

Drone medical deliveries in low and moderate income countries: insights from Vanuatu, Malawi, Rwanda, and Ghana.

Samuel Harshe, Gavin Trostle, Ryan Teoh.

NASA Aeronautics Research Institute.

Correspondence: sam.harshe@yale.edu.

ABSTRACT.

Drones are a uniquely promising solution in healthcare logistics, especially in areas not easily served by traditional transportation. This paper synthesizes lessons from four early adopters of drone delivery—Vanuatu, Malawi, Rwanda, and Ghana—drawing general conclusions about the prospects and perils of drone delivery in low- and middle-income countries

KEYWORDS.

Drone; UAV; medical delivery; Vanuatu; Malawi; Rwanda; Ghana; LMIC.

I. INTRODUCTION.

Drones have been used by militaries for nearly a century, but in civilian life, they are still mostly theoretical.¹ After a decade of bold proclamations, Amazon’s “Prime Air” drone delivery system

¹ Vyas, Kashyap. “A Brief History of Drones: From Pilotless Balloons to Roaming Killers.” Drones have come a long way since their early days, June 29, 2020. <https://interestingengineering.com/innovation/a-brief-history-of-drones-the-remote-controlled-unmanned-aerial-vehicles-uavs>.

is still “preparing” for deliveries,² while startups like SkyDrop (formerly Flirtey) have yet to follow through on impressive promises.³

Despite the well-publicized disappointment so far in commercial drone delivery, medical drone delivery has already proven practical in several countries, and it promises to expand in the coming years.⁴ Drones are uniquely suited to making urgent deliveries to remote areas, quickly transporting medical supplies where road transportation is not available or too slow.⁵ Drones have been used to deliver AEDs for out-of-hospital cardiac arrest, frequently beating first responders to the scene;⁶ to deliver blood when there is none on hand at hospitals;⁷ to deliver

² Amazon Staff. “Amazon Prime Air Prepares for Drone Deliveries.” US About Amazon, June 13, 2022. <https://www.aboutamazon.com/news/transportation/amazon-prime-air-prepares-for-drone-deliveries>.

³ French, Sally. “Amazon’s First Prime Air Delivery Is Just More Drone Hype.” MarketWatch, December 14, 2016. <https://www.marketwatch.com/story/the-heavy-on-hype-light-on-substance-world-of-drone-delivery-2016-12-01>; Hidalgo, Jason. “Reno Drone Company SkyDrop Approved for Store-to-Door Delivery in New Zealand.” Reno Gazette Journal, April 11, 2023. <https://www.rgj.com/story/news/money/business/2023/04/11/skydrop-approved-for-store-to-door-drone-delivery-in-new-zealand/70103632007/>.

⁴ Amukele, Timothy. “Current State of Drones in Healthcare: Challenges and Opportunities.” *The Journal of Applied Laboratory Medicine* 4, no. 2 (2019): 296–98. <https://doi.org/10.1373/jalm.2019.030106>; Laksham, Karthik Balajee. “Unmanned Aerial Vehicle (Drones) in Public Health: A SWOT Analysis.” *Journal of Family Medicine and Primary Care* 8, no. 2 (2019): 342. https://doi.org/10.4103/jfmpe.jfmpe_413_18.

⁵ Haidar et al. “The Economic and Operational Value of Using Drones to Transport Vaccines.” *Vaccine* 34, no. 34 (2016): 4062–67. <https://doi.org/10.1016/j.vaccine.2016.06.022>; Scott, Judy E., and Carlton H. Scott. “Drone Delivery Models for Medical Emergencies.” *Healthcare Delivery in the Information Age*, 2019, 69–85. https://doi.org/10.1007/978-3-030-17347-0_3.

⁶ Choi et al. “Effect of Topography and Weather on Delivery of Automatic Electrical Defibrillator by Drone for Out-of-Hospital Cardiac Arrest.” *Scientific Reports* 11, no. 1 (2021). <https://doi.org/10.1038/s41598-021-03648-3>; Schierbeck et al. “Automated External Defibrillators Delivered by Drones to Patients with Suspected Out-of-Hospital Cardiac Arrest.” *European Heart Journal* 43, no. 15 (2021): 1478–87. <https://doi.org/10.1093/eurheartj/ehab498>; Sanfridsson et al. “Drone Delivery of an Automated External Defibrillator – a Mixed Method Simulation Study of Bystander Experience.” *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine* 27, no. 1 (2019). <https://doi.org/10.1186/s13049-019-0622-6>.

⁷ Ling, Geoffrey, and Nicole Draghic. “Aerial Drones for Blood Delivery.” *Transfusion* 59, no. S2 (2019): 1608–11. <https://doi.org/10.1111/trf.15195>; Nyaaba, Albert Apotele, and Matthew Ayamga. “Intricacies of Medical Drones in Healthcare Delivery: Implications for Africa.” *Technology in Society* 66 (2021): 101624. <https://doi.org/10.1016/j.techsoc.2021.101624>.

vaccines to an island nation with little transportation infrastructure;⁸ and to respond flexibly to medical emergencies in a warzone.⁹ While drones are currently too expensive to profitably deliver food and other cheap goods, they are already cutting costs and saving lives with urgent deliveries of medical supplies. “We believe the value of new technology is most valuable where it is clearly needed...that’s why we wanted to focus on drones delivering medicine and not delivering pizzas,” said one drone executive.¹⁰

The expansion of drone delivery faces several obstacles. One is the range of commercially available drones, which is typically 10 miles or less.¹¹ Another is technological know-how. Reports from the UN cite a “skill deficit,” with low- and moderate-income countries lacking qualified drone operators.¹² A more discreet obstacle is regulation. Drone technology has developed so quickly that many states, out of concern over drone malfunction and abuse, have adopted suffocating regulation.¹³

⁸ Enayati, Shakiba, James F. Campbell, and Haitao Li. “Vaccine Distribution with Drones for Less Developed Countries: A Case Study in Vanuatu.” *Vaccine: X* 14 (August 2023): 100312. <https://doi.org/10.1016/j.jvacx.2023.100312>; “PROJECT REPORT Vanuatu Drone Trial: Phase 1 and 2.” UNICEF, September 2019. <https://www.updwg.org/wp-content/uploads/2020/10/UNICEF-Vanuatu-Drone-Report-Final-Executive-Summary.pdf>.

⁹ Sciarpelletti, Laura. “Saskatoon Company Donates Drones to Deliver Medical Supplies to Ukrainians in Russian-Occupied Cities | CBC News.” CBCnews, March 26, 2022. <https://www.cbc.ca/news/canada/saskatchewan/saskatoon-draganfly-drones-to-deliver-medical-supplies-to-ukrainians-in-russian-occupied-cities-1.6398094>.

¹⁰ French, Sally. “Amazon’s First Prime Air Delivery Is Just More Drone Hype.”

¹¹ Crumley, Bruce. “Draganfly Introduces Three New Drone Products at Las Vegas Expo.” DroneDJ, September 8, 2022. <https://dronedj.com/2022/09/08/draganfly-drones/>; “HS720 GPS Drone with 4K Camera.” Holy Stone. Accessed July 5, 2023. <https://www.holystone.com/en/Drones/Premium/HS720GPSDroneWith4KCamera.html>.

¹² “Harnessing Drones for Development of African Least Developed Countries.” YouTube, March 23, 2021. <https://www.youtube.com/watch?v=VC8z5fwELTw>; “Low and Middle Income Countries (LMIC).” Low and Middle Income Countries (LMIC) | QES Climate Justice. Accessed August 2, 2023. <https://quesclimatejustice.info.yorku.ca/resources/eligible-countries/>.

¹³ Amukele, Timothy. “Current State of Drones in Healthcare: Challenges and Opportunities.” *The Journal of Applied Laboratory Medicine* 4, no. 2 (2019): 296–98. <https://doi.org/10.1373/jalm.2019.030106>; Amukele, Timothy. “The Economics of Medical Drones.” *The Lancet Global Health* 8, no. 1 (January 2020). [https://doi.org/10.1016/s2214-109x\(19\)30494-2](https://doi.org/10.1016/s2214-109x(19)30494-2).

But the strongest headwinds, addressed throughout this paper, are due to cost. Ghana's government took heavy flak after announcing its drone delivery contract as detractors argued that the money would be better spent on ordinary infrastructure upgrades.¹⁴ Drones have obvious technical advantages, but critics maintain that their cost will relegate them to a niche solution.

Despite these concerns, the prospect of human development from drone healthcare delivery is too great to disregard. 3.4 billion people live in rural communities, which often lack infrastructure and are poorer than and isolated from their urban counterparts.¹⁵ This leads to great disparities in access to critical healthcare and health outcomes.¹⁶ In drones lies the potential to reshape the geographic and developmental distinctions that divide the global population.

This study intends to integrate reports from four countries—Vanuatu, Malawi, Rwanda, and Ghana—where drone-based healthcare deliveries have been essayed, offering synthesized conclusions that further the understanding of the uses of medical drones in LMICs.

II. METHODOLOGY.

We sought out published papers pertinent to past, current, and future uses of drones for medical supply delivery. These papers fell into the following 3 categories: background on health systems and human development; background on current and prospective drone technology; and analyses of the four target countries and their drone systems.

