burden of chronic patients and reducing costs of their treatment on the practical example of deployment in a part of Texas, U.S. [15] [30]. This focus of research on the other hand shows that the aerial solutions in healthcare are just around the corner and the first preliminary studies for various purposes show promising results.

2.5 eVTOLs Technology

There are numerous different styles of this brand new transportation mode being invented, designed and engineered. Around 150 [8] companies are now actively involved in the race to become the new Volkswagen or Audi of the air travel which is about to become another norm as one of the means of transport. Companies ranging from industry giants such as Airbus and Boeing to small garage-based startups like Volocopter, Aurora or Lilium are all creating their first takes on the cheap, sustainable and safe air travel problem. Some of the current concepts can be seen in Figure 2.1

Figure 2.1: eVTOLs in Different Stages of Readiness for Market

Every company is pursuing a different strategy in terms of the size, maximal flight time, number of passengers and many other features including complete autonomy versus initial usage of pilots [23]. There are multiple technical challenges that have to be overcome until the widespread usage of the technology can begin such as the battery life efficiency, implementing the technology into the urban landscape or the viability of mass travel [16]. There are, in general, multiple basic types of the eVTOLs chassis shapes that are trying to combat and tackle the various challenges as can be seen in Figure 2.2.

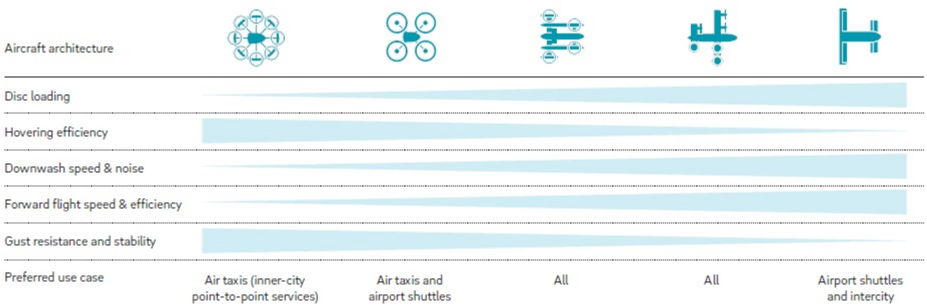

Figure 2.2: Strengths and Weaknesses of The eVTOLs Types

Each of the types including quadcopters and multicopters was created with a specific purpose to fulfill ranging from short-range taxis, through airport shuttles to air ambulances [6]. Of course, the eVTOLs themselves are only one part of the needed infrastructure with the landing sites purposed for eVTOLs usage being the second half. There are various concepts ranging from usage of the heliports already built on top of the hospitals and some prominent hotel complexes and offices to concepts designed exactly for the purpose of the eVTOL usage [29].

With all of the previously mentioned variations and possibilities in this newly emerging industry, it is hard to predict the sector for the earliest deployment into real-life usage. The ambulance usage was used as it restricts some of the variance of the overall problem, fixes the purpose and field of operations and also can build on top of the already used infrastructure for helicopter ambulances.

2.6 Acceptance of eVTOLs

One of the main issues of the technology is its acceptance rate by general the public. As every new technology various concerns arise with the introduction of eVTOLs, in particular about safety and noise pollution [6]. That is why many of the small manufacturers and startups are focusing on minimizing of what could be a critical crippling shortcoming of the technology. Recently, the noise levels have been taken down dramatically to levels acceptable by the public.[31] As the technology progresses and becomes more widely known, the citizens are starting to see its actual upsides instead of the complications connected with it [27]. Persuasion of customers for everyday usage of the eVTOLs could still be a challenge, for the medical purposes on the other hand, the usage seems very acceptable even by the public [13].

2.7 Benefits and Costs

To fully understand and appreciate the potential of the new technology, last part of the thesis is focused on counting the costs of transitioning to the new ambulance system and also on what public health benefits would it bring to the population and the government.

One of exemplary conditions where the survival of the patient is dependent strictly on the arrival time of the ambulance is cardiac arrest [4]. According to the result, decrease of 6 minutes in the urban arrival times of emergency vehicles would raise the number of survivals by at least 20,000 lives per year on a country of a size of the U.S. [26]. In terms of long term prospects, those patients show up to 70% long term survival rates [3]. Those numbers mean that just for this one disease, with the annually saved lives each being worth around $88,000, calculated from the U.S. GDP and average life expectancy, the annual yearly benefit would be nearly $18.3 billion dollars [17]. For New Zealand, the statistics show that Cardiac Arrest only is responsible for 81% of out-of-hospital deaths in the country [36].

When considering the costs, the average estimated costs per one of the eVTOLs across the potential manufacturers is around $250,000 [2] which is very competitive compared to around $6 million per helicopter. Then comes the break-down into fixed and variable costs for operating such an eVTOL vehicle. When considering the fixed costs, comprising of Ground Ambulance, its Facility and Labor, 80% of the costs (excluding the Ground Ambulance vehicle itself) could be reused for eVTOL purposes. The incremental price of the eVTOL vehicle would be comparable to a yearly salary of the crew maintaining and flying it which is already being paid [17]. For the variable costs, both the electricity and the eVTOL maintenance would be competitively lower than the price nowadays for ground ambulances (by approximately 50%) [17]. Therefore, from the analysis performed on the U.S. market, this option seems as a very interesting and viable solution even from financial perspective.

Chapter 3

Method

In this chapter, we first discuss the data needed for the Set Covering algorithm used to determine the ideal location of the Air Ambulance sites and counts and then, we focus on the model itself. Afterwards, a simulation that was used for evaluation of the correctness of the model is introduced. Finally, last part is focused on benefits and costs estimations and the comparison of the eVTOLs and the classical ground ambulance. In this section a base case for the analysis is set and its further perturbations are used in the next section.

3.1 Data Needed

The complex Set Covering problems can be simplified into Graph problems. In this case, the initial problem of how to cover as much of a population of a specific country as possible with the access to fast Air Ambulance services was simplified by representing the number of inhabitants and the possible ambulance sites as nodes and the respective distances between the nodes as the edges of the graph. The figure 3.1 shows an example of two hospitals as black nodes, the aggregated population of surrounding area units as red nodes and the distances between the hospital and the geographical center of the population clusters as red edges with the respective distances. In this way, the techniques used in Set Covering can be used to solved the problem at hand. In the Data Analysis section, more elaborate description of the procedure to achieve this setting is shown.

