Vaccine: X 14 (2023) 100312

Contents lists available at ScienceDirect

Vaccine: X

journal homepage: www.elsevier.com/locate/jvacx

Vaccine distribution with drones for less developed countries: A case study in Vanuatu

Shakiba Enayati *, James F. Campbell, Haitao Li

Supply Chain and Analytics Department, College of Business Administration, University of Missouri, St. Louis, United States

A R T I C L E   I N F O

Article history:
Available online 15 May 2023

Keywords:
Vaccine distribution
Drones
Network design
Optimization model
Less-developed countries
Vaccine supply chain
Alternate vaccine delivery system

A B S T R A C T

Drones (uncrewed aerial vehicles or UAVs) introduce new opportunities to improve vaccine distribution systems, particularly in regions with limited transportation infrastructure where maintaining the cold chain is challenging. This paper addresses the use of drones to deliver vaccines to hard-to-reach populations using a novel optimization model to strategically design a multimodal vaccine distribution network. The model is illustrated in a case study for distributing routine childhood vaccines in Vanuatu, a South Pacific island nation with limited transportation infrastructure. Our research incorporates multiple drone types, recharging of drones, a cold chain travel time limit, transshipment delays for switching transport modes, and practical limits on the vaccine paths and drone trips. The goal is to locate facilities (distribution centers, drone bases, and relay stations) and design vaccine paths to minimize transportation costs, including the fixed costs for facilities and transportation links and variable costs for transportation through the network. Results show large potential cost savings and improved service quality provided by incorporating drones in a multimodal vaccine distribution system. Results also show the impact of introducing drones on the usage of other more expensive or slower transport modes.

1. Introduction

Drones (uncrewed aerial vehicles or UAVs) provide new opportunities to improve vaccine distribution systems, especially in hard-to-reach regions where vaccination programs are challenged by limited and slow transportation systems and/or poor cold chains. Small drones are particularly suited for transporting small amounts of vaccines quickly across regions without transport infrastructure and for delivery to remote locations. Large drones, similar to small airplanes, can carry larger doses of vaccines to remote airstrips that do not have regular air service. In this paper, we apply optimization models to minimize transportation costs for the distribution of routine childhood vaccines using two types of drones, with a case study for Vanuatu. Vanuatu is a nation of 83 mountainous, primarily small islands stretching across about 800 km of the South Pacific Ocean. It was the site of drone delivery trials in 2018 [1,2], which included the world's first vaccination of a child using commercial delivery of vaccine by a drone [3]. In this paper, we focus on the first step of in-country distribution of vaccines by optimizing vaccine transportation using drones and other transport modes from the national depot to local health zone distribution centers (DCs). For research on optimizing the second step of vaccine delivery in Vanuatu from the local health zone DCs to clinics and remote aid posts using small drones, see [4]. For more details on our earlier optimization models, see [4,5]. While our focus is on drone use in less developed countries (LDCs) which include hard-to-reach areas, our models can easily be applied to regions with better infrastructure, though the benefits of drones are likely to be smaller when existing transportation options are efficient and effective.

The benefits of re-designing vaccine supply chains are well documented and studies on vaccine supply chain redesign for global health include projects in Benin [6], Nigeria [7], Zambia [8] and the Democratic Republic of Congo [9,10]. There are several recent surveys of vaccine supply chain optimization modeling [11–13]; however, none of these surveys address the use of drones. A common tool for optimizing vaccine supply chains is mathematical programming and several recent papers develop models for different settings. Rastegar et al. [14] develop a multi-period location-inventory mixed integer linear programming (MILP) model for equitable distribution of COVID-19 vaccines in LDCs. Lim et al.

---

* Corresponding author.

E-mail addresses: senayati@umsl.edu (S. Enayati), campbelljf@umsl.edu (J.F. Campbell), lihait@umsl.edu (H. Li).

https://doi.org/10.1016/j.jvacx.2023.100312
2590-1362/Published by Elsevier Ltd.

[15] use an MILP model to locate DCs and clinics in a network with three transportation modes for Sub-Saharan Africa. Lim et al. [16] present a linear programming (LP) model for multi-period vaccine distribution in LDCs, with an application in Niger. Chen et al. [17] develop an MILP model for multi-period influenza vaccine supply chain network design. Yang et al. [18] develop a vaccine network design MILP model to optimize intermediate facility locations between the national depot and clinics, with applications to Sub-Saharan Africa. Recent work has also addressed the distribution of vaccines for COVID-19, usually in more developed settings. Xu et al. [19] provide a simple integer programming model to design a hub-and-spoke system that maximizes coverage for COVID-19 vaccine distribution, with an application in New Jersey. Georgiadis and Georgiadis [20] provide an MILP model for operational decisions in vaccine distribution with a fixed set of facilities. They solve the model with a decomposition heuristic and provide a case study for COVID-19 vaccines in Greece. None of the works above consider drones, nor do they have a transportation time limit to ensure the cold chain is maintained across a long distribution path with multiple stops and multiple modes of transport.

However, drones are now playing an important role in global healthcare, especially in Africa [21], and some research has considered drones for vaccine distribution in less developed regions. Haidari et al. [22] use the HERMES simulation software to evaluate integrating drones into the vaccine supply chain in Mozambique, with case studies showing about 20% cost savings. Walia et al. [23] present a binary programming model for a three-level hierarchical distribution network with trucks and drones, where drones are limited to the lowest tier. Prosser et al. [24] employ commercial supply chain network design software to study alternative supply chain designs, including the limited use of small drones in Madagascar and Guinea. Several recent studies employ optimization modeling for health care drone delivery in developed regions, with reliable road networks where trucks and drones can work together, in disaster relief and emergency settings [25–28]. There is also a growing literature of reports from field testing of drone delivery in LDCs, summarized in the Medical Drone Delivery Database [29]. In our research, we use drone data based on field experiences with drone delivery in less developed regions from [30].

The key features of our research, compared to prior optimization models for vaccine distribution, are that we (i) focus on the use of drones, (ii) model multiple travel modes with transshipments, (iii) optimize the facility locations (rather than using given locations), and (iv) include a cold chain travel time limit (i.e., the maximum time that a vaccine can be out of refrigeration on a vaccine path from a national depot to a DC), all to serve hard-to-reach less developed regions. In our study, we determine both the cost to transport vaccines and the service level (time from the national depot to the local DC) for multimodal trips across a region spanning hundreds of km. We adopt a strategic network flow perspective, rather than assuming vaccines are sent through a hierarchical set of distribution facilities (e.g., from national depot to provincial depot, then to regional depot, then to local depot). Our case study is an island nation (Vanuatu) that poses different challenges than do land regions, as boat transport and plane transport are heavily used, and ground (truck) transport is very limited. In a review of 19 prior studies about accessing hard-to-reach vaccination sites, Ozawa et al. [31] suggested that total costs were 1.3–2 times higher than in other regions, with the main determinants of "hard-to-reach" being geography (distance and terrain). Only 3 of 19 studies addressed routine immunization for "hard-to-reach" populations in lower middle-income countries and none addressed transportation costs specifically. Cox et al. [32] provides a comprehensive overview and a complex "systems map" of the economic considerations for getting vaccines to hard-to-reach populations.

