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ORIGINAL PAPER

ENHANCING VACCINE DISTRIBUTION EFFICIENCY IN SRI LANKA'S COLD CHAIN THROUGH UNMANNED AERIAL SYSTEMS: A DISTRICT-BASED APPROACH

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ABSTRACT. Background: With their high speed and low response time, unmanned aerial vehicles (UAVs) have been suggested as a solution to overcome the systematic inefficiencies in the current vaccine cold chain of Sri Lanka. The implementation of unmanned aerial systems (UASs) at the district level is recommended to maintain the end-to-end effectiveness of the program. Under the suggested distribution network, vaccines are transported directly from the Regional Medical Supplies Division (RMSD) warehouse to the respective health facilities, bypassing the Medical Officer of Health (MOH) unit warehouse. However, the use of UAVs is not appropriate in every RMSD due to the high fixed cost of a UAS.

Methods: To determine an appropriate division, a suitability analysis was conducted by intersecting eight factors with their weights of importance. Suitable factors were determined using previous literature and weights of importance were calculated by an expert survey.

Results: From the analysis, it was determined that the Kurunegala division is the most appropriate for UAV implementation. Therefore, Kurunegala is recommended as a starting point for the implementation of the proposed UAV-inclusive delivery system in Sri Lanka to realize its potential benefits and practical implications. Furthermore, it was found that a uniform solution involving only UAVs offers greater advantages compared to a mixed solution involving both trucks and UAVs. Nonetheless, owing to limited technological expertise and resistance to change in low-income nations, it is advisable to begin with a mixed approach and gradually transition to a uniform strategy in the coming years.

Conclusions: The newly developed random search algorithm for the cyclic delivery synchronization problem gives results that are close to those obtained with mixed-integer programming. The main advantage of the algorithm is the reduction in computing time, which is relevant to the utilization of this method in practice, especially for larger problems.

Keywords: Vaccine delivery; Cold chain; Last Mile Delivery; UAV; Vehicle routing problem

INTRODUCTION

The Expanded Program on Immunization (EPI) has been the main component of the National Immunization Program since its implementation in 1978 [Jayasekara et al., 2016]. The program ensures the availability of routinely recommended vaccines to mothers and infants to prevent infectious diseases. Currently, Sri Lanka has more than 90% coverage in all vaccines under the program [Organization, 2021]. But the vaccine supply chain is suffering from issues in the distribution system, causing major cost increases and soaring wastage and consuming a great deal of time [Bank, 2001]. The complete reliance on the road network and the persisting issues in the cold chain are the main sources of these inefficiencies. A "cold chain" is a temperature-controlled supply chain used to maintain the integrity of perishable products like food, vaccines, and pharmaceuticals [Sripada et al., 2023].

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The continuous expansion of the vaccination program and the above-mentioned issues in the delivery network threaten the sustainability of the vaccination program. They not only burden the government with extreme costs but also endanger the quality of life of citizens. According to expert interviews, amidst the noticeable problem areas in the EPI program, the country has continued to execute the traditional delivery system with little to no technological advancements. Therefore, now is an appropriate time to identify technological improvements that may help reduce inefficiencies.

In the ongoing journey of development to find solutions and reduce inadequacies, UAVs are an effective way to overcome the physical and economic impediments in delivery networks [Haidari et al., 2016; Wurbel, 2017]. Previous studies have demonstrated the potential of UAVs to improve healthcare availability and deliver healthcare products to otherwise unreachable locations such as islands, swamps, or deserts [Haidari et al., 2016; Wright et al., 2018; Wurbel, 2017]. Additionally, UAVs have proven to be capable of successfully delivering small weights whilst ensuring reduced financial, environmental, and social impact [Borghetti et al., 2022; Zubin et al., 2020].

E-commerce and retail companies are seeking ways to cut delivery times and costs by exploring opportunities to use UAVs for last mile deliveries [Kitjacharoenchai & Lee, 2019]. Therefore, a replacement delivery network incorporating UAVs is proposed for Sri Lanka to overcome the issues in vaccine distribution. In this context, this research addresses the concept of a combined truck-UAV delivery network along with the idea of allowing autonomous UAVs to fly from delivery trucks, make deliveries, and fly back to delivery trucks nearby.

The implementation of a nationwide UAV delivery network would face challenges due to high fixed costs and technical limitations. To overcome this, it is crucial to identify the locations that would benefit the most from a UAV distribution system. This study focuses on assessing the suitability of local RMSDs for UAV implementation, providing a decision support tool for the initiation of such systems. The research aims to guide future studies on UAVs in healthcare logistics in Sri Lanka, addressing limitations and suggesting research trajectories. Through expert interviews and a literature review, a model for UAV execution in the Sri Lankan vaccine cold chain was identified, with a factor analysis determining the ideal implementation location.

In the section following the introduction, background information on Sri Lanka's vaccine cold chain is presented. In the next section, previous studies are presented in a literature review. The problem formulation and methodology implemented are elaborated in the fourth section. In the fifth and six parts, the processes of factor normalization and factor processing are presented. The next two sections are devoted to choosing the best division and delivery network design respectively. The last section summarizes the results obtained and presents suggestions for future research.

BACKGROUND

Sri Lanka vaccine cold chain. The EPI program is the fundamental component of the National Immunization Program [Amarasinghe & Ginige, 2016]. The primary purpose of the program is to reduce mortality associated with vaccine-preventable diseases [Amarasinghe & Ginige, 2016]. Accordingly, the program targets children (below 12 years of age), pregnant mothers, and females of childbearing age as the population categories for vaccine administration [Amarasinghe & Ginige, 2016]. Vaccine importation and distribution are complicated due to the value and sensitivity of vaccines. The Medical Supplies Division oversees vaccine imports for the EPI schedule's uninterrupted maintenance [Amarasinghe & Ginige, 2016]. Convoluted and strict financial guidelines and tender procedures maintain the quality of the vials imported. Even though the process is time-consuming, this ensures the transparency as well as the satisfactory condition of the vials [Amarasinghe & Ginige, 2016]. The imported vials are then transported to the Central Vaccine Store in Colombo to be distributed island-wide. Once they have arrived, the Epidemiology Unit assumes responsibility for the effective island-wide distribution of vaccines [Bank, 2001].