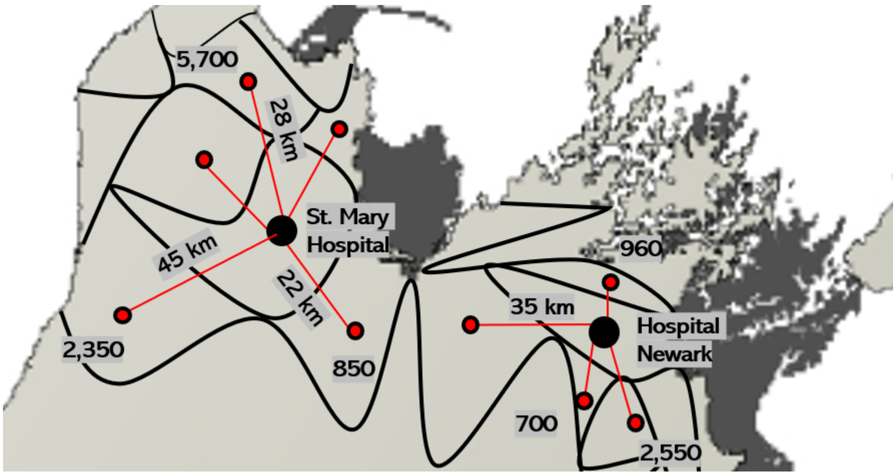

Figure 3.1: Graph Representation of the Set Covering Problem

3.2 DSM Model with further constrains

DSM Model introduced in the Literature Review part is considered a gold standard in the population coverage optimization for ambulances. Therefore, it is the starting point of this study and few adjustments such as some of the penalty functions introduced in [14] are be introduced. The main aim of the model is to maximize the cover of demand points by two ambulances within the distance of r_1.

We could define the problem on a graph $G = (V \cap W, E)$ with $V = \{v_1, ..., v_n\}$ being the set of demand points (clustered residential areas described before by red notes) and $W = \{w_1, ..., w_n\}$ being the set of potential locations of ambulances (described by black nodes before). Furthermore $E = \{(v_i, w_j) : v_i \in V, w_j \in W\}$ is an edge set (distances between the demand points and potential ambulance sites). The demand (amount of people) at the node $v_i \in V$ is equal to λ_i. The cumulative number of individual eVTOLs used as ambulances is equal to p. Next, for $v_i \in V$ and $w_j \in W$, we need to define γ_{ij} and δ_{ij} equal to one if v_i is covered within radii r_1 and r_2 respectively and equal to zero otherwise. Also, α is the proportion of the total demand that must be covered by an ambulance located within r_1 kilometers. Finally, y_j is the amount of ambulances located at w_j, p_j is the maximal limit of y_j for any point and x_i^k is equal to 1 if and only if v_i is covered k times within r_1.

The original paper introducing the DSM [10] states the optimization problem with the following set of equations. First, the function to maximize is given as:

$$max f = \sum_{i=1}^{n} \lambda_i x_i^2 \tag{3.1}$$

The model is simply trying to maximize the amount of people covered by two ambulances within the the distance of r_1. Afterwards, the constrains of the systems are given:

$$\sum_{j=1}^{m} \delta_{ij} y_j \geq 1 \tag{3.2}$$

$$\sum_{i=1}^{n} \lambda_i x_i^1 \geq \alpha \sum_{i}^{n} \lambda_i \tag{3.3}$$

$$\sum_{j=1}^{m} \gamma_{ij} y_j \geq x_i^1 + x_i^2 \tag{3.4}$$

$$x_i^2 \leq x_i^1 \tag{3.5}$$

$$\sum_{j=1}^{m} y_j = p \tag{3.6}$$

$$y_j \leq p_j \tag{3.7}$$

$$x_i^1, x_i^2 \in \{0, 1\} \tag{3.8}$$

$$y_j integer \tag{3.9}$$

Constraints 3.2 and 3.3 express the single and double coverage requirements. Constraint 3.2 states that all demand must be covered within r_2 units. The left-hand side of constraint 3.4 counts the number of ambulances covering v_i within r_1 units. The right-hand side is equal to 1 if v_i is covered once within r_1 units and equal to 2 if it is covered at least twice within r_1 units. Constraints 3.3 and 3.4 taken together ensure that a proportion of α of all demand is covered (constraint 3.3) and the coverage radius must be r_1 units since constraint 3.4), $x_i^1 + x_i^2 = 0$ whenever $\gamma_{ij} y_j$ for all j. By constraint 3.5, a vertex v_i cannot be covered at least twice if it is not covered at least once. Constraints 3.6 3.7 and 3.9 impose limits on the number of ambulances at each site.

After the initial implementation of the DSM model from the original paper, further adjustments were needed. As both the range and the time effectiveness of the eVTOLs is far superior to the ground ambulances used today as eVTOLs do not need to follow any already-built infrastructure that is slowing down the vehicle, the initial double coverage model was found inefficient and therefore some of the constraints had to be remodelled. The change performed as a base case scenario corresponds to 3.10 and 3.11 where the only new parameters are θ equal to number of people that are usually serviced by one ambulance vehicle and β which is a boolean variable equal to one if there is an eVTOL ambulance site on the specific potential spot.

$$\sum_{j=1}^{m} \gamma_{ij} y_j \geq 6 \tag{3.10}$$

$$p_j \theta \geq \sum_{i=1}^{n} d_i \gamma_{ij} \beta_s \tag{3.11}$$

The 3.11 is restricting maximal workload (number of people it has in its covering) for each of the eVTOLs potential stations and 3.10 was established after finding out that with the increased reach because of the new technology, the previous double covering standard in the DSM model alone was not sufficient. The reason is that with the usage of eVTOLs, every ambulance station is, thanks to the increased reach of the vehicles, servicing much larger parts of the territory and therefore the radii of the reach are more overlapping. Therefore, the double coverage model would not be sufficient.

3.3 Simulation of the proposed system

After setting up the optimization model, a clear way of assessing its performance was be needed. For that purpose, a simulation of the whole system was set up, also in Python, to see if the system ever runs into problems with servicing the inbound emergency calls. The simulation simply takes the results of the optimization, generates the emergency calls according to a distribution that is specified later and tries to address the calls as well as possible. The main criterion is not to have a single call that would not be possible to address with a free eVTOL ambulance.

3.3.1 Parameters and Execution of the Simulation

The simulation was set up according to the average number of daily emergency calls in New Zealand (around 700 [11]). The distribution of the calls was approximated according to [25] that, in short, found out that the amount of calls is twice as high during the day than during the night. To make things easier, this distribution was divided into 10-minutes intervals and number of emergency calls for that specific interval was established from the distribution 3.2. For every call drawn, its origin (being one of the demand points previously used for optimization) was distributed according to the population density. Simply, likelihood of the call coming from that specific area unit was calculated as number of people in location i divided by the total population of New Zealand.

