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Janani DEWMINI [0009-0001-4849-5079]*,
W. Madushan FERNANDO [0000-0003-4505-980X]**,
Izabela Iwa NIELSEN [0000-0002-3506-2741] ***,
Grzegorz BOCEWICZ [0000-0002-5181-2872] ****,
Amila THIBBOTUWAWA [0000-0002-5443-8839]**,
Zbigniew BANASZAK [0000-0001-7219-3903] ****

IDENTIFYING THE POTENTIAL OF UNMANNED AERIAL VEHICLE ROUTING FOR EMERGENCY BLOOD DISTRIBUTION

Abstract

This study is focusing on identifying the potential of Unmanned Aerial Vehicle (UAV) routing for blood distribution in emergency requests in Sri Lanka compared to existing transportation modes. Capacitated Unmanned Aerial Vehicle Routing Problem was used as the methodology to find the optimal distribution plan between blood banks directing emergency requests. The developed UAV routing model was tested for different instances to compare the results. Finally, the proposed distribution process via UAVs was compared with the current distribution process for the objective function set up in the model and other Key Performance Indicators (KPIs) including energy consumption savings and operational cost savings. The average percentage reduction in distribution time, reduction in energy consumption costs and reduction in operating costs per day using UAVs was 58.57%, 96.35% and 61.20% respectively for the instances tested using the model, highlighting the potential of UAVs. Therefore, the deficiencies in Sri Lanka's present blood delivery system can be addressed using UAVs' potential for time, cost, and energy savings. The ability to save time through the deployment of UAVs to the fleet during emergency situations plays a crucial role in preventing the loss of human lives.

* University of Moratuwa, Department of Transport Management & Logistics Engineering, Sri Lanka, jananidewmini97@gmail.com
** University of Moratuwa, Center for Supply Chain, Operations and Logistics Optimization, Sri Lanka, madushanfernando69@gmail.com, amilat@uom.lk
*** Aalborg University, Department of Materials and Production, Denmark, izabela@mp.aau.dk
**** Koszalin University of Technology, Faculty of Electronics and Computer Science, Poland, bocewicz@ie.tu.koszalin.pl, Zbigniew.Banaszak@tu.koszalin.pl

1. INTRODUCTION

Due to the complexity of blood supply chain management, the accessibility of blood and blood products remains a challenge in numerous nations. Perishable and having a short shelf life, fluctuating and unpredictable blood demand in hospitals, and longer distribution times for remote locations are the primary factors contributing to the complexity of blood supply chain management (Nisingizwe et al., 2022). According to the comprehensive analysis conducted by (Nisingizwe et al., 2022), it has been demonstrated that the distribution of blood between health facilities in Rwanda using UAVs was significantly faster than the traditional road distribution methods. By comparing estimated driving times and Google Maps estimates, the UAVs were able to save approximately 79 minutes and 98 minutes, respectively. Furthermore, the introduction of UAV delivery resulted in a notable decrease of 7.1 blood unit expirations per month. Over 12 months, this reduction converted to a remarkable 67% decrease in blood unit expirations. In addition, a separate study conducted by (Amukele et al., 2017) examined the impact of UAV transportation on the temperature of blood products. The findings revealed that there were no significant temperature changes observed in Red Blood Cells, Plasma units, and Platelets when they were placed in a cooler during the transportation process. Consequently, these results strongly indicate that using UAV distribution systems is a viable option for safely transporting blood products. Previous studies in this domain have employed the Vehicle Routing Problem as the primary methodology, and their objective functions have been to minimize the total distance traveled and the number of UAVs deployed (Al-Rabiaah et al., 2022; Ozkan, 2023; Wen et al., 2016).

Considering the proven feasibility of UAVs in healthcare logistics, this study attempts to identify the potential of Unmanned Aerial Vehicle routing for blood distribution during emergency requests in developing countries. The current blood distribution process in Sri Lanka was analyzed as a case study in this study. When it comes to the Sri Lankan context, the National Blood Transfusion Service (NBTS) is a specific initiative operating under the Ministry of Health. It holds the exclusive responsibility of providing blood and blood products to all government hospitals and a significant number of private-sector hospitals in the country (NBTS, 2021). The routine delivery services provided by the National Blood Centre are limited to the 12 blood banks located in the Colombo cluster. However, in emergency situations, requests for rare blood groups such as Bombay can be raised from any of the blood banks spread across the country. Currently, in such cases, a vehicle from the respective hospital, even if it is far away, must travel to the National Blood Centre to obtain even 1 or 2 units of blood. This process introduces delays that can have severe consequences, potentially leading to loss of lives. Moreover, the situation worsens when the only available ambulance in certain hospitals is dispatched to Colombo, putting the well-being of numerous individuals within the local community at risk. The existing process is time-consuming, resulting in prolonged waiting times and posing challenges in critical scenarios. Additionally, the current distribution process incurs high costs, consumes significant energy, and contributes to increased CO_2 emissions, further amplifying inefficiencies and environmental impact. Therefore, it is crucial to urgently address these concerns and investigate alternative methods for blood distribution that emphasize high responsiveness, energy efficiency, cost-effectiveness, and environmental sustainability. Drawing inspiration from (Thibbotuwawa et al., 2020; Gunaratne et al., 2022), this study adopts UAV routing as a means to bridge the existing gaps in the blood distribution system in Sri Lanka compared to conventional road transportation methods.