¹⁴ “Imani Alert: Novelty Is Not Innovation – the Story of Fly Zipline Ghana.” Imani Africa, February 13, 2020. <https://imaniafrica.org/2018/12/imani-alert-novelty-is-not-innovation-the-story-of-fly-zipline-ghana/>.

¹⁵ “Number of People Living in Urban and Rural Areas.” Our World in Data. Accessed August 10, 2023. <https://ourworldindata.org/grapher/urban-and-rural-population>; Ritchie, Hannah, and Max Roser. “Urbanization.” Our World in Data, September 13, 2018. <https://ourworldindata.org/urbanization>; “Reducing Poverty and Inequality in Rural Areas: Key to Inclusive Development | DISD.” United Nations, June 2, 2021. <https://www.un.org/development/desa/dspd/2021/06/poverty-and-inequality-rural-areas/>.

¹⁶ “World's Rural Populations Excluded from Healthcare Access.” United Nations. Accessed August 10, 2023. <https://www.un.org/sustainabledevelopment/blog/2015/04/new-un-report-finds-bulk-of-worlds-rural-populations-excluded-from-healthcare-access/>.

We then researched the following background information about each target country: geography, topography, and climate; population statistics, including basic economic indicators and population dispersion; transportation infrastructure, especially airports, and roads; health outcomes, institutions, and infrastructure; governmental structure and potential sociopolitical complications; special requirements and difficulties in implementing a drone system.

We additionally searched for the following details about the drone system recently implemented: basic health problems addressed; sponsor, including the source of funding and technical expertise; financial viability; overview of the architecture of the drone system, including the takeoff and landing points; goods delivered; the technical specifications of the drones used.

Collating data and analysis from a broad range of sources using Google Scholar, Scopus, ScienceDirect, PubMed, Web of Science, and the bibliographies of papers already discovered, we built out a database that forms the basis of the claims and recommendations presented in this paper.

III. CASE STUDIES.

Vanuatu.

Background.

Vanuatu comprises 4,700 km² total in the South Pacific Ocean, where its 313,000 citizens live permanently on 65 of its 83 islands.¹⁷ Only 26% of Vanuatu's citizens live in urban areas, and its largest city, Port Vila, is home to only 35,000.¹⁸ Vanuatu's far-flung citizenry is connected by less than 100 km of paved roads and only 3 airports with paved runways.¹⁹ According to the WHO, "Limited access to quality health services remains a challenge [in Vanuatu]. Scattered populations, geographical isolation, poor infrastructure, costly transportation and logistics are

¹⁷ "Vanuatu." Central Intelligence Agency. Accessed August 9, 2023. <https://www.cia.gov/the-world-factbook/countries/vanuatu>.

¹⁸ Ibid.

¹⁹ Ibid.

major challenges in delivering essential health care.”²⁰ Vanuatu’s GDP per capita is \$2,997, and its current health expenditure per capita is \$114.23.²¹ Vanuatu’s UHC Service Coverage Index, a measure of the country’s coverage of essential health services, is 52.00, below the global average of 67.48.²² Vanuatu is ranked 140th of 191 in the Human Development Index.²³ A challenge unique to Vanuatu among the target countries is its vulnerability to natural disasters, including cyclones, earthquakes, and volcanic eruptions.

Drone program.

The drone program implemented in Vanuatu was in a trial done by two drone manufacturers, Wingcopter and Swoop Aero, under the guidance of UNICEF. A total of 17 kg of supplies was delivered from 2 distribution centers to 33 delivery sites as 1,066 women and children were vaccinated. The trial had 3 primary goals: (a) to determine whether communities would accept medical drones; (b) to determine whether drones could safely be incorporated into Vanuatu’s airspace; and (c) to determine whether drones could feasibly be incorporated into supply chains.²⁴

Vanuatu has the lowest immunization rates in the Pacific region, and 28% of Ni-Vanuatu mothers with non-vaccinated children said they simply “forgot” to have their children vaccinated. Despite this, UNICEF writes that “drone deliveries strengthened parental engagement that resulted in increased numbers of children presenting for vaccination, which, in turn, exceeded on-island vaccine supplies and resulted in a temporary stock-out.” Elsewhere, UNICEF adds that “the enthusiasm of nurses did need to be tempered to ensure contractors could comply with cold chain

²⁰ “Who Country Cooperation Strategy 2018-2022: Vanuatu.” World Health Organization, January 1, 2017. <https://www.who.int/publications/i/item/WPR-2017-DPM-025>.

²¹ “GDP per Capita (Current US\$).” World Bank Open Data. Accessed August 9, 2023. <https://data.worldbank.org/indicator/NY.GDP.PCAP.CD>.

²² “The Universal Health Coverage (UHC) Service Coverage Index.” Our World in Data. Accessed August 9, 2023. <https://ourworldindata.org/grapher/universal-health-coverage-index>.

²³ United Nations. “Country Insights.” Human Development Reports. Accessed August 9, 2023. <https://hdr.undp.org/data-center/country-insights#/ranks>.

²⁴ “PROJECT REPORT Vanuatu Drone Trial: Phase 1 and 2,” 40-44.

guidelines and observe their payload limitations.” Problems with community acceptance were problems of over-acceptance. Drone deliveries proved so charismatic that nurses and patients strained the fledgling system.²⁵

The drone program also proved safe in all deliveries. It suffered two accidents, neither of which caused significant damage.

The drone program also demonstrated that drones are a feasible solution to medical supply chain problems. UNICEF writes that it “proved unequivocally that drones are technically and operationally able to contribute to minimizing logistical bottlenecks in the ‘last-mile’ delivery of vaccines,” as “all vaccines were delivered within acceptable temperature limits.” While the trial was too brief to determine definitively its impact on vaccination rates, results were promising. 20% of Ni-Vanuatu mothers with non-vaccinated children said that the reason their children were not vaccinated was that the vaccine was not available. 19% said that they did not have a means of transportation to a clinic.²⁶ Drones dramatically shorten stockouts by providing just-in-time delivery, and they increase access by making delivery to remote areas easier. Given the causes of Vanuatu’s low vaccination rates, one would expect drones to raise them.

Drones also permitted new strategies for remote vaccination. During the trial, instead of following their typical procedure of lugging a “cold box” containing as many vaccines as they guessed they would need, Ni-Vanuatu nurses arrived at the site, “conducted a quick survey of non-vaccinated children, and placed a matching order of exact dose requirements.” Within 30 minutes, the vaccines were delivered.

Part of the trial was delayed a week by a cyclone, and several other flights were grounded by heavy rain. However, this does not expose a fragility particular to drone delivery. Vaccine delivery in Vanuatu currently relies heavily on boats, which are similarly vulnerable to rainy and windy weather, and which are further limited by the water conditions where drones are not.

²⁵ Ibid., 50-58.

²⁶ Ibid.

Moreover, due to their size and portability, drones are more easily protected against cyclones and other *forces majeures* than are planes and boats. UNICEF further states that the centralization of medical supply distribution centers may increase supply chains' reliability. "Community-level cold chain equipment could become redundant," which obviates "associated maintenance costs" and the need to "manage climate-related disruptions to the delivery of [immunization program] services." "Tropical cyclones occur frequently, for instance," UNICEF continues, "which have a tendency to damage solar panels that are essential to the cold chain."²⁷ In other words, drones reach remote areas more easily, allowing supplies to be kept together in a few regional distribution centers rather than spread out near the point of service. By reducing the amount of infrastructure they rely on, drones fortify supply chains against disasters.

Due to its effectiveness, the Vanuatu drone program gradually grew in scope over its course. "Nurses on the ground organically expanded delivery requests to include additional commodities, with Swoop Aero delivering paperwork, oral hygiene kits and relocating supplies from one island health facility to another as demand called," UNICEF writes.

But one delivery was out of the norm. "A drone was used to urgently and unexpectedly deliver an emergency shipment of the life-saving medicine oxytocin to stop a postpartum hemorrhage. For the mother who had just delivered a baby in the remote and unstaffed [remote] dispensary, this delivery proved critical to saving her life," UNICEF writes. An oxytocin delivery that would have taken 5 hours took less than 1 hour by drone, saving the mother's life, even though the trial system was not designed with such deliveries in mind.²⁸

It was not a goal of the trial to investigate the cost-effectiveness of drone delivery. UNICEF equivocally writes that "the costs for [drone] services would not be necessarily cheaper than [previous] transportation modes ... especially given that delivery of vaccines by [drone] does not

²⁷ "Vanuatu: Revolutionary Technology for Vaccine Delivery." UNICEF Office of Innovation, June 11, 2017. <https://www.unicef.org/innovation/drones/technology-for-vaccine-delivery-vanuatu>; "PROJECT REPORT Vanuatu Drone Trial: Phase 1 and 2."

²⁸ Ibid.

eliminate the need for nurses to travel to ... administer vaccinations.” The report noted that the trial’s greatest cost by far was personnel, and drones may not significantly reduce the personnel requirements of vaccination. However, this applies specifically to vaccination, which requires a trained professional on-site. Cost savings seem much more likely in the delivery of other medical supplies that do not require professional accompaniment. In any case, drone delivery promises many other benefits that traditional delivery cannot.

Malawi.

Background.

