

White Paper

What should you deliver by unmanned aerial systems?



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*The role of geography, product, and UAS type in
prioritizing deliveries by UAS*

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JSI's inSupply project improves the performance and efficiency of contraceptive, vaccine, and essential medicine supply chains by increasing the effective use of data and introducing management best practices to strengthen system outcomes. With a regional focus in East Africa and the goal of replicability across the region and globally, inSupply is increasing data visibility and the use of data to drive strategic and operational supply chain decision-making, demonstrating the feasibility of innovative solutions for the last mile, and strengthening local and regional supply chain capacity.



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Acronyms

CCE	Cold Chain Equipment
DBS	Dry Blood Spot
HF	Health Facility
JSI	JSI Research And Training Institute, Inc.
MDR	Multidrug Resistant
PEP	Post-Exposure Prophylaxis
TAT	Turnaround Time
TB	Tuberculosis
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
USAID	United States Agency For International Development
VTOL	Vertical Takeoff And Landing
WHO	World Health Organization

Executive Summary

As more low- and middle-income countries (LMICs) explore opportunities to improve efficiency and performance in their public health supply chains and diagnostics networks, they face myriad choices about how best to use unmanned aerial systems (UASs) to improve public health outcomes and reach the last mile. JSI Research & Training Institute, Inc. (JSI) and our partners LLamasoft and the Nichols Group wrote this paper to provide countries and public health stakeholders with objective guidance on how to make informed decisions about which health products to prioritize for delivery and by which type of UAS platform to achieve the six ‘rights’ of a supply chain.

The team undertook a cost-effectiveness analysis to compare various transport options for a variety of delivery categories using UAS vs. well-managed traditional modes of last-mile delivery, such as land cruisers and motorcycles. The analysis took into account geography, UAS characteristics, and characteristics of products and their demand patterns. We also mined and analyzed 12 months of health-facility data from three country datasets in sub-Saharan Africa to identify five use cases that would allow us to define the cargo characteristics and examine cost-effectiveness for each of the following product types: a) safe blood for transfusion; b) long-tail products (small quantity, unpredictable demand products); c) program and essential medicines; d) vaccines; and e) diagnostic specimens.

Overall, our findings show that UAS cost-effectiveness is driven by the number of flights per year and increasing flight numbers is dependent on facility density within the UAS range area. Similarly, with the exception of safe blood for transfusion, the results clearly demonstrate that using UAS for single-product category deliveries is not optimal from a cost-effectiveness perspective, and that layering multiple use-cases will increase the UAS cost-effectiveness by increasing the number of flights the UAV will be used for. For safe blood for transfusions, small, fixed-wing UASs can offer both cost and speed/responsiveness advantages over land transport to deliver rare blood types and support-products on-demand. We estimate that for a region of average facility density, approximate annual costs to serve 500 health facilities will range from US\$ 1–5 million, depending on the UAS and cargo categories. Ultimately, even projecting rapid improvements in cost and performance, most UASs are still 3+ years away from being transport-cost competitive with motorcycles.

The case for using UASs must be examined within the context of the total system costs (considering factors such as inventory holding costs and capital investment for storage capacity), other supply chain objectives such as speed and availability, and broader health benefits. UAS cost-effectiveness is substantially driven by the number of flights per year that can defray fixed costs. Flight numbers can be increased by operating in areas of higher health

facility density and selecting UASs that have longer ranges. Flight numbers can also be increased by layering multiple use-cases. Unmanned aerial systems have significant potential to improve the availability of health products in hard-to-reach locations. Every potential use case must be considered individually factoring in geography, UAS characteristics, and product and demand characteristics. However, the following sets of factors are broadly indicative of a potential value-adding use case for UAS:

- High density of health facilities (within range of UAS).
- Difficult to access by road (large proportion of year).
- High financial value, scarce, or high health value (e.g., life-saving) products.
- Unpredictable demand (at level of individual facility) products.
- Expensive, short shelf-life, or difficult to store at last-mile products.

Introduction

Context – UASs in public health systems?

The use of drones, or unmanned aerial vehicles (UAV) and systems¹ (UAS), as a new option for transporting public health commodities, safe blood for transfusions, and laboratory samples to the last mile is generating a lot of interest. There are many questions about how best to use drones, what the costs will be compared to other options, and how they will be operated and maintained. For many public health systems, the decision will not be whether to use UASs at all, but how to use them cost-effectively within an integrated and networked set of transportation resources. Cost will be a major factor, but must be considered against improved responsiveness and timeliness of deliveries. One study on vaccine delivery by UAS found a net benefit for both cost to deliver and product availability (Haidari et al 2016). Another factor that hasn't garnered much attention yet is the potential reduction in carbon emissions, especially for low-delivery payloads, when replacing traditional petrol or diesel 4x4s or motorcycles with UASs in rural distribution (Figliozzi 2017).

A major benefit of UASs is their ability to fly over difficult terrain and improve speed of delivery. Given some of the major challenges that many public health supply chains face—high transport costs, chronic stockout rates coupled with notable waste, and inefficiency due to fragile and/or fragmented supply chains—UASs may offer a reliable last-mile delivery system for selected scenarios or “use cases” (USAID/PSM 2017). These include emergency or just-in-time deliveries of life-saving medicines or safe blood for transfusions (Rosen 2017); collection of patient specimens for delivery to labs for time-sensitive testing (Phillips 2016); resupply to resolve

¹Drones and UAVs are considered to be fairly synonymous, whereas a UAS describes the UAV along with the ground-based controller and the communications system that links the two.

stockouts and routine resupply of high-cost items; and vaccine deliveries for better cold chain control during remote outreach sessions (Haidari 2016).

There is an increasing number of UAS manufacturers that offer a range of specifications related to mechanisms of flight, payload weight, and delivery range and speed, all with varying business models of operation (FSD 2016). Many manufacturers are exploring new markets in which to refine their technology and/or the public health space as one of several potential markets (USAID/PSM 2017). While this delivery mechanism offers an exciting opportunity for countries, there is little documentation of optimal products for public health commodity delivery via UAS, given the current available technologies. This paper seeks to answer that question.

System objectives: how do UASs fit in?

Public health logistics systems should aim to support achievement of an overall country's health system objectives: saving lives, ensuring care, preventing harm, and empowering people to live healthy lives. To be effective, supply chains must ensure service, maintain quality, contain costs, and manage risks to achieve these six 'rights'—

1. the right product is delivered
2. in the right quantity
3. in the right condition
4. to the right place
5. at the right time
6. for the right cost

More and more countries and stakeholders are interested in exploring the use of UASs to improve public health outcomes. They will benefit from objective guidance to make informed decisions about which health products should be prioritized for delivery by which type of UAS platform to achieve the six rights most effectively and efficiently.

Project objectives

1. Develop a framework for scenarios/use cases for products that are likely candidates for consideration of a UAS as a last-mile delivery mode. Use cases were developed for the following products:
 - a. Safe blood for transfusion
 - b. Routine vaccines
 - c. Long-tail products²

²Products that have small and unpredictable demand at individual health-facility level and are not widely distributed. Examples include antivenom, rabies, and tetanus vaccines.

- d. Program and essential medicines (stockout response)
 - e. Diagnostic specimens
- 2. Conduct a literature review of the characteristics of existing UAS technologies available for public health settings that would be appropriate for each scenario/use case.
- 3. Conduct a cost-effectiveness and cost benefit analysis for various classes of products for transportation via UAS compared to the cost of traditional modes of last-mile delivery transportation (land cruisers, motorcycles) across different geographical terrains and taking into account seasonality.

Methods and Approach

Rules for comparison

To answer the question of whether UASs add value for a particular use case, we established some basic rules for comparison. These rules lay out the methods that the UASs were compared to and the factors that were taken into consideration for the comparison.

*Rule 1: Check if UASs offer advantage over **well-managed land transport**, not only over status quo.*

In many settings, the status quo land transport might be inefficiently run. For example, even in situations where multi-stop routes would be beneficial, the status-quo land transport may operate as point-to-point pick-up or delivery. In other cases, the status quo land transport may operate on a delivery frequency that is far from optimal and thus achieves a poor balance on the objectives of availability and cost. In these cases, one could examine the effect of improvements to status quo land transport (e.g., move to multi-stop routes, change delivery frequency) or examine the effect of introducing a whole new mode of transport (i.e., UAS). If improvements to land transport are possible and would offer substantial benefits, then that is clearly the lower-risk and easier-to-implement option and should be selected. Thus, to see if UASs can offer a true advantage, we compared them against the performance expected from a hypothetical well-managed land transport system, and not just the status-quo land transport in a particular region.

*Rule 2: Assess performance holistically; **across the logistics objectives** and end-to-end for an in-country supply chain.*

Supply chain performance can be measured across multiple objectives: cost, service level, availability, service time, speed/responsiveness, quality, risk, and more. When assessing if UASs can add value in a particular use case, performance across all important objectives should be

considered. For example, for delivery of safe blood for transfusion, in addition to cost and quality, increasing the speed of response (service time) is a critical objective. As the delivery of blood is often needed in life-threatening situations, even saving a few minutes could be of great value. Performance should thus be measured holistically, across cost, quality, and also service time (speed/responsiveness). Performance should also be measured across the end-to-end supply chain, not only at the level of immediate applicability (e.g., last-mile delivery). For example, if the introduction of UASs for last-mile delivery allows changes to the structure or inventory holding at different levels of the supply chain, those changes should be considered.

*Rule 3: Consider not only direct transportation costs, but **total system costs that** may not be directly apparent (inventory holding costs, expiry and wastage, capacity expansion costs, handling costs).*

Focusing specifically on the objective of cost, it is important to measure and compare not only direct transportation costs, but also changes in total costs from a system redesign that may be possible through introduction of UASs. For example, using UASs to increase delivery frequency (delivering smaller batches of product more frequently) will reduce the need to hold large quantities of stock at service delivery points. This means a reduction in inventory holding cost. The reduction of stock being held in failure-prone settings at rural service delivery points may also lead to reductions in spoilage and possibly avert the need to expand storage capacity at the service delivery point. All these savings must be factored into a total systems cost assessment when assessing the effect of introducing UASs.

Dimensions of importance

To meaningfully assess performance of UASs and identify niches where they may offer advantage over land transport, we identified three overarching dimensions for consideration for each use case.

1. Geography
2. UAS characteristics
3. Product/demand

Geography

Geography plays a large role in determining the performance of transport modes in a logistics system. Geographical factors that are important to consider in our context include:

Health facility density: how many health facilities (HFs) fall within a particular land area? How dense or sparse is the distribution of health facilities? This variable will impact how far a truck or motorcycle has to drive to get from one HF to another, and also how many health facilities fall within the serviceable-radius determined by the maximum range of a UAS.

(Measurement: number of health facilities per 10,000 sq.km of land area.)

Road network quality: Road density measures the number of kilometers of road in a particular land area. This determines how easy it will be to get to health facilities in a given area by road. Road density is closely tied to road circuitry factor. Road circuitry factor describes how much longer one has to travel to get from point A to point B by road vs. if one could travel in a straight-line or “as the crow flies.”

(Measurement: road density: kms of road per 100 sq.km of land area; road circuitry factor: road distance to travel a particular leg/straight-line distance to travel the same leg.)

In addition to the road density or circuitry factors mentioned above, it also matters if the road is a smooth tarmac highway or a bumpy narrow dirt-track. This will determine the average travel speed on a particular stretch of road.

(Measurement: avg. travel speed by road in km/h.)

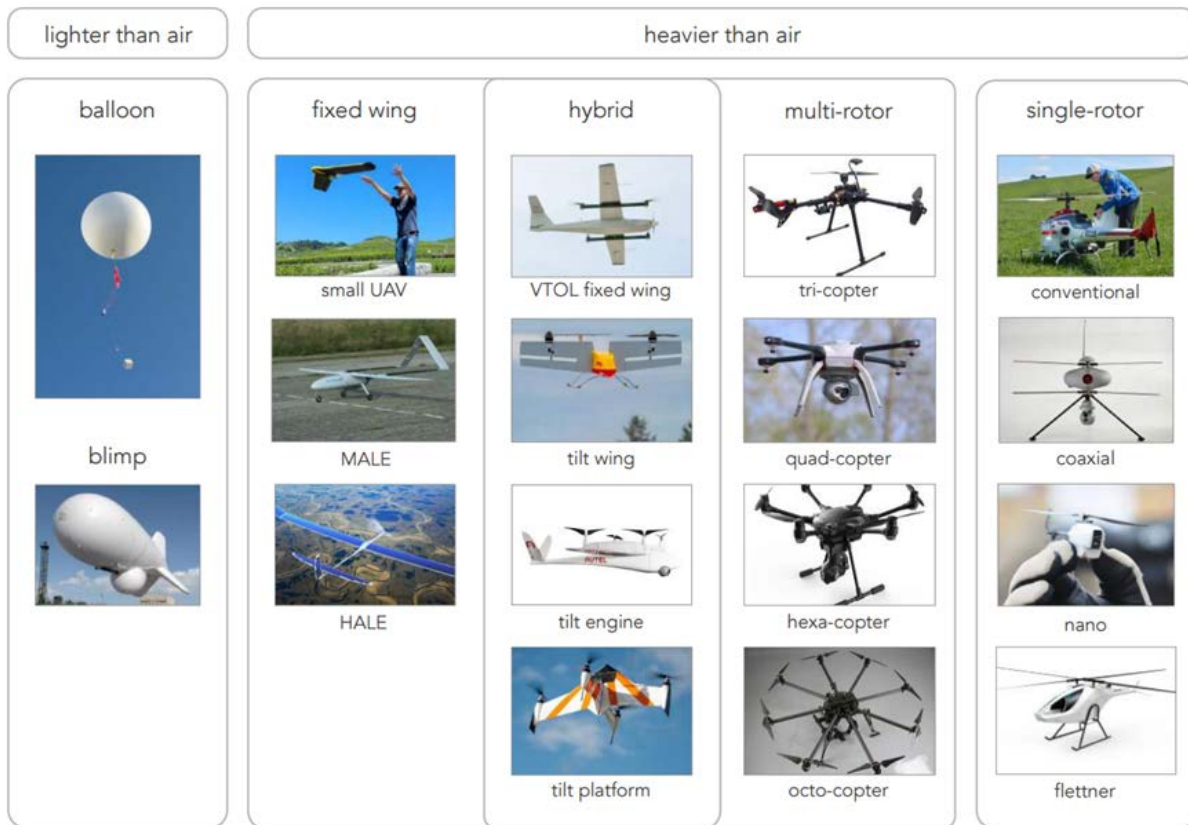
Health facility accessibility: Can the health facilities be reached by road or do they have to be accessed using other transport? For example, are they island facilities or located in riverine areas that are accessible only by boat? Are they located in extremely mountainous areas accessible only by foot or donkey? If they are inaccessible by road, for what fraction of the year are they inaccessible? Year-round or only for a portion of the year (e.g., due to seasonal flooding)?