2. LITERATURE REVIEW

An unmanned aerial vehicle (UAV) is an aircraft that functions without a pilot on board and can be operated either autonomously or through remote control, following a predetermined path, or through an automation system (Zhang et al., 2016). Unmanned aerial vehicles have emerged as a sophisticated technology utilized across various sectors, including defense, search and rescue applications, manufacturing procedures, agricultural activities, and environmental monitoring (Thibbotuwawa, 2019; Thibbotuwawa et al., 2019a; Radzki et al., 2020; Yafrani et al., 2022). UAVs have the capability to cover expansive areas in the field without requiring any alterations to the existing infrastructure, such as the installation of floor guiding lines or wall-mounted deployment stations (Thibbotuwawa et al., 2019b).

The vehicle routing problem (VRP) involves finding the most cost-effective set of vehicle routes to fulfill all or some of the transportation requests using a given fleet of vehicles. Furthermore, it determines the assignment of requests to specific vehicles and the order in which they are handled, ensuring the feasibility of all vehicle routes (Desaulniers et al., 2014). In contrast to typical vehicle routing problems, UAV routing problems involve a significant amount of stochastic information as UAVs need to dynamically adapt, adjust, and optimize their trajectories in real time. UAV routing serves specific objectives such as decreasing distribution times, reducing individual UAV expenses, maximizing profitability, increasing the system's load capacity, and improving operational safety, distinguishing it from generic vehicle routing problems (Coelho et al., 2017).

UAVs have proven to be effective in resolving prevailing inefficiencies within the healthcare system, such as elevated fixed and operational costs, geographical obstacles, and inadequate infrastructure (Balasingam, 2017; Haidari et al., 2016; Nyaaba & Ayamga, 2021). Furthermore, UAVs have emerged as a promising method for enabling diagnosis and treatment in remote locations, facilitating the collection of blood and tissue samples, delivering emergency kits, and transporting diverse medical products (Nyaaba & Ayamga, 2021; Rabta et al., 2018; Sivakumar & Naga Malleswari, 2021). Earlier studies have showcased the capability of UAVs to enhance healthcare accessibility by transporting medical supplies to regions that are otherwise challenging to reach, such as deserts, islands, and marshes (Radzki et al., 2019). Additionally, there has been a growing interest in employing UAVs for the regular distribution of medical products. This approach has become increasingly appealing due to its cost-effectiveness, achieved by spreading the initial setup costs across multiple flights. As a result, healthcare coverage has improved significantly, providing exceptional service quality (Wright et al., 2018).

When it comes to the use of UAVs for blood distribution, the introduction of UAVs for blood distribution in Rwanda holds the promise of achieving shorter distribution times and minimizing damage to the transported blood components, primarily attributed to limited exposure to challenging road conditions (IEEE, 2016). The organization 'Matternet' has deployed UAVs to distribute blood samples for HIV/AIDS tests from clinics to hospitals in Maseru, Lesotho. This innovative approach has significantly reduced distribution time compared to the time-consuming process of using conventional land transportation, which is often impeded by limitations in road infrastructure. Additionally, flat-wing UAVs, which can vertically take off and autonomously fly horizontally, are employed for the transportation of blood and stool samples to the central laboratory of Madagascar (Moshref-Javadi & Winkenbach, 2021).

As per the investigation carried out by (Yakushiji et al., 2021), it was demonstrated that utilizing UAVs for blood transport can effectively address the urgent need for blood transfusions across Japan, even in remote island locations. The transportation of packages containing Red Blood Cells through both aerial and terrestrial means displayed no significant indications of hemolysis. In a pilot study conducted by (Homier et al., 2021) to deliver simulated blood products, it was demonstrated that the use of UAVs for transportation purposes significantly outperformed ground delivery. Moreover, the study showed that the temperatures of the simulated blood products remained within acceptable ranges throughout the entire distribution process. Furthermore, the research undertaken by (Yakushiji et al., 2020) evaluated the efficiency of employing UAVs for transporting Red Blood Cells in Japan. During the experiment, the study progressively extended the distance covered by UAVs, monitored the temperature of the blood samples, and performed laboratory tests to assess the blood samples' integrity. Although the study revealed a partial inability to consistently uphold the temperature within the specified range, the variation fell within the safety margin.

Based on the economic evaluation conducted by (Zailani et al., 2021), it has been concluded that while the per-minute cost of UAV distribution for blood products is higher than that of ambulances, the significant reduction in travel time achieved by UAVs compensates for this cost difference. Moreover, the study recommends promising economic opportunities for the implementation of UAVs in blood product transportation, especially in developing countries. However, the realization of these prospects depends on a decrease in UAV prices and an extension of their operational lifespan. Furthermore, the research conducted by (Niglio et al., 2022) has focused on verifying the effectiveness of a drone-driven distribution system integrated with a smart capsule for transporting blood products within metropolitan areas. The findings indicate that the use of the capsule successfully maintained the required temperature parameters for preserving the quality of the blood products, and no negative consequences occurred during the transportation process.