Malawi, a landlocked country in Southern Africa, comprises 118,484 km², with a population of 21,000,000.²⁹ The eastern half of Malawi borders Lake Nyasa, which extends from the far north to the middle of the country. Containing 32 airports, of which 7 are paved, and 15,452 km of road, of which 4,074 are paved, Malawi has undeveloped infrastructure, especially in regions with low population densities, which are mostly in the northern half of the country.³⁰ Malawi suffers from a heavy disease burden, especially from tuberculosis, malaria, and HIV, and its health system faces a “critical shortage of capacity in institutions implementing development programmes.”³¹ Malawi’s GDP per capita is \$1,500, and its current health expenditure per capita is \$35.28.³² Malawi’s UHC Service Coverage Index, a measure of the country’s coverage of essential health services, is 48.26, below the global average of 67.48.³³ Malawi is ranked 169th of 191 in the HDI, making it the least developed target country.³⁴

²⁹ “Malawi.” Central Intelligence Agency. Accessed August 9, 2023. <https://www.cia.gov/the-world-factbook/countries/malawi/>.

³⁰ Ibid.

³¹ Malawi - World Health Organization, May 2017. https://apps.who.int/iris/bitstream/handle/10665/136935/ccsbrief_mwi_en.pdf.

³² “Malawi.” Central Intelligence Agency.

³³ “The Universal Health Coverage (UHC) Service Coverage Index.” Our World in Data. Accessed August 9, 2023. <https://ourworldindata.org/grapher/universal-health-coverage-index>.

³⁴ United Nations. “Country Insights.” Human Development Reports. Accessed August 9, 2023. <https://hdr.undp.org/data-center/country-insights#/ranks>.

Drone program.

In 2016, UNICEF and the government of Malawi opened a 5,000 km² “humanitarian drone testing corridor” in Malawi to test the “potential humanitarian use of UAVs.”³⁵ One study done in this corridor, conducted by UNICEF in partnership with VillageReach, set out to investigate whether drones were cheaper than motorcycles, which are currently used, in healthcare delivery.³⁶ Under three of the four tested conditions, drones were more expensive than motorcycles, which could carry more samples per trip, reducing the overall distance traveled. Drones were slightly cheaper when motorcycles were not allowed to take multiple samples per trip. An analysis of this study found that in non-emergency situations, the 95% CI for per sample transport costs by motorcycle was (\$0.01, \$2.85), while by drone it was (\$0.56, \$5.05).

A comparable study, “The economic and operational value of using drones to transport vaccines,” found drones “raised...availability and saved costs over traditional land transport,” and “with sufficient [drone] utilization, cost savings were robust to sensitivity analyses.”³⁷ The contradictory conclusions and large error bars of these studies should alert readers to the current uncertainty in the cost-effectiveness of healthcare drone deliveries.

“With increasing range and operational lifespans,” drones became more cost-effective. “Drones are well-suited to overcoming unique challenges where traditional forms of transportation and distribution prove too slow or too unreliable to be effective. Emergency medicine deliveries, supplementary distributions in between routine drops, accessing remote locations, and

³⁵ “Humanitarian Drone Corridor Launched in Malawi.” YouTube, August 15, 2017. https://www.youtube.com/watch?v=_yURGGIVqgA&ab_channel=UnicefMalawi; Fabian, Chris. “Malawi’s Unique Drone Corridor.” UNICEF Office of Innovation, July 3, 2017. <https://www.unicef.org/innovation/drones/malawi-unique-drone-corridor>.

³⁶ Phillips, N., Blauvelt, C., Ziba, M., Sherman, J., Saka, E., Bancroft, E., and Wilcox, A. Costs Associated with the Use of Unmanned Aerial Vehicles for Transportation of Laboratory Samples in Malawi. Seattle: VillageReach; 2016.

³⁷ Haidari, Leila A., Shawn T. Brown, Marie Ferguson, Emily Bancroft, Marie Spiker, Allen Wilcox, Ramya Ambikapathi, Vidya Sampath, Diana L. Connor, and Bruce Y. Lee. “The Economic and Operational Value of Using Drones to Transport Vaccines.” *Vaccine* 34, no. 34 (2016): 4062–67. <https://doi.org/10.1016/j.vaccine.2016.06.022>.

overcoming roadblocks are a few examples of where this tool may prove most effective,” the study concluded.³⁸

In addition to its lack of robust data regarding cost, this study suffered from uncertain applicability. There are indications that motorcycle deliveries in Malawi do not usually function as tested, and are frequently delayed and unreliable due to staffing shortages. Drones, which fly autonomously, would alleviate staffing burdens. One clinic worker testified that motorcycles are supposed to come weekly, but “due to financial problems, and no money for fuel, they don’t come.” This is particularly undesirable because the deliveries in question are of blood samples, meant to test children for HIV (of which Malawi has one of the highest rates in the world—in 2014, two years before the trial, 10,000 Malawian children died of HIV).³⁹ Mortality rates among HIV-positive children decrease significantly if they take antiretroviral medications. Of course, children do not know to take antiretroviral medication unless they have been diagnosed with HIV.

In the current system, it takes up to 10 weeks for HIV results to be returned to the health center, and “even then, close to half of the sample test results never made it back because either the samples or the results were lost in transport.” With drones it takes hours. A study on the reliability and speed of drone delivery in Malawi found that drones “achieved faster and more reliable delivery of patient diagnostic samples and results.”⁴⁰ This means that “HIV-positive patients begin antiretroviral treatment sooner,” improving the efficacy of treatments and allowing

³⁸ Ochieng, Walter O, Tun Ye, Christina Scheel, Aun Lor, John Saindon, Sue Lin Yee, Martin I Meltzer, Vikas Kapil, and Kevin Karem. “Uncrewed Aircraft Systems versus Motorcycles to Deliver Laboratory Samples in West Africa: A Comparative Economic Study.” *The Lancet Global Health* 8, no. 1 (2020). [https://doi.org/10.1016/s2214-109x\(19\)30464-4](https://doi.org/10.1016/s2214-109x(19)30464-4).

³⁹ “HIV Rates by Country 2023.” HIV rates by country 2023. Accessed August 1, 2023. <https://worldpopulationreview.com/country-rankings/hiv-rates-by-country>.

⁴⁰ Dublin, Scott, Ashley Greve, and Ryan Triche. “Drones in International Development.” UPDWG. Accessed August 10, 2023. https://www.updwg.org/wp-content/uploads/2020/11/Drones_in_International_Development_Innovating_the_Supply_Chain_to_Reach_Patients_in_Remote_Areas_2_1.pdf.

doctors to check whether treatments are working.⁴¹ This also aids authorities in “identifying local prevalence rates,” allowing communities to plan to reduce the spread of disease.⁴² It is therefore their speed and reliability that make drones attractive, although they could be more expensive. “This innovation could be the breakthrough in overcoming transport challenges and associated delays experienced by health workers in remote areas of Malawi,” stated the UNICEF representative in Malawi.⁴³

A report on the ethical considerations of the Malawi drone program concluded that “no severe ethical tensions, tradeoffs, or dilemmas are observed in this case study,” but noted several ethical considerations for future drone systems. The system must be safe, with the drone operators taking extra care when delivering biological samples. It must be operational, with drones thoughtfully integrated into the logistics system, not treated as a “silver bullet.” It must also be sustainable “among the involved stakeholders,” which means that the incentives of stakeholders must be sufficiently aligned, without, for example, funders coming in with goals completely at odds with those of the community affected.⁴⁴

While the humanitarian corridor project ended in 2018, Swoop Aero continues its operations in Malawi, making Malawi’s drone program one of the longest-running in the world. It serves 650,000 people in Malawi’s Nsanje and Chikwawa districts. It strengthened its system during COVID, and to date it has completed 5,831 flights, delivering 62,899 doses of vaccines alongside an additional 9,672 pathology test samples for infectious diseases and another 149,581

⁴¹ McNeish, Hannah. “Malawi Looks to Drones to Bolster Healthcare in Remote Communities.” *The Guardian*, March 28, 2016. <https://www.theguardian.com/global-development/2016/mar/28/malawi-turns-to-drones-to-bolster-child-healthcare-in-remote-communities>.

⁴² *Ibid.*

⁴³ “Drone Testing for HIV Early Infant Diagnosis.” UNICEF Office of Innovation, March 14, 2016. <https://www.unicef.org/innovation/stories/drone-testing-hiv-early-infant-diagnosis>.

⁴⁴ “World’s Rural Populations Excluded from Healthcare Access.” United Nations. Accessed August 10, 2023. [https://www.un.org/sustainabledevelopment/blog/2015/04/new-un-report-finds-bulk-of-worlds-rural-populations-excluded-from-healthcare-access/..](https://www.un.org/sustainabledevelopment/blog/2015/04/new-un-report-finds-bulk-of-worlds-rural-populations-excluded-from-healthcare-access/)

antibiotics for various other diseases.⁴⁵ There are no academic papers on Swoop Aero's operations in Malawi beyond the UNICEF test corridor.

Rwanda.

Background.

