Stop TB Partnership

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Unmanned Aerial Vehicles: A Tool for Tuberculosis Care

Overcoming the logistical challenges limiting access to TB care and treatment

A guide to the use of unmanned aerial vehicles for the delivery of TB treatment and diagnostic samples

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About Stop TB Partnership

The Stop TB Partnership is a unique United Nations hosted entity based in Geneva, Switzerland, committed to revolutionizing the tuberculosis (TB) space to end the disease by 2030. The organization aligns more than 2,000 partners worldwide to promote cross-sectoral collaboration. The Stop TB Partnership's various teams and initiatives take bold but measured risks to identify, fund and support innovative approaches, ideas and solutions to ensure the TB community has a voice at the highest political levels and that all TB-affected people have access to affordable, high-quality and people-centered care. **Learn more at www.stoptb.org and follow us at @StopTB.**

The Stop TB Partnership's **TB REACH**, established with an initial award from Global Affairs Canada in 2010, has funded groundbreaking approaches and technologies to support the Stop TB Partnership's global mission. TB REACH combines fast-track, results-based financing and rigorous, external monitoring and evaluation, so that other donor agencies and national governments can scale up successful approaches and maximize their own investments.

The Stop TB Partnership's **Digital Health Technology Hub (DHT Hub)** is a unifying virtual platform that brings together the organization's expertise and work in the digital health technology space to support the achievement of the United Nations High-Level Meeting on Tuberculosis (UNHLM on TB) commitments and targets.

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About this guide

Objectives

Drones, also called **unmanned or uncrewed aerial vehicles** (UAVs) and **unmanned or uncrewed aircraft systems** (UASs), are emerging as a real prospect for improving access to TB diagnosis and treatment and therefore for advancing the international goals to end TB by 2030. **The purpose of this guide is to provide experiential learning on the implementation of cargo drones in TB care that is generalizable to other humanitarian use cases, specifically:**

1. To provide an overview of drone types and uses for delivering humanitarian services, with a focus on health-related work;
2. To scope the current applications of cargo drones in strengthening health care supply chains;
3. To identify and document challenges and successes across drone pilot projects from the TB space and present these under the key themes of community engagement, human resources, drone technology, regulations, site selection, and drone operations.

Target audience

This guide was written primarily for the benefit of public health implementers seeking a solution to the 'last-mile' problem in health care delivery. Although the guide refers to examples from the TB space, our conclusions are relevant to other health areas. For innovators, we hope that this guide provides useful insights to inform the further development of drone technology that is better suited to a humanitarian context.

Structure

This guide begins by summarizing the potential applications of drones, particularly within humanitarian work, before focusing on their implementation in the TB field. We synthesize insights from interviews with teams implementing drone technologies for the transport of TB diagnostic samples and medicines with those from a literature review to derive insights applicable to TB and other health care applications.

- **Section 1** presents an introduction to the guide and methodology.
- **Section 2** introduces cargo drone technology and the types of drones available.
- **Section 3** presents the results of our literature review exploring drone technology, stakeholders, regulations, legalities and perceptions related to the use of drones for cargo delivery in a humanitarian context.
- **Section 4** focuses on the application of drones for the delivery of TB treatment and care. This section presents insights from interviews exploring three case studies using drones for the transport of TB diagnostic samples and medicines, with information grouped into six themes related to the implementation of drones to support access to TB treatment and diagnosis: drone technology, regulations and legalities, site location, drone operations and navigation, and community engagement.
- **Section 5** presents the conclusions gleaned from our analysis, first looking at the challenges encountered by the drone implementation projects in this report and then looking at the bigger picture to evaluate how drones can support TB and other health care supply chains.

Executive summary

Every year, millions of people with tuberculosis (TB) do not receive treatment and care. A solution is urgently needed for those living in hard-to-reach communities with poor links to central health facilities. **Cargo drones circumvent the need for traditional infrastructure to deliver medical supplies and are an emergent potential solution to the 'last-mile' problem in health care.** This guide synthesizes lessons learned from three pilot projects using drones to deliver TB diagnostic samples and medicines in Nepal, Madagascar, and Papua New Guinea to glean insights into the application of medical cargo drones in key populations to end local TB epidemics.

Although cargo drones are technically fit-for-purpose, early implementers cite numerous issues with the technology when applied in high TB-burden countries. Their **light weight** and **lack of waterproofing** make drones unsuitable for flying in certain weather at some field locations. Meanwhile, drone navigation may be **jeopardized by nearby cellular network towers**. Because of drones' potential to crash, **safety is a key concern** during implementation, and detailed mapping of flight paths and the terrain around landing sites is necessary to ensure safe and successful flights. Until the technology improves, drone use should be **restricted to sparsely populated regions** and **drone-dependent supply chains may be unreliable**.

This literature review reveals that there are **diverse perceptions on drones** globally that vary according to the local culture. Drones can be predominantly associated with military or surveillance activities and the **rural communities served by projects often lack awareness** of the potential of drone technology for health care applications. Central to both short-and long-term success, **community engagement and education** on the use of drones for delivering medical cargo can be used to manage perceptions and ensure that projects are received positively by communities. **Landscaping community attitudes** to drones and **engaging local partners** enables the tailoring of such engagement strategies.

This guide identifies local regulations as a key initial hurdle faced by projects. **Few low- and middle-income countries have drone-specific regulations,** and this makes it difficult to navigate local regulatory authorities when acquiring approval for takeoff. Where regulations do exist, they may **limit the distance drones can travel** or the **method of cargo delivery,** which may have repercussions on application. **Knowledge of local regulations, engagement of key stakeholders from the early stages,** and **employing appropriate legal expertise** are key for overcoming regulatory hurdles.

Drone project scalability and sustainability are threatened by the geographical disconnect between project sites in high-TB burden communities, and those of drone manufacturers, services and expertise. **Reliance on international supply chains** prevents the timely and cost-effective delivery and maintenance of drones at implementation sites. Compounding this is the potential of drones to breakdown and the occasional necessity of **outsourcing drone expertise**. **Upskilling local people to manage drone operations** should be a key inclusion in future projects to improve scalability, sustainability, and transfer project ownership to local communities.