The study conducted by (Al-Rabiaah et al., 2022) has investigated the routing of UAVs for emergency blood transportation to patients with the objective of minimizing both the number of UAVs needed and the overall distance traveled during the routing process. The investigation carried out by (Ozkan, 2023) focuses on the multi-objective optimization of blood product transportation via UAVs from distribution centers to hospitals in Istanbul. Furthermore, the research conducted by (Wen et al., 2016) has examined the multi-objective blood supply challenge using UAVs in emergency scenarios. The study addresses various aspects of this complex problem, including the preservation of blood temperature during transportation, the efficient scheduling and route planning of UAVs to accommodate multiple sites requesting blood, and the constraints imposed by limited carrying capacity. In both studies (Ozkan, 2023; Wen et al., 2016) the objective functions have been to minimize the total distance and the number of UAVs.

Tab. 1. Summary of literature focused on the application of UAV routing problem for blood distribution

Citation	Research objective	Key findings
(Al-Rabiaah et al., 2022)	Assign UAVs for delivering blood to patients in emergency scenarios, aiming to reduce the number of UAVs required, battery consumption, and the overall routing distance	Developed Greedy Battery Distance Optimizing Heuristic (GBDOH) exhibits enhanced efficiency with reduced computational complexity and delivers a superior objective value, surpassing the best state-of-the-art methods by approximately 27%
(Wen et al., 2016)	Investigate the temperature variations of blood resulting from external conditions, the refrigerant, and the duration of transportation and suggest an optimal approach for determining the appropriate mixing ratio between blood and additives under diverse circumstances	The used combination of decomposition based multi objective evolutionary algorithm and local search method yields improved optimization outcomes and time efficiency
(Ozkan, 2023)	Transport blood products from distribution centers to hospitals in cities aiming to minimize the number of UAVs required and the total travel distance while addressing the blood product requirements of hospitals and the supply capabilities of distribution centers	The developed multi-objective integer programming (MOIP) model is effective in small-size instances while single solution-based metaheuristics such as MOSA (Multi-objective simulated annealing) and MOLS (Multi-objective local search) yield superior outcomes for large-size instances

According to the literature focused on applying the UAV routing problem for blood distribution, there are no studies which considered travel time minimization as the objective function. Moreover, to the best of our knowledge, there are no studies attempted on the application of UAV routing problem for blood distribution during emergency requests in developing countries. Therefore, this research will focus on filling the gap in applying the UAV routing problem with the objective function of minimizing the total delivery time for blood distribution in emergency requests in developing countries.

3. METHOD

3.1. Data collection

The existing blood distribution process was identified by visiting the National Blood Centre, Narahenpita, Colombo, and interviewing two resource persons: Medical Officer In-charge, Donor Section, and Consultant Transfusion Physician. The routine delivery process to blood banks, the procedure of handling emergency requests, modes of transportation used, the weight of one unit of RCC (Red Blood Cell Count), the method of maintaining optimum temperature during transportation using cool boxes, types of blood components requested in emergency cases, inventory control and expiry period of different blood components were the major findings of the data collection process. Moreover, blood banks that made emergency requests between 17.03.2023 and 17.04.2023 were obtained. Locations of blood banks were obtained through the Annual Statistics Reports of the National Blood Transfusion Service (NBTS), Sri Lanka.

3.2. Methodology

Unmanned Aerial Vehicle Routing Problem was used as the methodology for this study. Capacitated Vehicle Routing Problem (CVRP) was used as the form of VRP since CVRP considers the limited carrying capacity of UAVs to ensure that the packages to be delivered do not exceed the maximum carrying capacity of UAVs (Khoufi et al., 2019). The hybrid method of heuristic and metaheuristic was used as the approach to solving VRP. That approach was selected due to the easiness of finding near-optimal solutions within feasible computational time and the ability to customize for different types of problems (Fernando et al., 2022). Path Cheapest Arc (PCA), a widely used heuristic algorithm for vehicle routing problems, was selected as the first solution strategy in the UAV routing model. The metaheuristic chosen for the UAV routing model was Guided Local Search (GLS) , which is widely recognized as the highly efficient metaheuristic for vehicle routing problems, as indicated by (Perron, 2011). Further, GLS used neighborhood search strategy to improve the initial feasible solution (Fernando et al., 2022). The use of neighborhood strategy in current research is shown in Fig. 1.

Algorithm1: Neighborhood search

Input – Initial solution obtained by PCA (x_0)

Stop criteria; accepted neighbors

Output – Near-optimal solution

$x \leftarrow x_0$

while stop criteria not violated do

1. Find neighborhood (N_x)
2. Find “best” solution in Nx; x_{best}
3. $x \leftarrow x_{best}$

end while

Fig. 1. Algorithm for neighborhood search using PCA and GLS (Fernando et al., 2022)

The UAV routing model was developed to assign UAVs to the blood banks directing emergency requests while minimizing the total distribution time. The developed UAV routing model was tested for different instances to compare the results. Finally, the proposed distribution process via UAVs was compared with the current blood distribution process via ambulance.

3.3. Mathematical formulation of the problem

The unmanned aerial vehicle routing problem can be depicted as the following graph-theoretic problem. Let $G=(N,E)$ be a graph representing a transportation network where $N = \{0,1,\cdots,n\}$ is a set of nodes and $E = \{\{i,j\} \mid i,j \in N, i \neq j\}$ is a set of edges. While vertex 0 represents the depot, vertices $j = \{1,\ldots,n\}$ represent the clients, each with a known non-negative demand, D_j.