Rwanda is a landlocked country in Central Africa. Rwanda is one of the most densely-populated countries in Africa, but it is also one of the least urban: Rwanda has 533 people per km² (compared to 48 in Sub-Saharan Africa on average), yet only 17.9% of its population is urban.⁴⁶ Rwanda has only one city, Kigali, with more than 150,000 people.⁴⁷ To serve its population of 13,000,000 distributed throughout 260,000 km², Rwanda has only 1,200 km of paved roads and 4 airports with paved runways, making healthcare supply delivery a serious challenge.⁴⁸ Rwanda has a severe rainy season from March through May, receiving 6 inches of rain in April alone, rendering all secondary roads “very difficult to travel across.”⁴⁹ It is therefore pertinent that Zipline, the current operator of Rwanda's drone system, boasts all-weather performance.⁵⁰

⁴⁵ “Swoop Aero Triples Malawian Fleet Size to Support COVID-19 Response.” sUAS News - The Business of Drones, June 12, 2020. <https://www.suasnews.com/2020/06/swoop-aero-triples-malawian-fleet-size-to-support-covid-19-response/>; “Malawi.” Swoop Aero. Accessed August 10, 2023. <http://website.swoop.aero.s3-website-ap-southeast-2.amazonaws.com/solutions/malawi/>.

⁴⁶ “Rwanda.” Central Intelligence Agency. Accessed August 10, 2023. <https://www.cia.gov/the-world-factbook/countries/rwanda/>.

⁴⁷ “Population Density (People per Sq. Km of Land Area) - Rwanda.” World Bank Open Data. Accessed August 10, 2023. <https://data.worldbank.org/indicator/EN.POP.DNST?locations=RW>; “Population of Cities in Rwanda 2023.” Population of cities in Rwanda 2023. Accessed August 10, 2023. <https://worldpopulationreview.com/countries/cities/rwanda>.

⁴⁸ “Rwanda.” Central Intelligence Agency.

⁴⁹ Mendes, Christine. “2.3 Rwanda Road Network: Digital Logistics Capacity Assessments.” 2.3 Rwanda Road Network | Digital Logistics Capacity Assessments, May 16, 2023. <https://dlca.logcluster.org/23-rwanda-road-network>.

⁵⁰ Zipline. “Most Common Question We Get: ‘Does It Work in the Rain?’” Twitter, February 20, 2019. <https://twitter.com/zipline/status/1098334424309981184>.

Rwanda's GDP per capita is \$822.30, and its current health expenditure per capita is \$57.50.⁵¹ Rwanda's UHC Service Coverage Index, a measure of the country's coverage of essential healthcare services, is 53.74, below the global average of 67.48.⁵² Rwanda is ranked 165th of 191 in the Human Development Index.⁵³

Drone program.

Rwanda's drone system is implemented by the US-based company Zipline. The Rwandan Zipline drone system comprises two distribution centers, one in the country's west and one in its east, each of which services hospitals within an 80km radius.⁵⁴ They often deliver blood, but they can carry other essential medical supplies, too. Together, they cover approximately 80% of Rwanda's hospitals.⁵⁵

Zipline uses fixed-wing drones that are launched by a catapult, which accelerates them immediately to their cruising velocity of 100 km/h. Instead of landing on a runway, they are pulled out of the air by a cable that grabs their tailhook. They have a cargo capacity of 1.75 kg, enough to carry up to 3 units of blood.⁵⁶ They deliver goods by dropping a package with a wax parachute. They cannot pick up supplies because they do not have VTOL capacity. Zipline's

⁵¹ "GDP per Capita (Current US\$)." World Bank Open Data. Accessed August 10, 2023. <https://data.worldbank.org/indicator/NY.GDP.PCAP.CD>.

⁵² "The Universal Health Coverage (UHC) Service Coverage Index."

⁵³ United Nations. "Country Insights." Human Development Reports. Accessed August 10, 2023. <https://hdr.undp.org/data-center/country-insights#/ranks>.

⁵⁴ Ackerman, Evan, and Michael Koziol. "In the Air with Zipline's Medical Delivery Drones." IEEE Spectrum, February 30, 2022. <https://spectrum.ieee.org/in-the-air-with-ziplines-medical-delivery-drones>.

⁵⁵ Okertchiri, Jamila Akweley. "From Muhanga to the Rest of Rwanda; How Zipline Is Providing Smarter Blood Distribution Service." Modern Ghana, November 24, 2018. <https://www.modernghana.com/news/899872/from-muhanga-to-the-rest-of-rwanda-how-zipline-is-providing.html>.

⁵⁶ Ibid.

drones are fully autonomous from the moment of launch, but they are responsive to a control center that can update their routes if needed.⁵⁷

Zipline distribution centers routinely receive blood products by truck, which are then transferred into refrigerators, where they sit until an order is received by phone, website, WhatsApp, or text.⁵⁸ To fulfill orders, Zipline employees pack a box, attach a parachute, and load the drone. The drone is loaded and launched 5-7 minutes after the order is received.⁵⁹

The Rwandan drone system delivers 65% of all the blood that leaves the country's central distribution center, providing access to blood products to 12 million Rwandans.⁶⁰ Before the drone system, Rwanda would lose around 6% of its blood supply to expiration; now, since it can rely on just-in-time delivery, waste is 0%, saving Rwanda's health system nearly \$300,000 annually.⁶¹ (Another study found that waste decreased by 67%, not 100%, implying a commensurate reduction in savings. The cause of this discrepancy is unclear.)⁶² Between 17 March 2017 and 31 December 2019, 43% of deliveries were emergency deliveries. This number has likely decreased as drone operations have expanded (no newer data is available), but emergency deliveries remain a main use case for Rwanda's drones.⁶³

⁵⁷ Ibid.

⁵⁸ Ackerman, Evan, and Michael Koziol. "In the Air with Zipline's Medical Delivery Drones."

⁵⁹ Ibid.

⁶⁰ Uwaliraye, Parfait, Patrick Ndimubanzi, Andrew Muhire, and Valencia Lyle. "INTEGRATION OF HEALTH AND MEDICAL INNOVATIONS IN RWANDA TO PROMOTE HEALTH EQUITY." WIPO, 2019. https://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii_2020.pdf.

⁶¹ Jamila Akweley Okertchiri, "From Muhanga to the Rest of Rwanda; How Zipline Is Providing Smarter Blood Distribution Service," *Modern Ghana*, November 24, 2018, <https://www.modernghana.com/news/899872/from-muhanga-to-the-rest-of-rwanda-how-zipline-is-providing.html>; "A Blood Transfusion in Africa? It's Free in Rwanda, Unaffordable in Zimbabwe." *Global Press Journal*, October 15, 2021. <https://globalpressjournal.com/africa/blood-transfusion-africa-free-rwanda-unaffordable-zimbabwe/>.

⁶² Nisingizwe, Marie Paul, Pacifique Ndishimye, Katare Swaibu, Ladislav Nshimiyimana, Prosper Karame, Valentine Dushimiyimana, Jean Pierre Musabyimana, Clarisse Musanabaganwa, Sabin Nsanzimana, and Michael R Law. "Effect of Unmanned Aerial Vehicle (Drone) Delivery on Blood Product Delivery Time and Wastage in Rwanda: A Retrospective, Cross-Sectional Study and Time Series Analysis." *The Lancet Global Health* 10, no. 4 (2022). [https://doi.org/10.1016/s2214-109x\(22\)00048-1](https://doi.org/10.1016/s2214-109x(22)00048-1).

⁶³ Ibid.

Drone deliveries in Rwanda were found to take a median of 41 minutes, compared to a median of 139 minutes by road for the same deliveries, saving a median of 98 minutes per delivery.⁶⁴

Thanks to this speed and reliability, mortality rates for in-hospital postpartum hemorrhage, which rely on the availability of blood transfusions, have fallen 51% since the introduction of medical drones in Rwanda.⁶⁵ Drones also delivered tests and PPE during the COVID-19 pandemic.⁶⁶

In 2022, Rwanda elected to expand Zipline's operations with the goal of completing 2,000,000 deliveries by 2029, including "financial payments, postal service items, food and agricultural products." A massive leap beyond the roughly 400,000 deliveries Zipline had completed by December of 2022, this would seem to indicate the government's contentment so far with its Zipline program.⁶⁷ The inclusion of provisions beyond blood supplies further hints at a more robust and fully integrated interwoven drone delivery system in Rwanda.

Zipline Rwanda has been criticized for being expensive. Critics argue that the program is a band-aid fix and that money spent on drone delivery would be better spent on roads. (For general reference: the African Development Bank estimates that the median road longer than 100 km costs \$147,100 per lane-km to pave, in 2023 USD.)⁶⁸ This argument can be reversed and made in favor of drones, which allow nations to leapfrog expensive infrastructural investments. As the

⁶⁴ Ibid.

⁶⁵ Jeon, H. Harriet, Claudio Lucarelli, Jean Baptiste Mazarati, Donatien Ngabo, and Hummy Song. "Leapfrogging for Last-Mile Delivery in Health Care." *SSRN Electronic Journal*, 2022. <https://doi.org/10.2139/ssrn.4214918>.

⁶⁶ Lewis, Noah. "A Tech Company Engineered Drones to Deliver Vital COVID-19 Medical Supplies to Rural Ghana and Rwanda in Minutes." *Business Insider*, May 12, 2020. <https://www.businessinsider.com/zipline-drone-coronavirus-supplies-africa-rwanda-ghana-2020-5?international=true&r=US&IR=T>.

⁶⁷ Shankland, Stephen. "Rwanda Orders 2 Million More Drone Deliveries by 2029 with Zipline Deal." *CNET*, December 15, 2022. <https://www.cnet.com/tech/computing/rwanda-orders-2-million-more-drone-deliveries-by-2029-with-zipline-deal/>.