After drawing of the emergency calls, simulation iterated through every ambulance that covers the location of the call and dispatched the eVTOL

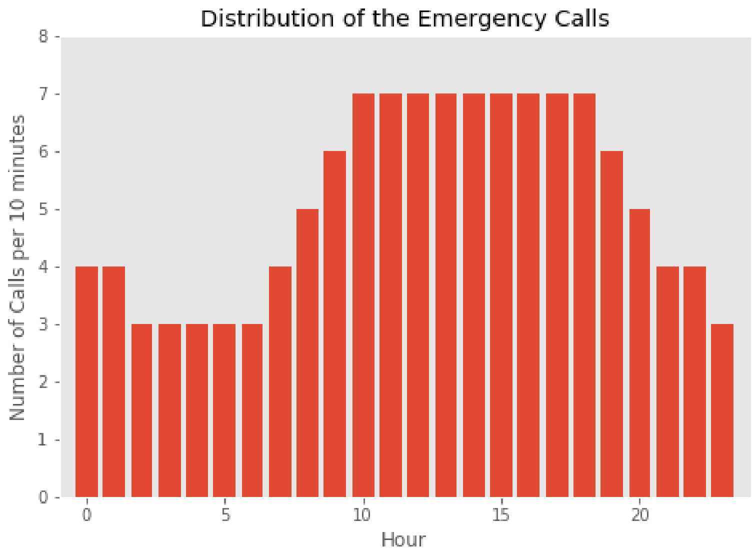

Figure 3.2: Distribution of Emergency calls throughout the day

from the one with the highest number of available vehicles. The time of the dispatching of the eVTOL was registered and when reached specific number of minutes after the dispatch, the vehicle was returned to the set of available vehicles. The main parameter studied was the number of unsuccessful dispatches, being the amount of emergency calls without a single available eVTOL that could respond to the call.

The parameters of the simulation such as the length of each mission (time between the dispatch and the readiness of the eVTOL for another flight) is the focus of the further parts of this master thesis. The main focus is on the potential flying range of the eVTOLs as the parameter makes the planning of the locations rather flexible. Also, the focus is on how many eVTOLs need to cover every possible demand location as we later see that the DSM model needs to be adjusted with the usage of the new eVTOLs technology and on length of each of the dispatches that reduces the need of numerous vehicles at each of the spots.

3.4 Costs Cut and Lives Saved

Last section of the master thesis focuses on the financial and public health implications of the newly proposed eVTOLs Air Ambulance systems. As a baseline for the calculations, the current use of the ground and helicopter ambulances, its costs and lives saved are taken from [17] and then compared with the proposed eVTOLs system. As the New Zealand's healthcare system is a hybrid of private and government funded institutions, this measure can be used as the deciding variable that can help to grasp the actual improvements and the potential of the system.

The enumerated costs presented for the U.S. case (in literature review) are in this part recalculated to the country of New Zealand's size. For the proposed scenarios, all costs are bench-marked to the publicly available information. The costs are separated into fixed and variable parts for both the current system and the eVTOLs. The fixed costs include the purchases of the vehicles and the facilities needed whereas the variable costs include personnel, which means pilots, medics and drivers, maintenance and running costs.

Multiple scenarios are introduced as the result of this part of the thesis. Scenarios vary from full transition into the eVTOLs-era through partial merge of the two ideas into simple keeping the system as it is to-date. For each of the scenarios, total costs and potential public health improvement is presented.

Chapter 4

Data Analysis

In this section, we firstly look at the data manipulation and aggregation performed in order to acquire the needed data set for the hospital network on the New Zealand islands and for the population density in the various geographical regions. Afterwards, the python implementation of the algorithm with the use of Google's OR-Tools package is explained. Furthermore, the different parameters of the simulation is explored, which helps us to understand what needs to be achieved in order to make the idea of usage of eVTOLs as Air Ambulances feasible.

4.1 Data set Gathering

For the purpose of the work, two main sources of information were needed, information concerning the hospitals and information describing the density of population.

Firstly, the hospitals and clinics, used as the potential sites for the ambulances, were located. The lists of the objects were downloaded from a portal of New Zealand's government health organization. Afterwards, the addresses were used to acquire the GPS latitude and longitude of each of the objects through paid Google Maps API. In this way, total of 145 state and private owned hospitals for potential ambulance sites were gathered and further used throughout the study. The hospitals range from mid-sized clinics to large regional hospitals taking care of numerous hundreds of patients at once.

Secondly, the data about New Zealand's population density were taken from the country-wide 2013 Census available on the websites of the New Zealand's Bureau of Statistics. Data were aggregated on a level of so called "area units" being various parts of land ranging from city block to vast parts of countryside, all with aggregated population ranging from few inhabitants to a few thousand people. Sadly, those regions could not be found on Google Maps as they serve just for internal statistics of the Bureau and therefore their GPS location scraping could not be automated and all of the approximately 2,000 GPS records had to be found and recorded by hand. For each of the regions, its geographical center was used as the representation for which the GPS coordinates were written down.

Afterwards, the data sets were merged together and around 1,900 of the regions were used for further analysis, deleted regions either had no inhabitants (oceans, rivers, bays...) or were unreachable by the current reach of the eVTOLs from the potential sites. The number of people excluded from the study was around 21,000 being 0.005% of the overall population. The mean of population in the regions is 2,247 and the median is 2,038. The size of the various regions ranges from 0.7 m^2 to almost 5,000 m^2.

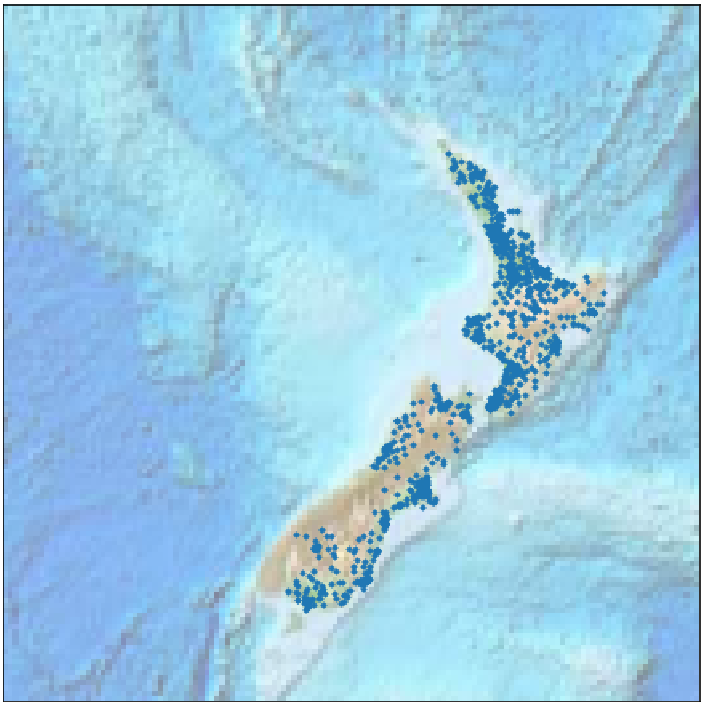

Figure 4.1: Population density on the two New Zealand's islands

After acquiring all the needed data, respective distances of all the v_i (aggregated demand points) and w_j (potential ambulance locations) were calculated from the GPS using the Haversine formula stated below.

$$distance = 2r \arcsin \sqrt{(\sin^2(\Delta\varphi/2) + \cos\varphi_1 \cos\varphi_2 \sin^2(\Delta\lambda/2))} \qquad (4.1)$$

Where $\Delta\varphi$ is the the difference of latitudes of the two point we are calculating distance between. $\Delta\lambda$ is the difference in longitude and r is Earth's radius.