3.3.1. Parameters

$G=(N,E)$: Graph representing transportation network
$N = \{0\ldots n\}$ is a set of nodes
$E = \{\{i,j\} \mid i,j \in N, i \neq j\}$ is a set of edges
D_i: Demand at node $i \in N, i \neq 0$
$d_{i,j}$: Travel distance from node i to j (Length of edge $\{i,j\}$)
$t_{i,j}$: Travel time from node i to j
K: Size of the homogeneous fleet of UAVs available at the depot 0
Q: Maximum loading capacity of the UAV
v_{ij}: Speed of the UAV traveling from node i to j
r: Range of the UAV (The maximum distance that UAV can travel within a single battery charge)
s_i: Average service time at node i
w: Time spent for take-off and landing of the UAV
y_i^k : Time that kth UAV arrives at the node i
c_i^k : Payload weight amount delivered to node i by kth UAV
φ: A large number

3.3.2. Decision Variable

x_{ij}^k : Binary variable used to indicate if k^{th} UAV travels from node i to j

$$x_{ij}^k \begin{cases} 1, & \text{if k}^{\text{th}} \text{ UAV travels along from node i to node j} \\ 0, & \text{otherwise} \end{cases}$$

3.3.3. Objective Function

Minimizing total distribution time

$$\text{Min} \quad \sum_{i \in N} \sum_{j \in N} x_{i,j}^k y_j^k \tag{1}$$

3.3.4. Constraints

If a UAV k is flying from node i to j, then the arrival time to node j; y_j^k is equal to the sum of arrival time to node i; y_i^k, average service time at node i; s_i, travel time between node i to j; $t_{i,j}$, and time spent for take-off and landing of a UAV; w.

$$(x_{i,j}^k = 1) \Rightarrow (y_j^k = y_i^k + s_i + t_{i,j} + w) \; \forall (i,j) \in N, \forall k \in K \tag{2}$$

The demand allocated to a UAV should not surpass its capacity.

$$\sum_{i\in N} \sum_{j\in N} x_{i,j}^k \, c_j^k \le Q \qquad k = 1 \ldots . K \tag{3}$$

The total distance traveled by the UAV per trip should not exceed its range.

$$\sum_{i\in N} \sum_{j\in N} x_{i,j}^k \, d_{i,j} \le r \qquad k = 1 \ldots . K \tag{4}$$

When a UAV arrives at a node, that UAV must depart from that node.

$$\sum_{j\in N} x_{i,j}^k - \sum_{j\in N} x_{j,i}^k = 0 \qquad k = 1 \ldots . K, \forall i \in N_0 = N \cup \{0\} \tag{5}$$

Each node should be served by exactly one drone.

$$\sum_{j\in N} x_{i,j}^k = \sum_{i\in N} x_{j,i}^k = 1 \qquad k = 1 \ldots . K \tag{6}$$

Each UAV that leaves the depot (Node 0) must return to the same depot.

$$(x_{i,j}^k > 0) \Rightarrow \sum_{i\in N} x_{0,i}^k = \sum_{i\in N} x_{i,0}^k = 1 \qquad k = 1 \ldots . K \tag{7}$$

Sub-tour elimination

$$(x_{i,j}^k = 1) \Rightarrow y_j^k \ge y_i^k - \varphi(1 - x_{i,j}^k) \quad \forall (i,j) \in N, \forall k \in K \tag{8}$$

3.3.5. Assumptions used in the UAV routing model

- All UAVs in the fleet are homogeneous and are equipped with full energy capacity before the commencement of the flying time window.
- No recharging happens during the journey.
- All emergency requests are known before the UAV fleet begins operations.
- The time spent for take-off and landing of the UAV and the service time is considered constant at each node. The total time spent for take-off, the landing time of the UAV, and the service time at the respective blood bank were considered to be 3 minutes.
- All UAVs move at the same uniform speed.
- The effect of weather conditions on the travel speed of the UAV is not considered. A constant wind direction and speed are assumed.
- More than one UAV can start to fly from the base at the same time

- All UAVs start their distribution operations from a centralized location and return to the initial point of origin after fulfilling service requirements at assigned blood banks. National Blood Centre, Narahenpita is considered as the depot for this study.
- Split deliveries are restricted ensuring that each blood bank is exclusively assigned to a single designated UAV for service.
- The packages delivered to the blood banks are of the same type and only the number of units differs. Packages are stackable.
- No temperature change occurs during transportation by UAVs since blood packs are placed in a cool box. 500 g of the payload capacity of the UAV was allocated for the cool box.
- UAVs do not collide with each other as long as they do not cross the same arc at the same time during takeoff.

3.4. Selected UAV type and its characteristics

Zipline's Medical Delivery Drone used for blood delivery in Rwanda was used as the most suitable type of drone for this study. Characteristics of the UAV are; Payload: 1.75 kg, Range: 160 km, Speed: 101 km/h, and Energy source: Lithium-ion battery packs (Roberts, 1977; IEEE, 2016). Based on the maximum distance a UAV can travel on a single battery charge, the total distance covered by a UAV per route was set at 160 km.