*(Measurement: % of facilities inaccessible by road * % of year inaccessible by road.)*

UAS characteristics

UASs vary widely in their configurations, capabilities, and costs.

UAV Configuration Types



MALE: medium altitude long endurance (15,000 – 45,000 ft.), HALE: high altitude long endurance (>45,000 ft.)

Source: Wackwitz, Kay, et al. Drone Business Development Guide: The Comprehensive Guide for a Successful Start into UAV Operation. Drone Business Development Guide: The Comprehensive Guide for a Successful Start into UAV Operation, Drone Industry Insights, 2016.

The type and the characteristics of a particular UAS being considered has an important role in determining if the UAS can add any value in a particular use case.

Vertical takeoff and landing capability:

Fixed-wing UASs may have difficulty landing at health facilities, as they typically require a large open area or custom-design apparatus to enable landing or take off. Multi-rotor or multi-copter and hybrid UASs will typically have vertical takeoff and landing (VTOL) capabilities, which means that they require much smaller area to land and therefore will have an easier time landing at health facilities. If a particular use case involves bringing cargo back from health facilities (e.g., diagnostic specimens) then landing at health facilities is necessary. So for particular use cases, only UASs with VTOL capability may be considered.

(Measurement: Yes or No binary rating.)

Payload:

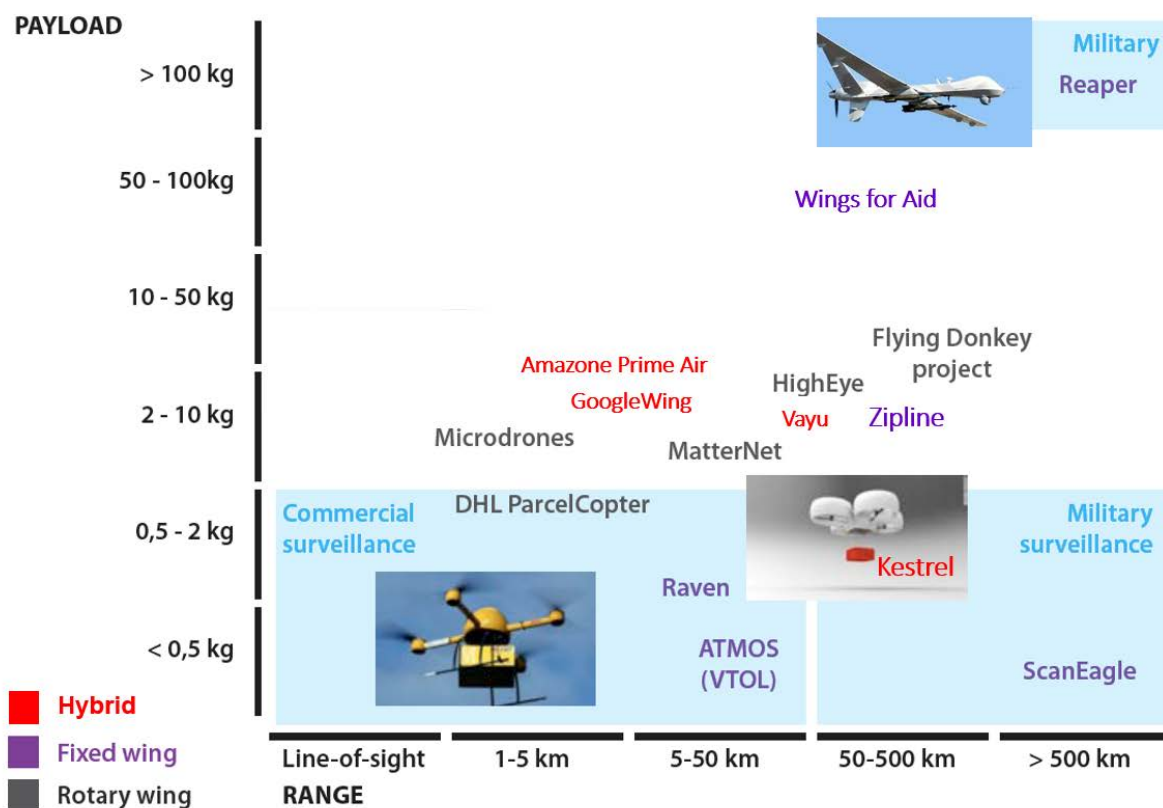
Individual UASs have a wide range of payloads, which is the maximum cargo they can carry on a trip. This payload can be expressed in terms of weight and volume.

(Measurement: payload in Kgs, payload in liters.)

Range:

Individual UASs also vary widely in their range, or the maximum distance they can cover on a single trip. The range can vary from <10 kilometers to several hundred kilometers.

(Measurement: range in kilometers when fully loaded.)



Source: Defawe, Olivier. "Can UAVs Fill the Delivery Gap for Global Development?" Village Reach Starting at the Last Mile. Final Mile Logistics Working Group, 20 July 2016.

Costs:

Cost characteristics can vary widely across UASs. Costs are driven by a number of different factors, including the cost of each individual airframe, the cost of batteries/engines and other components, operator costs, insurance, the number of cycles airframe and individual components can last, maintenance requirements, and cost of other base infrastructure. The

particular balance of these costs will also drive the proportion of costs that are fixed (incurred annually regardless of how many flights are undertaken) vs. variable (incurred per flight).
(Measurement: USD per km; USD per flight; fixed cost vs. variable cost allocation per flight.)

Product/demand

The characteristics of the cargo to be transported and the pattern of their demand have an important role in determining if UASs offer any advantage over land transport for a particular use case. The characteristics to consider under this dimension include:

Weight and volume: How much does a unit of the cargo weigh? How much space does a unit of the cargo occupy? These factors will determine how many units of cargo can fit in the cargo bay of any transport mode, land or air.

(Measurement: kgs per unit, liters per unit.)

Financial value (specific to commodities): What is the financial value of each unit of cargo? This will impact how expensive it is to hold stock of that particular cargo and thus influence supply chain design.

(Measurement: USD per unit)

Health value: What is the health value of a particular cargo type? If a particular cargo type is out-of-stock, is it a matter of life or death for a patient, or is it merely an inconvenience? As an example, safe blood and specimens have no financial value but have high health value; they are priceless to the patient and for public health systems (to detect, prevent, and respond to outbreaks).

(Measurement: subjective rating of health value e.g., 1 = life-saving; 2 = vital; 3 = essential; 4 = non-essential.)

Shelf-life or difficulty to store: Does a particular cargo category have a short shelf-life before it can no longer be used (e.g., expires or loses potency)? Does a particular cargo category need to be maintained in carefully controlled conditions (e.g., temperature between 2°–8° C) to remain useful?

(Measurement: shelf-life in days, months, or years; description of storage conditions needed for each cargo category.)

Quantity of demand (specific to commodities): What is the average quantity of this product consumed by an average health facility in a particular period of time? This characteristic, when

paired with weight and volume, will describe how long a period of demand can be served by a single delivery using any specified transport mode.

(Measurement: average quantity per week.)

Unpredictability/variability of demand: How unpredictable or variable is the health-facility level demand for this cargo category when comparing one time period to another? Is the demand steady and easily predictable? Or does demand fluctuate wildly from one time period to another, making it difficult to predict with confidence how much will be needed in any particular time period? In the case of diagnostic specimens for transport, the unpredictability/variability is in the supply of specimens to be transported, and the window in which transport is required, and not the 'demand' for their use. In either scenario, unpredictability/variability in quantities over a period is an important factor to understand.

(Measurement: standard deviation of weekly demand/average quantity of weekly demand at health facility level.)

Current extent and duration of stockouts (specific only to commodities):

What is the current extent and incidence of stockouts for this particular cargo category? When stockouts occur, how long do they typically last? These factors explain current performance on the objective of availability, and when paired with quantity of demand, will determine how much product will be needed to tide an average health facility over until its next routine delivery when it suffers a stockout.

(Measurement: percentage of health facilities that suffer a stockout of this cargo category in a given time period; percentage of replenishment cycle that a typical stockout lasts.)

Importance of objectives: The characteristics above will also drive the relative importance of different logistics objectives for each particular cargo category. For this particular cargo category is cost the most important driver, or is it superseded by service level availability, or service time (speed)? Based on the characteristics above, we present a subjective rating of the importance of the logistics objectives for each cargo category.

(Measurement: subjective rating of the importance of the logistics objectives for each cargo category on a scale of 1–5.)

Data collection and analysis

For each dimension, we collected reference data and formed reasonable and representative assumptions.

Geography

We used public data on facility density (number of health facilities in a given region or country and the area of the region or country in square kilometers). From previous LLamasoft projects on transportation routing for last-mile delivery, we were able to extract reasonable assumptions for road circuitry factor and travel speeds.

In addition, from these same transport optimization projects, we also had data on land transport characteristics (payload and cost) for different vehicle types (motorcycle, land cruiser, 4-ton trucks etc.). We were able to validate these assumptions by triangulating with published data¹¹ and review by experts with long experience of road transport in sub-Saharan Africa.

UAS characteristics

This dimension represents the area of most uncertainty in terms of data collection and assumptions used. This is because:

- The technology is new and rapidly evolving, so new UASs with different designs and capabilities are being introduced every month.
- There are limited data from actual ongoing operations or deliveries. What is available is generally information on websites of UAS manufacturers, which may reflect ideal conditions and performance.
- The companies developing the technology are proprietary start-ups operating in a competitive environment, so they are hesitant to share the details of their costs and capabilities.
- There are few sources of collated and aggregated data on comparative costs and performance of different UASs.

Nevertheless, because LLamasoft and JSI have each engaged on a few different projects involving UASs in public health systems, we were able to contact a number of existing UAS companies, review the available public sources (e.g., references 1, 4, 7, 8, and 9), and aggregate the existing data. We were also assisted by IRIS Drone Technologies (<http://irisdronetech.co.uk/>), which shared its tabulation of a subset of available UASs with their comparative cost and performance metrics.

However, we fully understand that the data included in the analysis are only starting assumptions. These data must be refined and updated as more information becomes available, particularly from actual implementations of UAS delivery. To account for this, we have deliberately made the data easy to update in an Excel screening tool that is an output of the project.

Product/demand

We collected health-facility level commodity data across one year from three country data sets in sub-Saharan Africa. These data were collected from countries in which JSI has a significant presence. We analyzed the data at the product category and individual product levels extensively to obtain estimates of average demand quantities at the facility level, demand variability, current stockout rates, and more. We supplemented the data with public sources such as UNICEF's reference for vaccine weights and volumes, and USAID | DELIVER's reference product weight and volume list.