2. Problem description

This research is motivated by recent testing of vaccine delivery using drones undertaken by the government of Vanuatu and UNICEF [33], which provided instrumental data and practical information for this research. Vanuatu is an LDC in the South Pacific with poor transportation infrastructure consisting of 63 inhabited islands in 6 provinces (see Fig. 1). The recent drone tests included two companies (Swoop Aero and Wingcopter) [34], and documented the feasibility of vaccine delivery by drones under real-world conditions in Vanuatu, and by extension in other LDCs. In this paper, we complement this documented practical success with an optimization model and case study to design a national-level vaccine distribution network with multiple transportation modes including drones. The goal is to identify what role drones would play in optimal vaccine distribution for LDCs, where there are challenges from long distances, infrastructure limitations, difficult terrain, and cold chain requirements. Drones possess unique advantages to overcome these challenges.

We model the strategic design of a distribution system for routine childhood vaccines (not emergency medical supplies). Vaccines that originate from a national depot must be distributed on a regular basis (e.g., monthly) to each local health zone vaccine distribution center (DC) (e.g., a hospital or clinic), where each DC stores the vaccines needed for its own health zone. The vaccine distribution network consists of a set of facilities and connecting transportation links that allow vaccines to be transported via various modes (boats, planes, trucks, drones, etc.). Each transportation link reflects the use of a particular mode (vehicle) to move vaccines

Fig. 1. Vanuatu map including the borders of 6 provinces. The national depot is in Shefa province. Black dots represent the DC candidates.

between two facilities, and each mode has a corresponding capacity, speed, cost, etc. The endpoints of the transportation links are the facilities in the network, and transport modes have associated facilities, as with airports for plane transportation. Because we are especially interested in the role of drones, we consider two types of drone facilities to be located: a drone base (DB) facility must be located at the beginning of any drone trip, and a drone relay station (RS) facility allows drones to be recharged (or have the battery swapped, or be refueled). Recharging allows a drone with a limited flight range to carry vaccines over a long distance. In general, the facilities in the vaccine distribution network model include one or more national depots, candidate locations for DCs, DBs and RSs, and transshipment locations (such as airports) to allow connection of two transport links. Each transportation link in the network reflects a particular transportation mode, so more than one transportation link may connect the same two facilities (locations). For example, two locations can be connected by boat, road, and drone transport. A vaccine path is a set of connected travel links, possibly via different modes, that provide a path for vaccines to be sent from the national depot to a health zone DC. This usually involves transshipments between multiple links (e.g., from a truck link to a boat link). Transshipment may incur a time to load/unload and switch vehicles, if needed.

The objective of our strategic vaccine distribution problem is to minimize the transportation costs for the vaccine flows through the network by: (1) selecting the locations of DCs, DBs, and RSs from a set of candidate locations, and (2) determining the vaccine paths from a national depot to one selected DC in each health zone. Each health zone has a given (monthly) demand for vaccines that must be delivered via some path (i.e., a sequence of transportation links) that does not violate the cold chain time limit, or other practical constraints. To ensure the drone range limits and the cold chain time limit are not violated, it is necessary to track both the vaccine travel time from leaving the national depot and the drone flight time once it begins a trip. The set of vaccine flows determines the amount of vaccine carried on each transportation link, as several paths may use the same link, and the cost to traverse a link depends on the vehicle type and the amount of vaccine sent. In some cases, as with small drones, multiple trips on a link in one month may be required to transport the needed vaccine. Finally, both the decisions on the facilities to open and the transportation links to use should be made concurrently.

To illustrate the problem for Vanuatu, Table 1 summarizes the characteristics of each province in Vanuatu to highlight the geographical disparity and demand variability. Demand is expressed in kg required per month, based on 17 doses of vaccines in the first year of a child's life; see Appendix B for details. These data reflect how provinces and health zones vary greatly, with the farthest province, Torba, having 14 widely separated islands grouped into 6 health zones with low demands (low population). In contrast, Sanma has 8 health zones on one large island (including small populations from five neighboring islands), and one health zone comprised of three smaller islands, where the largest health zone in Sanma has a demand over twice as large as the total demand for Torba Province. The last two columns of Table 1 show the distance from the national depot and the distance between the farthest DC candidates for each province.

3. Methodology

One approach to model vaccine distribution is to assume a hierarchy of facilities (e.g., provincial depots, regional depots, local depots) and allow transportation only between adjacent levels in the hierarchy (e.g., from the provincial depot to a regional depot). This may reflect administrative operations and it simplifies the distribution planning considerably, as well as the modeling (the set of decisions is restricted). However, it does not necessarily lead to an optimal distribution network. An alternative approach is to allow more freedom in the design by not assuming an exogenous hierarchy of facilities or restrictions on vaccine flows. This approach leads to better (lower cost) solutions, but also a larger and harder problem, as vaccine paths may be longer and more complex. In our research, we adopted this latter approach to seek better solutions and to explore how large are the benefits from using drones.

A key element for modeling vaccine distribution (and other perishable products) is tracking the time out of refrigeration. This is especially important in LDCs where reliable refrigeration during transport and in storage is limited. Our models include a cold chain travel time limit (e.g., 7 h) to ensure all vaccines traveling on any path to a DC remain viable on arrival at the DC. Further, because drones have a limited range (distance or endurance) our models track the drone travel time from the start of a drone trip or its most recent recharging, which may include multiple drone transportation links. We handle the time dimension implicitly in our models by encoding the time for both vaccine flows and drone trips into a layered ”feasible path network” (FPN). This virtual FPN is generated from the initial network (which reflects the real-world locations and transportation links) by tracing feasible vaccine paths and creating duplicate network nodes (locations) to reflect the different arrival times at a location (the use of ”layered” reflects the duplication of nodes into separate layers based on arrival time at the node). The FPN has more nodes (locations) than the initial network, due to the duplication of nodes for arrival times on different vaccine paths, but it has a simpler structure with directed links tracing the paths. For details on generating the layered FPN, see [5]. In spite of its size, the FPN allows for very efficient optimal solutions with a straightforward MILP. Another advantage of using an FPN is that it allows a wide variety of practical considerations (e.g., limiting the number of transshipments in a path) to be incorporated into solutions.

Our optimization model differs from earlier work in [5] by including mode transfer times (e.g., from plane to boat), setup times at the start of trips, and refined costs for drone transportation that depend on the payload (weight) carried. Our modeling framework is presented in four steps in Fig. 2. The first step is to collect the needed data on transportation modes and vehicles, demand for vaccines, transshipments, transportation links, and

Table 1

Characteristics of provinces of Vanuatu. Demand is in kg of vaccines (with diluent and ice/cooling packs). Distance from National Depot is to approximate center of the Province in km. HZ = health zone.

Province	# of Health zones	# of Inhabited Islands	Monthly Demand	Min Demand in a HZ	Max Demand in a HZ	Distance from National Depot	Size of Province
Torba	6	14	18.4	0.9	5.7	472.8	213.7
Sanma	9	9	89.1	3.6	37.1	294.9	123.3
Penama	10	3	48.1	2.2	6.5	267.9	75.6
Malampa	12	15	47.2	1.3	9.4	180.5	121.7
Shefa	3	15	28	3.6	14.2	-	122.8
Tafea	8	5	61.3	0.5	25.9	226.9	189.9

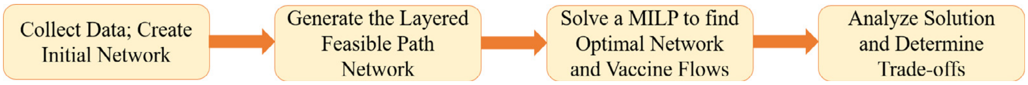

Fig. 2. Modeling framework of the vaccine network optimization.

available facility locations. The transportation links and facility locations provide the initial model network that reflects the real-world physical network. This includes geographic locations of the various (candidate) facilities and the relevant transportation links between them (e.g., drone links are shorter than the drone flight range, plane links reflect scheduled airline services, etc.). Each location in the model (as in the real-world) can correspond to more than one facility type (i.e., a location may be an airport, and a candidate DC and RS). Every transportation link is mode specific and may have an associated capacity, distance, travel time, fixed cost to establish the link, and a variable cost per unit of distance or time, all reflecting travel by the appropriate vehicle type (e.g., boat, scheduled airline, truck, small drone, etc.).