Many challenges identified in this report are related to the fact that **drone application in public health and development is in its infancy**. If high-profile interest in utilizing cargo drones for these purposes continues, the wider drone ecosystem could benefit from **capacity building, improved public perception, streamlined regulatory processes,** and **better adaptation of cargo drone technology to humanitarian applications.**

In summary, drones are a **multi-disease tool** that could help overcome the 'last mile' to reach remote communities with a high TB burden underserved by current infrastructure**.** There are few successful examples of national drone delivery networks in healthcare generally, while our case studies imply the **short-term feasibility** of implementing the technology for TB specifically. Lessons presented in this report should be used to better inform feasibility and suitability assessments**.** With further development, the potential for drone technology to improve access to diagnosis and treatment and end local TB epidemics is undeniable.

01. Introduction

The term ‘drone’ refers to any aircraft without a human pilot on board. The types and applications of drones are wide-ranging – from remote sensing to aerial surveillance, package delivery and recreational use. Drones have been applied across sectors, including for military, commercial, humanitarian, civil and hobbyist uses.

1.1. Application of drones in humanitarian work

The use of drones to provide humanitarian assistance is relatively new but has grown significantly in recent years. Cargo drones are a versatile tool. By overcoming the logistical constraints faced by traditional transport networks when reaching hard-to-access areas [1], they can ensure rapid delivery of medicines, vaccines and diagnostics to remote communities, as well as the rapid delivery of diagnostic samples from such communities to centralized testing laboratories [2]. For humanitarian assistance, drones may be utilized for a variety of campaigns, such as disaster prevention and relief and public health. The most evolved application is surveillance and mapping (commonly in disaster relief) [2], but other applications include search-and-rescue, data collection and delivery of cargo including medical supplies.

Since 2014, a number of international organizations have explored use of the technology for humanitarian missions, including Médecins Sans Frontières (MSF) [3], World Health Organization (WHO) [4], UNICEF [5], United Nations Population Fund (UNFPA) [6], United Nations Development Programme (UNDP) [7] and the Stop TB Partnership. Drone technology has developed considerably since the first drone implementation projects and continues to advance at a rapid pace.

1.2. Application of drones in TB care

Tuberculosis (TB), despite being curable and preventable, is still one of the top 10 causes of mortality worldwide and was the leading cause of death from an infectious disease until COVID-19 [8]. TB is caused by the bacteria *Mycobacterium tuberculosis* and is easily spread through the air. Tremendous progress has been made over the past decade to reduce the incidence of TB. However, the current decline in incidence of 2% falls short of the annual decline (4–5%) needed to meet the key commitments stipulated by the United Nations High-Level Meeting (UNHLM) Political Declaration as well as the mission of the Stop TB Parntership to end TB by 2030 [9,10]. The disruptions caused by the COVID-19 pandemic demands even greater efforts and accelerated innovation to drive progress towards ending the TB epidemic [11].

Every year, millions of people with TB are not diagnosed and do not receive care [8]. Many are in key populations that face a multitude of challenges in accessing health care, including geographical barriers resulting from living in hard-to-reach regions of the world. Reaching individuals in the most remote communities therefore remains a key challenge to TB programmes worldwide. A key feature of the Stop TB Partnership’s Global Plan to End TB is the ambition to reach 90% of people in key populations that need TB treatment and prevention [9]. Because of cargo drones’ ability to go where traditional infrastructure has yet to reach, they present an opportunity to bring TB diagnostics and medicines to these remote communities (Box 1). Delivery networks for TB are also adaptable and can be used to carry medical cargo pertaining to other communicable, non-communicable and chronic diseases, reinforcing population health comprehensively. For hard-to-reach communities, cargo drones can be the difference between receiving treatment and care or not, for TB and other diseases.

Box 1. Applications of cargo drones for delivery of TB care

People living in remote regions may face a combination of physical, geographical, and financial barriers to travelling to access TB diagnosis and complete treatment.

Use case 1 – Facilitating TB diagnosis in remote communities

The samples necessary for TB diagnosis need to be transported to a laboratory within a limited amount of time after collection. Therefore, time constraints present a challenge to providing TB diagnostic services in remote, hard-to-access communities. Drones can overcome poor infrastructure to provide a rapid diagnostic sample transfer service between TB services in remote communities and central laboratories.