Range considered in each dimension

Geography

Country	Region	Facilities	Population (M)	Sq.km	Facilities per 10,000 sq km	Pop per facility
Nigeria	Niger Delta (expanded)	2,516	21.8	55,407	454	8,665
Nigeria	Niger Delta (Rivers, Bayelsa)	547	9.21	21,850	250	16,837
Rwanda	Rwanda	450	11.92	26,338	171	26,489
Tanzania	Mwanza	1,080	8.51	75,393	143	7,880
Tanzania	Morogoro and Pwani (Dar Zone)	473	3.32	103,171	46	7,019
DRC	Bandundu	1,127	8.86	295,658	38	7,862
DRC	Equateur	1,000	7.5	403,292	25	7,500
Mozambique	Gaza	126	1.38	75,334	17	10,952
Mozambique	Tete	102	2.43	98,417	10	23,824
Namibia	Namibia	446	2.48	824,292	5	5561

UAS characteristics

	Multi-copter	Small fixed wing	Small fixed wing - very low fixed cost	Large fixed wing (needs runway)	Hybrid - small	Hybrid - small (alternative fuel)	Hybrid - medium
Range (KMs)	20	150	70	500	60	300	100
Weight capacity (Kgs)	2	1.5	1	100	2	1.5	20
Volume capacity (Liters)	10	10	0.4	230	8	8	25
Reverse logistics capability (VTOL)	Yes	No	No	No	Yes	Yes	Yes
Assumption for flights per year (from a hub)	10,000	10,000	10,000	10,000	10,000	10,000	10,000
Estimated total (fixed and variable) costs per flight - given above flights per year	11	20	14	186	38	91	126
Estimated total (fixed and variable) costs per KM - given above flights per year	0.83	0.20	0.31	0.56	0.95	0.45	1.89
Total cost per ton-km (USD)	416	135	306	6	476	303	94
Total cost per m3-km (USD)	83	20	765	2	119	57	75

Note that for illustration and comparison in table above we have assumed 10,000 flights per year for each UAS-type (multiple drones operating from a single hub). In reality, depending on

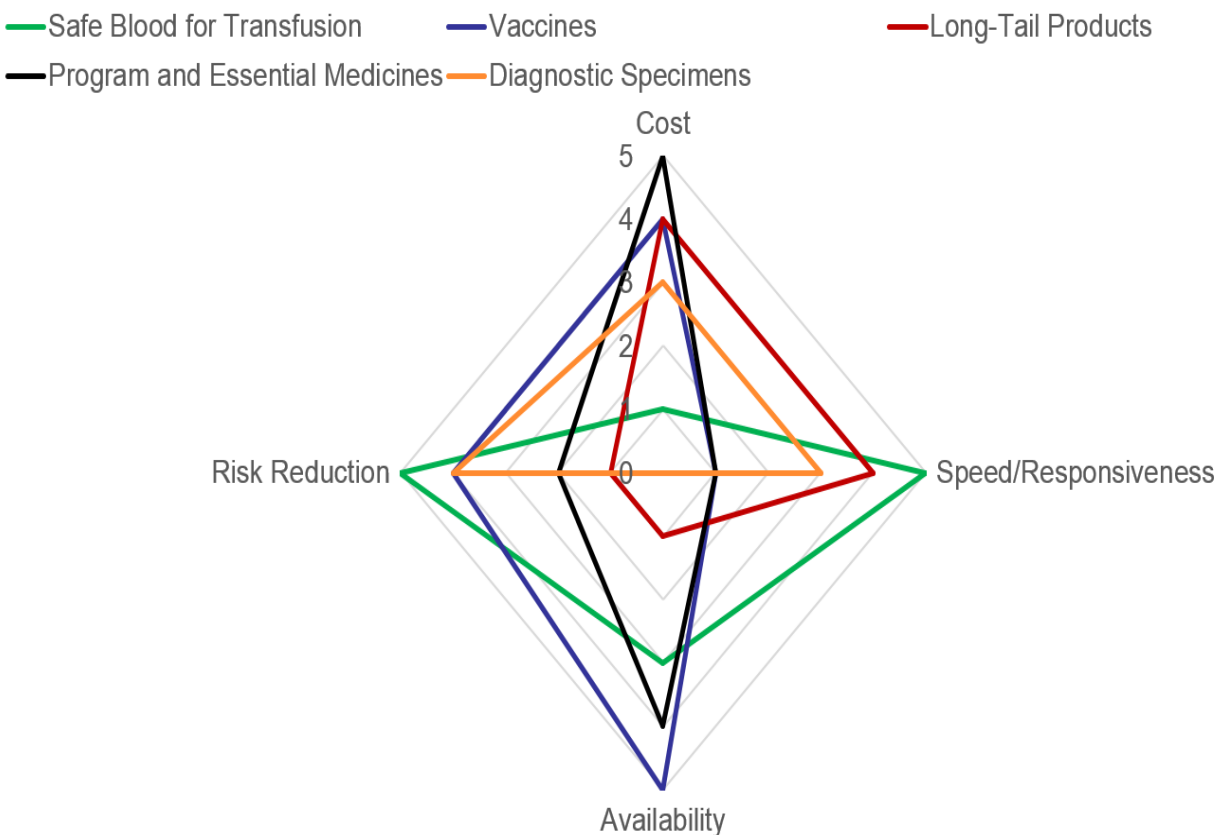
range and payload by UAS-type, the feasibility of achieving 10,000 flights annually from a single hub will vary greatly. Analysis is not restricted to assuming any particular flight number.

Product/demand

- Safe blood for transfusion
- Long-tail products
- Program and essential medicines
- Vaccines
- Diagnostic specimens

The following spider diagram rates the relative importance of objectives by cargo category **subjectively** on a scale of 1–5. The exact ratings for importance of objectives can be adjusted easily, and are included here primarily to illustrate that different cargo categories will have different priorities. Risk-reduction as mentioned here primarily refers to reducing spoilage/expiry and maintaining quality of cargo. It does not refer to reducing the risk of stockout, which is covered by availability.

Illustrative - Importance of Objectives by Cargo Category



Safe blood for transfusion

Objective	Rating	Reason
Speed/responsiveness	5	Minutes are essential when emergency transfusions are needed.
Availability	3	If safe blood is provided on-demand with speed, then having availability by storage at facility-level matters less.
Risk reduction	5	Non-expired and safe blood is essential.
Cost	1	Can be life-saving; high cost is acceptable.

Vaccines

Objective	Rating	Reason
Speed/responsiveness	1	Vaccines are typically not provided to health facility on demand. Each child walks in so vaccines are stored at service delivery point to be consumed as needed. Availability covers this aspect.
Availability	5	Health facilities need to have vaccines available to maintain and increase coverage.
Risk reduction	4	Need to maintain vaccine potency. Further, a health system would want to reduce wastage/expiry, but note that the reduction of wastage/expiry is a component of inventory-holding costs.
Cost	4	Vaccination is provided at broad scale nationwide under limited budgets. For many LMICs, transitions from Gavi funding is looming and they will need to self-finance a higher proportion of their vaccine procurement and distribution costs.

Program and essential medicines

Objective	Rating	Reason
Speed/responsiveness	1	Vaccines are typically not provided to health-facility on demand. Each individual walks in so vaccines are stored at service delivery point to be consumed as needed. Availability covers this aspect.
Availability	4	Medicines in this category have high health value, even if not every medicine in this category is life-saving.
Risk reduction	2	Product shelf-lives are quite long and products don't easily expire/spoil or lose potency, so this is a smaller issue than for other cargo categories.
Cost	5	Medicines are provided at large scale nationwide in quite large quantities under conditions of scarce budgets.

Long-tail products

Objective	Rating	Reason
Speed/responsiveness	4	These products are good candidates to be provided on demand as each patient need occurs, and many of them can be of high health value or even life-saving. e.g., antivenom.
Availability	1	If these products are provided on demand, the need to stock at facility is reduced, and important only to ensure availability at hub-level, which is supplying the health facilities on-demand.
Risk reduction	2	Some products in this category have long shelf-lives and don't easily expire/spoil or lose potency, so this is a smaller issue. However, some products in this category do need to be maintained in a temperature controlled environment, thus our rating.
Cost	4	These products are provided at large scale nationwide under conditions of scarce budgets. However, by definition, these products are consumed in smaller quantities than program and essential medicines.

Diagnostic specimens

Objective	Rating	Reason
Speed/responsiveness	3	Turn-around time is very important for some tests, especially for diseases that are highly contagious. However, for other chronic diseases, the difference of a day or two does not matter as much, e.g., viral load monitoring, as long as the specimen is properly separated/stored.
Availability	1	Patients provide specimen, so availability essentially does not apply to this cargo category.
Risk reduction	4	Need to maintain specimen quality for diagnosis.
Cost	3	Diagnostic services are provided at large scale nationwide under limited budgets. However, current systems may have high cost and poor performance because they are fragmented. A systematic and harmonized/integrated approach may be more cost-efficient and would reduce the budget pressures.

Results

While initial analysis and results are presented by product category, our findings clearly demonstrate that the single use case approach to introducing UASs is not optimal from a cost-effectiveness perspective. However, it is an important starting point for countries to identify and articulate the biggest driver for introducing UASs. Thus, while countries and stakeholders will naturally begin with the use case that is most relevant to their context, we encourage them to consider all relevant use cases when reviewing results.

Findings by product category

Safe blood for transfusion

Safe blood for transfusions is often in scarce supply, especially outside central blood banks and for rare blood types (Rh-) and supporting products (platelets, plasma). Blood for transfusion is also relatively difficult to store and has limited shelf-life (see table below).

Storage and Transport Conditions for Whole Blood and Red Cells

Condition	Temperature range	Storage time
Transport of pre-processed blood	+20 °C to +24 °C	Less than 6 hours
Storage of pre-processed or processed blood	+2 °C to +6 °C	Approx. 35 days
Transport of processed blood	+2 °C to +10 °C	Less than 24 hours

Source: Abu Amin, Noryati, et al. "Manual on the Management, Maintenance and Use of Blood Cold Chain Equipment." World Health Organization Geneva. SAFE BLOOD AND BLOOD PRODUCTS.

All these factors make it difficult to keep stock close to where it is needed and point to the advantage of pooling inventory and supplying on-demand. Blood groups with relatively predictable demand may be stocked at the hospital or health-center level, if cold storage is available. However, due to the challenges in predicting demand for rare blood types, these items are even more difficult to stock at point of transfusion.

In LMICs, transfusions are primarily for women who are experiencing complications related to pregnancy and severe anemia in children.³ Even if an emergency trip to the nearest stocked blood bank can be made, it takes time and resources (financial, human). In emergency situations, such as a woman in complicated labor requiring a transfusion, it could be life-or-death so timeliness of safe blood for transfusions will determine her survival.

³<http://www.who.int/mediacentre/factsheets/fs279/en/>.

Transfusions typically only require two-to-three units of blood per patient. For common blood types (with a higher level of certainty), if the blood can be stored onsite, well-managed land transport (likely a land cruiser or motorcycle) may be the most efficient delivery mechanism based on weekly drop-offs, especially if a multi-stop route is used. However, this individual transfusion volume could also be supplied by a single on-demand small drone flight. Compared to the option of picking up/delivery via land cruiser for less-predictable demand groups (Rh-, plasma, etc.), a drone would save time and cost. Previous analyses of small-fixed wing UAVs for blood delivery in Rwanda and Tanzania showed that compared to transport by land cruiser or van, UAVs could reduce delivery time from an average of more than 2 hours to fewer than 30 minutes. As only a small quantity of cargo was delivered (typically 2–3 units of blood for an individual case), the delivery by UAV was also lower in transport cost compared to round-trip transport by land cruiser or van. It may even make sense to deliver by a small drone than a motorcycle, based on the speed/timeliness required in a life-saving instance and cost efficiency if there are enough flights to defray the fixed cost of the UAS (more than approximately 5,000 flights per year). The cost and performance advantage is enhanced when road-circuitry factor⁴ is high, the motorcycle cost to operate is high, and there is a large number of facilities in range. For example, if there are 20 hospitals/health centers in a given radius, then each hospital would require 250 flights a year, or 5 flights per week (less than 1 per day), which may be accounted for by rare blood/products to be more cost-efficient than a motorcycle. However, if facility density is low, there may not be enough flights to make it cost-competitive. The most suitable and cost-efficient option would be a small, fixed-wing UAS, which has a relatively high range, a cost that can be lower than a motorcycle, and does not need to land to pick up cargo at the delivery site, so it is uni-directional. Speed/responsiveness is a significant additional advantage of delivering by UAS, as there is no road circuitry factor, and small fixed-wing UASs (~100 km/h) are much faster than motorcycles (~40-50 km/h).

In conclusion, small, fixed-wing UASs can offer both cost and speed/responsiveness advantages over land transport to deliver rare blood types and supporting products on demand.

Vaccines

Vaccines for routine immunization are typically delivered monthly via cold boxes on motorcycles or 4x4s, or picked up by health care workers traveling to district or sub-district cold stores. Demand is predictable and supply is normally based on annual forecasts divided into 12 monthly allocations, or with more advanced supply chains, on routine orders based on demand. A typical small health facility (HF) requires a total volume of about 70 to 100 liters annually. In addition, there are periodic campaigns—supplementary immunization activities—that focus on

⁴ The circuitry factor is a percentage added to the straight-line distance between two locations to accommodate hilliness, road network density and travel obstacles such as mountains, lakes, and parks.

specific disease prevention, such as measles or polio, that are more focused and intense, but also planned in detail to achieve coverage targets in which demand is predicted for supply planning.

A critical feature of vaccines is their dependence on a cold chain to maintain potency to the last mile. Cold chain equipment (CCE), management, and maintenance are major cost drivers in the vaccine supply chain. Older health facility refrigerators are prone to breakdown, and many rely on kerosene or liquefied gas for fuel, which is expensive to procure and transport. Cold boxes must be stocked at distribution levels, and freezers must be used to condition cold boxes in preparation for use and to freeze ice packs. Preparing cold boxes takes time, which affects both lead time and total cost of distribution. Furthermore, a major challenge with many cold boxes currently used is the risk of freezing vaccines, which can render many antigens ineffective.

Closed-vial wastage also affects inventory holding costs. Data from Tanzania suggest it is not a significant problem (1–2% of total volume annually), but data on CCE functionality show as much as 10% of fridges are non-functional at any given time, and Gavi states that up to one-third of fridges in a country malfunction in a year. If a fridge is non-functional at an HF, health care workers often have to travel to the district or neighboring HF to store vaccines. In many countries, the distance from HF to district averages 50 kms one-way; a round trip can be 3–4 hours and cost more than USD 30.