The second step is to generate the layered feasible path network (FPN) from the initial model network. The FPN ensures that all vaccine paths to be considered in the optimization step obey the cold chain travel time requirement, and that all drone trips do not exceed the drone range (i.e. that drones are recharged at an RS before exceeding the drone flight range). The FPN can also reflect a limit on the number of transshipments in a vaccine path, as too many transshipments may endanger the cold chain and require more complex coordination and synchronization in practice. Generating the FPN is implemented using the ”all-simple-edge-paths” algorithm from NETWORKX library in PYTHON.

The third step in the modeling framework is to solve an MILP using the FPN that minimizes the total transportation cost to meet all health zone demands. This provides the optimal set of DC, DB, and RS facilities and the optimal vaccine flows on the transportation links. The cost in our model includes: (i) fixed costs for opening and operating DCs, DBs, and RSs, (ii) fixed costs of establishing transportation links, and (iii) transportation costs based on the amount and distance that vaccines must travel. The transportation cost reflects the capacity of the transportation vehicle, as large vehicles (e.g., a truck) may make a single trip per month carrying all the vaccine needed for that month, while a smaller vehicle (e.g., a small drone) may make multiple trips per month to carrying the required vaccine. Thus, when the vehicle capacity is large relative to the demand, monthly transportation cost is a fixed cost (i.e., the cost is independent of the vaccine volume being sent). Alternatively, when the volume of vaccines on a link exceeds the vehicle capacity, then multiple vehicle trips on the link are needed, and the cost depends on the volume transported on the link. The cost function is detailed in Appendix A.

The main constraints for the optimization (MILP) model can be categorized as follows:

1. Select (open) exactly 1 DC in each health zone.
2. Ensure each health zone receives the required vaccine volume (demand) at its selected DC.
3. Ensure the total amount of vaccine shipped out of each national depot does not exceed the depot supply.
4. Ensure conservation of vaccine flows (the vaccine flowing into a location equals the vaccine used to satisfy demand at the location plus the vaccine flowing out of the location).
5. Ensure that no transportation link carries more vaccine than its monthly capacity.
6. A DB is located at the start of every drone path, where a drone path is a sequence one or more drone flights.
7. An RS to recharge drones is located when needed, to ensure no drone paths exceed the drone range.

This model provides considerable flexibility for the vaccine paths as DC locations may serve as transshipment points. For example, a vaccine path might include five transportation links using three modes (including three links by a small drone using a recharge) as follows: (i) from a national depot to an airport by plane; (ii) from the airport to the DC for HZ 1 by truck; (iii) from the DC for HZ 1 to the DC for HZ 2 by small drone; (iv) from the HZ for DC 2 to an RS; (v) from the RS to the DC for HZ 3 by small drone. Our model allows multiple types of drones, where each has a distinct DB and RS. The MILP optimization model is solved using an off-the-shelf solver, e.g., Gurobi Optimizer.

Step 4 of the framework is to analyze results, generate service performance for the optimal vaccine paths and assess the cost and service trade-offs. One important trade-off is between the complexity and length of the vaccine path and the transportation costs (longer paths with more transshipments and slower, lower-cost transportation may provide lower transportation costs). However, our optimization model provides flexibility to the decision maker to adjust the service requirements while systematically determining the minimal cost network design; see Section 4.3. For details on the methodology and examples see [5].

4. Case study of Vanuatu

In this section, we describe the implementation of our modeling framework on a case study in Vanuatu. To keep the results clear, we focus on three scenarios and highlight key insights about drone use.

4.1. Data

Vanuatu consists of 6 provinces with a total population of about 307,000, with about 9000 children born each year. It is divided into 48 health zones, with 3 to 12 health zones per province, where large islands may include several health zones and small neighboring islands may collectively form a single health zone. Vanuatu includes three main airports and 24 other minor ”airports”, that are mostly grass or dirt airstrips, on 20 of the islands. Currently, vaccines from foreign countries arrive and are stored at a single national depot in the capital city Port Vila, in Shefa Province. (The inbound vaccine supply chain to Port Vila is not considered in this research.) There are very limited roads, and limited plane service, with extensive opportunities for boat transport. In addition to planes (reflecting scheduled airline service of Air Vanuatu), boats and trucks, we consider two types of drones: large fixed-wing drones (LFW) and small fixed-wing drones (SFW). SFWs are small battery-powered drones that can take off from and deliver to sites without additional infrastructure, and can have their batteries changed or charged. LFWs are like small aircraft, have a large payload capacity (greater than the monthly demand of any province), require runways for takeoff and landing, and use liquid fuel (e.g., gasoline). Thus, a ”recharge” for a LFW is actually a refueling. We assume a transfer time for every transshipment which depends on the incoming and outgoing transportation modes. Based on the drone characteristics, and geographic and health data for Vanuatu, we created data sets for all provinces including relevant airports, boat ports, candidate locations for DC, DB, and RS, and the relevant transportation links between pairs of locations. The demand for each health zone is the average monthly weight of vaccines, including diluents and cooling packs, for 17 doses of nine types of vaccines in a child’s first year, from [33]. Data details are included in Appendix B.

4.2. Scenarios

The goal of our case study is to estimate the value of employing two types of drones for multi-modal vaccine distribution in Vanuatu. In the next section, we compare cost and service measures for all six provinces of Vanuatu, and for the country as a whole, in three scenarios:

- Baseline scenario (B): this is based on current practice without any drones. For the baseline, vaccine distribution is organized by province with vaccines first sent from the national depot by airplane to six provincial depots; then, vaccines are sent from the provincial depots to the health zone DCs by combinations of boats, trucks, and airplanes.
- Optimized with no drones (OND) scenario: this is the minimum cost solution from our optimization modeling using only airplanes, boats, and trucks as available modes. This scenario does not require transportation first to the provincial depot.
- Optimized with drones (OD) scenario: this is the minimum cost solution from our optimization modeling with all transportation modes available, including both LFW and SFW.

For OND and OD scenarios, the cold chain limit is assumed to be 7 h. This is based on the general guidelines in [35] to transport vaccines for a maximum of 8 h (even though repeated replenishment of cold packs might be able to keep vaccines cooler for longer). We consider a 1-h ”cushion” for unexpected delays. Also, in the OND and OD scenarios, the maximum number of transshipments on a vaccine path is set at either 3, 4, or 5 (depending on the distance of the province from the national depot). The maximum number of drone stops per vaccine path is set to 3, to allow flexibility beyond single drone flights. These limits are based on our preliminary results on the added value of allowing longer and more complex paths, see Section 4.3.

4.3. Results

Fig. 3 shows the total transportation cost for the three scenarios for each province. The percentage savings for the OND solution range from 0% to 27%, which shows that in some cases optimizing distribution without adding drones can be useful. Farther provinces from the national depot tend to have larger costs, as expected, but the relative savings seem little related to distance from the national depot. The percentage savings from using drones (scenario OD versus scenario B) ranges from 40% to 61% across the six provinces. This shows strong potential for drones to reduce transportation costs in all provinces. While the amount of savings tends to be larger in the provinces with a more expensive baseline (i.e., more remote provinces), the relative savings as a percentage of baseline cost seem rather stable at 45–61% for the provinces that do not include the national depot. For Vanuatu as a whole, the aggregated savings total 53%. The savings with drones (OD) relative to optimized distribution without drones (OND) (not shown in Fig. 3) is a little smaller at 35% to 52% across the six provinces, and totals 47% in aggregate for Vanuatu.