Use case 2 - Delivery of TB treatment to remote communities

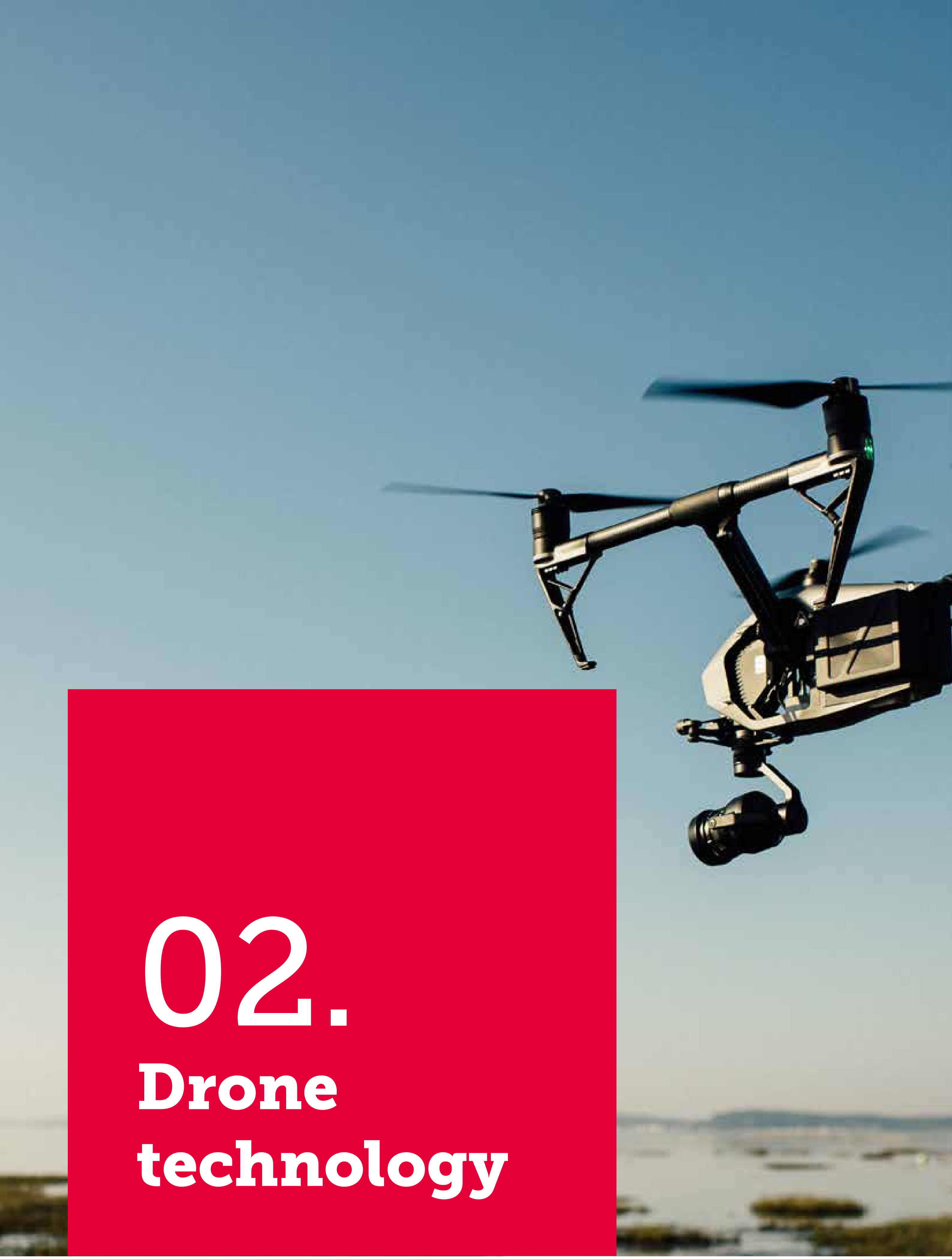
Drones can be used to deliver treatment to remote communities, thereby overcoming the significant logistical constraints that stand in the way of achieving the UNHLM TB treatment targets.

1.3.
Scope of work and methodology

In our literature search, we reviewed scientific papers and reports documenting the uses of drones for cargo delivery to improve population access to healthcare. We focused on cargo drones for their applicability to TB care.

To supplement our findings, we also interviewed staff from three projects (hereafter referred to as 'case studies') exploring the use of cargo drones to deliver TB care to remote communities. The Stop TB Partnership's TB REACH initiative provides a competitive funding mechanism for those seeking to implement transformational technologies or approaches to better the TB response. As part of its mission, TB REACH previously funded two drone implementation projects in Madagascar and Nepal. We contacted these grantees to participate in interviews and were subsequently made aware of another drone project in Papua New Guinea, which we also approached for interview.

Semi-structured interviews were conducted with the teams (project managers, engineers, epidemiologists, and members of technical implementation teams) from the drone projects identified. Members of project communities were not available for remote interview due to logistical challenges. The questions and responses obtained from each interview are provided in Annex 1.



02. Drone technology

2.1.
Technical specifications of cargo drones

Our report focuses on the uses of drones for cargo delivery for public health. The technical requirements of cargo drones differ from those of other drones, such as hobbyist or military drones, and vary depending on the size of the cargo. Small, lightweight drone systems tend to be used for the delivery of medical cargo because of their affordability, portability, and suitability for small cargo (e.g., samples, medicines, vaccines).

To successfully deliver to communities in need, cargo drones should be able to range widely while carrying a small payload. Our literature search suggests that this is possible, with drones quoted to range up to 160km carrying weights of ~9kg [13]. Depending on the drone type, takeoff can be vertical, use a landing strip, or a launcher. Drones delivering cargo also often need to fly out of the range of sight. This is achieved by pre-defining the flight path and piloting the drone remotely, if necessary. At the landing site, drones must be able to deliver their cargo safely, without damage to the contents. Cargo delivery can take one of two forms: either the drone lands to deliver its load, or it deploys the cargo while in the air and the attached parachute ensures the safe landing of the cargo [2]. Both approaches have advantages and disadvantages in terms of reliability and safety, but the latter approach is prohibited in some countries.

The currently available cargo drones include fixed-wing, multi-rotor, and hybrid models, each with its own capacities and features (Section 2.2, Table 1). The choice of which type is most suitable depends on the implementation context, e.g., application (flight path, cargo), environmental conditions, supporting infrastructure, human resources, and budget, among other factors. Currently available drone technologies are mostly powered by rechargeable batteries, which can restrict flight distance. The alternative is to use a gas-powered engine to support ranging over longer distances with heavier payloads [14,15].

2.2
Types of cargo drones

FIXED-WING

Fixed-wing drones are similar in design to a small airplane, with two fixed wings. Typically, the fixed-wing drone can fly at speeds around 100 km/hour with a payload ability of up to 4.5kg [2], although many are limited to lower weight cargo. These drones can cover long distances, with roundtrips of up to 150km. As such, they are suitable for medical supply chain delivery [1,2]. These drones are also able to operate in higher wind speeds than multi-rotor drones (below) [1,16]. However, fixed-wing drones are not designed for vertical takeoff or landing (VTOL) and require a launcher for takeoff and have different strategies for landing. As such, they are incapable of bidirectional delivery [1].

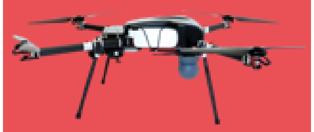
MULTI-ROTOR

Multi-rotor drones have one or more rotors, allowing the drone to move in any direction and takeoff and land vertically. Recent development in multi-rotor technology have enabled distances of up to 20km (round-trip) with a payload of 2kg [16], but longer ranging models are more expensive. While multi-rotor drones are more maneuverable, they are less stable and therefore less suitable for windy or poor-weather conditions. Their complex design also requires greater expertise to operate [1]. Multi-rotor drones are commonly named after the number of rotors they have, a common example being the ‘quadcopter’ with four rotors.