Following the calculation, matrix representing demand points and potential ambulance sites with the entry of 1 in the fields where the demand point is within the reach of the potential ambulance site was used as the input to the optimization model together with the list of population sizes in each of the points.

4.2 DSM model implementation

For the model itself, library called "or-tools" developed by Google was used. The library serves as a numerical solver for Discrete Optimization NP problems such as Traveling Salesman Problem, Knapsack Problem, or Set Covering problem. The constraints have to be modeled in a linear way and clear distinction between the previously obtained data and variables with changeable values has to be set. The variables are encoded with the help of the or-tools package and the ranges of their values and types have to be added. The relationships between the various variables have to be also added as the input and then the model can be run. The code very much resembles the mathematical description used above for the constraints. All the constrains have to be linked through some of the variables defined before.

4.3 Simulation Parameters Perturbation

As mentioned before, the best way how to evaluate the models performance and to understand the needs of the technology is through the perturbation of the models assumptions and parameters used throughout the code. Four different subsections are be introduced here that helps to estimate not only today's need but also how the actual layout of the eVTOL stations could change as the technology proceeds further. As some of the parameters are also influence the other ones, their impact on each other is also be studied.

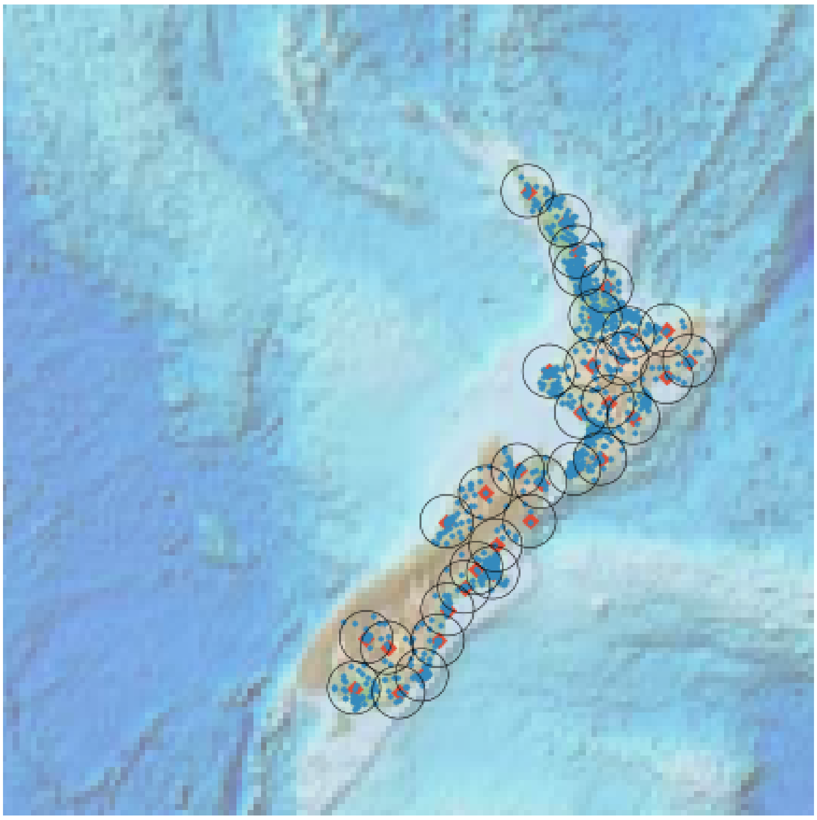

Figure 4.2: Baseline Coverage of the optimized model, without the simulation perturbations

The coverage of population in 4.2 shows the results with the reach of eVTOLs of 70 kilometers, the average time per mission of 60 minutes, the needed coverage of every potential demand point by 6 eVTOLs and the average number of emergency calls set to the actual average over last years in New Zealand. This scenario is from now on taken as the baseline for next studies and it is able to pass the simulation without any significant errors, meaning there was sufficient amount of eVTOLs at any station at any time. This baseline scenario uses 34 out of the 145 potential air ambulance sites with the use of 272 eVTOLs altogether, which is roughly half of the number of ambulances used on the two islands today. Figure 4.1 shows a sample of resulting hospitals used for the eVTOLs locations even with the number of eVTOLs stationed. The blue points in 4.2 represent the different aggregated demand points, the orange points refer the picked hospitals for the eVTOLs Ambulance Sites and the circles around are the range distances of individual hospitals equipped with the eVTOLs.

Hospital Name	Number of eVTOL Ambulances
Winton Maternity Centre	6
Oamaru Hospital	6
Kaikoura Hospital	8
Waikari Hospital	7
Hawkes Bay Health Centre	13
Grey Base Hospital	6
Wilson Center	7
Whanganui Hospital	7
Taranaki Base Hospital	8
Pembroke Street Ward	10
MacKay Street Thames	7
Lakes District Hospital	9

Table 4.1: Sample of the resulting 34 hospitals

4.3.1 eVTOLs Maximal Range

One of the main parameters used in this study is the maximal reach of the eVTOLs. Currently, the reach of eVTOLs of Wisk and other companies would correspond to approximately 70 kilometers radius useful for the Air Ambulance purposes [2]. As seen in technologies using similar electric batteries technology, such as electric cars, especially at the beginning of the technology use, those parameters are improving rapidly. Therefore, as a baseline for this study, 70 kilometers radius was used and other ranges of 40, 60, 100, 110 and 150 kilometers are further studied and the results are summed up in the Figure 4.3. Throughout the simulation, the optimization model was run with the respective maximal range radius, and then the number of eVTOLs needed in order to answer all of the emergency calls without a single failure for the span of 300 days was found together with the Coverage Multiple.