Fig. 4 illustrates the cost per dose and service for each province and for Vanuatu in aggregate. The service measure is the average delivery time to the selected DCs weighted by their required demands. Arrows connect the same province from the Baseline solution (blue) to the Optimized with Drones solution (orange). This clearly shows that: (1) Drones reduce costs for every province, sometimes substantially (e.g., Torba), (2) Drones reduce the average delivery times for farther provinces (on the right), but may increase the average delivery time a small amount for some provinces (e.g., Tafea and Sanma), (3) In aggregate (summed over all provinces), drones both reduce cost and improve service.

However, Fig. 4 with average service times does not capture the distribution of delivery times across the provinces. Fig. 5 illustrates the percentage of vaccine doses delivered within every hour for 3 provinces (Malampa, Tafea, and Sanma) that have the same average delivery time of 2.5 h (see the three vertical blue dots in Fig. 4). Observe in Fig. 5 that Sanma has a maximum delivery time of over 8 h, while Malampa has a maximum delivery time of 5 h and Tafea has a maximum delivery time of only 4 h. The OD solution with drones does not include any deliveries above 7 h due to enforcing the cold chain time limit. Fig. 6 provides aggregated delivery time results for Vanuatu to illustrate how optimizing cost also improves service in aggregate (relative to the baseline), especially by increasing the percentage of vaccine doses delivered in 2-3 h and eliminating any long deliveries.

To illustrate the differences in vaccine distribution with drones, Fig. 7 shows the Baseline scenario, and Fig. 8 shows the OD solution for Malampa Province. In the Baseline, the total demand of the province (51 kg) is sent by plane from the national depot (not shown in the figure) to the provincial depot (location 14). From the provincial depot, the vaccine demands of all health zones are distributed by either truck, plane, or boat. The unusual plane paths (e.g., locations 14 to 101 and then 100) are due to the limited availability of plane flights in the Air Vanuatu schedule. The total transportation cost in the baseline scenario is 53, 400 ¢. Under the OD

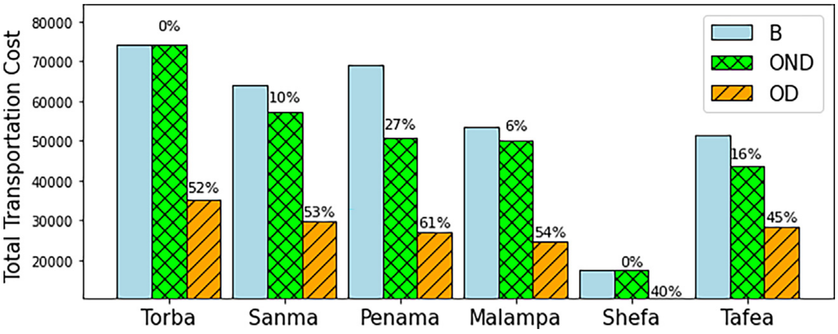

Fig. 3. Total transportation cost for each province under the Baseline (B), optimized with no drones (OND), and optimized with drones (OD) scenarios. The numbers atop the bars show the percentage savings relative to the baseline scenario.

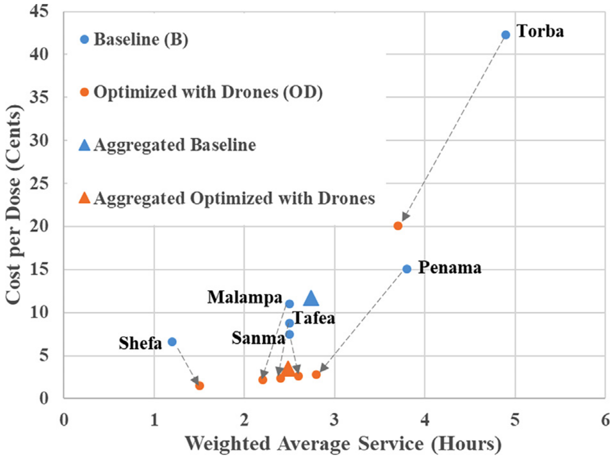

Fig. 4. Cost and service trade-off for the Baseline (B) versus the Optimized with Drones (OD) scenario for each province and for Vanuatu in total (”Aggregated”).

scenario (Fig. 8), the total demand of the province (51 kg) is sent by LFW drone to location 19, and then the LFW drone continues on to the provincial depot 14 with 27 kg to be distributed by SFW drones for health zones in the far north of the province. The rest of the health zones are served by SFW drones from a drone base at location 19. Thus, there are two SFW drone bases, at locations 19 and 14, and one LFW drone base at location 0 (the national depot). The total transportation cost under scenario OD is 24, 829 ¢ (53% lower than the Baseline scenario). Even though the maximum number of drone stops (for each drone type) was set to 3, in the optimal solution every vaccine path includes only 1 or 2 drone stops for LFW or SFW. Interestingly, in the OD solution, the demand at location 17 (4.5 kg) is met via 2 vaccine paths; 0.5 kg from location 19 to 18 to 17, and 4 kg through provincial depot 14. This is to make efficient use of the limited capacity of SFW (4 kg), and shows how optimization provides the flexibility to meet the demand using alternative paths that minimize total cost. A similar distribution plan is used to meet the 4.6 kg demand at location 30 (4 kg through location 19 and 0.6 through location 36). If each DC was required to be served on a single vaccine path, that condition could be easily added to the optimization model. In this example, adding such a limitation would increase costs by about 12% (The alternative solution to meet the demand at DC location 17 is to send 31.5 kg by LFW from 19 to the provincial depot 14, and then use two SFW trips to send 4.5 kg from 14 to 17; the alternative to meet demand at DC location 30 is to use two SFW trips to send 6.5 kg from 19 to 36, and two SFW trips to send 4.6 kg from 36 to 30.).

The above results for scenario OD used a limit of 3 transshipments per vaccine distribution path. This was determined after an initial analysis of the trade-off between solution quality (cost and service) and required computational time. We observed that considering 4 transshipments instead of 3 would only result in less

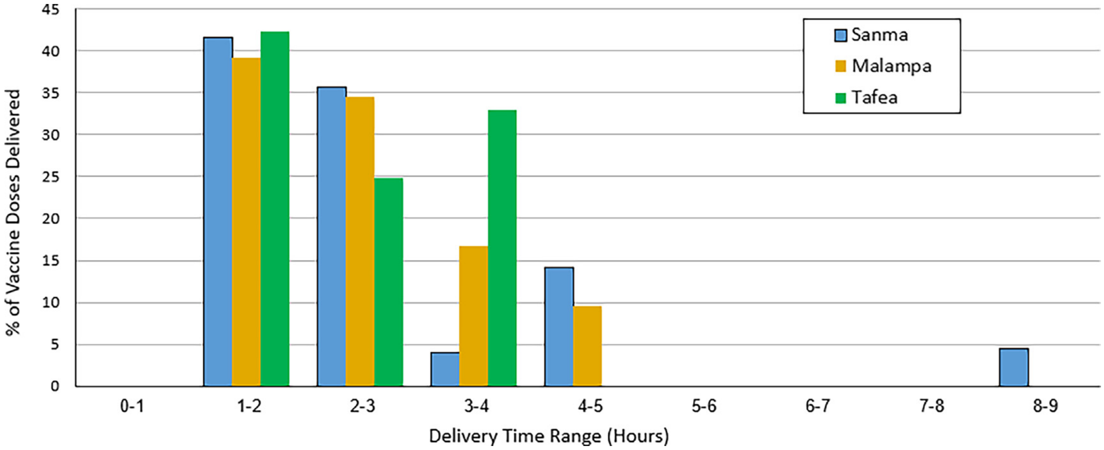

Fig. 5. Distribution of delivery time under the baseline scenario for 3 provinces with a weighted average service of 2.5 h.