HYBRID

Hybrid drones have recently been developed that have both fixed wings and rotors, making them capable of long-distance horizontal flights as well as VTOL [16]. Hybrid drones can also carry greater payloads and fly longer distances than multi-rotor drones [1,2].

Table 1. Overview of the properties of different drone types

	Fixed-Wing	Multi-Rotor	Hybrid
Range	Up to 150km	Up to 20km	Up to 80km
Payload	4.5kg	2kg	4kg
Takeoff & Landing	May require a runway or launcher and landing strip or catch mechanism.	Vertical	Vertical
			

2.3. Drone navigation and control

A drone's flight path is programmed using a pre-determined series of waypoints to mark the route from the take-off site to the destination. Drones can use different navigation methods to fly between these waypoints. Originally, drone navigation relied on communication between the drone and Global Navigation Satellite Systems (GNSS). However, GNSS-based navigation can be limited since natural and man-made structures can block the navigation signals, causing navigation to fail in urban areas or forests, for example. [17] GNSS-based navigation can be used in combination with other methods such as sensor-based navigation, on-board cameras and, increasingly, artificial intelligence. An onboard flight controller computer uses information from such sources to travel along the pre-defined route of waypoints. In some drones this may also include input from a ground-based pilot using a tablet, computer, or even a mobile phone to communicate with the drone via radio frequency or WiFi. Further, specific drone actions can be pre-programmed and triggered when necessary, such as landing, parcel delivery, and a "return to base" command. [18] Some drones can also use of sensor-based navigation to detect and avoid obstacles along the flight path.

Autonomy is the ability of a drone to operate without external control by a pilot. Available drones have varying degrees of autonomy, ranging from no autonomy (always controlled by a ground-based pilot) to partial autonomy (can detect obstacles and automatically avoid collisions, but may prompt the pilot to control navigation if needed) to full autonomy (operation without a pilot in all environments). Partially autonomous drones are sufficient for projects set in sparsely populated rural areas as the need for advanced features associated with autonomy, such as obstacle avoidance, is reduced. Lower autonomy drones are also less expensive for projects that may be limited by budget.

03. Literature review

3.1.
Current applications

Our literature search identified pilot studies across the world utilizing drones to serve remote populations where more traditional infrastructure is not available or fit-for-purpose (Figure 1, Annex 2). Drones are used to connect central hospitals or laboratory facilities to remote towns and villages, delivering supplies during medical emergencies, or as a routine service. Cargo includes diagnostic samples (for HIV [19], TB [20], and COVID-19 [21]), vaccines, emergency supplies (particularly blood for transfusions), and medicines. The projects were generally collaborations between manufacturers specializing in civil-use drones, international multilateral or non-profit organizations, and national governments. Annex 2 contains a table of projects identified using drones to carry medical cargo in the development context, while the UAV for Payload Delivery Working Group website provides up-to-date information on past and present drone projects.

Drone implementation, for the most part, is in the pilot stage, and there are reports of projects struggling to find scale-up funding [22,23]. That is not to say larger scale implementation is not possible. In 2016, the Government of Rwanda launched the world's first national drone delivery service in partnership with the drone manufacturer Zipline. A fleet of Zipline fixed wing autonomous drones called 'Zips' are used to deliver health care supplies and laboratory samples on-demand, with up to 150 flights a day [24] (Box 2). Zipline networks have also been established in Ghana [25], the United States [26] and the United Republic of Tanzania [27], while further projects are planned in India, Nigeria, and the Philippines.

Following a successful pilot, UNICEF and the Government of Malawi launched the first drone-testing corridor in Africa to pilot innovations in drone technology that have the potential to benefit local communities [28]. The Malawi corridor has since trialed drones for malaria control and for medical cargo delivery. Meanwhile, three other drone testing corridors have been established in Vauatu, Kazhakstan, and Sierra Leone [29]. In 2020, the Drone and Data Academy opened in Malawi, funded by UNICEF and the Government of Malawi, to build local capacity in the use of drones for humanitarian, development, and commercial purposes across Africa. Currently the school has over 400 graduates from 25 countries [30].