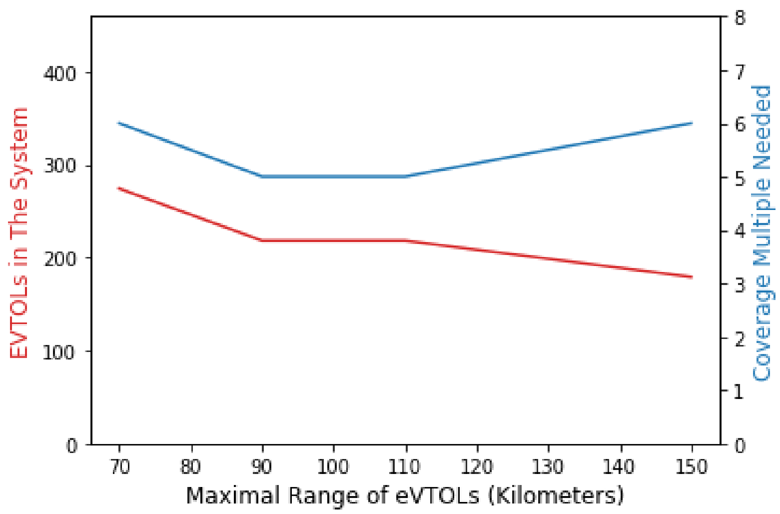

Figure 4.3: Simulation of the Number of eVTOLs Needed for Different Maximal Ranges

As we can see from the results, the number of needed eVTOLs and coverage multiple are declining with the increasing maximal range as expected. The only unexpected result is for the 150 kilometers range where the coverage multiple needed to serve all the calls without any failures has increased because of the too vast distances between the ambulance stations. Also such a high ranges would mean that in order to fulfill the international standard of 30 minutes from the emergency call to the inbound of the ambulance, the eVTOL would have to fly at speeds of 300 kilometers per hour, those speeds are, so far, impossible to achieve with such a vehicle. While talking about the unfeasible results, this simulation was also tested for the range of 40 and 60 kilometers, where both of the results turned out to be infeasible as there would be way too many regions that would not be covered at all due to the short possible reach.

Most interesting and promising outcome of this simulation is the fact that with the increase to potential 90 kilometers in the reach, only 20 kilometers increase when comparing to the current state, there would be a significant drop of 46 needed eVTOLs. Further more, there is no difference in the number of needed vehicles between the 90 and 110 kilometers of reach meaning that the technology would be able to reach its maximal potential if only the companies were able to increase the maximal flight distance by 40 kilometers (20 kilometers each way).

4.3.2 eVTOLs Coverage Multiple per Demand Point

As explained before, the initial assumption of dual coverage used as the constraints with the older ground ambulance technology had to be restated due to the increased range of each of the vehicles used. In this section, we study the effects of lower and higher coverage multiples, meaning how many ambulance vehicles cover each of the potential demand points (one of the aggregated areas). The usage of 2,3,4, 5, 6, 7 and 8 multiples is used to check the precision of the solution. The simulation of which the results are shown in Figure 4.4 was performed by rerunning the optimization model while replacing the constraints 3.10 right side with the previously stated values. During the simulation a tracking the amount, of emergency calls that the system failed to address due to the lack of eVTOLs at the ambulances covering the demand point from which the call came, was registered.

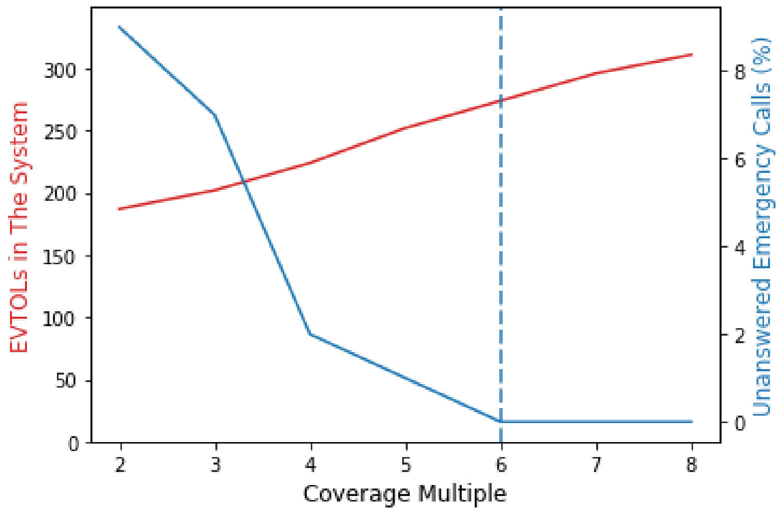

Figure 4.4: Simulation of Number of Unanswered Emergency Calls for Various Coverage Multiples

As expected, the percentage of unsuccessfully addressed emergency calls over 300 simulated days drops to zero with the previously stated multiple of 6 ambulance vehicles covering each of the potential demand points. The number of required eVTOLs per every increment of the coverage multiple stabilizes on the examined interval on around 25 vehicles which shows that the location of the ambulance sites of the optimized system is not changing drastically while perturbing this parameter. The only difference is therefore the amount of vehicles on each of the 34 ambulance sites that are chosen by the optimization. Also, the fact that the percentage of unanswered calls decreases steeply already at around the coverage multiple of 4 shows the stability of the chosen solution of 6 as the system seems to stabilize and slowly converge.

4.3.3 Time per Mission

One of the main aspects of the results of the optimization model and the necessity of the amount of vehicles stationed on each of the ambulance stations is how long every response flight takes. Every response consists of multiple steps, from which only some can be regulated. According to [17] right after the dispatch call, the eVTOLs could take-off in around one minute. After landing at the site, certain amount of time is needed for the patient pick-up and stabilization, the main component we can therefore reduce is the travel time. With the average limits for response of 12 minutes in urban areas to 30 minutes in rural areas for ground ambulances [24], the travel time can take up a significant portion of the whole emergency response. Therefore, values of 20, 40, 60, 70, 80 and 90 minutes for the average duration of the whole operation is tested in the simulation. During the simulation, first the respective length of the whole operation is chosen and then the optimization algorithm is rerun to establish the smallest amount of eVTOLs needed for running the simulation of 300 days without a single failure to respond to the emergency call. Results can be seen in Figure 4.5.

In general, the number of needed eVTOLs and the required coverage multiple are both increasing with the increase in the time required for the response to the emergency call. Interestingly, with the overall increase from 20 minutes to almost an hour and half per flight, being an increase of 450%, the amount of needed eVTOLs only increases by 50%, from 202 to 311 for