Our study looked at the routine resupply system based on the model of monthly direct delivery to the health facility by multi-stop motorcycle, and compared that to a more frequent delivery by UAS or motorcycle. A typical small health facility that gets monthly deliveries can carry in excess of USD 2,500 worth of vaccines in inventory (cycle + buffer stock), with a volume of 6L–8L (3kg–4kg). While 2–3 flights per month would provide a month's supply, we considered a weekly supply model, which would reduce HF inventory holding levels, transport time, and risk of freezing in transit or wastage due to CCE failure at the HF.

One benefit of reduced vaccine inventory could be mitigating capital investments in expanding CCE capacity, especially as new, higher-volume and -cost vaccines like human papilloma virus (HPV) are introduced and as health services expand access to cold chain-dependent medicines (e.g., insulin, oxytocin). For the purposes of this analysis, we limited our considerations to the impact on CCE capacity of HPV introduction, which will substantially increase the value and volume of vaccines in the supply chain, and therefore increase inventory holding cost at the last mile.

In terms of cost alone, we found that UASs are not competitive with a motorcycle with a multi-stop route, even if motorcycle delivery frequency is weekly. UAS costs would have to be reduced by half or more to be cost-competitive with a multi-stop route by motorcycle. This finding is different from Haidari et al., which we found to be too aggressive on UAS cost

assumptions and, as we understand it, used status quo transport for land (point-to-point), rather than multi-stop delivery routes.

In terms of potency, UASs would offer advantages by reducing dependence on cold boxes that require ice packs and conditioning, thus reducing the risk of freezing in transit, since UAS flights would be direct and significantly faster than a motorcycle on a multi-stop route.

We did not investigate use of UASs in periodic outreach activities or supplementary immunization activity campaigns largely because transport is required not only for the vaccine but also for the health worker who is administering the vaccines.

In conclusion, while UASs are not necessarily competitive with multi-stop motorcycle routes for vaccine distribution, they should be considered in a system-design optimization context, especially considering benefits in inventory optimization or alternatives to expansion of CCE capacity. Other conditions in which UASs might add value for vaccine distribution include new vaccine or other CCE-dependent product integration; places where there is a high risk of surface transport disruption, especially hard-to-reach areas; and layering UAS use cases with other cargo categories, which will help to reduce costs.

Long-tail products

Long-tail products are defined as those having small and unpredictable demand at individual health facilities. They include treatments for relatively rare patients who are exposed to potentially fatal viruses or toxins, such as rabies post-exposure prophylaxis (PEP), snake antivenom, and tetanus toxoid (for an emergency booster case). Long-tail products might also describe treatments for severe conditions of more common diseases and are therefore unpredictable. They include medicines to treat multidrug resistant-tuberculosis (MDR-TB) like amikacin, second- and third-line antiretroviral drugs for HIV, artesunate injection for treating severe malaria, and furosemide injection for severe edema or hypertension. Because these conditions are unpredictable, in general, the products are not widely distributed or widely stocked at the HF level. Long-tail products share similar characteristics with the case for serving rare blood types described previously.

As a result, the most effective approach to managing demand for long-tail products is to stock them at a central hub and provide them on-demand to individual HFs when the need arises. This on-demand model aggregates demand across many individual health facilities, which makes it more predictable, allows for lower buffer stock, and therefore saves money, especially on high-value commodities. This is known as the inventory pooling effect, commonly recognized in commercial systems with high demand-variability across the system.

The benefits offered by stocking long-tail products centrally and serving on-demand are higher when—

- Demand is more unpredictable: product/demand characteristic.
- Financial value of the product is high (so there is a larger inventory cost benefit to holding smaller quantities at central point): product/demand characteristic.
- Health value of the product is high: product/demand characteristic.
- Demand can be pooled across a larger number of health facilities within range: geography and UAS characteristics.

For each individual product and situation, we need to determine if it is better to stock the products at HF level only or to distribute on-demand by UAS. We can do this by applying a cost-effectiveness formula comparing supply-on-demand via UAS to stocking at HF for each product. To illustrate this, we compare two potential long-tail products that have similar demand unpredictability and demand quantity per facility, but different financial values:

- Antivenom; USD 150 per treatment.
- Rabies PEP; USD 10 per treatment.

Our formula is:

$$\begin{array}{c} \bullet \quad \bullet \quad \bullet \\ \text{Number of facilities in range} * \text{average number demanded per facility per cycle} * \text{cost per flight} \\ < \text{number of facilities in range} * \text{multiple of average number to be held as safety stock} * \text{average} \\ \text{number demanded per facility per cycle} * \text{product value} * \text{inventory holding cost \%}. \\ \bullet \quad \bullet \quad \bullet \end{array}$$

Taking the case of a small fixed-wing UAS serving an area of medium facility density, we assume that ~100 facilities will be in range.

We express safety stock as a multiple of average demand at HF level, and assume that for these highly variable products, safety stock is 4x the average demand (variability factor). We can now cancel the average demand quantity from both sides of the equation.

We assume inventory holding cost at 10% for both products.

Cost per flight can be approximately assumed as \$25.

Canceling the duplicates simplifies the cost-effectiveness formula to—

$$\begin{array}{c} \bullet \quad \bullet \quad \bullet \\ \text{cost per flight} < \text{multiple of average number} * \text{product value} * \text{inv cost \%}. \\ \bullet \quad \bullet \quad \bullet \end{array}$$

The cost for **antivenom** delivery on demand to 100 HFs is calculated as—

$$\begin{array}{c} \bullet \quad \bullet \quad \bullet \\ \text{additional transport cost (number of facilities} \times \text{cost per flight)} + \text{hub inventory holding cost} \\ \text{(SQRT [number of facilities]} \times \text{variability factor} \times \text{product value} \times \text{inventory holding cost \%)} \\ = \\ (100 \times 25) + (10 \times 4 \times 150 \times 10\%) = 2,500 + 600 = \textbf{USD 3,100} \\ \bullet \quad \bullet \quad \bullet \end{array}$$

The cost for stocking **antivenom** at each HF is calculated as—

$$\begin{array}{c} \bullet \quad \bullet \quad \bullet \\ \text{HF-level inventory holding cost (number of facilities} \times \text{variability factor} \times \text{product value} \times \\ \text{inventory holding cost \%)} \\ = \\ 100 \times 4 \times 150 \times 10\% = \textbf{USD 6,000} \\ \bullet \quad \bullet \quad \bullet \end{array}$$

Cost of on-demand supply by UAS (USD 3,100) is almost half the cost of stocking at each HF (USD 6,000) and therefore *is cost-effective*.

For the **rabies PEP** use case, because of the lower cost of the product, delivery on demand is more than six times the cost of holding stock at the HF level, and therefore *not cost-effective*:

Cost for delivery on demand:

$$\begin{array}{c} \bullet \quad \bullet \quad \bullet \\ (100 \times 25) + (10 \times 4 \times 10 \times 10\%) = 2,500 + 40 = \textbf{USD 2,540} \\ \bullet \quad \bullet \quad \bullet \end{array}$$

Cost for stocking at each HF:

$$\begin{array}{c} \bullet \quad \bullet \quad \bullet \\ 100 \times 4 \times 10 \times 10\% = \textbf{USD 400} \\ \bullet \quad \bullet \quad \bullet \end{array}$$

However, health objective benefits that should be considered for making long-tail products routinely available at HFs are increasing access and revealing true demand.

- Increasing access:
 - As the product catalog of countries expands, if each product was to be stocked at health facility level, the amount of inventory needed could make it cost-prohibitive for procurement and storage.
 - In this situation, the potential number and fraction of products to be served on-demand can increase. The on-demand model creates potential for substantial

access improvements, opening up the possibility of providing medicines previously deemed “unviable” for budgetary reasons.

- Revealing true demand:
 - Currently, as long-tail products are often not stocked at HF level, individuals do not come in to seek treatment, so the demand is invisible. If serving product on-demand makes them available, it could reveal hidden demand.
 - Once the demand is visible, it would have upstream consequences, such as influencing production decisions. A prime example of this is antivenom, for which manufacturing is currently very limited and always at peril because manufacturers do not see sufficient minimum quantities for viable production because a large portion of demand is hidden (WHO 2015) (Groneberg et al. 2016).

There is increasing effort to decentralize MDR TB treatment from a few centralized sites to many decentralized facilities as this has shown to improve access and increase treatment adherence. More accessible local treatment for MDR-TB, which can range from 6–24 months depending on the type of resistance, reduces barriers to continued treatment and reveals hidden demand.

Essential and program medicines – stockout resupply

Across program and essential medicines, and across geographies, stockouts are common and large, with 20%–30% of facilities experiencing a stockout of at least one-month duration in any quarter. Stockout rates do not vary by geography (e.g., distance from supplying hub), nor do they vary by health value or financial value.

Some portions of stockouts are caused by central shortages, but there is widespread evidence that stockouts are also caused by facility-level issues, even when the central level has the product in stock. This is due to incorrect ordering/forecasting of demand (likely a skill or data record/reporting issue, i.e., systemic challenges), or to variability in lead time of distribution/accessibility in wet season (these effects are reduced by direct distribution, but still occur).

There are a few distribution options for overcoming the widespread problem of stockouts caused by distribution problems (we do not address improved forecasting and ordering in this paper):

1. Deliver a top-up to maximum inventory when stockout occurs. Delivery could be by UAS or land transport.
2. Increase frequency of regular distribution from hub to HF, such as changing from quarterly distribution to every two months.
3. Cross-distributing across health facilities; if one HF has a stockout and another a surplus, a product transfer could be arranged. This would allow pooling demand.

Our study focuses directly on option 1 above and does not examine option 3. Option 2 is peripherally addressed.

In practice, we observe that health facilities commonly make extra pick-up trips (“emergency” resupply) in addition to receiving regular delivery to top-up. In some cases, HFs will not assess the stock situation for all commodities and will make several extra pick-up trips, depending on the urgency of the stockout. In other cases, HFs may wait and aggregate several stockouts before making a top-up trip, so the stockout duration for an individual product can be quite long. If a top-up delivery approach is used to resolve stockouts, a critical question is what is the volume of stockouts? The volume will dictate the appropriate transport mode; motorcycle, land cruiser, or UAS. Program and essential medicines often have large volumes consumed by individual HFs; for example, about 100L of HIV program medication can be consumed by an HF in a quarter.

Providing a top-up resupply service in case of stockout (using any mode of transport) poses several questions:

- Should top-up wait to bundle a few different stocked-out products before providing resupply? This will depend on the health value of stocked-out products.
- If top-up delivery service is provided, will it create perverse incentives to over-rely on top-up deliveries, as opposed to the hard work of improving forecasting and ordering?
- Can a stockout resupply top-up program be designed (e.g., by allocating fixed delivery points/budgets to facilities) to mitigate the risk of perverse incentives?

Given these complexities, we cannot make a definitive conclusion about the viability of using UASs to address stockouts of program and essential medicines. The advantage of a UAS or any other transport mode must be evaluated case-by-case depending on the volume and the health-value of the products that are stocked out. UAS for stockouts might offer a good example of where the value is achieved through a layered use case, rather than stockouts being a stand-alone use case for UASs.

Diagnostic samples

Specimen transport networks share characteristics with, but are ultimately distinct from, medical commodity supply chains. Specimens considered in this analysis include:

- Dry blood spots (DBS) for early infant diagnosis (EID) or viral load (VL).
- Whole blood/serum for HIV-related testing and monitoring.
- Sputum for TB diagnostics.
- Other sample types for disease surveillance systems.

We used data from previous projects and publicly available academic papers to determine typical numbers of specimens and volumes for individual health facilities, per specimen type, as follows:

DBS card numbers are small (even for EID and VL together)

- Lesotho ~91 per facility per year (high facility density)
- Mozambique ~85 per facility per year (low facility density)
- Uganda ~650 per facility per year

Sputum samples will depend on TB incidence and extent of GeneXpert in a country

- Lesotho referred ~520 per facility in a year
- Uganda referred ~364 per facility in a year

Whole blood

- Lesotho ~1,650 per facility per year
- Uganda ~600 per facility per year

Across all types of specimens

- Zimbabwe per facility ~350 samples in total per year (~7 samples per week)

For specimens used for surveillance systems, we assume a negligible volume (based on a team member's experience in this area), which would only be an add-on to the other specimens previously mentioned. Also, specimens in an outbreak are difficult to predict and of course unscheduled so were not included in our analysis. However, based on the international disease surveillance and response framework,⁵ it is important to have a system in place for movement of specimens, both for routine surveillance and during outbreaks.

If we use Lesotho numbers, which are at the upper end of range as it has very high HIV and TB incidences, we could expect the following number of samples from an average facility per week:

- DBS - 2
- Sputum - 10
- Whole blood - 33

This translates to an average weight and volume from an average facility per week of 2 liters and 0.65 kilograms. However, in any dataset there are large-volume facilities (top 10%) that will be about four times the average (which is already high because of the disease profile in Lesotho). As such, we could assume that the highest volume facilities would have an average

⁵ <https://www.cdc.gov/globalhealth/healthprotection/idsr/about.html>.

weight of 2.7 kgs and volume of 8 ls. Thus we see for an average facility, a single UAS flight (even for smallest UASs) can comfortably fit a week's worth of diagnostic specimens.