A four-tier administrative system is pivotal in the nationwide distribution of vaccines, facilitating efficient healthcare services. This decentralized structure, complemented by healthcare regulations, ensures primary healthcare access, even in remote areas. The system operates through an extensive network, making healthcare, including vaccines, widely accessible. Public healthcare, following this system, relies on each tier for proper vaccine storage and distribution. The Central Vaccine Store, housing a six-month vaccine stock, dispatches supplies to 26 RMSD warehouses every two months. Each district has one RMSD warehouse – except Kaluthara, which has two. These warehouses then distribute vaccines to MOH units within their jurisdiction, maintaining a four-month stock for timely replenishment. The number of MOH units served varies based on population density, ranging from five to twenty-three units per RMSD. Refer to Fig 1 for a visual representation of this administrative system within the vaccine cold chain [Amarasinghe & Ginige, 2016].

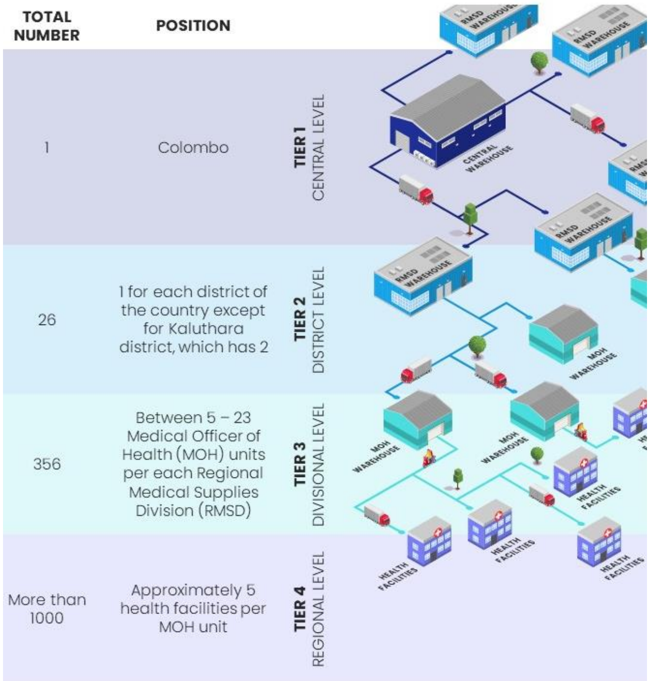

Fig. 1 Administrative Levels in the Sri Lankan Cold Chain

The healthcare system's vaccine distribution entails a four-tier process, starting at the MOH warehouse and reaching hospitals and MCH clinics. Limited vaccine storage in hospitals and coordination challenges in MCH clinics create distribution efficiency problems despite the push-based system achieving high population coverage.

Issues in the cold chain of Sri Lanka. The central cold room complex efficiently manages vaccine storage and distribution, utilizing modern temperature control and reefer trucks for delivery to twenty-six RMSD warehouses. Delivery to main towns via class A roads minimizes disruptions. However, at the district and divisional levels, challenges arise with high costs, time-consuming processes, and wastage [Bank, 2001].

Sri Lanka's road network, though dense, scores 3.9 in quality, below the global average of 4.07. Only 40% of the total length of the road network consists of Class A or B roads or expressways, with the rest being Class C or D roads, mainly in rural areas. Class C roads, suited for one vehicle, are agricultural and local, while Class D roads, graveled and weather-dependent, are less accessible. The primary roads link major cities, causing congestion, while distribution in rural regions relies on Class C and D roads. The challenging terrain exacerbates the transportation challenge, affecting overall road network effectiveness.

Sri Lanka's diverse topography, ranging from plains to mountains in a compact space, poses challenges for efficient deliveries. With 78% of the population based in rural areas with subpar infrastructure, vehicles often face damage and high fuel consumption. Given the sensitivity of vaccine vials to temperature and shaking, swift and careful delivery is imperative in this context.

While these issues pose challenges in rural areas, urban and suburban areas suffer from heavy traffic congestion. This has hindered the maintenance of a reliable and dependable delivery network in urban areas. Furthermore, due to the annual monsoon season, certain areas in Sri Lanka are often flooded and face crises due to landslides [De Alwis & Noy, 2019]. Some areas often become temporarily inaccessible, challenging the continuous supply of vaccines [Dilhani & Jayaweera, 2016]. This not only hinders the reliable delivery of vaccines but also endangers people's health. The issues in the cold chain further add to the problems caused by the poor road network.

The central level boasts robust cold storage facilities and reefer trucks for bulk vaccine delivery via main roads, ensuring vial quality. However, district and divisional levels rely on aging trucks, leading to frequent breakdowns, vehicle rentals, and subpar temperature control using cool boxes and ice packs. Small loads also hinder truck efficiency, with a larger number of trucks exacerbating fuel and labor costs. Addressing these issues is crucial for an efficient vaccine distribution system.

Moreover, the high number of employees in the healthcare system is also a major factor contributing to higher costs. Nevertheless, considering the repetitive work and multiple distribution rounds, the employment of a large number of workers is inevitable. In fact, employee salaries are the second highest cost in the district level network, only exceeded by the vaccine purchase cost [Jayasekara et al., 2016]. According to expert interviews, the distribution process takes longer than required due to long lunch and tea breaks necessitated by the high level of human intervention in the delivery network. When such problems pile up, huge inefficiencies and a substantial waste of resources can be observed in the cold chain network.

Considering the cold chain in its entirety, it is evident that the last miles are the problematic areas which require improvements and solutions. The poor road quality, difficult terrain, urban traffic conditions, and high number of employees result in considerable delays and high fuel consumption per delivery round [Bank, 2001; Jayasekara et al., 2016]. Furthermore, the reliance on the road network along with poor cold chain equipment (CCE) result in high wastage of vials [Bank, 2001]. This results in a costly logistics network with limited efficiency. Considering the huge financial burden upon the government to continuously provide free healthcare services, reducing these inefficiencies would aid immensely. In fact, securing finances for vaccine purchasing is one of the main challenges in the National Immunization Program [Gamage, Kapuge & Abeysinghe, 2021]. Efficient vaccine delivery networks can save government funds, enabling more to be spent on vaccine purchases. Decentralized administration leads to repetitive tasks and higher maintenance costs. Despite expert advice, traditional methods persist without technological upgrades, highlighting the need for advancements to address inefficiencies and enable the delivery network to remain globally competitive.