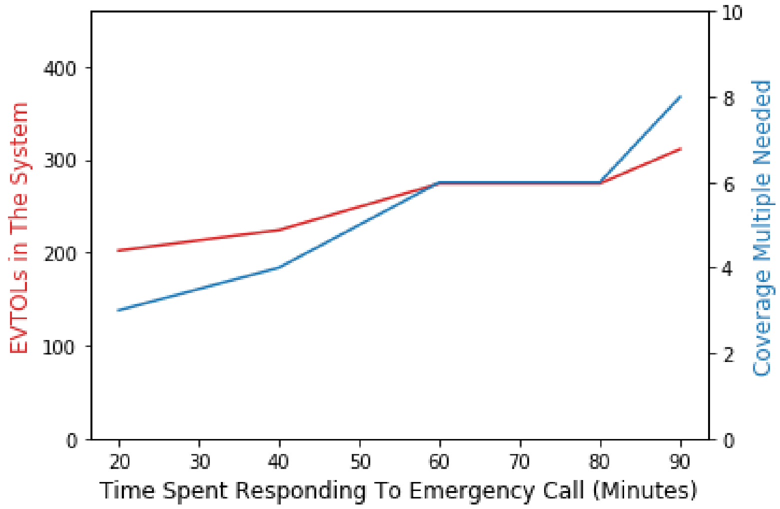

Figure 4.5: Simulation of Different Time Intervals Needed for Rescue Operation

the respective lengths. The previous result is mainly due to the fact that the required amount of eVTOLs plateaus at the value of 274 from the values of 60 to 80 minutes per flight. Therefore, the result of coverage multiple of 6, stated before as the base case, gives space to 20 minutes per flight, whole 1/3 of the expected flight time, which the system can use as a buffer in case of unexpected circumstances or delays during the mission.

4.3.4 Number of People Per Ambulance

The international standard of one vehicle servicing around 50,000 people was developed for the usage of ground ambulances. Therefore, this rule of thumb is another perfect candidate for the perturbation and is tried with different values of 30, 40, 50, 55, 60, 70 and 80 thousand potential demand points per one ambulance vehicle. The simulation is run by first rerunning the optimization algorithm with the values stated before used as θ in the left side of Equation 3.11. Then, the result of the optimization, being the number of eVTOLs, is written down and the simulation of the 300 days of emergency calls is run. The resulting percentage of failures to respond to the calls by dispatching one of the eVTOLs is registered. The result can be seen in Figure 4.6.

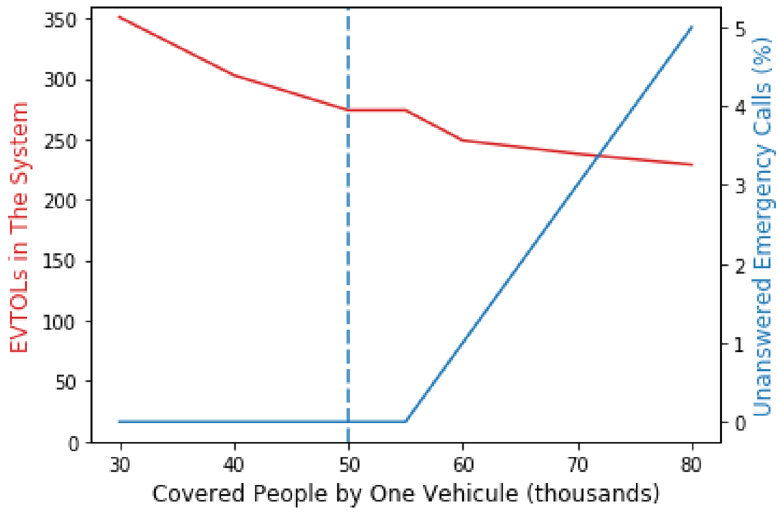

Figure 4.6: Simulation of Different People Per Ambulance Vehicle Ratios

The results show the expected increase in the failure rate, beginning at 60,000 people covered by one ambulance vehicle, from none to approximately 5% connected to the decrease of the number of eVTOLs in the system. Also, the figure clearly shows that more stringent rulers are not necessary as the number of failed responses falls down to zero well before the 50,000 mark, which is the base case scenario. The most interesting results nevertheless, is the plateau of 274 eVTOLs needed for both the 50,000 and 55,000 potential patients per vehicle. In the setting of the study, this result shows that the whole system again provides some space to operate in in terms of the population. Even with the increase of 10% of the total population of New Zealand (the country's annual population growth is estimated to be between

1.4-2.0% [21]) the proposed system would be able to maintain its functionality. Therefore, even multiple years after its launch, the system would not have to be reconfigured due to the population growth.

4.3.5 Number of Emergency Calls

Another very significant assumption made in the study is the amount of emergency calls occurring every day. As the data for New Zealand were taken to come up with the amount and distribution of the calls, the approximation should be very reliable, nevertheless the stress test for the amount of calls is more than appropriate at this point. Therefore, the amounts going from 500 to twice times the average demand (1,400 calls per day) with the same distribution is tested as well as how would the system perform in case of a massive emergency. The last scenario is modeled as a very high demand in two separate parts of the day. All three distributions of the calls (one for normal demand on the left side and two for morning extreme and evening extreme demand on the right side) can be seen in Figure 4.8. The scenario on the right is very likely to occur in the case of a natural disaster or a massive highway car crash.

The simulation is run by multiplying the base case demand distribution 4.1 by factors of 0.5, 1, 1.25, 1.5 and 2 in the first part, then the optimization model is rerun and the optimal coverage multiple with which all the calls are satisfied is found by putting it into the 300 days simulation. For the extreme demand scenarios, that are the focus of the second part, distributions according to the right side of Figure 4.8 are run for the base case scenario of 274 eVTOLs (coverage multiple of 6). In the morning extreme scenario, the demand for 6 hours is increased from 18 to 54 calls per hour. In the evening extreme scenario, the already high demand is for 6 hours increased from 42 to 60 call per hour.