3.5. Comparative analysis

A comparative analysis was conducted to identify the potential of using UAVs in the blood distribution process compared to existing transportation modes. Ambulance is the mode of transport currently used for blood distribution from the National Blood Center, Narahenpita to the respective blood banks. The Traveling Salesman Problem (TSP) model was developed to find the optimal route for the ambulance at the National Blood Centre considering blood units are distributed to the respective blood banks on the night before the respective date by the National Blood Center, Narahenpita itself.

3.5.1. Inputs used for time calculation

The average speed of an ambulance was considered as 50 kilometers per hour. The service time at the respective blood bank was considered to be 6 minutes in the existing distribution process by ambulances.

3.5.2. Inputs used for energy consumption calculation

Since the UAVs selected for the study are battery-powered, the energy consumption of UAVs was calculated using the following equation (Zhang et al., 2021).

$$Rate\ of\ energy\ consumption\ of\ UAV\ (kWh/km) = Battery\ capacity\ (kWh)/Range\ (km) \quad (9)$$

The battery capacity and range of Zipline's Medical Delivery Drone were considered as 5 kWh and 160 km respectively. Therefore,

$$Rate\ of\ energy\ consumption\ of\ UAV = 5\ kW/160\ km = 0.03125\ kW\ per\ km \quad (10)$$

The fuel consumption of ambulances was calculated using the following equation (Hess & Greenberg, 2011).

$$Fuel\ consumption\ rate\ of\ an\ ambulance\ (l/km) = 1/Fuel\ economy\ (km/l) \quad (11)$$

The fuel economy of an ambulance was taken as 6.89 miles per gallon (11.086 kilometers per liter) (Hess & Greenberg, 2011). Therefore,

$$Fuel\ consumption\ rate\ of\ an\ ambulance\ (l/km) = 1/11.086\ km/l = 0.09\ liters\ per\ km \quad (12)$$

3.5.3. Inputs used to calculate the cost of energy consumption

Since the UAVs chosen for the study are battery-powered, the cost of energy consumption of UAVs was computed based on the number of kilowatt hours (kWh) required to complete all routes and the price of electricity per kWh. The price of electricity was taken as LKR 39 per kWh according to the rates specified by (LECO, 2023). The rate for the general-purpose category for off-peak hours was taken for the calculation since it is assumed that the distribution of blood from the National Blood Center, Narahenpita to the respective blood banks is done on the night before the respective day. The reason for that assumption is that not requiring major operational changes to the current blood distribution process.

$$\text{Cost of energy consumption } of\ UAV\ (LKR) = Rate\ of\ energy\ consumption\ (kWh/km) \times Total\ distance\ traveled\ (km) \times Electricity\ price\ (LKR/kWh) \quad (13)$$

The cost of energy consumption of ambulances was calculated based on the amount of diesel needed to complete all routes in liters and the price of diesel per liter. The price of diesel was taken as LKR 310 per liter according to the rates published by Ceylon Petroleum Corporation (2022).

$$\text{Cost of energy consumption } of\ ambulance\ (LKR) = Rate\ of\ fuel\ consumption\ (l/km) \times Total\ distance\ traveled\ (km) \times Diesel\ price\ (LKR/l) \quad (14)$$

3.5.4. Inputs used for operational cost calculation

The following two cost components were used for operational cost analysis.

– Cost of energy consumption for all trips per day

For UAVs, the cost of electricity for total kWh consumed was considered as the energy consumption cost. For ambulances, the cost of fuel for all the kilometers traveled was considered as the energy consumption cost. Costs were calculated using the inputs mentioned in the previous section.

– Wages of vehicle operators per day

Based on the average monthly salary given in (World Salaries, 2023), the average salary of an ambulance officer and paramedic officer was taken as LKR 2500 per day. Moreover, it was considered that both the ambulance officer and the paramedic would travel on each visit according to the minimum crew member requirement in an ambulance as stipulated in (Auditor General's Department - Democratic Socialist Republic of Sri Lanka, 2011). Since UAVs are not yet used for operations in Sri Lanka, UAV operator salaries could not be ascertained. Therefore, based on the monthly salary range of aircraft pilots and related allied professionals in Sri Lanka stated in (WageIndicator, 2023), LKR 4000 per day was considered as the wage level of UAV operators.

3.6. Software, programming language, and tools used

Open-source software and Visual Studio Code were used to develop both models. Python was used as the programming language in models. Models were run for different sets of blood banks randomly selected from the blood banks that made emergency requests between 17.03.2023 and 17.04.2023. The distance matrix for the UAV routing model was created using the Euclidean distance since it computes the straight-line distance between two points, without considering obstacles or geographical features. The study employed the GeographicLib API to compute the Euclidean distance between locations for the UAV routing model. Moreover, the OSRM API was used to calculate the road distance between locations for the TSP model (Fernando et al., 2022).

4. RESULTS

4.1. Comparative analysis between the existing delivery process and the proposed delivery process

The proposed blood distribution process via UAVs was compared with the existing blood distribution process via ambulance. Locations of blood banks that made emergency requests between 17.03.2023 and 17.04.2023 were used for the initial analysis consisting of 20 locations.