The ever-growing technology industry has continued to impress the world with new and innovative technological solutions for many problems. Transportation and delivery are two areas in which the technology industry has continued to invent novel and impressive solutions. Among many inventions, UAVs or drones for delivery are one of the most significant. Their use has been piloted in the healthcare field and has successfully provided solutions to pressing problems [Wright et al., 2018]. Hence, they are suggested as a possible solution to the problem of inefficiencies in the Sri Lankan cold chain.

Delivery using UAVs in healthcare. The central cold room complex ensures optimal temperature control for vaccines and accommodates an expanding schedule. Reefer trucks facilitate vaccine delivery to 26 warehouses, maintaining quality. Utilizing major roads from Colombo to district towns minimizes disruptions in the central delivery network. On the contrary, district and divisional level networks struggle with soaring costs, time-consuming processes and excessive wastage [Bank, 2001]. In fact, 64% and 30% of a vaccine’s direct costs come from the divisional level and district levels respectively, while the central level only accounts for 6% [Jayasekara et al., 2016]. One of the main causes of such inadequacies in the last mile of the network is the complete reliance on the road network.

Among the many public use cases of UAVs in delivery, its adoption in the healthcare field is one of the most promising applications. Universal access to proper healthcare is a basic human right, emphasizing its importance to quality of life. But many physical and economic impediments, such as expensive operational and fixed costs, improper infrastructure, and natural barriers, limit the widespread availability of quality healthcare [Moshref-Javadi & Winkenbach, 2021; Wurbel, 2017]. In the context of the continuing adoption of technology to find solutions and reduce inefficiencies, UAVs have proven to offer effective solutions to the above-mentioned challenges. The faster and more efficient healthcare delivery they can provide will not only improve people’s quality of life but also help healthcare suppliers to further expand their services [Wurbel, 2017].

Evidently, vaccines, emergency kits, organs, blood, and laboratory samples are all healthcare products that could be delivered by UAV. Their capacity to respond quickly, high speed and lack of dependence on physical infrastructure have made UAVs immensely popular in emergency situations [Johnson et al., 2021]. UAV applications in disaster relief campaigns in Haiti and Taiwan after the 2010 and 2016 earthquakes and emergency blood or anti-venom dose delivery are recent examples [20]. Over the years, their application in the routine delivery of medical items has also become more common, not only because the large number of flights that can be made defrays the initial set-up cost but also because they improve health coverage, providing a better service in the medical field [Wright et al., 2018; Peter et al., 2023].

However, within the healthcare system UAVs only offer advantages over existing delivery networks in selected scenarios, such as just-in-time delivery of emergency medicine, the collection of time-sensitive lab samples, the routine resupply of high-cost items, and vaccine delivery for better cold chain control [Wright et al., 2018]. This is because the success of UAVs in delivery is dependent on the number of flights, the product parameters (such as weight and volume), and the importance of UAV value addition [Wright et al., 2018]. Identifying the right applications is thus important, and when the technology is properly applied, major benefits can be realized.

PROBLEM FORMULATION AND METHODOLOGY

The Sri Lankan cold chain is an ideal use case for UAV implementation considering the existing issues hindering the routine supply of important and costly vaccines [Gunaratne et al., 2022; Wright et al., 2018]. However, using UAVs at the central level wouldn’t yield many benefits because of the considerable availability of CCE and the use of main roads. In contrast, the district and regional levels are more suitable targets for UAV adoption considering the severity of logistical issues. As a rule of thumb, it is crucial to identify applications that will yield benefits in end-to-end delivery rather than over a portion of the network [Wright et al., 2018]. To achieve this, the implementation of Unmanned Aerial Systems (UAS) at the district level for direct vaccine transfer from the RMSD warehouse to health facilities, bypassing MOH unit warehouses, is recommended. This would streamline delivery, cutting the need for excessive resources, reducing wastage, and maintaining an efficient end-to-end program. The suggested novel delivery network is illustrated in Fig. 2.

Fig. 2. Scheme of a network where synchronization of cyclic deliveries to logistic centers is needed.

The proposed system excludes the MOH warehouse but maintains divisional levels of administration. Due to high fixed costs and technical constraints, implementing UAV delivery networks in all 26 RMSDs would be challenging. To address this, the RMSDs should be ranked based on the potential economic benefits a UAV-based last-mile vaccine delivery system would offer them, and the RMSD that would benefit most should be prioritized.

Methodology. A suitability analysis was conducted to rank the RMSDs based on the value addition of a UAV distribution network [Berninzon & Vongasemjit, 2021]. Suitability analysis is a decision support tool that is used to evaluate the appropriateness of a location for a certain use and is conducted by intersecting social, ecological, economic, physical, biological, or other criteria [Helmut Flitter, Patrick Laube, Patrick luscher, Stephanie Rogers, 2013]. The technique is often used to support decisions in a planning process, most often to identify a suitable spot for a certain objective [Flitter et al., 2013]. In this phase, the objective is to identify locations that are most in need of a UAV distribution network. Therefore, the appropriateness of RMSDs for UAV implementation is identified by intersecting factors that reflect the value addition the UAVs can provide.

The WLC method incorporated into this research is similar to that used in Berninzon & Vongasemjit [2021], who identified suitable districts for UAV implementation in Nepal. In this method, a set of criteria are identified that can be used to measure or determine the purpose. Assuming the criteria have a linear influence on the purpose, weights of importance of each of the criteria are determined. This results in a linear combination of criteria, yielding a numerical result that represents the purpose. Hence the suitability of each alternative for the purpose can be calculated. The adaptation of the said WLC method in this study consisted of four steps, as explained below [Flitter et al., 2013].

Factor identification. As mentioned above, the objective of the analysis was to identify the locations most in need of a UAV distribution network. In this step, criteria to determine the extent of the value addition UAVs could offer over the existing delivery network were identified. The criteria that were used had to measure value addition along with comparability to contrast the alternatives. According to Wright et al. [2018], there are three parameters an analysis should take into account when determining whether a UAV-inclusive delivery network can offer benefits over an existing delivery network: UAS characteristics, geography and product.