⁶⁸ "Inflation Rate between 2006-2023: Inflation Calculator." \$147,000 in 2006 → 2023 | Inflation Calculator. Accessed August 10, 2023. <https://www.in2013dollars.com/us/inflation/2006?amount=147000>.

IMF asks, “What’s the best solution to a lack of infrastructure? Find a solution that doesn’t require infrastructure.”⁶⁹

Zipline’s Rwandan program has received extremely positive media attention, including a short video by YouTuber Mark Rober with 22 million views and others from news organizations including CNBC and Bloomberg.⁷⁰

Ghana.

Background.

Ghana’s 34,000,000 citizens live in 238,533 km² in Sub-Saharan West Africa. 59.2% of its population is urban, which means that Ghana still has a significant rural population, mostly in the south near the coast.⁷¹ To serve this population, Ghana has 10 airports and 65,725 km of roads, of which 14,948 km are paved, putting it significantly ahead of both Rwanda and Vanuatu in terms of local infrastructure development.

The quality of healthcare in Ghana depends highly on the region in which it is delivered: according to the US Department of Commerce, “urban centers are well served,” while “rural areas often have no modern healthcare services.”⁷² “Medical practice in rural Africa faces extremely limited resources,” writes another source, continuing, “it has proven very difficult to extend medical training to rural areas, where health care facilities are particularly short of personnel...because of the working conditions and financial limitations.” Ghana’s GDP per

⁶⁹ IMF Blog. “No Roads? No Problem: The Leapfrogging Drones of Rwanda.” IMF, January 12, 2018. <https://www.imf.org/en/Blogs/Articles/2018/01/12/no-roads-no-problem-the-leapfrogging-drones-of-rwanda>.

⁷⁰ Rober, Mark. “Amazing Invention- This Drone Will Change Everything.” YouTube, March 18, 2023. <https://www.youtube.com/watch?v=DOWDNBu9DkU>; “Zipline Releases New Drone Designed for Rapid Home Deliveries.” YouTube, March 15, 2023. <https://www.youtube.com/watch?v=BtKdLrJLZ5I>; “The Medical Drone Delivery Pilot.” YouTube, August 16, 2018. <https://www.youtube.com/watch?v=NBdB3G9Qvqs>.

⁷¹ “Ghana.” Central Intelligence Agency, August 1, 2023. <https://www.cia.gov/the-world-factbook/countries/ghana/>.

⁷² “Ghana - Healthcare.” International Trade Administration | Trade.gov, July 22, 2022. <https://www.trade.gov/country-commercial-guides/ghana-healthcare>.

capita is \$2175.90, while its current health expenditure per capita is \$221.33.^{73,74} Its UHC Service Coverage Index, a measure of the country's coverage of essential healthcare services, is 45.09, below the global average of 67.48 and the worst of all target countries.⁷⁵ It is ranked 133rd of 191 in the Human Development Index.⁷⁶

Drone program.

Ghana also employs Zipline's services to make medical deliveries, with 6 Zipline distribution centers together serving 2,300 facilities or approximately 15 million Ghanaians.⁷⁷ The drones themselves are the same as those used in Rwanda, but Ghana employs more of them in a larger system, being a larger and more populated country. Each of Ghana's distribution centers houses 30 drones and has the capacity to make 600 deliveries per day, although the contract with the Ghanaian government only requires an average of 150 deliveries per day per distribution center.⁷⁸ For this service, the government pays \$12.5 million. Zipline built all necessary infrastructure for this operation (though VAT fees for construction materials were waived). Zipline employs exclusively Ghanaian citizens in its distribution centers.⁷⁹

⁷³ Drislane FW, Akpalu A, Wegdam HH. The medical system in Ghana. *Yale J Biol Med.* 2014 Sep 3;87(3):321-6. PMID: 25191147; PMCID: PMC4144286.

⁷⁴ "GDP per Capita (Current US\$) - Ghana." World Bank Open Data. Accessed August 10, 2023. <https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=GH>.

⁷⁵ "The Universal Health Coverage (UHC) Service Coverage Index."

⁷⁶ Roser, Max. "Human Development Index (HDI)."

⁷⁷ "Zipline Delivers 1 Million Covid-19 Vaccines in Ghana." Zipline Legacy - Instant Logistics, March 30, 2022. <https://legacy.flyzipline.com/press/zipline-delivers-1-million-covid-19-vaccines-in-ghana>.

⁷⁸ Asiedu, Kwasi Gyamfi. "An Ambitious Drone Delivery Health Service in Ghana Is Tackling Key Logistics Challenges." *Quartz*, April 25, 2019. <https://qz.com/africa/1604374/ziplines-drone-delivery-launches-in-ghana-with-vaccines>.

⁷⁹ Amoh, Emmanuel Kwame. "Kintampo, 3 Others to Get Zipline Drone Centers." *3News.com*, November 2, 2021. <https://3news.com/kintampo-3-others-to-get-zipline-drone-centers/>.

The Ghanaian drone system has proven crucial for delivering blood and many other medical supplies, completing 500,000 deliveries in its first two years alone.⁸⁰ (More up-to-date figures are not available.) Drones have shortened vaccine stockouts by an average of 60% and decreased missed vaccination opportunities due to inventory by 42%.⁸¹ When a vaccine clinic in Ghana is out of doses, instead of waiting several days for routine replenishment, it can request the supplies it needs and immediately be refilled by drones. For the same reasons, Ghanaian health centers serviced by drones experienced fewer stockouts of severe malaria treatment, anti-snake serum, and non-vaccine medical products in general.⁸²

Another study affirmed that districts covered by drones had superior vaccination rates. Moreover, “infectious diarrhea cases in children between 5 and 9 years old were reduced by 41.6%” in such districts, suggesting that the increased vaccination rates have been effective at preventing illness.⁸³ Drones have also been used to deliver Oral Rehydration Salt (ORS) to rural students experiencing acute diarrhea.⁸⁴ During the COVID-19 pandemic, drones were an essential part of the healthcare supply chain in Ghana, providing contactless delivery of over 1 million

⁸⁰ U.S. Embassy in Ghana. “United States Honors Zipline Ghana with the Award for Corporate Excellence.” U.S. Embassy in Ghana, December 8, 2021. <https://gh.usembassy.gov/united-states-honors-zipline-ghana-with-the-award-for-corporate-excellence/>.

⁸¹ Connor, Alison, Dan Stein, Rachel LuSava, Valentina Brailovskaya, and Young Mkandawire. “Measuring Zipline’s Impact on Health Access, Availability, and Supply Chain in Ghana.” IDinsight, June 6, 2022. <https://www.idinsight.org/publication/measuring-ziplines-impact-on-health-access-availability/>.

⁸² Ibid.

⁸³ Pedro Kremer et al., “An impact assessment of the use of aerial logistics to improve access to vaccines in the Western-North Region of Ghana, June 19, 2023,” <https://www.sciencedirect.com/science/article/pii/S0264410X23007016>.

⁸⁴ “Zipline Drone Rescues 113 Students from Acute Diarrhoea.” Ghanaian Times, June 27, 2019. <https://www.ghanaiantimes.com.gh/zipline-drone-rescues-113-students-from-acute-diarrhoea/>.

COVID-19 vaccines.⁸⁵ They also delivered PPE to election workers.⁸⁶ As a result, “Healthcare workers in [Ghanaian] Zipline facilities expressed an overall positive perception regarding Zipline,” one study found, affirming the drone system’s convenience and their improved access to medicine.⁸⁷ For its work, Zipline Ghana was recognized as a winner of the US Department of State’s Awards for Corporate Excellence.

Critics initially lambasted the agreement between Zipline and the Ghanaian government for being, in the words of the Minority Spokesperson on Finance, a “rip-off.”⁸⁸ Ghana had fewer than 55 ambulances total when the deal was signed (more recent data is unavailable), and critics argued that Ghana would be better off spending \$12 million on basic infrastructure and supplies.⁸⁹ Ghanaian think tank IMANI took a particularly strong stance against the program, arguing that upgrading standard delivery technologies, even using trotro trucks equipped with freezers, would be cost-superior and equally effective.⁹⁰ Drones would not “transform the entire public health supply chain,” IMANI argued, as they would provide “a very niche service to address very narrow concerns” at an exorbitant rate. The Director-General of the Ghanaian Health Service responded that the Ghanaian system was 25% cheaper per delivery than the already highly-regarded Rwandan system, emphasizing that the drone system would reduce

⁸⁵ “Zipline Delivers 1 Million Covid-19 Vaccines in Ghana.” Zipline Legacy - Instant Logistics, March 30, 2022. <https://legacy.flyzipline.com/press/zipline-delivers-1-million-covid-19-vaccines-in-ghana>.

⁸⁶ Protecting Ghana’s Election: Instant Agility With Zipline’s Autonomous Delivery Network, February 2021. https://assets.ctfassets.net/pbn2i2zbvp41/3yrQaMNdJ1u1J2aSEucjzt/4412ea5d12896d15b7eb41a2212d0295/Zipline_Ghana_PPE_Global_Healthcare_Feb-2021.pdf.

⁸⁷ Connor, Alison, Dan Stein, Rachel LuSava, Valentina Brailovskaya, and Young Mkandawire. “Measuring Zipline’s Impact on Health Access, Availability, and Supply Chain in Ghana.”