Fig. 2. Optimal route provided by the UAV routing model

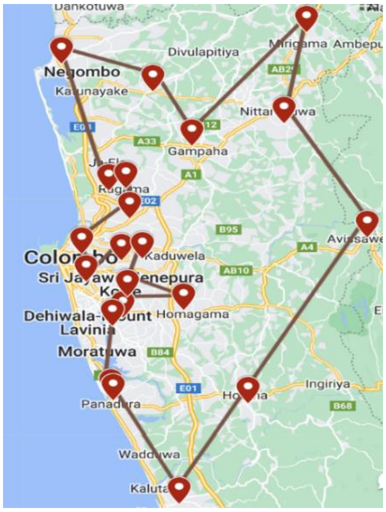

Fig. 3. Optimal route provided by the TSP model

Tab. 2. Comparison of blood distribution process via UAVs and ambulance

KPI	Distribution by UAVs	Distribution by ambulance
Total distribution time	218.13 min	361.3 min
Energy consumption	11.45 kWh	27.1 l
Energy consumption cost	446.55 LKR	8401 LKR
Operational cost per day	4446.55 LKR	13401 LKR

Tab. 3. Percentage of reductions

KPI	Percentage of reductions
Total distribution time	39.63%
Energy consumption cost	94.68%
Operational cost per day	66.82%

Below are 7 different instances created with 5 blood banks per data set using locations randomly selected from blood banks that made emergency requests between 17.03.2023 and 17.04.2023. The reason for selecting 5 blood banks per data set was that it was the average daily number of locations directing emergency requests during the aforementioned month.

Tab. 4. Total distribution time for delivery by UAVs and ambulance

Instance	Total distribution time (min)		Percentage of distribution time reduction using UAVs
	Distribution by UAVs	Distribution by ambulance	
1	113.32	243.27	53.42%
2	132.09	327.14	59.62%
3	95.37	240.77	60.39%
4	95.17	225.55	57.81%
5	108.19	216.73	50.08%
6	93.07	258.79	64.04%
7	94.61	267.48	64.63%

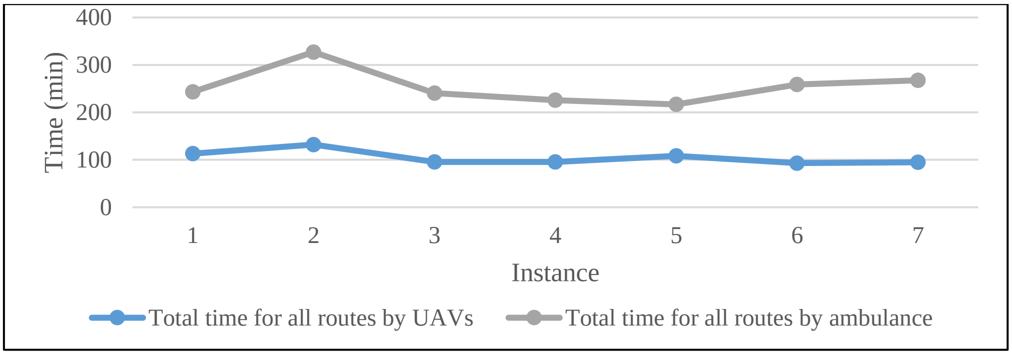

Fig. 4. Total distribution time for delivery by UAVs and ambulance

Tab. 5. Energy consumption of UAVs and ambulance

Instance	Energy consumption	
	Distribution by UAVs (kWh)	Distribution by ambulance (Liter)
1	5.95	18.25
2	6.93	24.54
3	5.01	18.06
4	5.00	16.92
5	5.68	16.26
6	4.89	19.41
7	4.97	20.06

Tab. 6. Energy consumption cost of UAVs and ambulance

Instance	Energy consumption cost (LKR)		Percentage of energy consumption cost reduction using UAVs
	Distribution by UAVs	Distribution by ambulance	
1	232.05	5657.5	95.90%
2	270.27	7607.4	96.45%
3	195.39	5598.6	96.51%
4	195.00	5245.2	96.28%
5	221.52	5040.6	95.61%
6	190.71	6017.1	96.83%
7	193.83	6218.6	96.88%

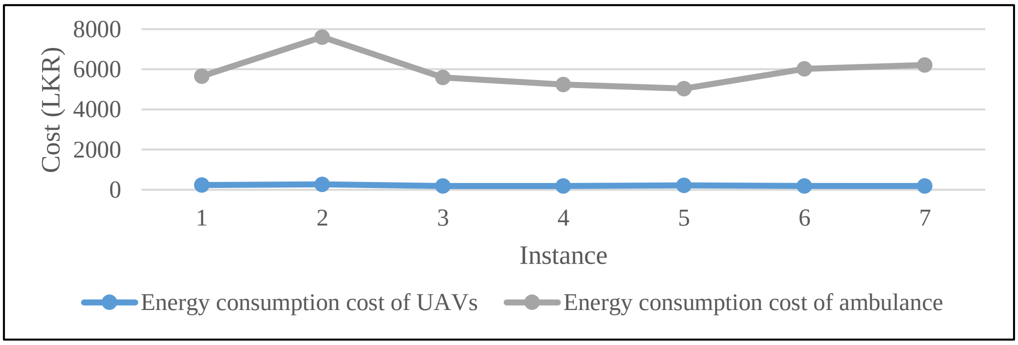

Fig. 5. Energy consumption cost of UAVs and ambulance

Tab. 7. Operational cost per day for UAVs and ambulance

Instance	Total operational cost per day (LKR)		Percentage of operational cost per day reduction using UAVs
	Distribution by UAVs	Distribution by ambulance	
1	4232.05	10657.5	60.29%
2	4270.27	12607.4	66.13%
3	4195.39	10598.6	60.42%
4	4195.00	10245.2	59.05%
5	4221.52	10040.6	57.96%
6	4190.71	11017.1	61.96%
7	4193.83	11218.6	62.62%