When it comes to UAV characteristics, identifying the most suitable UAV type and characteristics (such as vertical take-off capability, energy source, payload and range) is crucial to gain the maximum benefit [Wright et al., 2018]. To explain the statement further, if the use case is to deliver vaccine vials, using a UAV which can carry 100kg would be associated with disadvantages, because the UAV capacity wouldn’t be optimally utilized and there would be unnecessary fuel and maintenance costs. However, in our analysis the UAV characteristics were common to all RMSDs. Therefore, while UAV characteristics are a crucial parameter to realize maximum benefits, they cannot be used to contrast the value addition amongst the RMSDs. Thus, UAV characteristics was not used as a criterion in this analysis. Instead, geographic and product parameters were utilized. To represent the product parameters, demand was considered. And to represent the geographic parameters, accessibility and road network quality aspects were utilized. Furthermore, since the suitability analysis was focused on logistics, a third parameter, namely Supply Chain, was identified using previous literature [Berninzon & Vongasemjit, 2021; Kawa & Golinska, 2010; Golinska & Hajdul; Ikram et al 2022]. In all, eight factors were realized under the four aspects, as described below.

Demand factors: Characteristics of the cargo and demand patterns influence UAV value addition [Wright et al., 2018]. Nevertheless, since the type of product is common to all divisions, product factors such as financial value, health value, and shelf life cannot be used to compare division suitability. Instead, the level of demand was considered a significant factor. The level of demand has a positive impact on UAV implementation because more demand requires faster supply [Berninzon & Vongasemjit, 2021].

Accessibility factors: The extent of accessibility to healthcare centers also reflects the suitability and value addition UAVs can offer in a given location [Wright et al., 2018]. To represent accessibility, road density and average elevation were considered as factors. Road density represents the total length in kilometers of the road network within one square kilometer. The lower the road density, the more difficult it is to access health centers, resulting in better value addition from UAV implementation. Meanwhile, the average elevation represents the topographical condition of the area. Higher average elevation indicates that an area is more mountainous, causing transportation difficulties when roads are used. Therefore, higher average elevation suggests better value addition from a UAS, because UAVs can cruise faster and more easily in difficult terrain.

Road network quality factors: UAVs' lack of reliance on the road infrastructure brings benefits over a delivery system using a low-quality road network. To represent the quality of the road network within each division, class D road density and the number of damaged roads were used as factors. Class D road density (gravel roads that are usually usable during dry weather only) denotes the number of kilometers of class D road in one square kilometer [Lanka, 2019]. Further, the number of damaged buildings reflects the damage to critical infrastructure within the division due to environmental disasters. Higher values of the above parameters suggest better value addition from UAVs due to their lack of road dependency.

Supply chain factors: Health facility density, vehicle density, and area of service were considered as supply chain factors. Health facility density represents the number of health facilities available in one square kilometer. The lower the health facility density, the further apart the facilities are located, increasing delivery problems. UAVs offer more benefits in such circumstances [Wright et al., 2018]. Since all rural and urban districts were considered in our research, vehicle density had to be included as a factor to reflect the traffic conditions. Finally, the area of service also influences the benefits that can be gained from UAV implementation. If the service area is larger, the fuel cost and journey time are higher when trucks are used, suggesting that UAV usage is more appropriate.

FACTOR NORMALIZATON

Each of the criteria identified above was measured and represented in different units and value ranges. For example, the average elevation was measured in hundreds, whereas the target number of doses criteria was measured in thousands. If such different criteria with values in different ranges are considered together, the criteria with high value ranges have an inordinately high influence on the ultimate result. This influence is not scientifically derived, hence creates a bias, resulting in inaccuracies and errors. Therefore, the values in all the criteria considered for the WLC had to be normalized to a common scale [Berninzon & Vongasemjit, 2021]. This means adjusting values measured using different scales to the same scale [Sinsomboonthong, 2022].

The literature suggests several statistical techniques that can be used to normalize values to a common scale. The statistical column, decimal scaling, adjusted decimal scaling and min-max methods are better methods as suggested by literature [Aksu et al., 2019; Ali &

Senan, 2017]. In this analysis, the min-max method was utilized for normalization, because it is a widely used technique for similar normalizations, and it returns better results compared to other methods when explaining variance [Aksu et al., 2019]. The min-max method allows the user to adjust the values to a scale of choice by allocating the maximum and minimum value as desired. The most common scale used to normalize is zero to ten. However, in this study values were normalized on a scale of one (least suitable) to ten (most suitable), because this allowed all the criteria to be represented in the final suitability score of the divisions. Otherwise, the lowest value would have been allocated zero on the normalized scale, removing it from the final score completely. Hence, the normalized values on a scale of one to ten were calculated using eq.(1).

$$N = c + ((X - Min) \times (d - c)/(Max - Min)) \tag{1}$$

N - Normalized value
X - Current value
c - Minimum value of the normalized scale
d - Maximum value of the normalized scale
Min - Minimum value in the existing value range
Max - Maximum value in the existing value range

Among the eight factors used in this research, health facility density and road density have an inversely proportional influence on suitability. Therefore, before normalizing, these two factors were converted to their negative form to reverse their effect on the scale.

FACTOR PROCESSING

Factor weight calculation. When the criteria identified previously are utilized to determine the suitability of a region for UAV implementation, it is vital to determine their individual weights of importance [Berninzon & Vongasemjit, 2021]. The reasoning for this statement is that the influence of each criterion on the area's suitability is different. Some criteria have more of an influence on UAV implementation, while other criteria do not have a significant influence. Three techniques have been used to calculate the weights of criteria in previous literature, namely weighting by ranking, weighting by rating and weighting by pairwise comparison. As the names themselves suggest, these methods derive weights using allocated ranks, rates and pairwise comparison respectively. Among the three methods, weighting by ranking was selected for this analysis, due to its leniency and suitability to small numbers of criteria [Helmut Flitter, Patrick Laube, Patrick luscher, Stephanie Rogers, 2013].

In the weighting by ranking method, weights of importance are determined using designated ascending or descending ranks. Accordingly, the factors first need to be ranked, assigning 1 to the most important factor, 2 to the second most important factor, etc. [Flitter et al., 2013]. To assign accurate ranks, individuals with a clear rationale on the subject are required [Berninzon & Vongasemjit, 2021]. Therefore, an expert survey was conducted, allowing professionals from the healthcare supply chain and UAV industries to rank the criteria based on their professional knowledge [Berninzon & Vongasemjit, 2021]. Equal contributions from the two fields were maintained to avoid any bias. After collecting the responses, the weight of importance of each criterion was determined using the three steps mentioned below [Flitter et al., 2013].