Specimens need reverse logistics capability as they move "upward" in the tiered health system to laboratories. Hence, only VTOL drones that can land and return with cargo are applicable (these are typically multi-copters and hybrid UASs). Although an average facility can comfortably fit a week's worth of specimens in a single UAS flight (even for the smallest VTOL UASs), the cost advantages are not clear for using multi-copter and hybrid UASs because they are more expensive on a cost-per-kilometer basis than fixed-wing, more expensive than motorcycles, and have a shorter range. If motorcycles take a multi-stop route, they are in fact cheaper yet, on a per-facility basis, often by a factor of four or greater depending on facility density, road networks, and estimates of route costs included in the Excel screening tool.

Therefore, it will be extremely difficult for UASs to be cost-competitive with motorcycles on multi-stop routes. Transporting specimens using VTOL drones is unlikely to make sense on costs as a stand-alone use case, unless the cost of VTOL UASs become significantly cheaper (by a factor of five) or land transport accessibility is very low (equivalent to circuitry factor of greater than five possibly due to seasonality, terrain, etc.), or facility accessibility by land transport is very low (island region, or region with perennially washed out roads). In these cases, the introduction of UASs could also reveal true demand as patients may be able to access diagnostics at the HF level reliably, where they previously could not. Transporting specimens could make sense as a layered reverse logistics use case to outgoing deliveries, as well.

It is also worth considering the entire diagnostic and treatment cascade to understand if transport is the major bottleneck in the turnaround time (TAT) of diagnostic results. There are many sources of delays within the cascade, including at the HF (due to batching or when specimens sit at various locations within a facility without coordinating when transport is actually available); waiting at the laboratory (due to equipment breakdown or reagent stockout, or batching); and a delay in results return. Therefore, a decrease in the time of transportation potentially offered by a drone would only affect one part of the cascade, which may offer only a small reduction in overall TAT. There is also the question of whether there is any advantage of the accelerated TAT that a drone can offer and this, in part, can only be answered depending on the timeliness of results needed (i.e., for a highly contagious disease such as Ebola, or multi-drug resistant TB), and, to a lesser extent, where the loss-to-follow-up and bottlenecks are within the cascade. For chronic diseases such as HIV, the speed/responsiveness advantage of UASs over motorcycles is unlikely to offer a sufficiently compelling advantage to outweigh cost considerations.

General findings

General Takeaway 1: The number of health facilities in the applicable area of delivery is an important driver of UAS use-case viability and varies greatly with UAS range and facility density

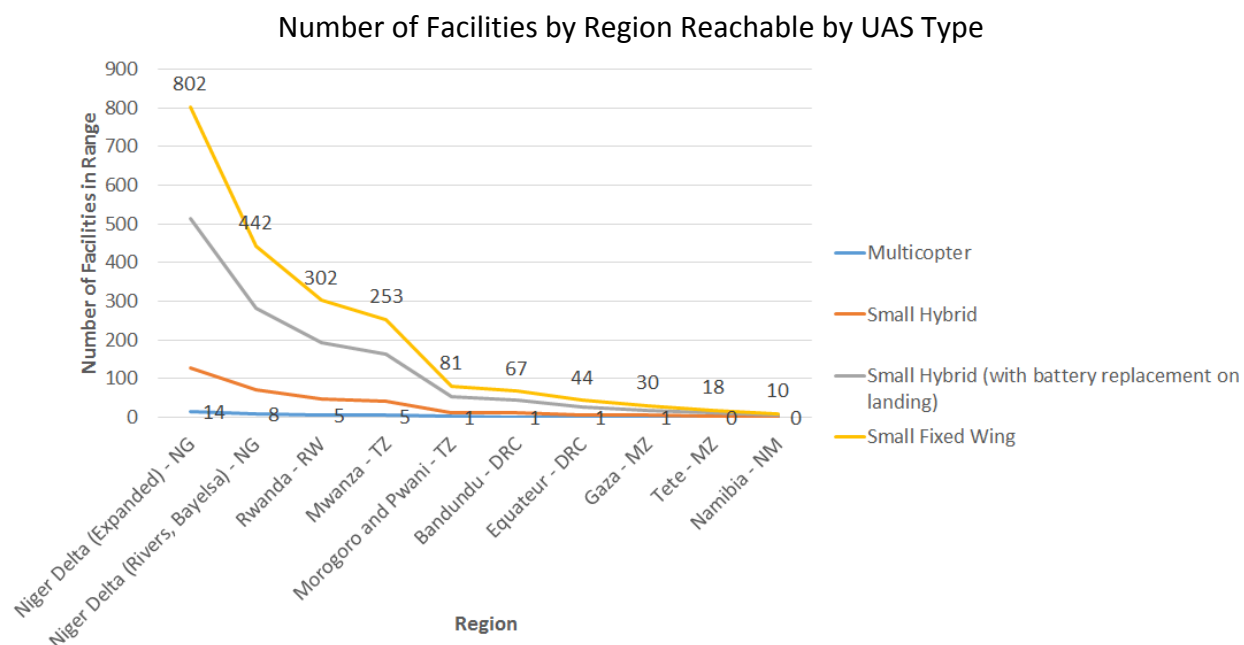
The number of health facilities that fall within the range of delivery by UASs is an important factor in viability of particular UAS use cases, because it drives the number of flights a UAS can operate in a year from a single hub (more HFs in range will mean more flights) and the magnitude of the benefits it can provide (more HFs in range means larger benefits). Please note that the point about increasing benefits only applies if the UAS offers any benefits over land transport in the first place.

The number of facilities in range of a UAS is driven by two factors:

- The range of the UAS.
- Facility density of a particular region.

Even between UASs of a similar small size with payload in the 1–2 kg range, range can vary widely. Multi-copter designs can have a range of 20 kilometers and small fixed-wing UASs a range of greater than 150 kilometers. This range represents total distance. If we consider a round-trip with departure from the hub, delivery at the health facility and return to the hub, the maximum applicable radius for delivery from a hub is half the total range (i.e., 10 kms for multi-copter and 75 kms for small fixed-wing). For multi-copter and hybrid UASs, which have VTOL capability, there is also the option of landing at the health facility and having the battery replaced there, so it is possible to consider the entire range of the aircraft as the applicable radius of delivery from a hub. However, this configuration of operations requires storage and charging batteries at HFs and extensive UAS handling by a large number of HF staff, which will add significant cost and complications.

The applicable area of delivery can be considered as a circle with its center at the hub location and its radius as half of the total range of the UAS. As the area of a circle increases in proportion to the square of its radius, the number of facilities that fall within the area of delivery also increase in proportion with the square of the range of a UAS. This is to say that the number of facilities in the applicable area of delivery is highly sensitive to increases in the range of the UAS. Considering the example above, comparing multi-copters to small fixed-wing, we see that the range differs by a factor of 7.5. This would mean that the number of facilities falling within the applicable area of delivery would differ by a factor of greater than 50. On the graph below, you can see the difference by comparing the blue line against the yellow line.



The facility density also has a strong effect on the number of facilities that fall within the applicable area of delivery. As facility density increases, the number of facilities within the applicable area increases linearly. In practice, as we saw in the *Geography* section of the *Methods and Approach* chapter of this whitepaper, looking across different regions in Africa, there is wide variation in facility density. Facility density can itself vary by more than a factor of 50, when comparing sparse areas such as Namibian regions with dense areas such as particular states in the Niger delta of Nigeria. This variation can be seen by looking at the different regions on the X-axis of the graph above.

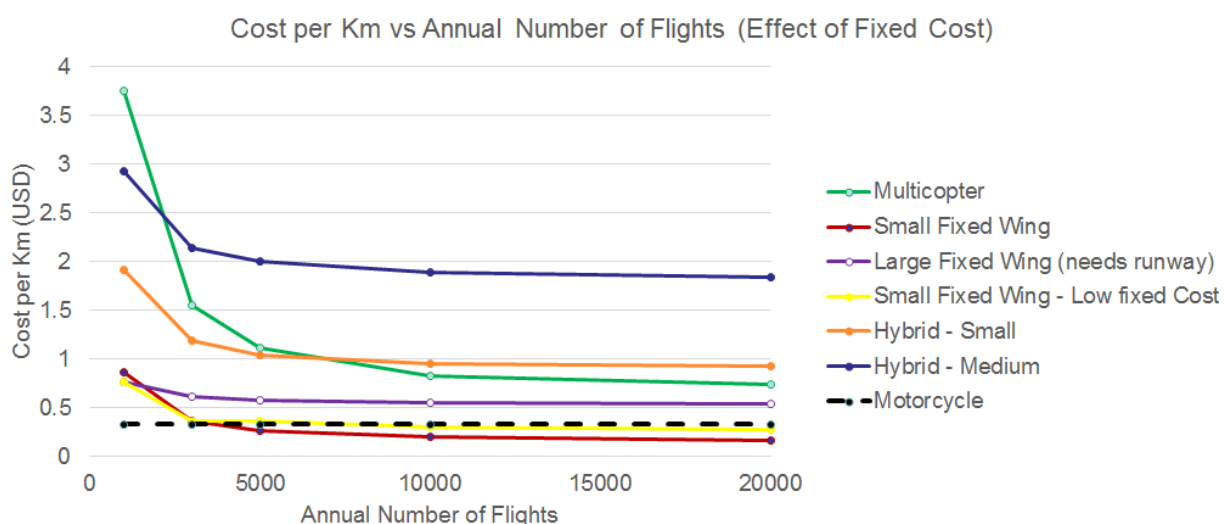
Thus we see that considering realistic ranges of alternatives, the number of health facilities falling within the applicable area of delivery can vary by a factor of greater than 50 with UAS-type (range being the important characteristic) and by a factor of greater than 50 with facility density.

General Takeaway 2: Fixed costs need to be defrayed over a large number of flights from a single hub for UASs to be cost-competitive (if looking at transport costs alone)

The cost of UASs can be divided into fixed costs (incurred each year regardless of number of flights) and variable costs (incurred for each flight). In practice, it is hard to draw a firm dividing line between fixed and variable costs, but it is common practice to do so and offers useful insights. Fixed costs may include costs such as hub infrastructure, insurance, and staff salaries. Variable costs may include energy needed for battery recharging, maintenance for each flight, and the depreciation of the airframe and battery/engine with each flight.

In calculating total transport costs per kilometer or per flight, the fixed costs of a UAS need to be defrayed across the total number of flights undertaken using that system. For example, if we look at a single hub, the total fixed costs incurred, the insurance, and the salary of the hub's staff over a year will need to be allocated across the number of flights that operate from that hub in a year to get their contribution to cost per flight or per kilometer.

As almost all UAS will have some fixed costs, and in many cases quite substantial, if only a small number of flights operate in a year from a given hub, the cost per flight or per kilometer will be very high.



Using the informed assumptions we could compile on UAS costs, we calculate the above cost-per-kilometer curves for different UAS types. The graph displays how cost-per-kilometer varies with the annual number of flights undertaken from a single UAS hub. We can clearly see that for low number of flights, the cost-per-kilometer is very high. For reference, we also include as a black dotted-line the average cost-per-kilometer for a motorcycle. As per our rules of comparison, this reflects costs for a motorcycle in a well-managed fleet.

We can see that all the UASs show improvements in cost-per-kilometer as the number of flights increase. Small fixed-wing UASs are the only ones that drop to lower cost-per-kilometer than motorcycles, and they do so only after ~5,000 flights.

The takeaway from this is that to lower effective transport costs for UASs, a single hub must operate a large number of flights per year. The larger the number of flights, the more the fixed costs can be defrayed.

Individual UASs will show different behavior in their cost-per-km curves against number of flights. This will depend on the make-up of fixed and variable costs for a particular UAS. For example, even when looking at small fixed-wing designs, there are different balances of fixed and variable costs. We can look at two options that have been used for delivery in public health settings. Zipline has a system with higher fixed costs (as they have a large hub with infrastructure for launch and recovery), and the E384 UASs used by WeRobotics for deliveries in the Peruvian Amazon have lower fixed costs (hand-launched systems with landing in football fields).



Source: Kayitare , Placide. "Drones Zitwara Amaraso Zizamarira Iki u Rwanda, Zizakora Zite, Zizishyurwa Gute?" INYENYERI NEWS, 15 Oct. 2016, www.inyenyerinews.org/truth-reconciliation/drones-zitwara-amaraso-zizamarira-iki-u-rwanda-zizakora-zite-zizishyurwa-gute/.



Source: And We're off! 2 Flying Robots Following Each Other Heading towards Amazon Village 40km Away, Carrying Diagnostics Tests and Other Supplies. WeRobotics, 19 June 2017, twitter.com/WeRobotics/status/876911565437579265/photo/1?ref_src=twsrc%5Etfw&ref_url=https%3A%2F%2Fwerobotics.org%2Fblog%2F2017%2F07%2F24%2Ffield-testing-cargo-drones-in-amazon-rainforest%2F.)

However, low fixed costs is not necessarily better. A system with low fixed costs may have higher variable costs (e.g., E384 may need more manual supervision of flights than Zipline's UAS, which only needs operating of the remote control, or may need higher maintenance, or may have a higher failure rate). WeRobotics notes 3 failures of 44 flights, with one failure leading to a lost UAS¹².