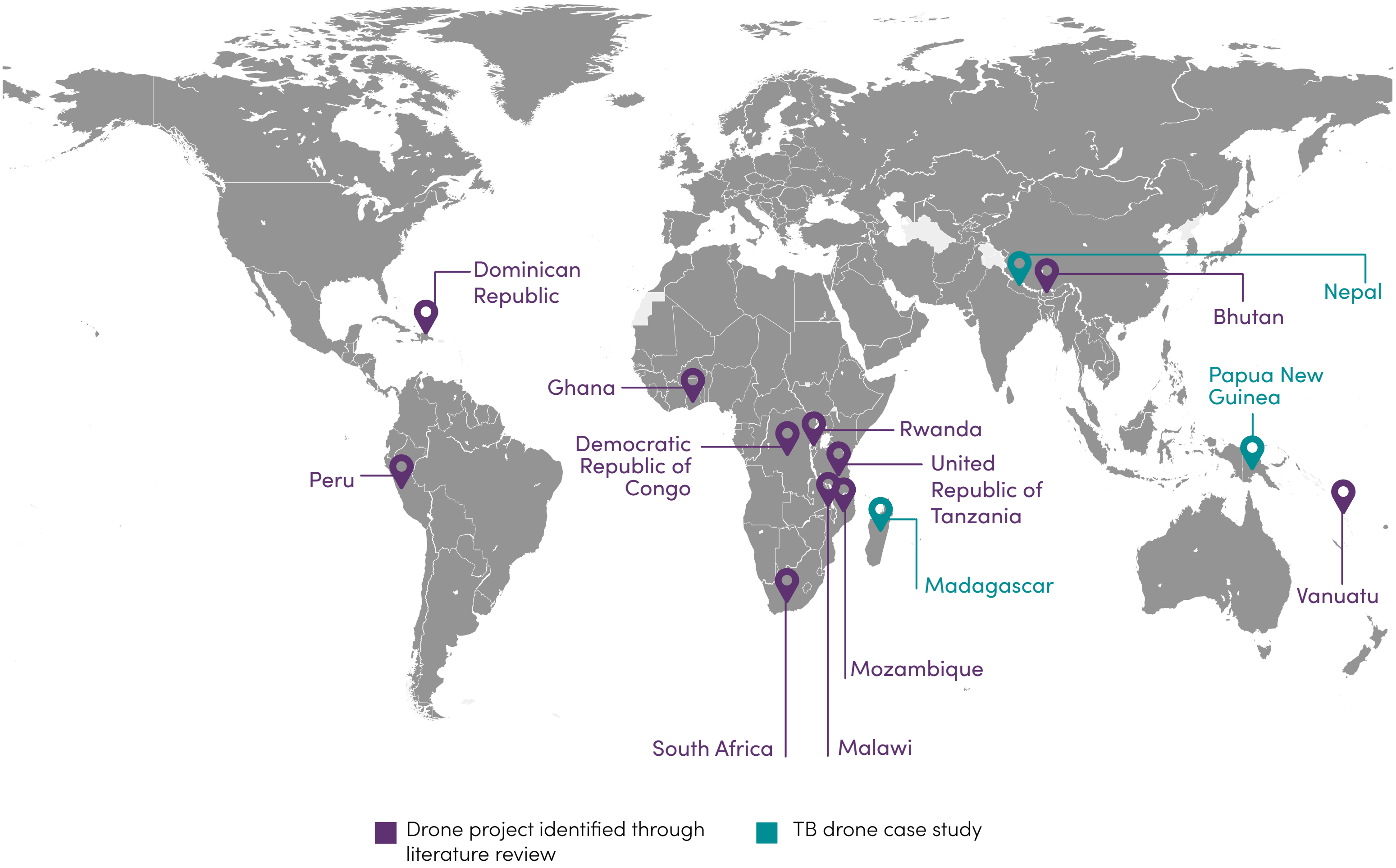
Box 2.
Rwanda's drone delivery network

Rwanda is a central African country with a mountainous geography. Around 83% of Rwandans live in rural areas and can struggle accessing health services, resulting in negative health outcomes [31, 32].

In Rwanda, a fleet of Zipline drones provides a national medical supply delivery network. Initially focusing on the delivery of blood supplies to reduce maternal mortality rates, the network has widened its scope to other medical cargo and played an important role in the country's response to the COVID-19 pandemic.

At the beginning of 2020, Zipline was delivering 75% of the nation's blood supply with drones flying 24 hours a day [33]. The network operates out of two distribution centers in Kayonza and Muhanga (east and west of the capital, Kigali) and is well integrated with existing national systems. The **National Center for Blood Transfusion (NCBT)** collects donated blood in Kigali and transports it to the two distribution sites using refrigerated vehicles. Health care workers from rural clinics can place orders for blood delivery via SMS, Whatsapp, or phone call. The blood is carefully packaged, and the drone is launched using a from the distribution center. Drone flights are coordinated with the **Rwandan Civil Aviation Authority (RCAA)** out of the distribution center control towers. At the destination, the drone releases its cargo which lands gently via parachute and does not require specific infrastructure of the delivery medical center and the health worker is notified of delivery. The drone then returns to the distribution center. The cold chain is maintained throughout.[34]

Figure 1. Drone projects identified in the literature review (details are provided in Annex 2)



Box 3.
Key stakeholders in projects

The implementation of drones in a humanitarian context requires intersectoral collaboration among stakeholders.

Beneficiary communities	The core of any drone project. Drone projects should be responsive to community needs. Communities may be engaged and sensitized to earn trust for the project. Community ownership of the project is an important end goal.
National health systems	A key partner to engage to ensure drones are fully integrated with existing health systems and supply chains.
Drone manufacturers	For procurement of drone equipment and services and may be involved in any product customization. Manufacturers will also provide part replacement or repair.
Drone service providers	For a fee, service providers can supply the onsite piloting, programming, and engineering expertise for drone operation.
Ministries of Health or similar	Should be engaged to support and oversee the project, may be instrumental in obtaining clearances from other authorities.
Aviation authority or similar	Control the local airspace, permissions to fly will need to be obtained from this authority (including permission to fly out of the line of sight). Drone flights may also have to be coordinated with existing air traffic.

With no common platform for discussion or institution to facilitate collaboration, lack of communication between different stakeholders can impede the progress of drone implementation projects.

3.2. Regulations

Drone technology is advancing more rapidly than the rules and regulations governing its application [2]. In the United States and Europe, regulations on drones are currently strict due to concerns over security and aviation interference [35]. Several countries in sub-Saharan Africa have granted permission to enable use of drones for various humanitarian projects, though in some countries drones must be registered and or operated by local people or organizations. In 2016, Rwanda launched a comprehensive national regulatory framework to coordinate the safe use of drones in the country [2,36]. However, the quality and quantity of drone regulation in other countries varies, regulations might be strict, complex, or non-existent.

Some national regulations may limit the potential applications of drones for medical cargo delivery. For example, regulations may stipulate that drones must fly within the visual line of sight (VLOS), limiting the distance they can travel and thus the potential to use drones for supply chain support. There can also be limitations to how the cargo is delivered, with some countries prohibiting use of a parachute to deposit cargo and therefore having important repercussions on drone operations.

In any case, gaining permission to implement drones remains a major stumbling block and point of complication. The Global Drone Regulations database compiles available information on national drone regulations worldwide to provide a global resource for actors seeking to implement drones. Additionally, UAVCode.org details a code of conduct for the humanitarian use of drones including best practices for community involvement and data handling. [37]

3.3. Perception

Globally perceptions around drones are heterogeneous. The acceptability of a medical cargo drone project could depend on local understanding of the project and technology, any prior perceptions of or experiences with drones, as well as cultural context and background.