First, a weight (w_i^{a}) was calculated for every factor for each separate expert response using the reciprocal ranking method, as in eq.(2) [Flitter et al., 2013], where r_i^a is the rank assigned by the expert to a particular factor and i is the respective expert index, while a is the factor for which the weight was calculated.

$$w_i^a = 1/r_i^a \tag{2}$$

Every expert opinion was given equal significance. Therefore, to combine the opinions of all experts, a composite factor weight (w^a) was calculated for each factor. To compute the composite factor weight, eq.(3) was used. In this equation, n is the total number of expert responses collected.

$$\mathrm{w}^{\mathrm{a}} = \sum_{i=1}^{n} w_i^{\mathrm{a}} \tag{3}$$

Finally, to bring the composite factor weights to a comparable state, eq.(4) was used [Flitter et al., 2013], where W_a is the comparable weight of the factor in question and m is the total number of factors used.

$$W_{\mathrm{a}} = \frac{\mathrm{w}^{\mathrm{a}}}{\sum_{\mathrm{a}=1}^{m} \mathrm{w}^{\mathrm{a}}} \tag{4}$$

The comparable weight calculated for each factor was used as their corresponding weight of influence in the analysis [Flitter et al., 2013].

Factor overlay. Overlaying the criteria allowed us to create a suitability score for each alternative. Thus, the score could be used to compare and contrast the value addition of UAV implementation for each RMSD [23]. Each alternative had its values normalized across the criteria, along with the criterion weights of importance. Therefore, the suitability score of the alternatives considered was derived by calculating the sum product of normalized criteria along with their respective weight of influence, as shown in the eq.(5) below.

$$S = \sum_{\mathrm{a}=1}^{m} N_{\mathrm{a}} \times W_{\mathrm{a}} \tag{5}$$

N_a - Normalized value of the alternative for the criteria a
W_a - Comparable weight of criteria a
A - Criterion index
M - Total number of criteria
S - Suitability score of the alternative

The higher the suitability score, the more value is added by utilizing UAVs for delivery. Therefore, the most suitable to least suitable divisions for UAV implementation were identified by arranging the suitability scores from highest to lowest.

Data collection. Table 1 depicts the sources used for data collection for the eight factors. Data was collected using online sources for 2019 to avoid any discrepancies caused by the influence of COVID-19. Additionally, for the data collection and analysis, twenty-five districts were considered instead of the twenty-six RMSD divisions.

The RMSD boundaries are equivalent to the district administrative boundaries in all cases except the Kalutara district. Unlike other districts, Kalutara is divided into two RMSDs. However, considering the ability of a UAV to serve both divisions and the availability of data, the two RMSD divisions at Kalutara were considered as one. Therefore, the data were collected with reference to the twenty-five administrative districts in the country.

Expert survey. To collect the expert responses, the quota sampling technique was used. Quota sampling is a non-probabilistic sampling technique that is used when certain specific characteristics are expected from the sample [Taherdoost 2016].

It was applied to our research because our sample focus was individuals with expert knowledge of the healthcare or UAV industry. Meanwhile, the number of damaged buildings and vehicle density showed little variation, with most values in the lower part of the spectrum [Taherdoost, 2016].

Table 1. Data Sources

Factor	**Measuring parameter**	**Data source**
Demand factors		
Level of demand	Number of childbirths	Annual Health Statistics 2019 [Medical Statistics Unit, 2019]
Accessibility factors		
Road density	Total road kilometers (km) / Total land area (km^2)	Economic and Social Statistics of Sri Lanka 2019 [Lanka, 2019]
Average elevation	Average elevation (m)	Topographic map.com [Maps, n.d.]
Road network quality factors		
Class D road density	Total class D road kilometers (km) / Total land area (km^2)	Economic and Social Statistics of Sri Lanka 2019 [Lanka, 2019]
Number of damaged buildings	Damage to critical infrastructure due to natural disasters	Natural Disaster Relief Services Center, situation summary report 2019 [Muthukuda, 2019]
Supply chain factors		
Health facility density	Number of health facilities / Total area (km^2)	Annual Health Statistics 2019 [Medical Statistics Unit, 2019] Economic and Social Statistics of Sri Lanka 2019 [Lanka, 2019]
Vehicle density	Number of vehicle registrations / Total land area (km^2)	Economic and Social Statistics of Sri Lanka 2019 [Lanka, 2019]
Area of service	Total area (km^2)	Economic and Social Statistics of Sri Lanka 2019 [Lanka, 2019]

Source: own work.

Because of the low heterogeneity in the areas of expertise, a smaller sample was sufficient [Programme, 2009]. Additionally, maintaining an equal contribution between the two fields was crucial to diminish result bias. Considering the above-mentioned requirements, six expert responses were collected and used to derive factor weights. In the form, the experts were asked to rank the criteria assigning a value from one to eight, where one is the most important and eight is the least important. The figure below displays the ranks received for each criterion through the six expert responses. The names of the experts are not revealed to maintain confidentiality.

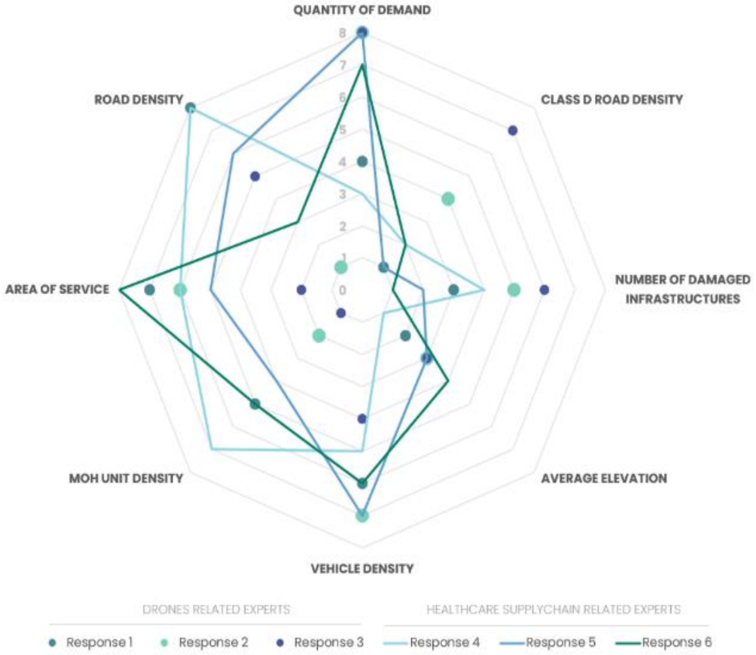

Fig. 3. Expert Survey Results

CHOOSING THE BEST DIVISION

Normalized factor score. Fig. 4 shows the normalized factor scores across the divisions. According to the reclassification, the level of demand, road density, and health facility density show frequent variations among divisions.