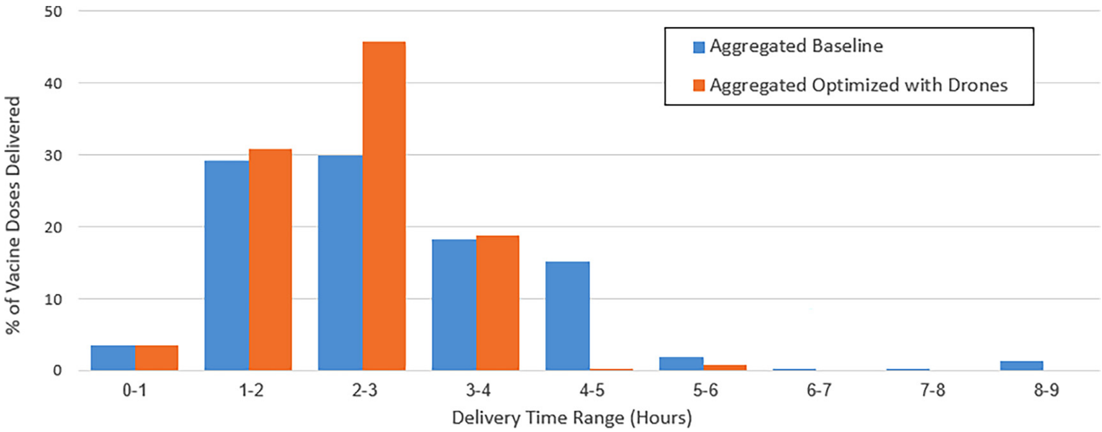

Fig. 6. Distribution of delivery time for the Baseline (B) and Optimized with Drones (OD) scenarios aggregated over all provinces.

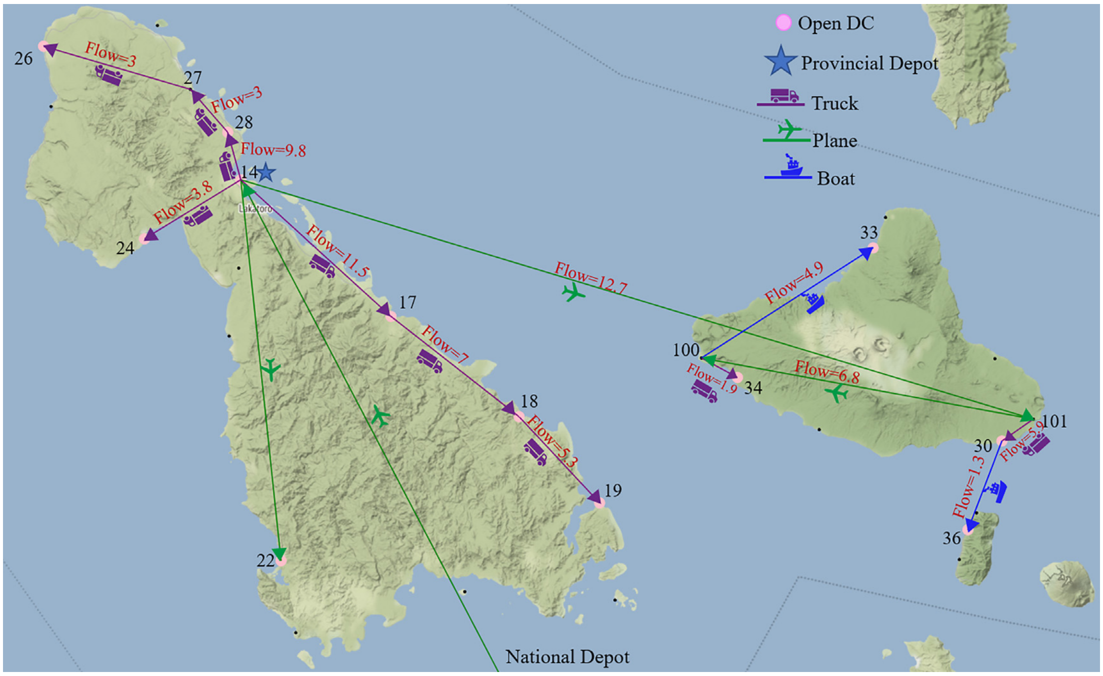

Fig. 7. Solution of the baseline scenario (B).

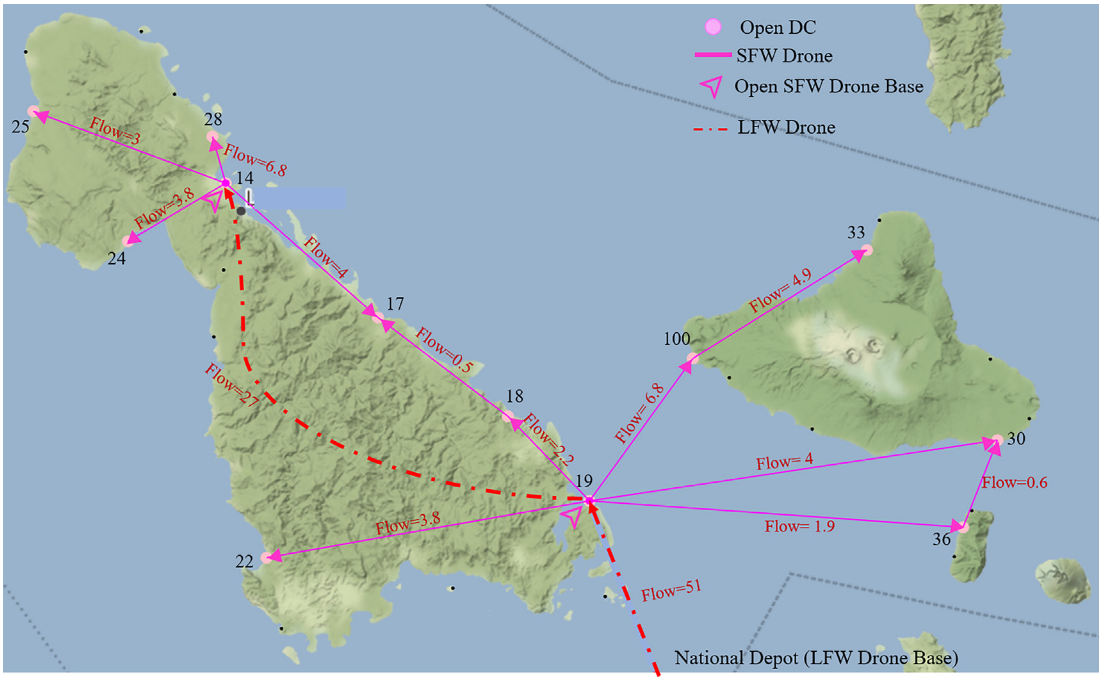

Fig. 8. Solution of the optimized scenario with drones (OD).

than 1% lower total cost while increasing the computational time over 500%. Interestingly, while allowing more transshipments per vaccine path can reduce the total cost, it may worsen service. For instance, in Torba, moving from 3 and 4 transshipments per path increases the average weighted delivery time (weighted by the vaccine demands) from 3.7 to 3.9 hrs, while the cost decreases by 0.85%. We observed small savings when moving from 4 to 5 transshipments per vaccine path (less than 3%), which may be considered not significant.