⁸⁸ Ansah, Marian. “Parliament Approves Deal for Delivery of Medical Supplies via Drones.” Citinewsroom, December 11, 2018. <https://citinewsroom.com/2018/12/parliament-approves-deal-for-delivery-of-medical-supplies-via-drones>.

⁸⁹ “Ghana Drones: Row over Blood-Delivery Devices.” BBC News, December 12, 2018. <https://www.bbc.com/news/world-africa-46543442>.

⁹⁰ “Imani Alert: Novelty Is Not Innovation – the Story of Fly Zipline Ghana.” Imani Africa, February 13, 2020. <https://imaniafrica.org/2018/12/imani-alert-novelty-is-not-innovation-the-story-of-fly-zipline-ghana/>.

waste, increase efficiency, and improve health outcomes throughout Ghana. Zipline claimed that its cost is “on par with the...cost of delivery ... [by] car, truck or motorcycle.”⁹¹

Peer-reviewed data from either side of this argument is unavailable, so it is impossible to speak directly to the cost-effectiveness of Ghana’s drone system or to compare it to the other healthcare investments that could be made in its stead. It is notable, however, that there has been no public criticism of the system by IMANI or others since the government’s original signature of the contract with Zipline. Meanwhile, the system has received extensive international attention and accolades.

IV. SYNTHESIS AND CONCLUSION.

The above analysis reveals several patterns of interest to LMICs studying the potential use of drones in their healthcare systems.

Country characteristics.

The target countries, chosen for having uniquely instructive or developed drone systems, share much in common. They all have significant rural populations and underdeveloped infrastructure, which means that they suffer from rural-urban health inequities and have difficulties providing service to significant portions of their population. All target countries have worse-than-average scores on the UHC Service Coverage Index, which reflects this.

No system extended beyond 240,000 km², roughly the area of Ghana, as the target countries are small and used drones only in selected zones. Given current technological limitations, such restrictions are vital, but innovation may expand the appropriate target area.

Moreover, all target countries are critically constrained by medical resources: each has a below-average GDP per capita and also a below-average current health expenditure per capita. Thus, these countries must either turn to innovative techniques to stretch their healthcare dollars

⁹¹ “Parliament Approves Medical Drone Agreement.” GhanaWeb, December 11, 2018. <https://www.ghanaweb.com/GhanaHomePage/NewsArchive/Parliament-approves-medical-drone-agreement-707944>; “Ghana Eyes World Record in Medical Drone Service.” Phys.org, April 24, 2019. <https://phys.org/news/2019-04-ghana-eyes-world-medical-drone.html>.

further, or concede unsatisfactory health outcomes. The target nations also contain relatively few aerodromes, which simplifies the coordination of drones with planes in their airspaces. Three of the countries—Ghana, Rwanda, and Malawi—have recently undertaken initiatives to improve their digital infrastructure, augmenting connectivity critical to drone operation. Lastly, despite international criticism of the Ghanaian and Rwandan governments in particular, all countries have stable enough governments to support long-term investment in novel human-development technology.

Drone system architecture.

The differences between the architectures of the respective drone systems reflect their divergent goals. In Rwanda and Ghana, Zipline was contracted to oversee all operations. Zipline's unique strengths made it a good fit for these countries, as it would not have been able to fulfill the functions required in Malawi and Vanuatu. Zipline drones, being fixed-wing, require takeoff and landing infrastructure, giving them higher capital costs than other systems. Zipline drones lack VTOL capacity, so they cannot pick up samples as in Malawi and have a more difficult time navigating small delivery zones as in Vanuatu. However, they are more fuel-efficient when cruising, which allows them to cover such significant portions of Ghana and Rwanda, and also makes them cheaper per kilometer.

Vanuatu and Malawi both used drones by Swoop Aero, and Vanuatu additionally used drones by Wingcopter. Wingcopter and Swoop Aero are direct competitors, fighting for a different niche than Zipline. Both have VTOL capacity, carry larger payloads (5 kg for Swoop Aero and 6 kg for Wingcopter, compared to 1.75 kg for Zipline), and have higher max speeds (200 km/h for Swoop Aero and 144 km/h for Wingcopter) than Zipline. The cost of the drones is not publicly available, but it would appear that Wingcopter's and Swoop Aero's drones are significantly more expensive, and also more expensive per marginal kilometer flown, than Zipline's.

In short, Zipline has higher capital costs but lower marginal cost. Its function is limited because it lacks VTOL. Swoop Aero and Wingcopter do not take advantage of the economies of scale that Zipline does, but they have lower capital costs, higher payload capacity, and better

maneuverability, making them the logical choice for smaller programs like those in Malawi and Vanuatu.

In all cases, the placement of the distribution centers was chosen based on ordinary logistical considerations. Accounting for the range of the drones and the locations of the health centers to be serviced, health authorities placed the drone distribution centers so as to maximize coverage, whether with 6 centers as in Ghana, 2 as in Rwanda and Vanuatu, or 1 as in Malawi.

Service provided.

Ghana's delivery goals were the most ambitious in its significant up-front commitment to its drone system. From the start, it attempted to deliver not only blood, but vaccines, antibiotics, and other medical supplies. This was not technically difficult, but it stipulated the delivery of many low-value and low-urgency goods, with many critics complaining of the ratio of the cost of the delivery to the cost of the goods themselves.

Rwanda, on the other hand, began with a much higher proportion of blood deliveries, which are valuable and urgent. However, Rwanda is expanding its drone system to service lower-value and -urgency goods, indicating that it believes it financially sensible to use drones for cheap deliveries. Whether this is because drones out-compete other strategies on the basis of cost or because drones are faster and more convenient is not clear. Data on the average value of the goods delivered is not available, nor is data on the average cost of delivery by drones or by their competitors. However, Ghana's and Rwanda's increasing appetite for drone delivery, along with the decrescendo in the criticism of their programs, provide evidence in favor of drones.

The delivery goals of the drone systems in Vanuatu and Malawi were more explicitly circumscribed. In Vanuatu, the system was constructed only to deliver vaccines, while in Malawi good data was only available on programs seeking to improve the reliability of biological sample delivery, in particular, to improve the treatment of HIV. Both programs impressed in their reliability and speed but left questions of cost-effectiveness largely unanswered. In both cases, the community response was positive, and despite the official trial period ending, both Malawi

and Vanuatu have continued efforts to further integrate healthcare drones into their logistics systems.

V. REQUEST FOR FURTHER RESEARCH.

The greatest outstanding question is under what conditions drones will be cost-competitive with traditional delivery methods. A comparison of the historical costs of medical delivery in Rwanda and Ghana to the current costs using Zipline would be extremely informative and could easily be done by anyone with access to the relevant data. It is only for a lack of available data that there remain questions about the cost-effectiveness of these drone systems, which are of particular interest because they are the only two that have truly availed themselves of economies of scale. Less specifically, analysis of the costs of drone delivery systems under various estimates of capital costs, interest rates, amortization periods, and delivery volumes would contribute greatly to the understanding of the prospects of drone delivery as an economically viable means of improving healthcare accessibility.

REFERENCES.

- Ackerman, Evan, and Michael Koziol. "In the Air with Zipline's Medical Delivery Drones." *IEEE Spectrum*, February 30, 2022. <https://spectrum.ieee.org/in-the-air-with-ziplines-medical-delivery-drones>.
- Ackerman, Evan, and Michael Koziol. "The Blood Is Here: Zipline's Medical Delivery Drones Are Changing the Game in Rwanda." *IEEE Spectrum* 56, no. 5 (2019): 24–31. <https://doi.org/10.1109/mspec.2019.8701196>.
- Amazon Staff. "Amazon Prime Air Prepares for Drone Deliveries." US About Amazon, June 13, 2022. <https://www.aboutamazon.com/news/transportation/amazon-prime-air-prepares-for-drone-deliveries>.
- Amoh, Emmanuel Kwame. "Kintampo, 3 Others to Get Zipline Drone Centers." 3News.com, November 2, 2021. <https://3news.com/kintampo-3-others-to-get-zipline-drone-centers/>.
- Amoh, Emmanuel Kwame. "Kintampo, 3 Others to Get Zipline Drone Centers." 3News.com, November 3, 2021. <https://3news.com/kintampo-3-others-to-get-zipline-drone-centers/>.
- Amukele, Timothy. "Current State of Drones in Healthcare: Challenges and Opportunities." *The Journal of Applied Laboratory Medicine* 4, no. 2 (2019): 296–98. <https://doi.org/10.1373/jalm.2019.030106>.
- Amukele, Timothy. "The Economics of Medical Drones." *The Lancet Global Health* 8, no. 1 (January 2020). [https://doi.org/10.1016/s2214-109x\(19\)30494-2](https://doi.org/10.1016/s2214-109x(19)30494-2).
- Ansah, Marian. "Parliament Approves Deal for Delivery of Medical Supplies via Drones." Citinewsroom, December 11, 2018. <https://citinewsroom.com/2018/12/parliament-approves-deal-for-delivery-of-medical-supplies-via-drones/>.
- Asiedu, Kwasi Gyamfi. "An Ambitious Drone Delivery Health Service in Ghana Is Tackling Key Logistics Challenges." Quartz, April 25, 2019. <https://qz.com/africa/1604374/ziplines-drone-delivery-launches-in-ghana-with-vaccines>.
- "A Blood Transfusion in Africa? It's Free in Rwanda, Unaffordable in Zimbabwe." Global Press Journal, October 15, 2021. <https://globalpressjournal.com/africa/blood-transfusion-africa-free-rwanda-unaffordable-zimbabwe/>.
- Choi, Dong Sun, Ki Jeong Hong, Sang Do Shin, Chang-Gun Lee, Tae Han Kim, Youngeun Cho, Kyoung Jun Song, Young Sun Ro, Jeong Ho Park, and Ki Hong Kim. "Effect of Topography and Weather on Delivery of Automatic Electrical Defibrillator by Drone for Out-of-Hospital Cardiac Arrest." *Scientific Reports* 11, no. 1 (2021). <https://doi.org/10.1038/s41598-021-03648-3>.