Communities may initially associate drones with photography, surveillance, the supernatural and military activity [39,40]. Minority communities may associate them with surveillance or attack [40]. Briefing communities on the application of cargo drones for the delivery can aid understanding of the potential benefits of the project and improve acceptability [39,41]. However, even after education on the intended use, concerns about drones crashing and causing damage, not arriving, or proving unreliable can persevere, as can distrust of drone-delivered medicines [39]. Drones may be distrusted where the community has a history of 'outsiders' exploiting natural resources or acting with disregard for local people in other ways [41]. Health care workers may be concerned about drones replacing human jobs [39]. Drone projects should therefore be conducted by or with the involvement of individuals and organizations who are trusted by the local communities [39]. Implementers should obtain a thorough understanding of drone perception in the beneficiary communities prior to drone launch to plan effective engagement strategies.

Local government officials are more likely to be aware of drones and their various applications than the general population [40,41]. Although officials may be more familiar with the technology, they may still be skeptical of using drones to deliver health supplies and can perceive drones as expensive. [40,42] This can be a barrier to implementation. When presented with a range of drone applications, local officials in the United Republic of Tanzania were most uncomfortable with using cargo drones to deliver medicines, citing fears of misuse or interception; however, acceptability was still high overall [40].

The Swiss Foundation for Mine Action (FSD) conducted a survey in 2016 exploring the viewpoints of **humanitarian professionals** working in 61 different countries regarding the use of drones in their sector [42]. The majority of survey respondents expressed confidence in drones' potential to strengthen humanitarian work. However, the survey revealed that a significant amount of work needs to be done before the use of drones in the humanitarian sector is more widely accepted.

When asked what more needs to be done for drones to be useful, organizations cited the following:

1. Organizations need more experience (87%);
2. Clear guidance and rules are needed (86%);
3. Dedicated service providers should be available to work with humanitarian actors (61%);
4. Coordination needs to be improved and institutionalized (55%).

Box 4.
Site selection and no-fly zones

Drone flight paths should be carefully planned to be cognizant of areas where drones may be unable to fly. Reasons why drones may be unable to fly in an area could include:

- Local regulation may put constraints on how high, how far, and where drones can fly.
- Local police or military may restrict flight paths because of the association between drones and surveillance [41].
- Communities may also have views as to when and where it is appropriate to fly drones, such as planning flight paths around refugee settlements [40], and not flying over schools.
- Cellular network towers can interfere with drone GPS navigation, so drones may be technically incapable of flying in some areas [22].
- Drone use may not be appropriate for medical cargo delivery in areas currently experiencing, or with a history of, conflict.

Because drones have a limited range, thorough mapping of the terrain should be done in consultation with relevant stakeholders when planning flight paths.

3.4. Cost

Drone interventions will entail additional upfront and operating costs. Initial expenditure includes, but is not limited to, the purchase of the drone and accompanying ground equipment (including batteries) and indirect costs such as additional training for personnel and the cost of securing the required permits. Customs charges, taxes and shipment fees may also apply to items procured internationally. Depending on local drone regulation, additional cost may be incurred to register the drone, while some regulations also make drone insurance mandatory. Operational costs include the cost of drone flights and drone equipment maintenance, as well as fees for drone service providers, if necessary.

When choosing a drone, the upfront and operational costs should be considered alongside the delivery capacity and suitability for the use case, including the drone's ability to range long distances and fitness for the project site's climate. Drone prices can vary widely [43]. Opting for more expensive hybrid drones could result in a higher service level [44], but these may be more technologically complex and therefore unable to be repaired or maintained locally. Alternatively, a cheaper commercial drone may be purchased and modified to fit the project's needs [45].

The purchase price of the drone, its lifespan and failure rates significantly impact whether an intervention is cost-effective [46]. Drones are reportedly cost-effective for vaccine distribution and as part of a package of interventions to improve TB care [47,48]. Broadly, drones may become more cost-effective in the future as the market becomes increasingly competitive. However, the epidemiological and economic context of the intervention site will dictate project cost-effectiveness; so this should be assessed relative to the particular use case.