As noted in General Takeaway 1, since different UASs may have different number of health facilities in the applicable area of delivery (depending on their range), there may be different degrees of feasibility to operate a large number of flights from a single hub. For example, if there are only 10 HF in the applicable area of delivery of a hub and a particular UAS, each HF would need to be served with 500 flights per year to reach 5,000 flights annually from the hub. This would mean >1 flight/day. However, if there are 100 HF in the applicable area of delivery, each HF would only need to be served with 50 flights per year, (one per week), to reach 5,000 flights per year.

In general, if flight volumes are necessarily low (e.g., operating in a sparse area, or delivering a limited set of cargo), carefully consider UASs that have low fixed costs, as their costs can be defrayed against smaller number of flights. However, systems with low fixed costs must be examined closely for their variable cost components and capabilities.

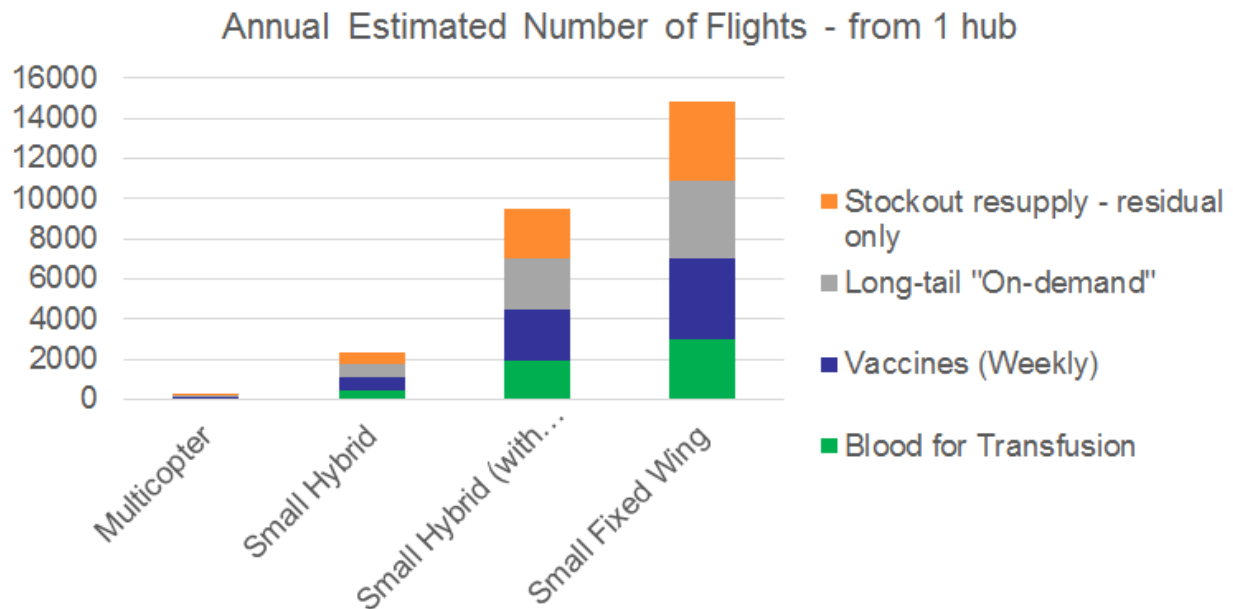
General Takeaway 3: To effectively use this new transport mode, we need to consider layering use cases across programs to build flight numbers

As we've seen in the previous graph, the cost per flight or per kilometer of UASs is greatly improved by increasing the number of flights operating from a hub. Using currently available assumptions on UAS costs, small fixed-wing designs can become transport-cost competitive with motorcycles (on a cost-per-kilometer basis) beyond ~5,000 flights. The number of flights can be simply stated as: number of health facilities in applicable delivery area multiplied by the number of flights to each HF in a year. In General Takeaway 1, we explored how the number of HFs in the applicable delivery area is affected by the UAS range and facility density. We now explore how we can increase the number of flights to each HF in a year.

The number of flights to each HF can be increased by delivering or picking up a variety of cargo types. For example, the same UAS could deliver vaccines as well as long-tail products on demand. We refer to delivering multiple types of cargo using the same UAS as "layering use cases," which increases the number of flights from a single hub, increases the use of UASs, and lowers the cost per flight or per kilometer of operating UASs.

We provide an illustration of how different use cases can be layered to build flight numbers for a particular UAS. We look at a hypothetical region with the facility density similar to Morogoro and Pwani regions in Tanzania. These regions are quite rural and of about average facility density in the range of regions we have considered. For such a hypothetical region, we consider operating a single hub with different types of UASs, ranging from a set of small multi-copters (with a total range of 20 kms, applicable delivery radius 10 kms) to a set of small fixed-wings (with total range of 150 kms, applicable delivery radius of 75 kms). With multi-copters, 1–2 health facilities would fall in the applicable area of delivery from a single hub, and with small fixed-wing UASs, approximately 80–100 HFs would fall in the applicable area of delivery from a single hub.

Using estimated average demand quantities for various cargo category use cases (which we calculated from our product data, detailed in *Methods and Approach* chapter), we can estimate how many flights would be necessary from a single hub to serve different cargo category use cases.



In the graph above, we show the effect of layering use cases on increasing the number of flights from a single hub. The different colors in the stacked bar graph represent the different cargo category use cases. The bars of different heights represent the estimated annual number of flights from a single hub for different UAS types. We can see that even with layering of use cases, a hub using multi-copters would only be able to operate a very small number of flights; after all, only 1–2 health facilities fall within the applicable area of delivery! Even focusing on small fixed-wing UASs, the estimated annual number of flights can be quite low if looking at a single cargo category in isolation. For example, even if the system was used to provide weekly delivery of vaccines to all health facilities in the delivery area, there would be <4,000 annual flights from the hub. However, by layering multiple use cases, including providing safe blood for transfusion to high-level health centers and hospitals, providing long-tail products to all health facilities on demand, and resupplying program and essential medicines when they are stocked out, we can increase the annual number of flights operating from a single hub to <14,000. This will reduce the UAS cost per flight and kilometer substantially. This example demonstrates how layering of use cases can build flight numbers and increase UAS cost-effectiveness.

We fully acknowledge the difficulty of layering use cases. Layering use cases involves working and ensuring collaboration across multiple health programs, which may each have its own funders, stakeholders, managers, and priorities. The topic of “integration” in health supply chains has been a long-running discussion. There has been significant difficulty in integrating storage and land transport across different health programs, so there is no reason that we

should expect it to be easy for UASs. However, despite the challenges, we see clear benefit in making UASs more cost-effective through layering use cases.

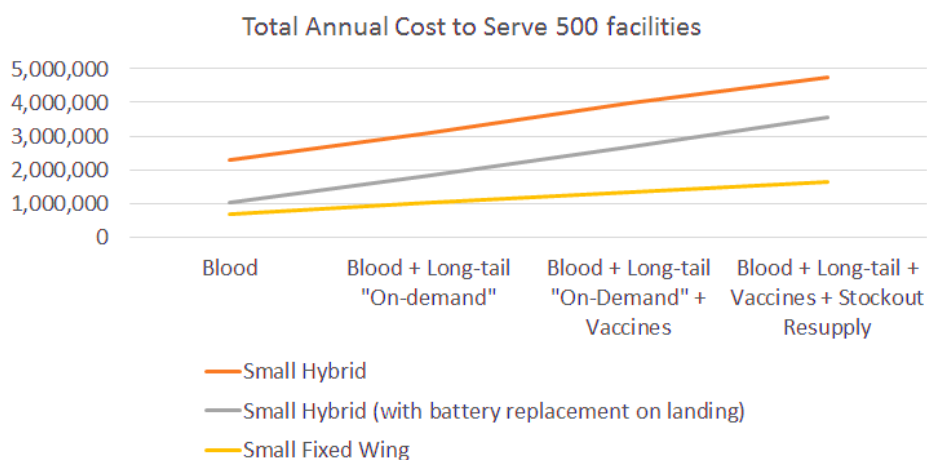
In fact, layering of use cases need not be limited to health. UASs can operate as logistics providers serving a variety of sectors. One sector that is potentially promising for UAS delivery is agriculture, particularly livestock. Vaccines to protect against livestock diseases and semen for artificial insemination of livestock are small volume, high-value items that are difficult to store and transport as they require temperature control. They are also demanded in the same rural regions that many HF may be located. With this example, we see that there could be an opportunity to layer commercial use cases from outside the health sector for delivery by the same UAS.

Ballpark costs for different use cases in context

General Takeaway 4: For a region of average facility density, order-of-magnitude estimate of annual cost to serve 500 HFs ranges from USD 1M–USD 5M depending on UAS type and cargo category

In General Takeaway 3, we estimated the annual flight numbers for different UASs operating from a single hub in a hypothetical region with the facility density of Morogoro and Pwani regions in Tanzania.

We now extend this analysis by taking those estimated annual flight numbers for a single hub and asking how many hubs and flights would be needed to serve an area of 500 health facilities. We link that with the estimated cost-per-flight for each UAS type (given the flight number) and thus calculate the **total estimated annual cost of serving 500 health facilities**. This is merely a ballpark figure intended to convey the order of magnitude of these system costs. It is not intended as guidance for any particular region or budget input.



We see that for a region with a hypothetical facility density of Morogoro and Pwani in Tanzania, the annual cost to serve 500 health facilities would vary between ~USD 1M and ~USD 5M, depending on the UAS type selected and which use cases are layered (i.e., which cargo categories are delivered). These costs are presented simply to convey the very rough magnitude of the undertaking.

Please note that while the total cost increases by layering more use cases (you are running more flights), the system is actually more cost-effective when use cases are layered. The cost per flight decreases as use cases are layered because the greater number of flights from a single hub allows the fixed costs to be widely distributed.

Reinforce importance of each dimension

General Takeaway 5: Each of the three dimensions—geography, UAS characteristics, and product/demand—are essential to determine if a particular use case adds value

In the results section covering individual cargo categories, we examined on-demand delivery of long-tail products. In that section, we compared antivenom (high financial product value) to rabies PEP (low financial product value) and showed that for those two products there were different recommendations about whether to stock the product at HF level or deliver on demand. The two products' financial value varied, demonstrating the influence of the "product/demand" dimension on determining the viability of any particular UAS use case.

We will now use the same example to illustrate the importance of considering all three dimensions: geography, UAS characteristics, and product/demand in determining the viability of a particular use case. We will make this point by taking the example of antivenom vs. rabies PEP and showing that if characteristics on any one of the dimensions change, the answer to the question of whether the product should be stocked at HF level or delivered on-demand may change, too.

In the original example, our calculations indicated that even though the demand patterns for both products were the same, it was cost-effective to deliver on-demand by UAS rather than stocking at the HF level because of the high financial value of antivenom. Meanwhile, the low financial value of rabies PEP made it more cost-effective to stock it at HF level, even with a large amount of buffer stock to protect against demand variability. We will now see how this answer changes when dimensions other than product value vary. Please note that in providing the answer we are not considering the health effects, only cost-effectiveness. The point of this exercise is to reinforce that if any one of the three dimensions is varied, the answer of viability can change.

For this exercise, we will examine the effect of changing:



- Geography: facility density
- UAS characteristics: UAS cost per flight and range
- Product/demand characteristics: variability factor (demand unpredictability)

Changing any one of these dimensions will change which alternative is cost-effective.



Facility density

If facility density is very low (e.g., even sparser than Namibia) and only four facilities are in range, then no changes—even antivenom—will improve the cost-effectiveness of delivering on demand.

Cost for delivery on demand:


$$\text{additional transport cost (number of facilities} \times \text{cost per flight)} + \text{hub inventory holding cost (SQRT [number of facilities] * variability factor * product value * inventory holding cost \%)} = (4 * 25) + (2 * 4 * 150 * 10\%) = 50 + 105 = 220.$$




Cost for stocking at HF-level:


$$\text{HF-level inventory holding cost (number of facilities * variability factor * product value * inventory holding cost \%)} = 4 * 4 * 150 * 10\% = 200.$$


UAS cost per flight and range

If we change UASs from small-fixed wing to small hybrid and keep everything else constant as we reduce range, we reduce the number of facilities in range from 100 to 12. The change in UAS type will also increase the cost per flight from USD 25 to USD 45. In this case it is not cost-effective to deliver anything, even antivenom, on demand.

Cost for delivery on demand:


$$\text{additional transport cost (number of facilities} \times \text{cost per flight)} + \text{hub inventory holding cost (SQRT [number of facilities] * variability factor * product value * inventory holding cost \%)} = (12 * 45) + (3.5 * 4 * 150 * 10\%) = 540 + 210 = 750.$$


Cost for stocking at HF-level:

$$\text{HF-level inventory holding cost (number of facilities * variability factor * product value * inventory holding cost \%)} = 12 * 4 * 150 * 10\% = 720$$

Product demand “variability factor”

If we change the multiple of average demand that is needed to be kept as safety-stock from 4 to 1.5 and keep everything else constant, it is not cost-effective to deliver anything, even antivenom, on demand.