Connor, Alison, Dan Stein, Rachel LuSava, Valentina Brailovskaya, and Young Mkwandawire. “Measuring Zipline’s Impact on Health Access, Availability, and Supply Chain in Ghana.” IDinsight, June 6, 2022. <https://www.idinsight.org/publication/measuring-ziplines-impact-on-health-access-availability/>.

“Drone Testing for HIV Early Infant Diagnosis.” UNICEF Office of Innovation, March 14, 2016. <https://www.unicef.org/innovation/stories/drone-testing-hiv-early-infant-diagnosis>.

Dublin, Scott, Ashley Greve, and Ryan Triche. “Drones in International Development.” UPDWG. Accessed August 10, 2023. https://www.updwg.org/wp-content/uploads/2020/11/Drones_in_International_Development_Innovating_the_Supply_Chain_to_Reach_Patients_in_Remote_Areas_2_1.pdf.

Enayati, Shakiba, James F. Campbell, and Haitao Li. “Vaccine Distribution with Drones for Less Developed Countries: A Case Study in Vanuatu.” *Vaccine: X* 14 (August 2023): 100312. <https://doi.org/10.1016/j.jvacx.2023.100312>.

Fabian, Chris. “Malawi’s Unique Drone Corridor.” UNICEF Office of Innovation, July 3, 2017. <https://www.unicef.org/innovation/drones/malawi-unique-drone-corridor>.

French, Sally. “Amazon’s First Prime Air Delivery Is Just More Drone Hype.” MarketWatch, December 14, 2016. <https://www.marketwatch.com/story/the-heavy-on-hype-light-on-substance-world-of-drone-delivery-2016-12-01>.

“GDP per Capita (Current US\$) - Ghana.” World Bank Open Data. Accessed August 10, 2023. <https://data.worldbank.org/indicator/NY.GDP.PCAP.CD?locations=GH>.

“GDP per Capita (Current US\$).” World Bank Open Data. Accessed August 10, 2023. <https://data.worldbank.org/indicator/NY.GDP.PCAP.CD>.

“Ghana - Healthcare.” International Trade Administration | Trade.gov, July 22, 2022. <https://www.trade.gov/country-commercial-guides/ghana-healthcare>.

“Ghana Drones: Row over Blood-Delivery Devices.” BBC News, December 12, 2018. <https://www.bbc.com/news/world-africa-46543442>.

“Ghana Eyes World Record in Medical Drone Service.” Phys.org, April 24, 2019. <https://phys.org/news/2019-04-ghana-eyes-world-medical-drone.html>.

“Ghana.” Central Intelligence Agency, August 1, 2023. <https://www.cia.gov/the-world-factbook/countries/ghana/>.

Haidari, Leila A., Shawn T. Brown, Marie Ferguson, Emily Bancroft, Marie Spiker, Allen Wilcox, Ramya Ambikapathi, Vidya Sampath, Diana L. Connor, and Bruce Y. Lee. “The

- Economic and Operational Value of Using Drones to Transport Vaccines.” *Vaccine* 34, no. 34 (2016): 4062–67. <https://doi.org/10.1016/j.vaccine.2016.06.022>.
- “Harnessing Drones for Development of African Least Developed Countries.” YouTube, March 23, 2021. <https://www.youtube.com/watch?v=VC8z5fwELTw>.
- Hidalgo, Jason. “Reno Drone Company SkyDrop Approved for Store-to-Door Delivery in New Zealand.” *Reno Gazette Journal*, April 11, 2023. <https://www.rgj.com/story/news/money/business/2023/04/11/skydrop-approved-for-store-to-door-drone-delivery-in-new-zealand/70103632007/>.
- “HIV Rates by Country 2023.” HIV rates by country 2023. Accessed August 1, 2023. <https://worldpopulationreview.com/country-rankings/hiv-rates-by-country>.
- “HS720 GPS Drone with 4K Camera.” Holy Stone. Accessed August 10, 2023. <https://www.holystone.com/en/Drones/Premium/HS720GPSDroneWith4KCamera.html>.
- “Humanitarian Drone Corridor Launched in Malawi.” YouTube, August 15, 2017. https://www.youtube.com/watch?v=_yURGGIVqgA&ab_channel=UnicefMalawi.
- “Imani Alert: Novelty Is Not Innovation – the Story of Fly Zipline Ghana.” *Imani Africa*, February 13, 2020. <https://imaniafrica.org/2018/12/imani-alert-novelty-is-not-innovation-the-story-of-fly-zipline-ghana/>.
- IMFBlog. “No Roads? No Problem: The Leapfrogging Drones of Rwanda.” IMF, January 12, 2018. <https://www.imf.org/en/Blogs/Articles/2018/01/12/no-roads-no-problem-the-leapfrogging-drones-of-rwanda>.
- “Inflation Rate between 2006-2023: Inflation Calculator.” \$147,000 in 2006 → 2023 | Inflation Calculator. Accessed August 10, 2023. <https://www.in2013dollars.com/us/inflation/2006?amount=147000>.
- Jeon, H. Harriet, Claudio Lucarelli, Jean Baptiste Mazarati, Donatien Ngabo, and Hummy Song. “Leapfrogging for Last-Mile Delivery in Health Care.” *SSRN Electronic Journal*, 2022. <https://doi.org/10.2139/ssrn.4214918>.
- Karam, Nicole, Daniel Jost, Xavier Jouven, and Eloi Marijon. “Automated External Defibrillator Delivery by Drones: Are We Ready for Prime Time?” OUP Academic, August 26, 2021. <https://doi.org/10.1093/eurheartj/ehab565>.
- Laksham, Karthik Balajee. “Unmanned Aerial Vehicle (Drones) in Public Health: A SWOT Analysis.” *Journal of Family Medicine and Primary Care* 8, no. 2 (2019): 342. https://doi.org/10.4103/jfmpe.jfmpe_413_18.

- Lewis, Noah. "A Tech Company Engineered Drones to Deliver Vital COVID-19 Medical Supplies to Rural Ghana and Rwanda in Minutes." *Business Insider*, May 12, 2020. <https://www.businessinsider.com/zipline-drone-coronavirus-supplies-africa-rwanda-ghana-2020-5>.
- Ling, Geoffrey, and Nicole Draghic. "Aerial Drones for Blood Delivery." *Transfusion* 59, no. S2 (2019): 1608–11. <https://doi.org/10.1111/trf.15195>.
- "Low and Middle Income Countries (LMIC)." Low and Middle Income Countries (LMIC) | QES Climate Justice. Accessed August 2, 2023. <https://qesclimatejustice.info.yorku.ca/resources/eligible-countries/>.
- "Malawi." Central Intelligence Agency. Accessed August 1, 2023. <https://www.cia.gov/the-world-factbook/countries/malawi/>.
- "Malawi." Swoop Aero. Accessed August 1, 2023. <http://website.swoop.aero.s3-website-ap-southeast-2.amazonaws.com/solutions/malawi/>.
- Malawi - World Health Organization, May 2017. https://apps.who.int/iris/bitstream/handle/10665/136935/ccsbrief_mwi_en.pdf.
- McNeish, Hannah. "Malawi Looks to Drones to Bolster Healthcare in Remote Communities." *The Guardian*, March 28, 2016. <https://www.theguardian.com/global-development/2016/mar/28/malawi-turns-to-drones-to-bolster-child-healthcare-in-remote-communities>.
- "The Medical Drone Delivery Pilot." YouTube, August 16, 2018. <https://www.youtube.com/watch?v=NBdB3G9Qvqs>.
- Mendes, Christine. "2.3 Rwanda Road Network: Digital Logistics Capacity Assessments." 2.3 Rwanda Road Network | Digital Logistics Capacity Assessments, May 16, 2023. <https://dlca.logcluster.org/23-rwanda-road-network>.
- Nisingizwe, Marie Paul, Pacifique Ndishimye, Katare Swaibu, Ladislas Nshimiyimana, Prosper Karame, Valentine Dushimiyimana, Jean Pierre Musabyimana, Clarisse Musanabaganwa, Sabin Nsanzimana, and Michael R Law. "Effect of Unmanned Aerial Vehicle (Drone) Delivery on Blood Product Delivery Time and Wastage in Rwanda: A Retrospective, Cross-Sectional Study and Time Series Analysis." *The Lancet Global Health* 10, no. 4 (2022). [https://doi.org/10.1016/s2214-109x\(22\)00048-1](https://doi.org/10.1016/s2214-109x(22)00048-1).
- "Number of People Living in Urban and Rural Areas." Our World in Data. Accessed August 10, 2023. <https://ourworldindata.org/grapher/urban-and-rural-population>.
- Nyaaba, Albert Apotele, and Matthew Ayamga. "Intricacies of Medical Drones in Healthcare Delivery: Implications for Africa." *Technology in Society* 66 (2021): 101624. <https://doi.org/10.1016/j.techsoc.2021.101624>.