We also highlight how the introduction of drones naturally changes the use of other transport modes. As shown in Figs. 7,8, for Malampa Province the LFW and SFW drones completely replace the other modes (boat, truck, and plane). However, in other provinces planes are still used (to meet the cold chain requirement), and other settings might well use some boat or truck links. In aggregate for Vanuatu, in the OD scenario, the percentage of distance traveled by SFW, LFW, and plane is 57.4%, 39.6%, and 2.9%, respectively. In contrast, in the Baseline scenario, the percentage

Table 2
Summary of the relevant notation for the input sets and parameters.

$E^{\mathscr{M}}$	set of transportation links from location i to location $j$for transportation mode m
$E_T^{\mathscr{M}}$	set of all possible layered links (i_r, j_t, m) (reached via different feasible paths) from location i arrived at time r to location $j$arrived at time t via transportation mode m.
$\mathscr{M}$	set of all transportation modes.
$\mathscr{M}^D$	set of drone modes, $\mathscr{M}^D \subseteq \mathscr{M}$, to allow for different types of drones
$\mathscr{S}$	set of national depots
$\mathscr{D}$	set of distribution center candidates
$\mathscr{B}^m$	set of drone base candidates for drone type m
$\mathscr{R}^m$	set of relay station candidates for drone type m
$\mathbb{f}$	set of facility types to be located; $\mathbb{f} = \{DC, DB, RS\}$
κ_1^m	vaccine capacity limit (kg) for a vehicle of transportation mode m
κ_2^m	mass (kg) of an empty vehicle of transportation mode m
$\mathscr{C}^{\{i,f\}}$	fixed cost of opening and operating facility type $f \in \mathbb{f}$ at location i
$\mathscr{F}^{(i,j,m)}$	fixed cost of establishing the transportation link from location i to location $j$using transportation mode m
$\Delta^{(i,j,m)}$	distance from location i to location $j$via transportation mode m
$\zeta^{(i,j,m)}$	variable cost of vaccine flow ($/traversal) on link between location i and j via transportation mode m

of distance traveled by boats, trucks, and planes is 73.2%, 18.2%, and 8.5%, respectively. Effectively, the availability of LFW and SFW drones allows the LFW drones to replace most plane trips and the SFW drones to replace the slower and more expensive truck and boat trips.

5. Conclusion

This paper presents an optimization-based modeling framework to strategically design a vaccine distribution network with drones and other modes of transport. The modeling framework is flexible to take practical considerations set by the decision maker as model inputs, such as the maximum number of transshipments and drone stops per trip, the transfer time when switching modes along the way, and the setup time at the start of the trip. Also, the transportation cost considers the limited capacity of a vehicle of a particular transport mode (e.g., small drone) in the calculation of required trips to make deliveries. The results show both cost savings and improvements in service (delivery time) as illustrated in a case study for Vanuatu, a less-developed country with limited transportation infrastructure. Results also show that using the proper type of drone (sometimes mixed with other available transportation alternatives) results in cost savings of 40% to 61% compared to a baseline where no drones are used and no optimization is performed. Furthermore, results illustrate that the value of drones is consistently high across different geographies (savings ranging between 35% to 52%) even if the optimization is performed for distribution without drones. Finally, the value of flexible network structure has become evident. That is, forcing all the required demands to be first shipped to a provincial depot and then distributed to all health zones in a province does not result in the lowest total cost and the most efficient delivery service. Our modeling framework is applicable to other LDCs, and more broadly to any other settings. However, it is expected that the greatest benefit from using drones and optimization of vaccine distribution network design is in hard-to-reach areas with limited transportation infrastructures. Real-world implementation would require the support of the ministry of health and local staff to explore integrating drones and optimization into their vaccine supply chain. Furthermore, variability in the real-world setting needs to be accounted for in any implementation. Future research can incorporate equity and uncertainty of delivery time to all health zones into the optimization process. Also, modeling bi-directional drones [36] is a promising and novel future research direction.

Data availability

Data will be made available on request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge support for this research from the Association for Supply Chain Management (ASCM) and the University of Missouri Research Board.

Appendix A. Model formulation details

The modeling framework used in this paper is built upon the Mixed Integer Linear Programming (MILP) layered network model developed in [5]. The decision variables of this optimization model are as follows:

- $u_{i,j}^m$: binary variable taking value 1 if the transportation link from location i to location j via transportation mode m is selected for the vaccine delivery, 0 otherwise.
- x_i: binary variable taking value 1 if DC candidate i is selected to operate, 0 otherwise.
- y_i^m binary variable taking value 1 if DB candidate i is selected to operate for drone type m, 0 otherwise.
- z_i^m binary variable taking value 1 if RS candidate i is selected to operate for drone type m, 0 otherwise.
- $f_{i_r,j_t,m}^{s,d} \geqslant 0$: continuous variable representing vaccine flow (kg) on the link from location i at time r to location j arriving at time t via transportation mode m that originated from national depot s and is to be delivered to DC candidate d.
- $t_{i,j}^m \geqslant 0$: integer variable representing the number of trips needed to distribute the vaccine flow from location i to location j by a vehicle of transportation mode m

For brevity, we here discuss only the new additions and modifications to the model from Enayati et al. [5]. Notation is in Table 2. To account for the cost of multiple trips due to the limited capacity of the SFW drone, we use the following objective function to compute cost:

$$\begin{aligned}\min \sum_{i\in\mathscr{D}} \mathscr{C}^{\{i,DC\}} x_i + \sum_{m\in\mathscr{M}^D} \sum_{i\in\mathscr{B}^m} \mathscr{C}^{\{i,DB\}} y_i^m + \sum_{m\in\mathscr{M}^D} \sum_{i\in\mathscr{R}^m} \mathscr{C}^{\{i,RS\}} z_i^m \\ + \sum_{(i,j,m)\in E^{\mathscr{M}}} \mathscr{F}^{(i,j,m)} u_{i,j}^m + \sum_{(i,j,m)\in E^{\mathscr{M}}} \frac{\kappa_2^m \times \zeta^{(i,j,m)}}{\kappa_1^m + \kappa_2^m} t_{i,j}^m \\ + \sum_{s\in\mathscr{S}} \sum_{d\in\mathscr{D}} \sum_{(i_r,j_t,m)\in E_T^{\mathscr{M}}} \frac{\zeta^{(i,j,m)}}{\kappa_1^m + \kappa_2^m} f_{i_r,j_t,m}^{s,d}\end{aligned} \tag{1}$$

The objective function (1) minimizes the total operating costs consisting of five terms. The first three terms include the fixed setup cost of opening DCs, DBs and RSs, respectively. The fourth term is the fixed cost of establishing the link (arc) between two locations via a particular transportation mode. The fifth term calculates the cost of multiple trips required to distribute the vaccine flow between two locations via a vehicle with limited capacity. The final term is the variable transportation cost of vaccine flow through the

Table 3
Summary of geographic data for all provinces

Province	# of Locations				# of Transportation Links				
	DC Cand.	**SFW DBs/RSs**	**LFW DBs/RSs**	**All**	**Boat**	**Truck**	**Plane**	**SFW**	**LFW**
Torba	8	9	4	9	49	2	8	64	11
Sanma	20	19	1	20	220	57	1	340	1
Penama	19	21	5	21	321	86	1	420	25
Malampa	26	27	6	27	628	105	10	667	36
Shefa	5	13	5	14	76	10	3	110	16
Tafea	13	15	6	17	44	77	13	134	27

network. In the Vanuatu case, given the monthly demand level, the SFW drone is the only vehicle with limited capacity. Therefore, the last two terms only apply to the SFW drones.