Factor weight. Table 2 represents the factor weights calculated for each parameter using experts' opinions. Class D road density had the highest weight of importance at 21%, while vehicle density and quantity of demand had the lowest at 7%.

Interestingly, 65% of the weights were distributed between the road network quality and accessibility factors, highlighting that those aspects had a greater influence on the value addition of UAVs than demand and supply chain factors.

Suitability score. Table 3 displays the suitability scores of each division arranged from largest to smallest. According to the results, the Kurunegala division (Score = 6.0) is the most suitable for the implementation of UAV systems, whilst Jaffna (Score = 2.3) is the least suitable. Further, the score gap between Kurunegala and Kegalle is the highest compared to other adjacent values in the table, highlighting that the value UAVs can add to Kurunegala is significantly greater than the value it can add to other divisions.

Factors / Divisions	Demand factors	Accessibility factors		Road network quality factors		Supply chain factors		
	Quantity of demand	Road density	Average elevation	Class D road density	Number of damaged infrastructure	Health facility density	Vehicle density	Service area
Ampara	5	10	3	2	1	9	1	6
Anuradhapura	5	9	2	4	1	10	1	10
Badulla	4	7	5	4	1	8	1	4
Batticaloa	4	10	1	1	1	9	1	4
Colombo	10	4	1	7	3	1	10	1
Galle	6	7	1	2	1	7	3	2
Gampaha	9	4	1	10	2	5	5	2
Hambantota	4	9	2	1	2	9	2	4
Jaffna	3	1	1	2	1	6	2	1
Kaluthara	5	7	1	4	2	9	3	2
Kandy	3	5	9	5	4	6	1	3
Kegalle	4	5	5	9	1	8	2	2
Kilinochchi	2	3	1	2	1	9	1	2
Kurunegala	8	8	3	4	10	8	2	7
Mannar	1	10	1	1	1	9	1	3
Matale	7	9	4	3	1	9	2	3
Matara	4	7	2	1	1	8	3	2
Monaragala	3	10	4	2	1	10	1	8
Mullativu	1	10	1	1	1	10	1	4
Nuwaraeliya	4	8	10	2	1	8	2	2
Polonnaruwa	3	10	2	1	1	10	1	5
Puttalam	5	8	1	4	2	9	2	4
Ratnapura	6	7	4	7	1	8	2	5
Trincomalee	3	10	1	2	1	9	1	4
Vavuniya	2	9	1	1	1	10	1	3

Fig. 4. Normalized factor scores across divisions

DELIVERY NETWORK DESIGN

The next step was to explore the potential of UAV-based solutions as an alternative to the current delivery plan. UAVs can be deployed as a standalone fleet or in combination with trucks for distribution purposes. To offer a comprehensive overview of UAV solutions, we analyzed both fleet types separately.

Numerous route optimization techniques to derive UAV solutions are available in the existing literature [Danancier et al., 2019; Sung & Nielsen, 2020; Thibbotuwawa et al., 2020]. These techniques involve various ways of incorporating UAVs alongside other modes of transport, such as trucks.

In this study, our primary focus was on reducing overall logistics costs within the healthcare supply chains of low-income countries. To address the PDSVRP problem using available techniques and obtain UAV delivery solutions, we utilized the Open-Source Vehicle Routing Problem Spreadsheet Solver available in Erdoğan [2017]. The VRP spreadsheet solver employs a metaheuristic algorithm programmed in Visual Basic to generate optimized route plans [Erdoğan, 2017]. Its primary goal is to determine a sequence of nodes that minimizes costs while adhering to specified constraints [Erdoğan, 2017]. This solver is particularly suitable for our study and has been widely employed in previous research due to its user-friendliness and effectiveness. In fact, studies by Karthik & Pavan [2019] have indicated that this VRP spreadsheet outperformed the Clark and Wright savings algorithm in terms of results. Additionally, research by Roddanavar & Mazumdar [2020] found that the solver consistently produces practical and realistic solutions.

Table 2. Weight of Importance of Factors

Factor	Weight of importance
Quantity of demand	6.75 %
Road density	11.96 %
Average elevation	16.86 %
Class D road density	20.81 %
No. of damaged infrastructure	15.02 %
Health facility density	14.06 %
Vehicle density	6.56 %
Area of service	7.98 %

Table 3. Suitability Score

Rank	Division	Score
1	Kurunegala	6.0
2	Kegalle	5.4
3	Kandy	5.1
4	Rathnapura	5.1
5	Gampaha	4.9
6	Anuradhapura	4.9
7	Monaragala	4.8
8	Nuwara Eliya	4.7
9	Badulla	4.6
10	Matale	4.5
11	Ampara	4.4
12	Puttalam	4.3
13	Kalutara	4.1
14	Colombo	4.1
15	Hambantota	4.0
16	Polonnaruwa	3.9
17	Trincomalee	3.9
18	Batticaloa	3.8
19	Mullaitivu	3.6
20	Vavuniya	3.5
21	Mannar	3.5
22	Galle	3.4
23	Matara	3.2
24	Kilinochchi	2.8
25	Jaffna	2.3

The solver is versatile and capable of handling various VRPs involving different types of vehicles. It also accommodates distance computations for UAVs or airplanes using distances as the crow flies. However, it is worth noting that the solver allows only one distance computation method to be employed at a time. Therefore, suitable duration multipliers were used for truck-related calculations. The solver takes inputs such as vehicle parameters, locations, demands, the distance computation method, and variable and fixed vehicle costs, ultimately generating a solution that minimizes costs while also providing optimal fleet allocation and destination sequences.