Cost for delivery on demand:

$$\text{additional transport cost (number of facilities x cost per flight) + hub inventory holding cost (SQRT [number of facilities] * variability factor * product value * inventory holding cost \%)} = (100 * 25) + (10 * 1.5 * 150 * 10\%) = 2,500 + 225 = 2,725.$$

Cost for stocking at HF-level:

$$\text{HF-level inventory holding cost (number of facilities * variability factor * product value * inventory holding cost \%)} = 100 * 1.5 * 150 * 10\% = 2,250$$

Thus we see that while in the original example it was cost-effective to deliver antivenom on-demand, but not cost-effective to deliver rabies PEP on-demand, by changing characteristics under any one of the dimensions, it may not be cost-effective to even deliver antivenom on demand. This reinforces the need to consider all three dimensions when assessing the viability of a particular UAS use case.

Effect of improvement rates

General Takeaway 6:

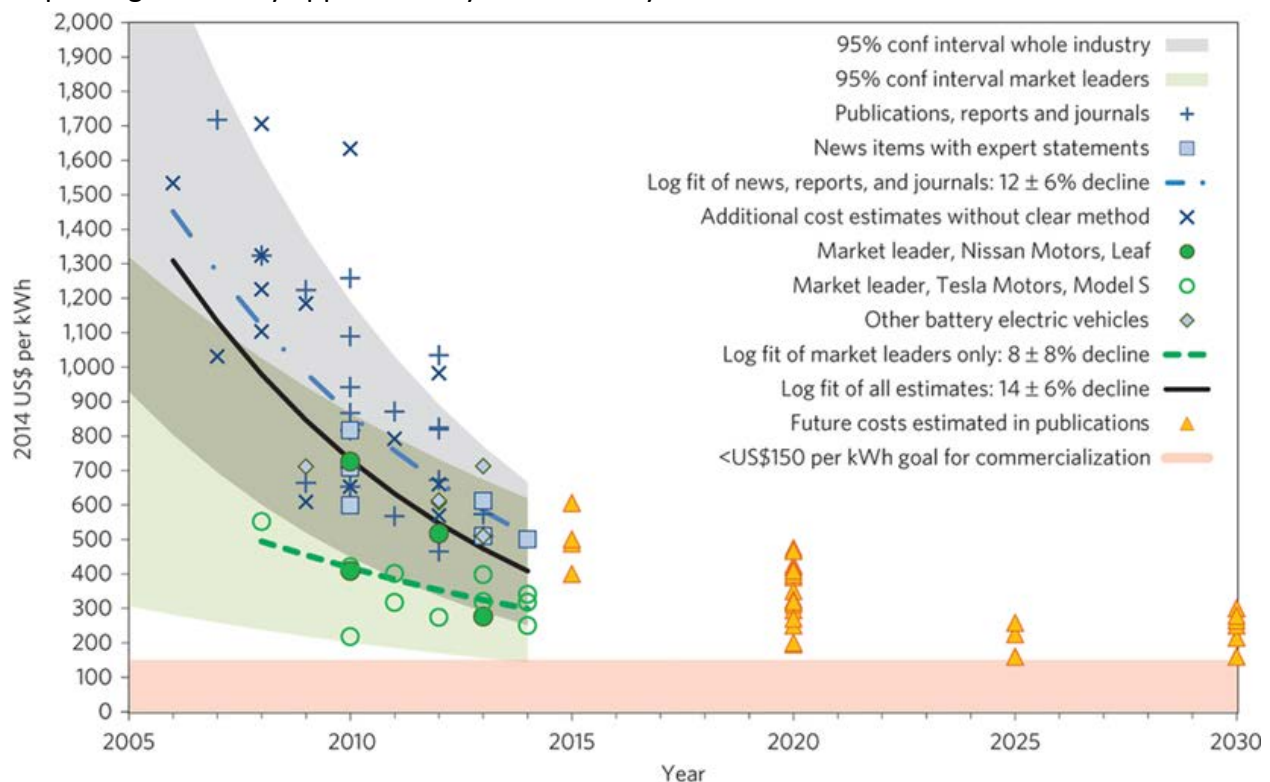
Even projecting rapid improvements in cost and performance, most UASs are still 3+ years away from being transport cost-competitive with motorcycles. The case for their use must be made on total system costs and benefits other than cost

As the technology underlying UAS is new and rapidly evolving, it is very reasonable to ask: how will comparison change in the future as cost and performance curves improve?

To answer that question, we must start with a reasonable assumption for improvement rates in cost and performance.

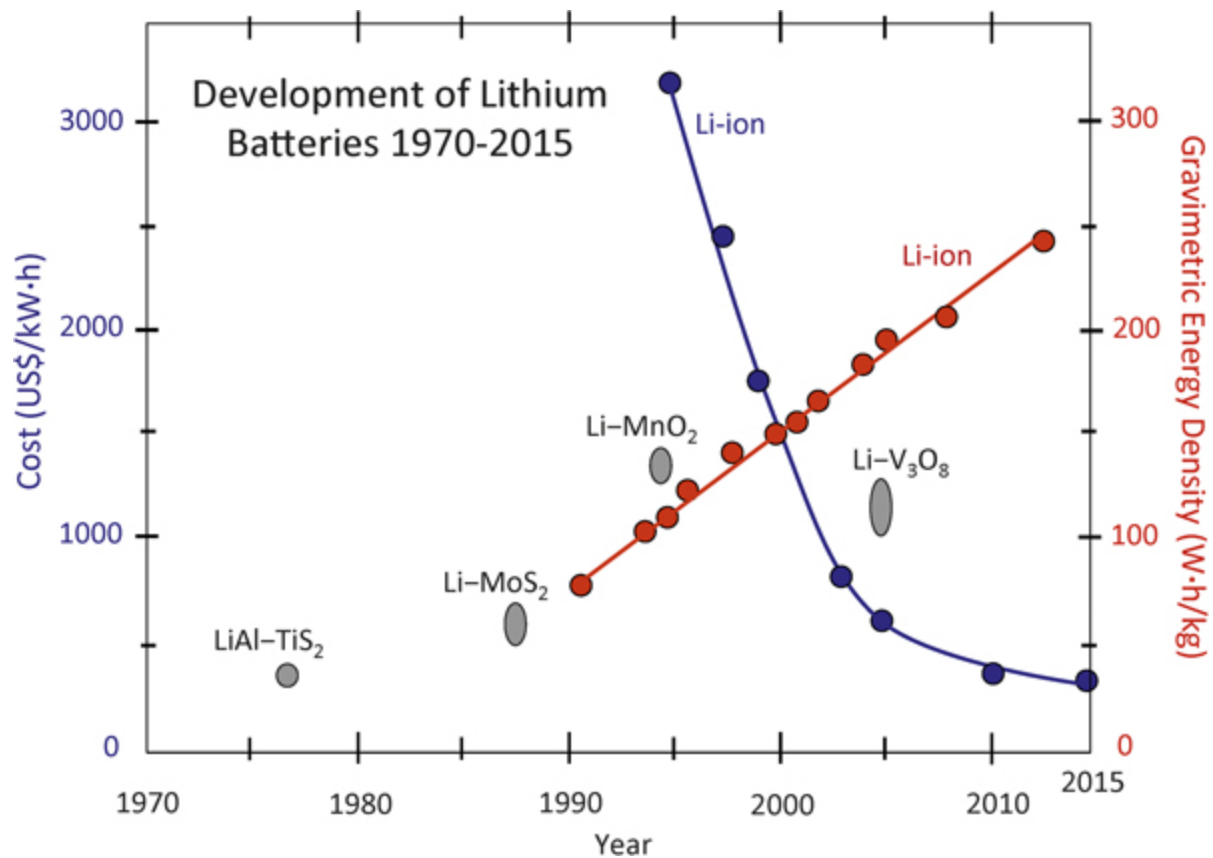
One key component of electric UASs are batteries (the majority of those considered here, although the large fixed-wing UAS is diesel powered). Battery energy limits determine the range and payload limits of UASs and have a large role in costs. Let's look closer at how cost and performance on batteries can be expected to improve.

An analysis from 2015 in *Nature: Climate Change* showed that lithium-ion batteries are improving on cost by approximately 14% annually.



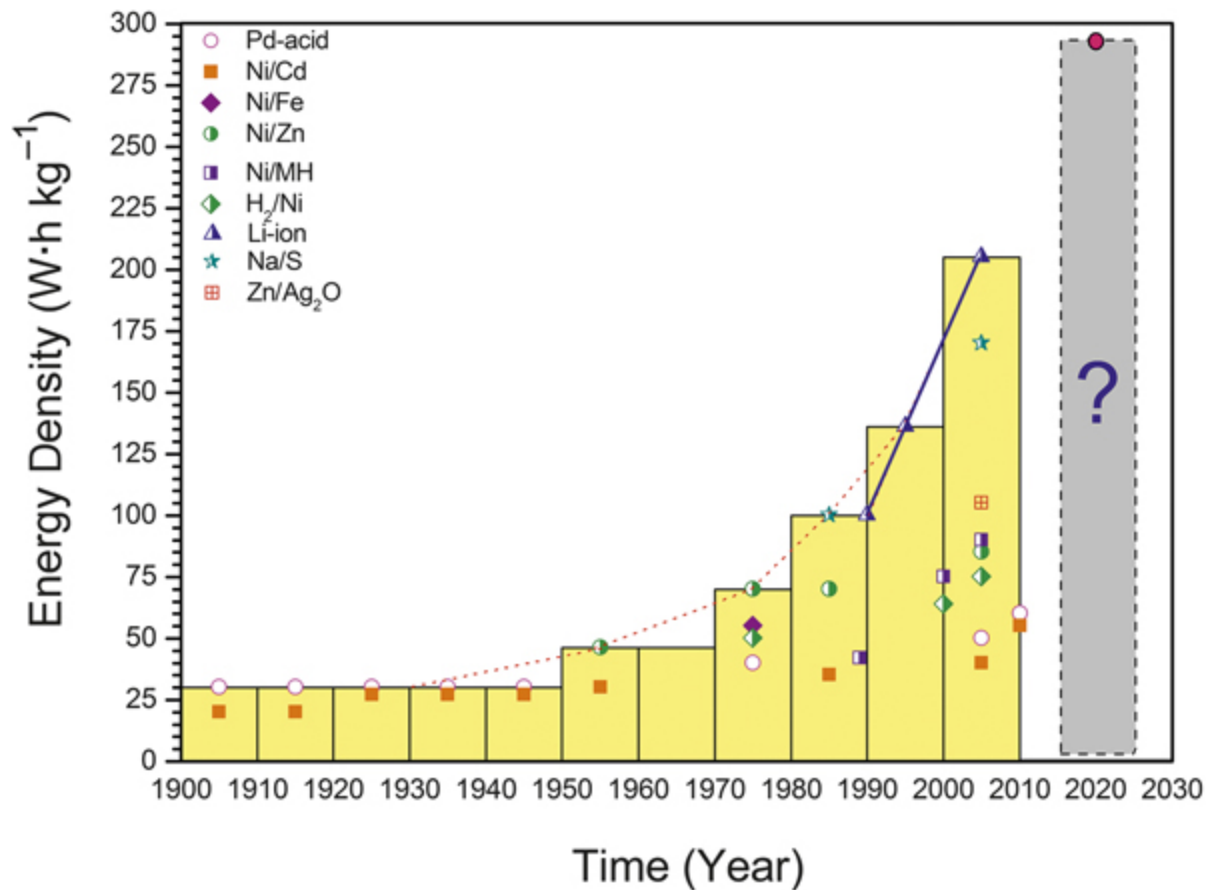
Source: Björn Nykvist and Måns Nilsson. 2015. "Rapidly falling costs of battery packs for electric vehicles." *Nature Climate Change*, 5:329–332.

Further, batteries are improving not just in cost, but as a key measure of performance; the energy-density of the batteries (how much energy they can store per unit weight) is also improving each year. Another academic paper from 2015 shows that the energy density of li-ion batteries steadily improved at an annual rate of at least 3% from their introduction in 1990 through to 2010 (see the red line in graph below).



Source: Crabtree, Kócs, Trahey. 2015. "The energy-storage frontier: Lithium-ion batteries and beyond." *MRS Bulletin* 40(12):1067–1078.

This improvement is not limited to lithium-ion; looking at previous generations of technology, it is historically true. Hence, even if lithium-ion batteries hit a limit, the energy density of batteries can be expected to continue to increase at least at 3% annually.