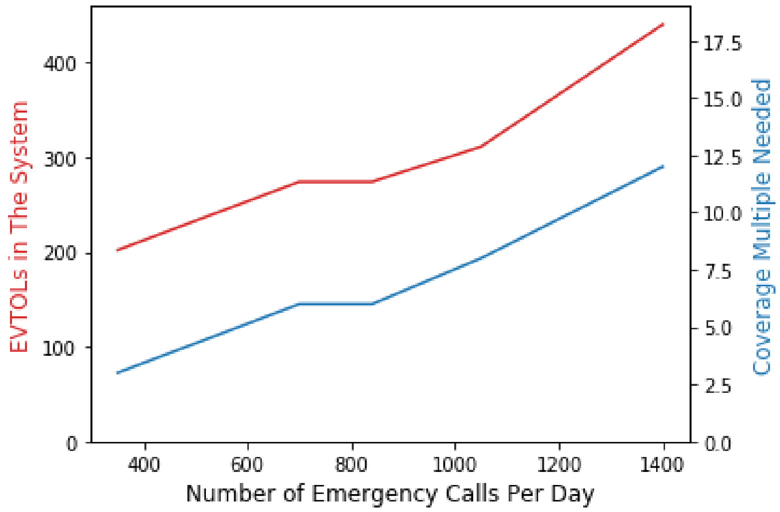

Figure 4.7: Simulation of Different Demands per Hour

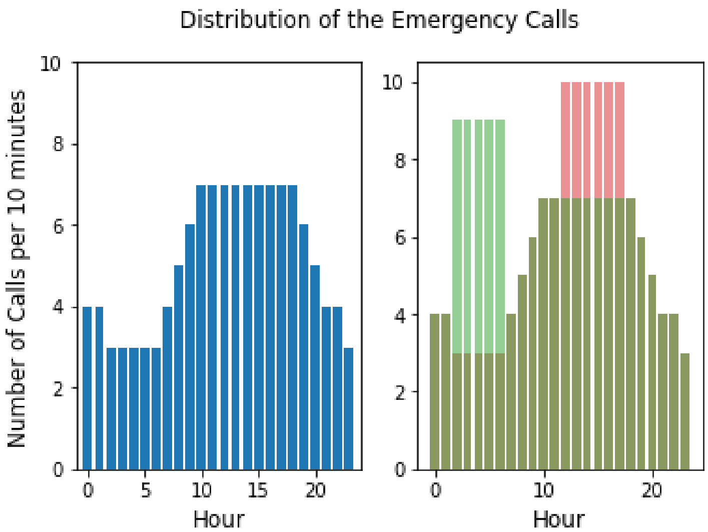

Figure 4.8: Simulation of Two Different Extreme Scenarios of Emergency Calls Distribution

The Figure 4.7 showing different amount of demands (multiples of the demand distributed according to the distribution 4.1) shows the increased number of eVTOLs needed to satisfy the increasing demand according to expectations. With the four times increased demand (from 350 calls to 1,400), the number of needed eVTOLs increases approximately twice (from 202 to 440). The most interesting part is again the plateau occurring from 700 until 850 calls per day. Again, this plateau is the result of the previously seen buffer the solution of coverage multiple of 6 the optimization has. Even if the demand increased from today's average by more than 20% the system would still be able to respond and address all the emergency calls in order. This result is another proof of the strength of the found solution used as the base case of 274 eVTOLs dispersed over 34 ambulance stations.

Lastly, in the test performed with two extreme scenarios of morning and evening raised demand shown in the right side of the Figure 4.8, the model of the base case scenario was able to perform without a single missed can on both scenarios. Therefore, it is not only able to absorb a uniformly increased workload spread out throughout the day, but also one time massive increases in the demand needed in states such as natural disasters or terrorist attacks.

4.4 Costs Cut and Lives Saved

This part is divided into two parts, costs reduction part and lives saved benefits. In the end, those two statistics are combined together to form the final opinion. Three different scenarios for each of the parts is presented. Scenario one called "Keeping Ground Ambulances" reflexes a situation when the country would decide against investing into the new technology. Furthermore, scenario two called "Mixed Scenario" reflexes a situation when the country would decide to implement a mixed strategy of partially servicing by ground ambulances and partially by eVTOLs. Finally, the third scenario called "eVTOLs Shift" counts with full shift from using ground ambulances to eVTOLs.

4.4.1 Reducing the Costs

First, concerning costs, few assumptions in Figure 4.2 from publicly available data were made. Cost per Trip was taken from [17] and involves all variable costs such as personnel, maintenance and depreciation. The amount of the vehicles needed for ground ambulance and helicopters is the current status on New Zealand and the number of eVTOLs is the result of the optimization with the base case of coverage multiple of 6.

Vehicle Type	Ground Ambulance	eVTOL	Helicopter
Price ($)	150,000	250,000	4,000,000
Life-span (years)	10	10	20
Cost per Trip ($)	1,000	350	10,000
Amount needed	700	274	10

Table 4.2: Assumptions on vehicle costs

Furthermore, the number of vehicles in each particular category for the next 10 years was projected for every scenario. Through the number of vehicles, as costs are per trip basis, number of trips with the individual types of ambulances was projected for years between 2020 and 2029 for the three scenarios. For the Mixed Scenario, number of trips on ground versus in the air was set to approximately 2:1. Also, for Mixed and eVTOL Shift Scenarios, approximately 50% of the air traffic currently serviced by the helicopter were shifted to the eVTOLs leaving the helicopters to serve only the most problematic locations and cases. The main assumption that need mentioning is that there was a projected increase in the number of emergency calls was set proportional to the growth of the population of New Zealand.

As the final step of the costs calculation part, the projected expenses for each of the three scenarios were calculated for the following periods until 2029. To sum up, the main variables taken into the account were the cost per trip for the different vehicle types comprising of all the variable costs, and new capital expenditures such as renewing of the fleet of vehicles and buying new ones to meet the increasing demand with population growth.

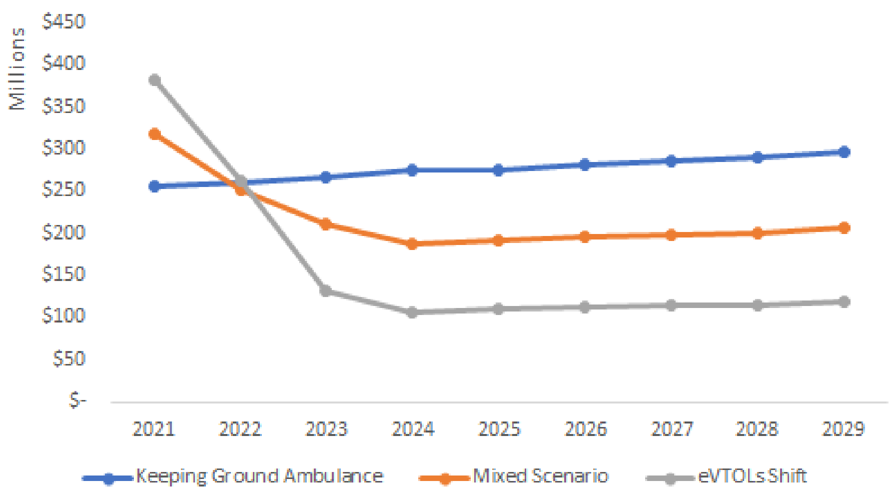

Figure 4.9: Costs scenarios for the three studied options

For the Keeping Ground Ambulance scenario, the annual costs of the Ambulance services are growing slowly to approximately $300 million in the year 2029. The main cost driver under this scenario is the extremely high average price per ride due to under-utilization of the individual vehicles especially in the rural areas. The country would have approximately one ambulance car per emergency call per day, after considering the bigger cities where the demand per vehicle is significantly higher, the result for rural areas is less than one emergency call per car in 2-3 days. Therefore, the price for the actual service includes 3 days of salaries for the whole crew, maintenance of the vehicles and other overheads and therefore climbs steeply.

For the Mixed scenario, the annual costs climb to approximately 2/3 of the first scenario thanks to the mix of the two technologies and simultaneous usage of eVTOLs and Ambulances. The Figure 4.9 shows the initial needed investment for reorganize the some of the stations and re-purpose them for the eVTOLs usage. The ideal combination in this case would be the usage of eVTOLs especially in less populated areas, exactly at places with the highest costs per ride, where empty spaces around the medical centers could be re-purposed and the costs of transforming the station would also significantly decline.