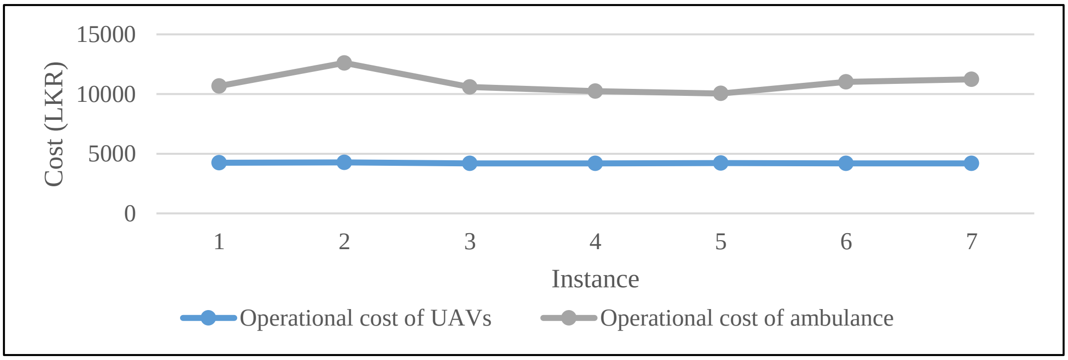

Fig. 6. Energy consumption cost of UAVs and ambulance

Tab. 8. The average percentage of reductions for all tested instances

KPI	The average percentage of reductions
Total distribution time	58.57%
Energy consumption cost	96.35%
Operational cost per day	61.20%

4.2. Analysis by changing the number of blood banks

The developed UAV routing model was tested for different instances by increasing the number of blood banks directing emergency requests by 5 each.

Tab. 9. Analysis by changing the number of blood banks

Number of blood banks	Total distribution time (min)	Total distance (km)	Total energy consumption (kWh)	Number of UAVs required
5	93.07	156.35	4.89	2
10	112.91	189.69	5.93	3
15	169.56	284.86	8.90	4
20	218.13	366.46	11.45	5
25	360.49	605.62	18.93	6
30	457.20	768.10	24.00	7

4.3. Analysis by changing the UAV type

The effect on the total distribution time, total distance, and total energy consumption by changing the characteristics of the UAVs was also analyzed. Below are the characteristics of selected UAVs for the analysis (Gunaratne et al., 2022). Results were obtained for the locations used in the initial analysis.

Tab. 10. Characteristics of selected UAVs for the analysis

Characteristic	UAV type 1	UAV type 2	UAV type 3
Average speed	101 km/h	70 km/h	72 km/h
Payload	1.75 kg	2 kg	6 kg
Range	160 km	150 km	288 km
Energy source	Electricity	Electricity	Electricity

Tab. 11. Analysis by changing the UAV type

UAV type	Total distribution time (min)	Total distance (km)	Total energy consumption (kWh)	Number of UAVs required
1	218.13	366.46	11.45	5
2	292.17	340.79	11.35	5
3	205.05	246.06	4.28	2

5. DISCUSSION

Achieving a significant 58.57% reduction in delivery time represents a noteworthy advancement in response times, enabling quicker accessibility to life-saving blood products. This finding illustrates the potential of UAVs to reduce the distribution time for emergency blood requests by more than half compared to existing transportation methods. Distribution time reduction holds immense importance in emergency scenarios where time plays a crucial role in saving lives. With a substantial decrease in delivery time, UAVs can make valuable contributions to enhanced patient outcomes and increased survival prospects for individuals requiring emergency blood transfusions.

UAVs exhibit evident benefits over ambulances in terms of energy consumption and cost. The analysis highlights that UAVs consume considerably less energy, measured in kilowatt-hours (kWh), compared to the fuel consumption of ambulances, measured in liters, for blood distribution in all tested scenarios. This finding highlights the superior energy efficiency of UAVs, resulting in cost savings and reduced environmental impact. The reduced energy consumption expenses further enhance the economic viability of incorporating UAVs into blood distribution operations.

The substantial average reduction of 96.35% in energy consumption costs achieved through the use of UAVs showcases a remarkable enhancement in cost efficiency compared to existing blood transportation methods. Integrating UAVs into the distribution system of healthcare institutions enables substantial cost savings, facilitating more effective resource allocation and directing saved funds toward other critical healthcare priorities. Moreover, the scale of energy consumption cost reduction emphasizes the potential of UAVs to promote environmental sustainability. With significantly lower energy consumption, UAVs can contribute to alleviating the carbon footprint linked with blood distribution. This energy consumption reduction aligns with global initiatives aimed at encouraging greener practices and reducing dependence on fossil fuels. Adopting UAV technology allows healthcare facilities to achieve improved financial efficiency while actively contributing to a sustainable and environmentally conscious approach to emergency blood distribution services.