Incorporating a "weather factor" into the Vehicle Routing Problem (VRP) for UAVs adds a crucial dimension to the logistics planning. Given Sri Lanka's diverse climate patterns and susceptibility to adverse weather conditions such as monsoons and unpredictable rainfall, accounting for weather-related challenges is essential. The "weather factor" involves assessing real-time weather conditions and forecasts along the UAV delivery routes. This information can be used to make dynamic routing decisions, enabling the system to adapt in response to changing weather patterns. For instance, UAVs may be rerouted or rescheduled to avoid flying in adverse weather, ensuring the safety of vaccine shipments and the reliability of the cold chain. Furthermore, integrating weather data into the UAV logistics framework can help optimize flight paths, reduce delivery delays, and enhance overall system efficiency, which would ultimately contribute to the success of the vaccination program in Sri Lanka.

UAV-based last-mile mission selection. It was imperative to identify a UAV possessing suitable attributes tailored to the specific use case to ensure a favorable outcome [Wright et al., 2018; Wurbel, 2017]. In this particular scenario, UAVs are tasked with transporting vaccine vials between established healthcare facilities. Consequently, it is essential to consider the spatial requirements necessary for the UAV's operational functionality. Furthermore, to promote environmental advantages, it is advisable to opt for electric-powered or hydrogen-powered UAVs instead of those fueled by traditional sources. Given these criteria, the recommendation is to employ compact electric-powered or hydrogen-powered vertical takeoff and landing (VTOL) UAVs [Wright et al., 2018]. Additionally, as this study also sought to address international donor support to set up the Unmanned Aircraft Systems (UAS), it was crucial to identify UAS providers with pre-existing relationships with international donors. With these parameters in mind, three established UAV providers within the industry were taken into account during this research (the actual names of these three service providers are withheld due to confidentiality concerns; instead, descriptive pseudonyms are used throughout the analysis).

The UAV’s performance is influenced by various factors, including its range, speed, payload, and service time parameters [Chodorek et al., 2021; Feng et al., 2017; Karthik, G.R.Pavan, 2019]. To determine the electricity consumption of the UAV, we referred to the research presented by Dündar et al. [2020]. This study focused on assessing the energy consumption of a small, fixed-wing VTOL UAV traveling at a speed of 72 km/h while carrying a 0.4 kg payload through simulations. We applied the same findings to calculate the respective energy consumption of the three UAVs used in our study. In heterogeneous solutions, both trucks and UAVs engage simultaneously to complete the delivery. Accordingly, Figs. 5, 6 and 7 display the three heterogeneous solutions derived using the three UAVs considered.

It is essential to note that in the following visuals, distinct line thicknesses represent each journey taken by a vehicle. Consequently, routes with comparable thicknesses traversing the RMSD suggest that a vehicle visited a location, returned to the RMSD for replenishment, and then serviced another destination.

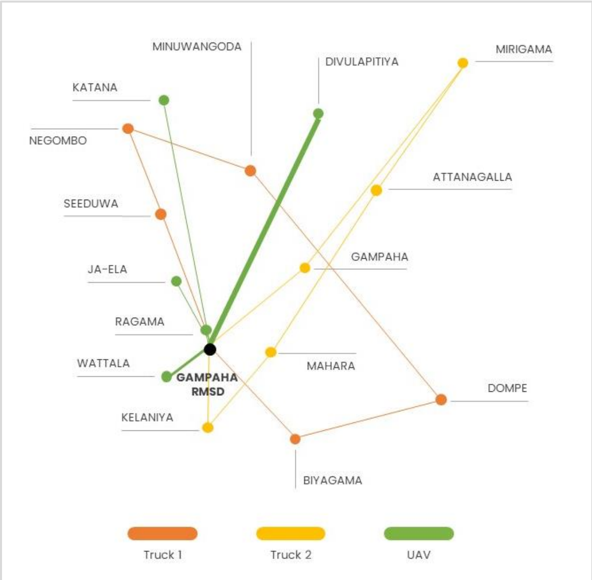

Fig. 5. Heterogeneous Solution with UAV A

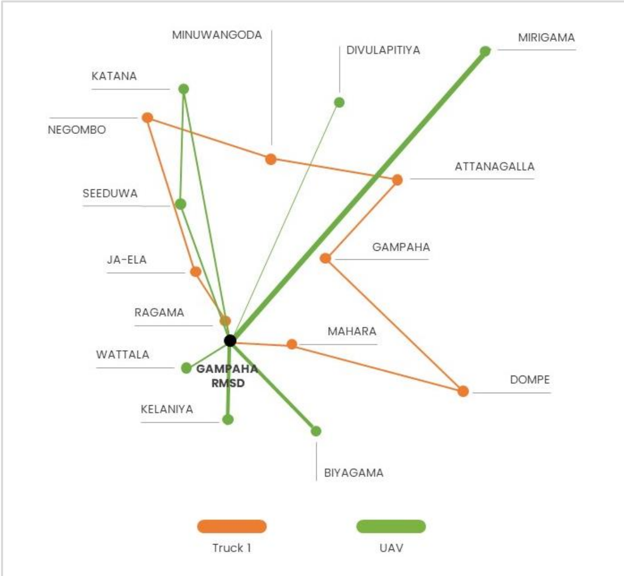

Fig. 6. Heterogeneous Solution with UAV B

Upon comparing the three delivery plans, it becomes apparent that UAVs B and C were able to substitute two trucks, unlike UAV A. As a result, the solutions involving UAVs B and C led to a more equitable distribution of contributions between the two modes.

Moreover, the constrained specifications of UAV A resulted in it serving just one destination per trip, while UAVs B and C managed to serve multiple locations. Interestingly, despite UAV B having a payload capacity similar to UAV A, its speed and range specifications allowed it to restock and serve another location within a single battery cycle.