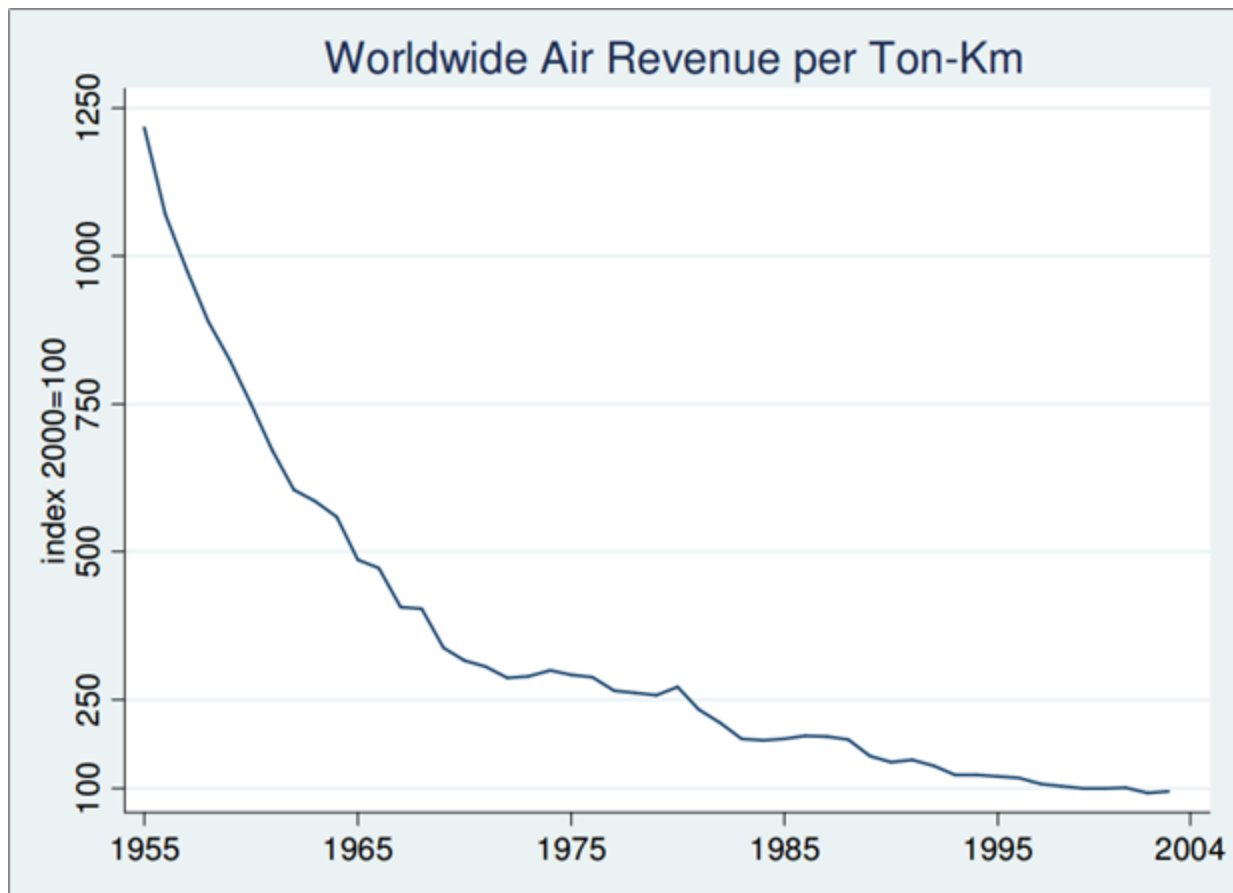


Source: Crabtree, Kócs, Trahey. 2015. "The energy-storage frontier: Lithium-ion batteries and beyond." *MRS Bulletin* 40(12):1067–1078.

Combining the annual improvements in cost (14%) with annual improvements in performance (energy density increasing 3%), we can reasonably expect that the performance per cost of batteries will increase 17% annually.

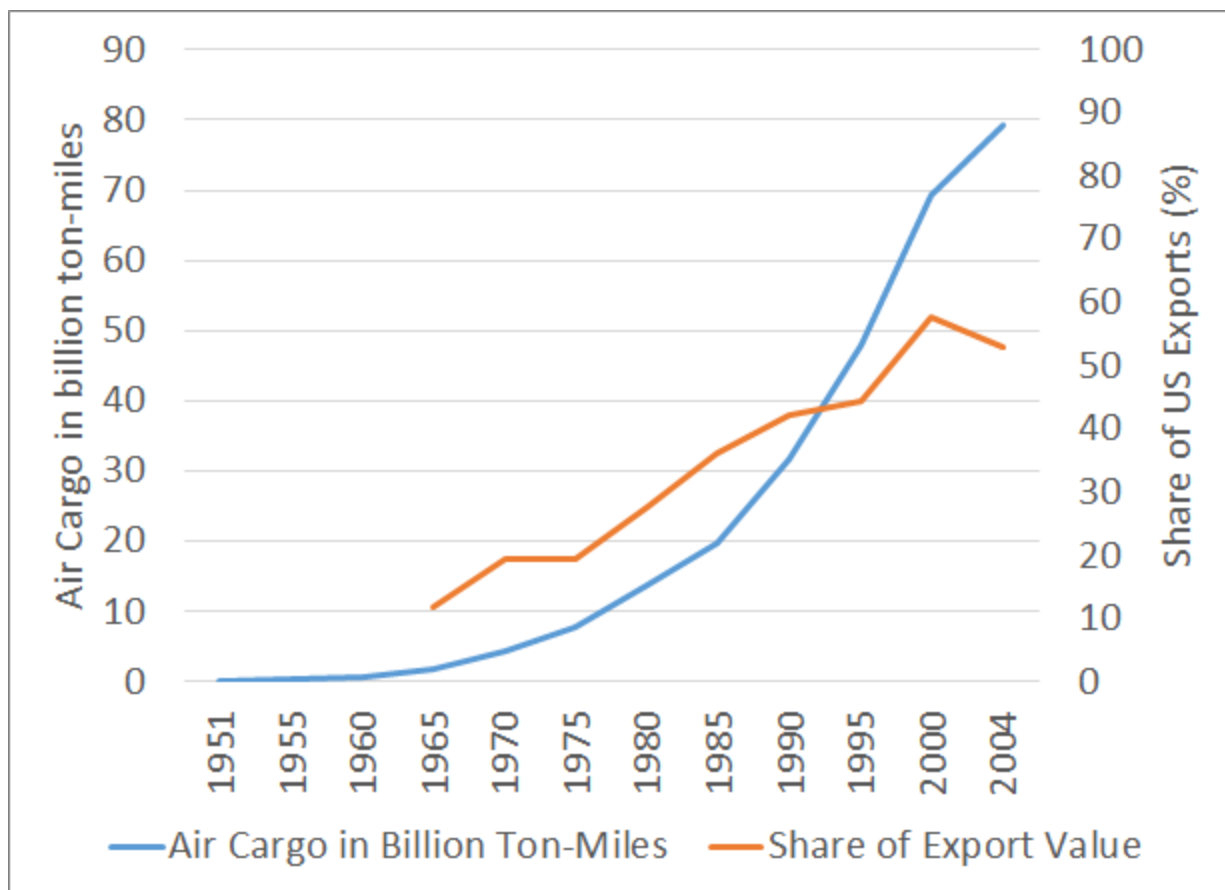
However, batteries are only one key component of a UAS. Can we look at other reference sources to estimate improvement rates in cost or performance? We can refer to a historical analysis of the commercial air-freight industry, which began in 1950.

Even in an industry subject to a lot of regulation and public scrutiny, improvement in an index measure of cost was 5% annually over 50 years, and 10% annually in the early years of the industry.



Source: Hummels, David. 2007. "Transportation Costs and International Trade in the Second Era of Globalization." *Journal of Economic Perspectives* 21(3):131–154.

As costs reduced, the volume and share of cargo that was transported using air freight steadily increased.



Source: Hummels, David. 2007. "Transportation Costs and International Trade in the Second Era of Globalization." *Journal of Economic Perspectives* 21(3):131–154.

Looking at the commercial air-freight industry, and considering that we are in the early years of transport using UASs, we can assume at least a 10% improvement in costs.

We thus have a reasonable set of assumptions for cost-improvement curves. Being conservative and comparing to the air-freight industry, we can estimate a 10% annual improvement in cost. Looking at improvements in a key component (batteries), we can estimate 17% improvement. Using this as a reference, we will consider a medium scenario of 20% annual improvement. We will also consider a very aggressive scenario of 30% annual improvement if the rate of improvement in the UAS industry exceeds expectations.

With these scenarios for assumed improvement rates, we can ask how many years until particular UASs become transport-cost competitive with motorcycles? From the graph in General Takeaway 2, we have seen that on cost per kilometer, with a medium- to high-number of annual flights, small fixed-wing UASs can already be transport-cost competitive with motorcycles. Note that the metric used here is cost per kilometer. On metrics such as cost per ton-km, motorcycles would clearly be more cost-effective, because they can transport a much

larger amount of cargo (60 kgs) than small UASs (2 kgs). However, for cases when only a small amount of cargo needs to be transported (e.g., diagnostic specimens, or providing a particular long-tail product on-demand), the cost-per-kilometer metric is still relevant.

We should also note that costs included in our calculations exclude the cost of carbon. Motorcycles and land transport run on fossil fuels and have carbon emissions, which have negative effects that are not currently fully costed into their operations. The introduction of carbon taxes or other costs of carbon may increase the cost of land transport (unless electric motorcycles or trucks become commonplace). However, for this analysis, we considered current costs and ignored potential cost of carbon.

Looking at UASs in our set other than the small fixed-wing designs, we may ask when they might become transport-cost competitive with motorcycles (on cost per kilometer). Our UAS set indicates that the most cost-effective option after small fixed-wing UAS is small hybrid. We will use our current assumptions to estimate how many years it will take for that small hybrid UAS to become transport-cost competitive with motorcycles.

The current cost per km for a motorcycle in a well-managed fleet in a rural African public health setting is USD 0.33. We should not use this number for comparison, as on any given trip a motorcycle will travel a longer distance by road and the UAS will fly in a straight line. Assuming a road circuitry factor of 1.5, the cost per km we can use for comparison is USD 0.5 per km.

The current estimated cost per kilometer for a small hybrid UAS with more than 5,000 flights annual from a single hub is approximately USD 1 per km.

Given the above numbers, the amount of time it will take for small hybrid UASs to become transport-cost competitive with motorcycles (on cost per km) is:

- Assuming 10% improvement per year: 7 years
- Assuming 20% improvement per year: little over 3 years
- Assuming 30% improvement per year: little over 2 years

Please note that this is based on our assumptions of small hybrid cost and capabilities. If the UAS range is higher than currently assumed (60 km), the costs are lower than currently assumed, or the geography is particularly inaccessible by road (higher road circuitry factor), it is possible that small hybrids may already be transport-cost competitive with motorcycles (on cost per km).

General conditions indicating favorable use case for UAS

General Takeaway 7: There are a list of factors to look for that indicate a value-add use case for UASs

Acknowledging the nuance and situation-dependence in the decision to use UASs, what should one look for? Can we identify a set of generally favorable factors that will indicate a value-adding use case for UASs?

From our analysis, we can point to the following set of factors as indicative of a value-adding use case:

- High density of facilities (within range of UAS).
- Difficult to access by road facilities (large proportion of year or time).
- High financial value, scarce, high health value (e.g., life-saving) product.
- Unpredictable demand (at level of individual facility) product.
- Product difficult/expensive to store at last-mile or has a short shelf-life.

Future Research

- **UAS cost data.** Current cost estimates are based on publicly available manufacturer data and industry expert estimates. Need to update cost numbers with real reliability figures and cost numbers from actual operations.
- **Better demand data.** Need to understand true variability in demand of individual products and HFs. Need fine-grained data on demand per period (e.g., daily demand) by product.
- **Market research of non-health use cases for UASs.** What is the potential volume of agricultural use cases such as livestock vaccines and artificial insemination? How much do they overlap with potential delivery networks for health products?
- **Potential benefits of innovative system design.** Could benefits be gained by pairing UASs with vans or barges (from which they would be launched)? How much advantage would be achieved by offering UASs that could be used for both cargo delivery and data capture?
- **Spillover effects on land transport.** What is the impact of land transport if the variable demand is handled by UASs? Can the land transport be improved and made more effective? On the flip side, if drone delivery is introduced, what about sites outside drone delivery radius? If those still need to be accessed by land, duplicate transport will be maintained.
- **Further quantification of health effects of improving supply chain outcomes.** What are the effects of improving availability, increasing access to particular medicines, and increasing access to diagnostic testing? These health effects, if substantial, may help justify increased system costs.

Implications of Findings & Next Steps

The use of UASs for distribution will continue to be a dynamic and evolving field as technology options expand and prices decrease. As countries embark on decisions related to integration of UASs within their delivery systems, our aim is to help them define those decisions, shape decisions based on their own priorities, and use an evidence-based approach for relating the results of this paper to their specific health objectives and budgets.

While this paper presents countries with a pathway and considerations for decision-making, it is important to note that these are general guidelines only, and specific decisions should be guided by country specific data on product/demand, geography and UAS characteristics. Ultimately, the aim is to develop a package of guidelines and tools for countries to use to inform their decisions about UAS choice, adoption, and implementation. However, given the emerging nature of the field and the considerations laid out in this paper, the findings from this exercise and the tool need to be validated through further application and use in more countries and with a variety of data sets and contexts. Our next steps thus will involve collaboration with interested countries to understand priorities; collect, organize, and input relevant data; and discuss options for moving forward. Such collaboration will allow countries to take advantage of our team's expertise and will allow us to further test and refine the methodologies, assumptions, analyses, and tools we have developed.

A typical engagement would begin with engaging the country or program decision makers to clearly identify their purpose and priority health objectives for introducing UAS, to facilitate the prioritization of use cases and to generate preliminary cost-effectiveness estimates. The ideal scenario would involve spending a week in-country, engaging in a consultative process with key decision makers and contextualizing data analysis and results. However, constrained budgets may dictate a desk-based screening of the same duration. Engagements may also be linked to ongoing tasks such as planned system design activities for supply chain and specimen referral system optimization, and be flexible in timing if data are available prior to the country consultation activities. Following initial screening, if plausible and potential for wide benefit, a detailed network design could be conducted. If considering layering of use cases and looking at wider sets of products like long-tail and stockout replenishment, the network design would be paired with a series of consultative design workshops to engage stakeholders across the different vertical programs.

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