Ochieng, Walter O, Tun Ye, Christina Scheel, Aun Lor, John Saindon, Sue Lin Yee, Martin I Meltzer, Vikas Kapil, and Kevin Karem. "Uncrewed Aircraft Systems versus Motorcycles to Deliver Laboratory Samples in West Africa: A Comparative Economic Study." *The Lancet Global Health* 8, no. 1 (2020). [https://doi.org/10.1016/s2214-109x\(19\)30464-4](https://doi.org/10.1016/s2214-109x(19)30464-4).

Okertchiri, Jamila Akweley. "From Muhanga to the Rest of Rwanda; How Zipline Is Providing Smarter Blood Distribution Service." *Modern Ghana*, November 24, 2018. <https://www.modernghana.com/news/899872/from-muhanga-to-the-rest-of-rwanda-how-zipline-is-providing.html>.

"Parliament Approves Medical Drone Agreement." *GhanaWeb*, December 11, 2018. <https://www.ghanaweb.com/GhanaHomePage/NewsArchive/Parliament-approves-medical-drone-agreement-707944>.

Phillips, N., Blauvelt, C., Ziba, M., Sherman, J., Saka, E., Bancroft, E., and Wilcox, A. *Costs Associated with the Use of Unmanned Aerial Vehicles for Transportation of Laboratory Samples in Malawi*. Seattle: VillageReach; 2016.

"Population Density (People per Sq. Km of Land Area) - Rwanda." *World Bank Open Data*. Accessed August 10, 2023. <https://data.worldbank.org/indicator/EN.POP.DNST?locations=RW>.

"Population of Cities in Rwanda 2023." *Population of cities in Rwanda 2023*. Accessed August 10, 2023. <https://worldpopulationreview.com/countries/cities/rwanda>.

"PROJECT REPORT Vanuatu Drone Trial: Phase 1 and 2." *UNICEF*, September 2019. <https://www.updwg.org/wp-content/uploads/2020/10/UNICEF-Vanuatu-Drone-Report-Final-Executive-Summary.pdf>.

Protecting Ghana's Election: Instant Agility With Zipline's Autonomous Delivery Network, February 2021. https://assets.ctfassets.net/pbn2i2zbvp41/3yrQaMNdJ1u1J2aSEucjzt/4412ea5d12896d15b7eb41a2212d0295/Zipline_Ghana_PPE_Global_Healthcare_Feb-2021.pdf.

"Reducing Poverty and Inequality in Rural Areas: Key to Inclusive Development | DISD." *United Nations*, June 2, 2021. <https://www.un.org/development/desa/dspd/2021/06/poverty-and-inequality-rural-areas/>.

Ritchie, Hannah, and Max Roser. "Urbanization." *Our World in Data*, September 13, 2018. <https://ourworldindata.org/urbanization>.

Rober, Mark. "Amazing Invention- This Drone Will Change Everything." *YouTube*, March 18, 2023. <https://www.youtube.com/watch?v=DOWDNBu9DkU>.

Roser, Max. "Human Development Index (HDI)." *Our World in Data*, July 25, 2014. <https://>

ourworldindata.org/human-development-index.

“Rwanda.” Central Intelligence Agency. Accessed August 10, 2023. <https://www.cia.gov/the-world-factbook/countries/rwanda/>.

Sanfridsson, J., J. Sparrevik, J. Hollenberg, P. Nordberg, T. Djärv, M. Ringh, L. Svensson, et al. “Drone Delivery of an Automated External Defibrillator – a Mixed Method Simulation Study of Bystander Experience.” *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine* 27, no. 1 (2019). <https://doi.org/10.1186/s13049-019-0622-6>.

Schierbeck, Sofia, Jacob Hollenberg, Anette Nord, Leif Svensson, Per Nordberg, Mattias Ringh, Sune Forsberg, Peter Lundgren, Christer Axelsson, and Andreas Claesson. “Automated External Defibrillators Delivered by Drones to Patients with Suspected Out-of-Hospital Cardiac Arrest.” *European Heart Journal* 43, no. 15 (2021): 1478–87. <https://doi.org/10.1093/eurheartj/ehab498>.

Sciarpetti, Laura. “Saskatoon Company Donates Drones to Deliver Medical Supplies to Ukrainians in Russian-Occupied Cities | CBC News.” CBCnews, March 26, 2022. <https://www.cbc.ca/news/canada/saskatchewan/saskatoon-dragonfly-drones-to-deliver-medical-supplies-to-ukrainians-in-russian-occupied-cities-1.6398094>.

Scott, Judy E., and Carlton H. Scott. “Drone Delivery Models for Medical Emergencies.” *Healthcare Delivery in the Information Age*, 2019, 69–85. https://doi.org/10.1007/978-3-030-17347-0_3.

Shankland, Stephen. “Rwanda Orders 2 Million More Drone Deliveries by 2029 with Zipline Deal.” CNET, December 15, 2022. <https://www.cnet.com/tech/computing/rwanda-orders-2-million-more-drone-deliveries-by-2029-with-zipline-deal/>.

“Swoop Aero Triples Malawian Fleet Size to Support COVID-19 Response.” sUAS News - The Business of Drones, June 12, 2020. <https://www.suasnews.com/2020/06/swoop-aero-triples-malawian-fleet-size-to-support-covid-19-response/>.

U.S. Embassy in Ghana. “United States Honors Zipline Ghana with the Award for Corporate Excellence.” U.S. Embassy in Ghana, December 8, 2021. <https://gh.usembassy.gov/united-states-honors-zipline-ghana-with-the-award-for-corporate-excellence/>.

United Nations. “Country Insights.” Human Development Reports. Accessed August 10, 2023. <https://hdr.undp.org/data-center/country-insights#/ranks>.

“The Universal Health Coverage (UHC) Service Coverage Index.” Our World in Data. Accessed August 10, 2023. <https://ourworldindata.org/grapher/universal-health-coverage-index>.

Uwaliraye, Parfait, Patrick Ndimubanzi, Andrew Muhire, and Valencia Lyle. “INTEGRATION OF HEALTH AND MEDICAL INNOVATIONS IN RWANDA TO PROMOTE

- HEALTH EQUITY.” WIPO, 2019. https://www.wipo.int/edocs/pubdocs/en/wipo_pub_gii_2020.pdf.
- “Vanuatu.” Central Intelligence Agency. Accessed August 9, 2023. <https://www.cia.gov/the-world-factbook/countries/vanuatu/>.
- “Vanuatu: Revolutionary Technology for Vaccine Delivery.” UNICEF Office of Innovation , June 11, 2017. <https://www.unicef.org/innovation/drones/technology-for-vaccine-delivery-vanuatu>.
- Vyas, Kashyap. “A Brief History of Drones: From Pilotless Balloons to Roaming Killers.” Drones have come a long way since their early days, June 29, 2020. <https://interestingengineering.com/innovation/a-brief-history-of-drones-the-remote-controlled-unmanned-aerial-vehicles-uavs>.
- Wang, Ning. ““As It Is Africa, It Is OK”? Ethical Considerations of Development Use of Drones for Delivery in Malawi.” *IEEE Transactions on Technology and Society* 2, no. 1 (2021): 20–30. <https://doi.org/10.1109/tts.2021.3058669>.
- “Who Country Cooperation Strategy 2018-2022: Vanuatu.” World Health Organization, January 1, 2017. <https://www.who.int/publications/i/item/WPR-2017-DPM-025>.
- “World’s Rural Populations Excluded from Healthcare Access.” United Nations. Accessed August 10, 2023. <https://www.un.org/sustainabledevelopment/blog/2015/04/new-un-report-finds-bulk-of-worlds-rural-populations-excluded-from-healthcare-access/>.
- Wurbel, Heike. “Framework for the Evaluation of Cost-Effectiveness of Drone Use for the Last-Mile Delivery of Vaccines.” Research Gate, June 2017. https://www.researchgate.net/publication/318112866_Framework_for_the_evaluation_of_cost-effectiveness_of_drone_use_for_the_last-mile_delivery_of_vaccines.
- “Zipline Delivers 1 Million Covid-19 Vaccines in Ghana.” Zipline Legacy - Instant Logistics, March 30, 2022. <https://legacy.flyzipline.com/press/zipline-delivers-1-million-covid-19-vaccines-in-ghana>.
- “Zipline Drone Rescues 113 Students from Acute Diarrhoea.” Ghanaian Times, June 27, 2019. <https://www.ghanaiantimes.com.gh/zipline-drone-rescues-113-students-from-acute-diarrhoea/>.
- “Zipline Releases New Drone Designed for Rapid Home Deliveries.” YouTube, March 15, 2023. <https://www.youtube.com/watch?v=BtKdLrJLZ5I>.
- Zipline. “Most Common Question We Get: ‘Does It Work in the Rain?’” Twitter, February 20, 2019. <https://twitter.com/zipline/status/1098334424309981184>.