For the eVTOLs Shift scenario, The initial investment would include transforming the picked 34 ambulance sites into sites able of dispatching and receiving eVTOLs, Which is also projected in the Figure 4.9. For the restructuring purposes, almost $190 million over a period of two years was used in the estimation. After the initial two-year investment, the annual costs would be 1/3 of the first scenario, which means that going into a full-eVTOLs model with the layout of the ambulances proposed by the optimization algorithm would cut the budget needed for running the ambulance services to one third.

4.4.2 Saving the Lives

In the end, we will have a look at what would the transition from ground ambulance to eVTOLs mean in terms of saving lives of the patients. According to [36], around 1,600 people pass away yearly due in New Zealand (population of only 4.86 million) alone due to out-of-hospital cardiac arrests that cause around 82% of all the out-of-hospital deaths in the country. As the [17] claim that with the reduction of arrival times using eVTOLs, it is possible to increase the survival rate by 10% we get to approximately 160 lives saved. With the average life expectancy of 82 years and GDP of $42.46 thousand, if we assume that the person that suffers the heart attack has another 20 years to live if saved, we get to $140 million that the yearly saved people will contribute to the country after saving. Therefore, with only taking the improvement of this one disease as an example, the country would be able to repay its annual costs for running of the eVTOLs ambulance system.

Chapter 5

Discussion

The main aim of this thesis was the optimization of the location and the number of ambulances used in the New Zealand emergency calls respond system. The costs and benefits analysis as well as the simulation of the system were mainly performed to justify and prove the functioning of the found optimization solution.

First, the DSM model was found inefficient for the studied care. The main reason is the increased range of the maximal distance covered by each of the ambulance sites because the diameters of the individual stations start overlaying each other even on vast territories and therefore, system with higher coverage multiple is needed. As we saw the proposed 6-fold coverage works very well in this case. This proposed change is inevitable as the previous theory was based of ground technology with much more restricted space of reach.

The simulation proved many interesting points, mainly the fact that the system with 274 eVTOL vehicles would be able to function even under stronger perturbation of the input parameters such as the daily demand, number of people on the islands and length of the missions. Also, when higher coverage multiple was needed under larger increase of the value of parameters, the solution still remained on the 34 ambulance location sites, only more vehicles were added to each of the site which would help the actual execution of the newly proposed strategy.

Result of the cost analysis show a clear superiority of the proposed new solution to both partial switch to the new technology and keeping the current system. The hybrid system with split between the classical ambulance and the eVTOLs nevertheless seems the most probable option as the full transition would for sure be difficult to push through the government. But even the partial solution would be able to save approximately one third of the costs the system is now facing. Therefore, the new eVTOL solution, in any form, proves to be a technology challenging the status-quo.

When taking into the account the current situation in New Zealand, this solution would provide multiple improvements. First, the country would be able to relax its now very tight budget on the ambulance system, where the passenger have to cover a past of the cost of each ride and the rest of the funding comes from a combination of donations and government funding. Second, the system would enable more centralized health care with higher utilization of medical professionals being concentrated in fewer locations and therefore have a better access to equipment and knowledge.

Chapter 6

Conclusions

Because the whole eVTOL industry is so far in early stage of development, most of the research is focused on the technology itself more than the applications. Nevertheless, the eVTOLs technology is emerging from the shadows of the start-ups world into the spotlight of international interest thanks to massive funding that is being poured into the idea. The involvement of some of the biggest transportation companies sped up the process and first fully autonomous flights have already taken place last year. Up until now, most of the theoretical work on the usefulness of the new emerging eVTOL technology was focused on its usage for air taxi and shuttle purposes. Most of the literature regarding the aerial usage of autonomous technology for healthcare purposes is so far focusing on light delivery drones that are more technologically advanced and we have already seen commercial applications in the past few years. Therefore, it is time to develop the knowledge that will help to put the eVTOL technology into one of the biggest short range aerial industries of today, into healthcare practice, which is the exact aim of this thesis.

After thorough study of the methods of location optimization of ground ambulances a Double Standard model, aiming at covering each demand point with two ambulance vehicles, was used at the beginning. The DSM model was later re-specified as for this new type of the technology with much larger potential distance coverage and larger concentration of the ambulances at fewer ambulance hubs, the final model used introduces a coverage multiple of 6 for every potential demand point. This newly proposed model is able to reduce the amount of ambulances used from the current 700 ground ambulances at approximately 400 different spots to 34 ambulance sites around the country with 274 eVTOL vehicles. This improvement of the original model shows the need of currently updating the state-of-art models used under the new technologies.

This proposed change was tested through simulation of a year long operations with various parameters and a few properties worth mentioning were found. First, this proposed ambulance layout is able to still cover all of the country's demand even with 10% increase in population or during events such as natural disasters or terrorist attacks. Second even under variation of time missions and delays of up to 1/3 of the average of on each mission, the system still works as intended. Third, when deploying such a fast changing technology, it is interesting to see if the system will not be obsolete in few years time, but as was studied in the simulation, even with substantial increase of reach of the eVTOLs, the proposed layout of the stations remains ideal.

As the ambulance needs to work efficiently due to funding challenges, the costs and benefits analysis had to be performed to understand the viability. The findings indicate that after a substantial initial investment that nevertheless could be cover by selling the abundant real-estate and vehicles that will no longer be used, the annual costs for such a proposed eVTOls system would be three times lower than the current state (the annual costs would drop from $300 million to $100 million). The decrease is caused by enormous increase in the usage effectiveness of the system where now some of the ambulances are being used more than sporadically. The per-trip costs would drop from $660 to $240. Also, the system would be able to save life worth more than $140 million annually which makes the proposition even more interesting.

When it comes to the limitations of the study, there are few things to consider. The technology is still in its infancy and therefore all of the financial projections are more of a ballpark estimate and will need to be specified as the technology progresses. Also, it terms of the optimization model itself some simplifications regarding the populations were many in order to reduce computational complexity. The potential demand points, that would need to be taken more accurately before the final decision is made, were aggregated into bigger areas. Furthermore, with the new technology proposed, significant changes would have to be made in the infrastructure of the ambulance stations, mainly the ones in bigger cities. This topic is nevertheless beyond the scope of the thesis. Also, as approximately 20,000 were deducted from the study simply because any of the current potential ambulance spots was not able to provide the coverage due to vast distances, another ambulances would have to be added newly specificaly for those places.

Overall, the proposed structure of the ambulance system in New Zealand would therefore bring many improvements in terms of duration of the responses to emergency calls, costs of the ambulance and lives saved. In terms of the theory, the work revealed the inefficiencies of the model used for previous technology and proposed a way how to improve the constrain optimization problem at hand.

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