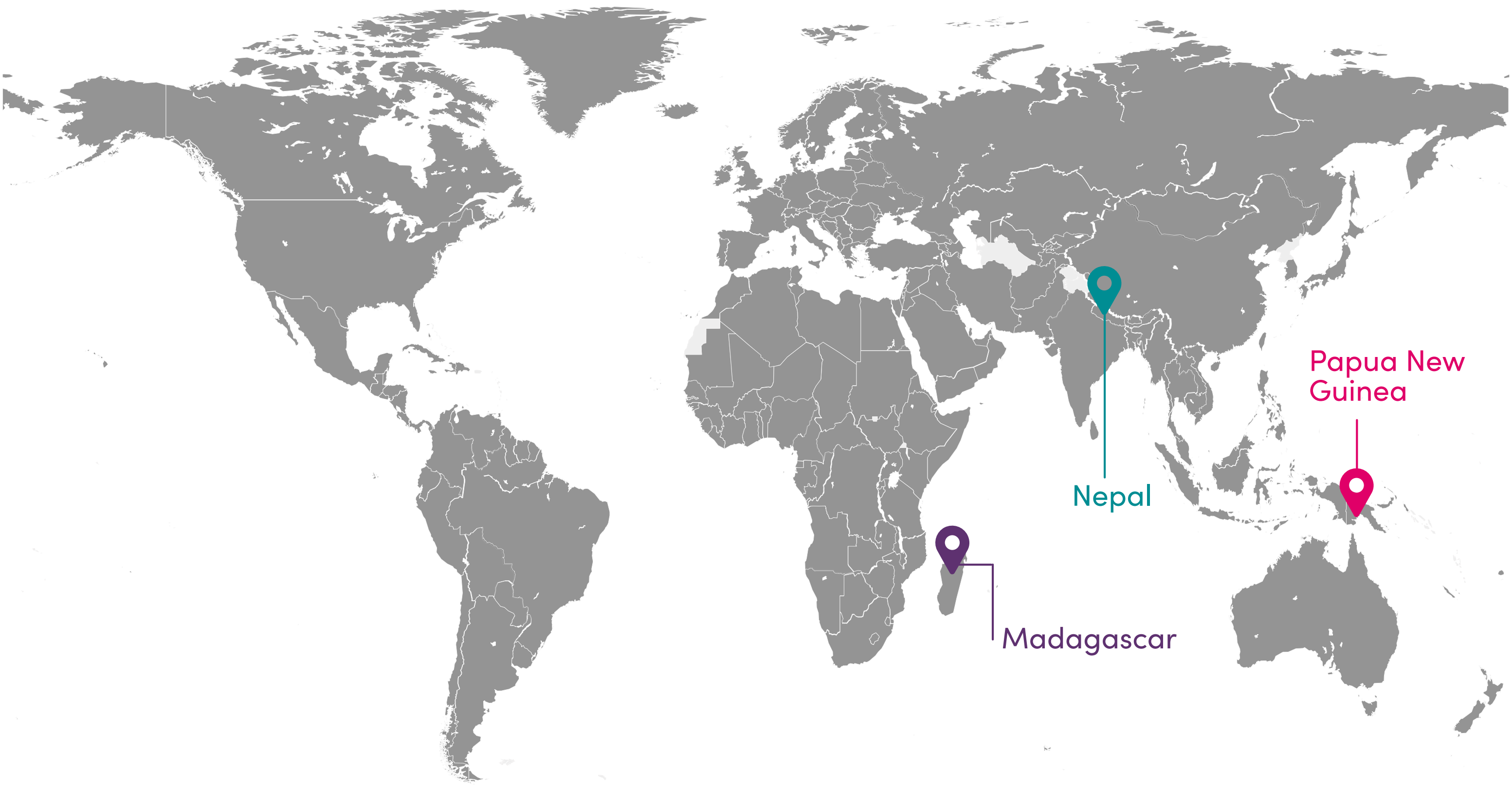
The cost of operating drones can be compared to the continued use of existing land-based transport systems, such as motorcycle networks. On a small scale, the cost per kilometer of using drones to deliver diagnostic samples currently compares less favorably to the cost of delivery by motorcycle [46,49]. On a larger scale, drone interventions can become cheaper to operate than motorcycle networks due to savings on vehicle, fuel and personnel expenditures. Although the ability to reach geographically unreachable populations is often quoted as an advantage of drones, in some simulations in Liberia 6.3-45.2% of clinics were out of range depending on the drone chosen [46]. However, where land-based transport infrastructure does not already exist or is impossible, investment in drone networks may be the only feasible option to provide access to health care in some communities.

© Photo credit: BNMT. Source: Nepali Times

04. Applying drones in TB: Case studies

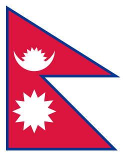
According to the current literature, drones have been applied for medical cargo delivery in a number of sites globally. The success achieved in some of these campaigns may indicate drones as a feasible solution for tackling the 'last-mile' problem in TB. In this section, we feature three case studies exploring the use of cargo drones to deliver TB care to remote communities. The Stop TB Partnership's TB REACH initiative previously funded two out of the three drone implementation case studies – those in Nepal and Madagascar.

Figure 2. Featured case studies using drones for TB



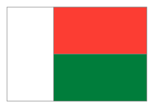
Nepal

Case Study 1: Nepal
Project to initiate an on-demand drone service to facilitate access to TB care in the mountainous areas of Nepal



Madagascar

Case Study 2: Madagascar
Pilot project to explore the feasibility of using drones to circumvent poor infrastructure between TB patients and health centers in rural Madagascar



Papua New Guinea

Case Study 3: Papua New Guinea
Pilot project to assess whether drones could overcome the country's 'last-mile 'problem of transporting TB samples from remote areas to the central hospital

4.1.

Insight themes

Insights obtained during the interviews were grouped into the following key themes:

DRONE TECHNOLOGY

What equipment was required by the project? What kind of drone was used and who provided the drones? What modifications were made to the existing equipment to ensure its suitability?

COMMUNITY PERCEPTION

How does the community perceive the drone technologies? How did the project team engage the community to communicate the purpose of the project and the drone technologies?

SITE LOCATION

What were the key considerations for site selection? What elements of the geography need to be considered when mapping flight paths?

HUMAN RESOURCES

What expertise was required for the successful implementation of the project? What expertise needed to be outsourced? How did the project leverage local expertise and human resources?