In addition to the MILP constraints in [5], we add the following constraint to determine the required number of trips depending on the vaccine flow:

$$\kappa_1^m t_{i,j}^m \geqslant \sum_{s\in\mathscr{S}}\sum_{d\in\mathscr{D}}\sum_{(i_r,j_t,m)\in E_T^{\mathscr{M}}} f^{s,d}_{i_r,j_t,m}, \;\forall (i,j,m)\in E^{\mathscr{M}}$$

Appendix B. Vanuatu Data

We used a wide variety of sources from Vanuatu and the global health community for the Vanuatu case study data. Monthly demand data for each health zone is based on the number of ”fully immunized children” (FIC) born over 12 months, from Gustiana [37]. In their first year of life, each FIC in Vanuatu is to receive 17 doses of 9 different vaccines which total 123.3 cc of vaccine (and diluent) weighing 178 grams. Transportation guidelines indicate a need for about 2.5 grams of icepacks for every gram of vaccine [33]. Thus, the average monthly demand is about 52 grams per FIC per month. Note that this weight includes all necessary packaging, cooling packs, sensors, etc. to ensure safe delivery of vaccines by drones.

We identified candidate DC locations in Vanuatu using detailed data from Vanuatu including Gustiana [37] and detailed ”Health Facility Location & Population Catchment Maps” from the Vanuatu Ministry of Health for each province, while verifying with images from Google Maps. LFW drones require a runway, and therefore the LFW DBs and RSs were at airports/airstrips in Vanuatu. These were identified from public sources, and verified with web searches and on Google maps. There are three large airports in Vanuatu, and to avoid conflicts between small drones and low-flying aircraft, these large airports were not considered as DB or RS candidate locations for SFW drones. All other airports and all DC candidates were considered as SFW DBs and SFW RSs. Truck and boat travel links were identified by detailed analysis of the ”Health Facility Location & Population Catchment Maps” and Google Maps. Airplane links were identified using the online airline schedules from Air Vanuatu and from Google Flights. We included LFW drone links for all airport pairs (LFW DB candidates) within the LFW drone range. We defined SFW drone links for pairs of SFW DB candidate locations within the SFW drone range.

Table 3 provides information on the locations and transportation links for all provinces. Column ”All” under ”# of Locations” consists of non-DC transshipment locations and airports in addition to DC, DB and RS candidates for each drone type. In our Vanuatu data set, every DB candidate of a drone type is an RS candidate as well. This table shows that 78% of the existing transportation links (for the Baseline) are for boats, 20% are for trucks and 2% are for planes. However, this varies across the provinces with Tafea having most of its health zones (and DC candidates) on Tanna Island with batter roads, so only 33% of the total links in the baseline are boat links and 58% are truck links. All other provinces have 78%-85% boat links. Once drones are introduced, then the majority of links are for SFW with 49% in aggregate, and ranging from 45% to 55% across the provinces. The LFW drone links are a small number (only 3.3% of the total links, since they must connect airports), but are valuable to allow expensive plane trips to be replaced. In summary, a large number of drone links are possible, and the total

Table 4
Mode-Specific Case Study Data

Parameter	Values				
	m=Boat	**m=Truck**	**m=Plane**	**m=SFW**	**m=LFW**
κ_1^m (kg)	200	200	3400	4	230
κ_2^m (kg)	-	-	-	16	-
$\mathscr{F}^{(i,j,m)}$ ($/month)	$2.0\times\Delta^{(i,j,m)}$	$1.0\times\Delta^{(i,j,m)}$	$0.75\times\Delta^{(i,j,m)}$	0.4	$0.55\times\Delta^{(i,j,m)}$
$\zeta^{(i,j,m)}$ ($/traversal)	-	-	-	$0.14\times\Delta^{(i,j,m)}$	-
drone range (hours)	-	-	-	2.14	2.5
speed (km/hr)	25	50	300	70	200

Table 5
Transfer times when switching modes and setup time at the start of every trip at the national depot.

	Transfer Times (hour)					Setup Time at National Depot (hour)
from/to	Truck	Boat	Plane	LFW	SFW	
Truck	0.2	0.2	0.3	0.3	0.3	0.1
Boat	0.2	0.2	0.3	0.3	0.3	0.2
Plane	0.3	0.4	0.5	0.3	0.3	0.2
LFW	0.2	0.4	0.3	0.2	0.3	0.2
SFW	0.2	0.3	0.3	0.3	0.2	0.1

number of links to consider in vaccine paths is more than doubled by adding the SFW and LFW drones.

Table 4 summarizes the transportation mode-specific data used in our case study. LFW drones have a long range of 500 km with a 2.5 h range (200 km/hr speed). SFW drones have a shorter range of 150 km with a 2.14 h range (70 km/hr speed). The fixed facility costs are $15 and $5 per month for DBs and RSs, respectively. Assessing fixed costs for DBs and RSs is a challenge because the number of drone operations for routine vaccine distribution is not likely to be large, and thus vaccine distribution should represent a small fraction of DB and RS operations, and costs. Further, drone service providers may incorporate fixed costs within the variable charges for drone flights. The values considered here reflect low levels of fixed facility cost to explore the extent that drones might be used. The fixed costs for all DC candidates are set to zero in the modeling, as using the same values for all DCs does not affect the optimization. The fixed and variable transportation link costs are reported in Table 4, using values from [30] as a transportation rate multiplied by the link distance $\Delta^{(i,j,m)}$ (in km), except for the fixed link cost for SFW drones, which is $0.4/month to account for the need to ensure a safe and reliable drone path. The large vehicles (boats, trucks, planes and LFW) will make only a single trip on a link per month, so the transportation cost is treated as fixed. The variable link cost (per link traversal) is required only for the SFW drone as it has a low payload capacity of 4 kg that may result in multiple drone flights per month on a link. Effectively, the SFW drone is the only transportation mode in the case study with a limited capacity in relation with the monthly demands.

The vaccine path travel time limit is set as 7 h. This follows the recommendations for keeping transport time to less than 8 h [38,39], which we operationalize as a 7-h time limit to allow a 1-h buffer for delays and transshipment. We consider mode transfer times and setup times at the start of the trip as shown in Table 5. The detailed data used in this research is available from the authors.

References

[1] Wingcopter. Comprehensive Summary - Vaccine delivery service in Vanuatu; (2019). Available at https://www.unicef.org/innovation/media/11956/file/Reference, Accessed August 1, 2021.

[2] Ltd Swoop Aero Pty. Transportation of Vaccine and Medical Supplies Using Drone - Vanuatu Final Report. Seattle: VillageReach; 2019.

[3] UNICEF, Child given world's first drone-delivered vaccine in vanuatu - unicef; 2018. Retrieved from https:https://www.unicef.org/press-releases/child-given-worlds-first-drone-delivered-vaccine-vanuatu-unicef, Accessed August 25, 2021.

[4] Pan D. Optimizing vaccine supply chains with drones in less-developed regions: multimodal vaccine distribution in Vanuatu Ph.D. thesis. University of Missouri-Saint Louis; 2021.

[5] Enayati S, Li H, Campbell J, Pan D. Multi-modal vaccine distribution network design with drones for less developed countries. Transport Sci 2023. Forthcoming).