The considerable reduction of 61.20% in daily operational costs presents a significant financial advantage for healthcare facilities engaged in blood distribution. This average reduction in daily operational costs highlights the long-term financial stability of deploying UAVs into blood delivery systems. Due to lower expenses related to energy, personnel, and maintenance, UAVs present a more economically viable solution compared to conventional fuel-based transportation methods. The cost-effectiveness provided by UAVs can play a crucial role in strengthening the resilience and overall stability of healthcare systems, especially in environments where resources are limited.

The findings of the analysis highlight the significant advantages that can be gained by incorporating UAVs into blood distribution processes within the healthcare sector. The accelerated distribution times, reduced energy consumption, and lower operational costs attributed to UAVs have the potential to enhance healthcare logistics, especially in emergency scenarios and challenging geographical areas. Moreover, the analysis highlights the contribution of the characteristics of different UAVs to im-proved patient outcomes by reducing the delivery time. The analysis offers valuable insights into the cost considerations and operational efficiency of utilizing UAVs for blood distribution, surpassing the capabilities of traditional ambulances. These findings emphasize the capability of UAVs to improve the efficiency and effectiveness of blood distribution systems, ultimately resulting in enhanced patient care and optimal resource utilization in healthcare settings. The conclusions drawn from this analysis can serve as a foundation for decision-making and policy formulation related to the adoption and integration of UAVs in blood distribution operations.

To summarize, the study was able to successfully address the research gap identified in the literature related to the application of UAV routing for blood distribution. This research appears to be a pioneering effort, with a strong focus on minimizing the total distribution time for blood delivery in emergencies, particularly in the challenging operational environments of developing countries. The findings of this study not only fill a gap in the existing literature, but also provide a robust framework for in-creasing the efficiency and effectiveness of blood delivery systems using UAV-enabled approaches, especially in resource-constrained settings.

Although the study briefly discussed cost savings, further research can focus on a comprehensive cost-benefit analysis to evaluate the economic viability and long-term financial stability of deploying UAVs into the blood distribution process. This analysis should incorporate not only operational expenses but also initial investments, training, maintenance, and infrastructure requirements associated with implementing UAV-based delivery systems. Furthermore, it is crucial to acknowledge that the analysis did not explicitly incorporate aviation regulations. Therefore, an important area for future research would be to investigate the impact and incorporation of aviation regulations into the UAV routing model.

Temperature changes during transportation via UAVs were not measured in the study, assuming that no temperature variations occur during the flight due to the use of cooler boxes. However, it is possible to extend the study to investigate whether temperature changes exist. Additionally, the study considered a limited number of blood banks per instance, taking into account the maximum range achievable by UAVs on a single battery charge. By incorporating charging stations into the study, it can be expanded to include a larger number of blood banks. These future trajectories would offer more robust and comprehensive insights into the potential of UAV routing for blood distribution in emergency requests.

6. CONCLUSION

Based on the research findings, it is evident that UAVs have substantial potential to improve the emergency blood distribution process in Sri Lanka compared to existing transportation methods. By investigating various scenarios and thoroughly analyzing the outcomes from different perspectives, several important conclusions can be drawn.

A prominent benefit of employing UAVs in the blood distribution process is the significant time reductions they offer. The analysis consistently revealed that UAVs effectively reduced the distribution time in comparison to conventional ambulance-based approaches. Time reduction holds critical significance in emergency situations, where the prompt delivery of blood can determine the outcome between life and death.

Furthermore, the incorporation of UAVs into the blood distribution system demonstrated significant cost savings. The operational costs related to UAV-based de-livery systems were consistently lower compared to those of ambulances. This cost-effectiveness holds the promise of benefiting healthcare facilities by ensuring long-term financial stability and optimum resource allocation.

Apart from time and cost benefits, the research findings emphasize the energy-saving potential of UAVs. UAVs demonstrated substantially lower energy consumption compared to ambulances during the blood distribution process. This energy efficiency not only contributes to environmental sustainability but also reduces the dependence on fossil fuels, aligning with wider efforts to adopt more environmentally friendly transportation practices.

To summarize, the research findings indicate that incorporating UAVs into the blood distribution process can yield substantial enhancements in terms of time efficiency, energy conservation, and operational cost savings. These benefits hold the promise of saving lives, optimizing the allocation of resources, and promoting sustainable healthcare practices. Therefore, it can be concluded that Unmanned Aerial Vehicle routing will be a feasible option for blood distribution during emergency re-quests in developing countries. It is recommended to conduct further studies and implement practical initiatives to validate the findings, address any potential limitations, and investigate additional factors that may influence the implementation of UAV-based systems for emergency blood distribution.

Author Contributions

Conceptualization, J.D. and A.T.; methodology, J.D., A.T., and M.F.; software, J.D., and M.F.; validation, A.T., I.N., G.B., and Z.B.; formal analysis, J.D.; investigation, J.D.; resources, A.T., and M.F.; data curation, J.D.; writing—original draft preparation, J.D.; writing—review and editing, A.T., I.N., G.B., and Z.B.; visualization, J.D.; supervision, A.T.

and M.F.; project administration, A.T. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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