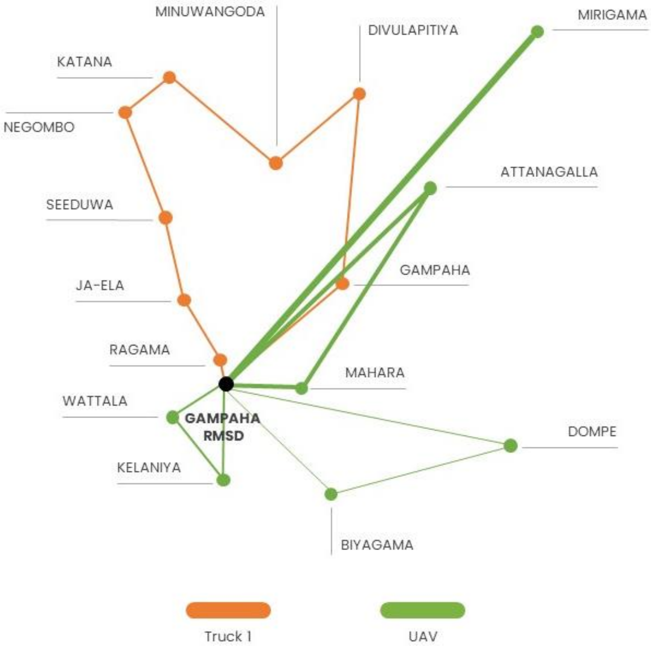

Fig. 7. Heterogeneous Solution with UAV C.

In contrast, UAV C, with its high payload capacity, concurrently transported cargo for two destinations during three out of the four UAV trips.

The uniform UAV solutions formulated a delivery strategy tailored for Gampaha RMSD that exclusively utilizes UAVs. Out of the three UAV service providers, both UAV A and UAV B lack the necessary payload capacity to transport the required items from Attanagalla, Gampaha, Minuwangoda, and Negambo. Consequently, UAV C was the sole contender qualified to generate the uniform solution, as depicted in Fig. 8.

Limitations to the application of UAVs. UAVs are a very promising tool to uplift the healthcare industry in Sri Lanka. Despite the limitation of this study to the vaccine cold chain, it is not the only plausible application of UAVs in the health field. Other suitable applications are blood delivery, anti-venom serum delivery, organ transportation, lab sample delivery and sanitization. Regardless of the many possible applications of UAVs in the Sri Lankan health care sector, there are limitations that have prevented them from being used in practice.

The lack of regulations surrounding the use of commercial UAVs in Sri Lanka is the main limitation which hinders the application of UAVs suggested in this study.

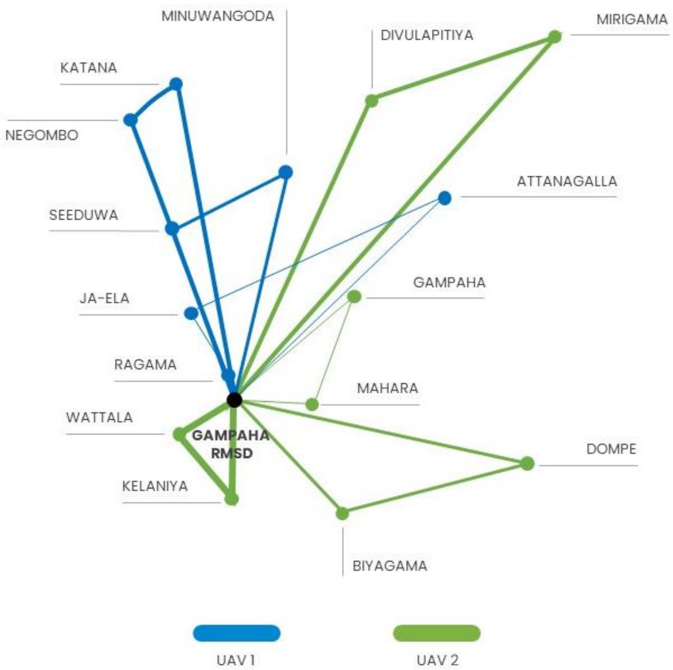

Fig. 8. Homogeneous Delivery Solution.

Currently, there are regulations implemented by the Civil Aviation Authority of Sri Lanka dealing with the application of UAVs for surveillance and recreational purposes [Dissanayake, 2019]. However, as the use case considered in this study is different to those applications, the existing regulations wouldn't cover it. Therefore, it would be appropriate to expand the existing legal framework further, supporting and encouraging novel UAV applications while defining appropriate boundaries and penalty schemes. The lack of proper jurisdiction results in privacy concerns for the public, security and theft threats to UAVs and a lack of insurance coverage. Most importantly it might discourage potential stakeholders and investors [Dissanayake, 2019]. Furthermore, standard operating procedures need to be developed and established for the usage of UAVs specifically in the healthcare field, setting guidelines for temperature control, altitude, and prohibited airspace to ensure the quality and reliability of UAV delivery systems [Jeyabalan et al., 2020].

CONCLUSIONS

The existing Expanded Program on Immunization (EPI) cold chain in Sri Lanka faces significant challenges that have long gone unnoticed. These challenges, compounded by high vaccination coverage, not only inflate program costs but also put the sustainability of the program at risk. The root causes include overreliance on road transportation and inadequate Cold Chain Equipment (CCE). Research and pilot projects have suggested that UAVs could provide a viable solution to these shortcomings.

To address these issues, we propose the creation of an innovative UAV delivery network. In this system, UAVs would directly transport vaccines from the RMSD warehouse to health facilities, bypassing storage at MOH unit warehouses. This approach promises faster delivery, reduced turnaround times, and optimal UAV utilization. It streamlines CCE management, human resources, and the use of vehicles while ensuring efficient vaccine distribution, reducing damage, stockouts, and wastage. Furthermore, transitioning to electric UAVs has environmental advantages over traditional fuel-based transport, contributing to financial relief and program sustainability.

However, the absence of clear regulations for large-scale UAV implementations in Sri Lanka could deter potential stakeholders and investors. Therefore, we strongly advocate the development of a regulatory framework to support such technological applications.

This research opens doors for further studies on the implementation of technological solutions in Sri Lankan healthcare logistics, particularly in UAV applications. Additionally, we recommend expanding the analysis to include factors like CCE condition, wastage volume, and holding costs. Quantifying the potential benefits of UAV implementation is crucial for understanding its true value. Exploring other UAV applications in healthcare logistics, such as lab sample collection and medicine delivery, offers promise for advancing the Sri Lankan healthcare system technologically, paving the way for a more efficient, cost-effective, and sustainable healthcare logistics ecosystem in Sri Lanka.

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