[6] Brown ST, Schreiber B, Cakouros BE, Wateska AR, Dicko HM, Connor DL, Jaillard P, Mvundura M, Norman BA, Levin C, et al. The benefits of redesigning benin's vaccine supply chain. Vaccine 2014;32:4097–103.

[7] Aina M, Igbokwe U, Jegede L, Fagge R, Thompson A, Mahmoud N. Preliminary results from direct-to-facility vaccine deliveries in Kano, Nigeria. Vaccine 2017;35:2175–82.

[8] VillageReach, Finding efficiencies in Zambia's immunisation supply chain; 2017. Available at http://www.villagereach.org/wp-content/uploads/2017/09/Finding-Efficiencies-in-Zambia-iSC_FINAL.pdf, Accessed August 1, 2021.

[9] Thomas D, Motomoke E, Crawford J, Defawe O, Makaya A, Ngwato JW, Bompongo J, Monzembela J, Ailstock G, Bancroft E, et al. Optimized supply chain model reduces health system costs in DRC. Vaccine 2021;39:4166–72.

[10] VillageReach, Increasing access to health products in the DRC to the next generation supply chain initiative; 2018. Available at https://www.villagereach.org/wp-content/uploads/2018/09/Increasing-Access-to-Health-Products-in-the-DRC.pdf, Accessed August 1, 2021.

[11] De Boeck K, Decouttere C, Vandaele N. Vaccine distribution chains in low-and middle-income countries: A literature review. Omega 2020;97:102097.

[12] Lemmens S, Decouttere C, Vandaele N, Bernuzzi M. A review of integrated supply chain network design models: Key issues for vaccine supply chains. Chem Eng Res Des 2016;109:366–84.

[13] Duijzer LE, van Jaarsveld W, Dekker R. Literature review: The vaccine supply chain. Eur J Oper Res 2018;268:174–92.

[14] Rastegar M, Tavana M, Meraj A, Mina H. An inventory-location optimization model for equitable influenza vaccine distribution in developing countries during the COVID-19 pandemic. Vaccine 2021;39:495–504.

[15] Lim J, Norman BA, Rajgopal J. Redesign of vaccine distribution networks. Int Trans Oper Res 2022;29:200–25.

[16] Chen S-I, Norman BA, Rajgopal J, Assi TM, Lee BY, Brown ST. A planning model for the WHO-EPI vaccine distribution network in developing countries. IIE Trans 2014;46:853–65.

[17] Hovav S, Tsadikovich D. A network flow model for inventory management and distribution of influenza vaccines through a healthcare supply chain. Oper Res Health Care 2015;5:49–62.

[18] Yang Y, Bidkhori H, Rajgopal J. Optimizing vaccine distribution networks in low and middle-income countries. Omega 2021;99:102197.

[19] Xu X, Rodgers MD, Guo WG. A hub-and-spoke design for ultra-cold covid-19 vaccine distribution. Vaccine 2021;39:6127–36.

[20] Georgiadis GP, Georgiadis MC. Optimal planning of the covid-19 vaccine supply chain. Vaccine 2021;39:5302–12.

[21] Stokenberga A, Ochoa MC. Unlocking the Lower Skies: The Costs and Benefits of Deploying Drones across Use Cases in East Africa. Washington, DC, World Bank: International Development in Focus; 2021.

[22] Haidari LA, Brown ST, Ferguson M, Bancroft E, Spiker M, Wilcox A, Ambikapathi R, Sampath V, Connor DL, Lee BY. The economic and operational value of using drones to transport vaccines. Vaccine 2016;34:4062–7.

[23] Walia SS, Somarathna K, Hendricks R, Jackson A, Nagarur N. Optimizing the emergency delivery of medical supplies with unmanned aircraft vehicles. In: Proceedings of the IISE annual conference and expo, Orlando, FL, USA. p. 19–22.

[24] Prosser W, Folorunso O, McCord J, Roche G, Tien M, Hatch B, Spisak C, Genovese E, Pare B, Donatien K, et al. Redesigning immunization supply chains: Results from three country analyses. Vaccine 2021;39:2246–54.

[25] Kim SJ, Lim GJ, Cho J, Côté MJ. Drone-aided healthcare services for patients with chronic diseases in rural areas. J Intell Robotic Syst 2017;88:163–80.

[26] Ghelichi Z, Gentili M, Mirchandani PB. Logistics for a fleet of drones for medical item delivery: A case study for Louisville. KY, Comput Oper Res 2021;135:105443.

[27] Gentili M, Mirchandani PB, Agnetis A, Ghelichi Z. Locating platforms and scheduling a fleet of drones for emergency delivery of perishable items. Comput Industr Eng 2022;168:108057.

[28] Rabta B, Wankmüller C, Reiner G. A drone fleet model for last-mile distribution in disaster relief operations. Int J Disaster Risk Reduct 2018;28:107–12.

[29] UPDWG, Medical Drone Delivery Database (2021). (UAV for Payload Delivery Working Group), Available at https://www.updwg.org/md3/, Accessed August 1, 2021.

[30] JSI Research & Training Institute Inc. and Llamasoft, What should you deliver by autonomous aerial systems? tool for determining cost effective use cases for AAVs, January 31, 2019 (2019). Available at https://www.updwg.org/resource-library/all-resources/page/11/, Accessed August 1, 2021.

[31] Ozawa S, Yemeke TT, Mitgang E, Wedlock PT, Higgins C, Chen H-H, Pallas SW, Abimbola T, Wallace A, Bartsch SM, et al. Systematic review of the costs for vaccinators to reach vaccination sites: Incremental costs of reaching hard-to-reach populations. Vaccine 2021;39:4598–610.

[32] Cox SN, Wedlock PT, Pallas SW, Mitgang EA, Yemeke TT, Bartsch SM, Abimbola T, Sigemund SS, Wallace A, Ozawa S, et al. A systems map of the economic considerations for vaccination: Application to hard-to-reach populations. Vaccine 2021;39:6796–804.

[33] Ministry of Health Vanuatu, Request for tender (RFT) physical services (2018). Retrieved from https://www.unicef.org/innovation/reports/vanuatu-drone-trial-report, Accessed February 12, 2021.

[34] Vanuatu Ministry of Health, Project report Vanuatu drone trial: Phase 1 and 2 (2019). September 2019, Available at https://www.updwg.org/wp-content/uploads/2020/10/UNICEF-Vanuatu-Drone-Report-Final-Executive-Summary.pdf, Accessed August 12, 2021.

[35] United States Centers for Disease Control, Vaccine Storage and Handling Toolkit, 2021. Available at https://www.cdc.gov/vaccines/hcp/admin/storage/toolkit/storage-handling-toolkit.pdf, Accessed January 29, 2022.

[36] Knoblauch AM, de la Rosa S, Sherman J, Blauvelt C, Matemba C, Maxim L, et al. Bi-directional drones to strengthen healthcare provision: experiences and lessons from madagascar, malawi and senegal. BMJ Global Health 4 2019.

[37] Gustiana R. Vanuatu immunisation microplanning for 2018 2018.

[38] World Health Organization, 2: The Vaccine Cold Chain, 2015. Available at https://www.who.int/immunization/documents/IIP2015Module2.pdf, Accessed January 29, 2022.

[39] UNICEF, UNICEF Procurement Guidelines - Vaccine Carriers and Cold Boxes, 2021. Available at https://www.unicef.org/supply/media/6391/file/VaccineCarrierColdBox- guideline-2021.pdf, Accessed January 29, 2022.