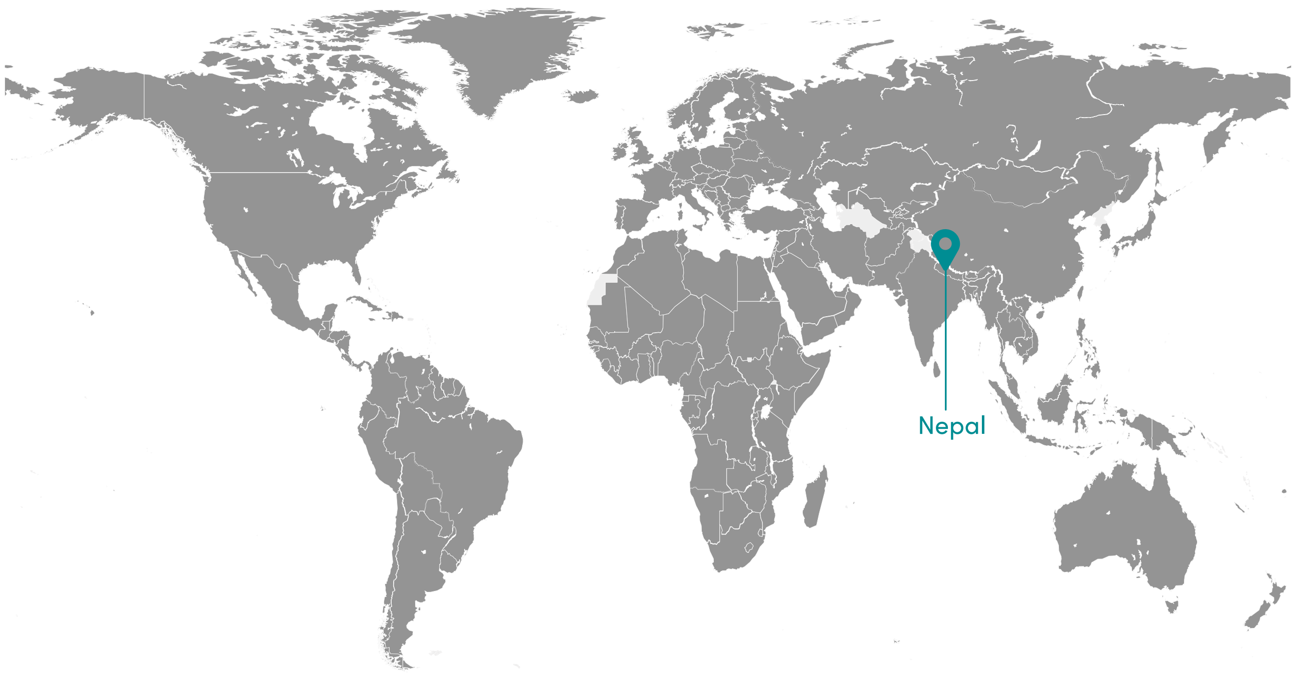
DRONE OPERATIONS AND NAVIGATION

How was the drone operated? How was the flight path set?

REGULATIONS AND LEGALITIES

How did the project team navigate regulatory and legal requirements for the project? To what extent did regulatory and government bodies support the technology and the proceedings required for its implementation?

4.2.
Case study 1: Nepal



COUNTRY PROFILE

TB is one of the leading public health challenges in Nepal, a country where 43% of the population live in hilly regions and a further 6.7% live in mountainous areas. In 2020, less than half of the projected 69,000 TB cases in Nepal were notified and TB treatment coverage was reportedly only 40% [50]. The situation in Nepal is made worse by poverty-related factors, HIV/TB/diabetes co-burden, and the logistical difficulties of providing health care to communities situated in the Himalayan terrain [50,51].

PROJECT OVERVIEW

Location: Pyuthan and Sworgadwari municipalities of Pyuthan district

Funding sources: The Nick Simons Foundation

Date of deployment: June 2019 – present

Drone type: Hexarotor drone, DJI M600

Cost: The start-up operational costs were within the range of US$ 350,000 with the drone costing US$ 6,000.

Birat Nepal Medical Trust (BNMT) partnered with the National Tuberculosis Control Center, Stony Brook University, WeRobotics, Liverpool School of Tropical Medicine, DroNepal, Nepal Flying Labs, and The Nick Simons Institute to initiate an on-demand drone service to facilitate access to TB care in the remote mountainous areas of the Pyuthan district of Nepal [48]. The drones are used to transport sputum samples collected from symptomatic individuals at health posts in rural villages to two medical laboratories that are equipped with GeneXpert machines for TB testing.

The TB samples are collected from individuals with signs and symptoms of TB identified by community volunteers. For the pilot study, drones were only used to transport sputum samples. However, the ultimate goal is to also transport treatment and smart pill boxes that are capable of electronically recording treatment adherence. The project has established that drones are useful to the community. The team has pioneered a permission framework for cargo drone projects in Nepal and acquired all the required government permissions from 12 ministries and local authorities for the use of drones for health care applications in the area. The drones have been able to fly successfully throughout the year in Nepal, including through the monsoon season, by implementing simple verbal pre-flight check protocols for dispatcher and receiver sites.

Drone-assisted sputum sample collection is now operational in eight of 12 health posts in the Pyuthan district. To date, over 300 drone flights have been carried out, delivering more than 1,000 sputum samples from eight remote health facilities directly to two laboratory hubs for rapid testing.

The team has pioneered the legal and regulatory process so that drones can be implemented on a wider scale in the region. A simple QR landing code system was developed and implemented to allow simple flight operation by health care workers and precision landing of the drones at networked sites.

DRONE TECHNOLOGY

The team chose to use a simple, relatively inexpensive hexarotor drone capable of VTOL: the DJI M600. As a the supplier, DJI provided technical goods and services, such as part exchange. The drone service provider- WeRobotics' Nepal Flying Labs- also provided their expertise to the project. Two drones were imported into Nepal and a third drone was used for testing purposes at the WeRobotics office in Switzerland.

The team made a number of modifications to the drone. The maximum payload is 6kg, with the range dependent on altitude changes in the flight path. A Raspberry Pi microcontroller was attached to load pre-planned routes using software custom-built by WeRobotics. Since the DJI drone was designed for imaging purposes, WeRobotics made a number of modifications to convert it into a cargo drone, adding a communication system, including a radio-frequency module, 4G connection and satellite communication unit, to enable it to communicate with multiple ground stations. WeRobotics also built additional safety mechanisms and added sensors to enable the drone to land by QR code. Obstacle-avoidance sensors were not applied but no issues have been encountered with unexpected obstacles in this remote area.

COMMUNITY PERCEPTION

Overall, the community reacted very positively to the initiative; they were proud to be the first community to implement this technology and understood its benefits. Through conversations with local people and health care workers, the team found that the community asked constructive questions about the potential of using the technology for other purposes such as transporting blood.

The team collaborated with local partners who suggested that the team set up demonstrations of the drone technology for students and mayors in the community. The team used radio broadcasts and held extensive engagement meetings with the community, including local influencers, authorities and schools, to raise awareness and respond to community questions about the project and its implementation. The team actively engaged the local community in the project: Local tailors made the cloth with the QR codes the drones use for landing, and the team trained local youth members and health care workers to pilot the drones.

SITE LOCATION

Pyuthan is a hilly, rural district in midwestern Nepal. The district was selected due to a high TB prevalence and inaccessibility to care and treatment. The region has a subtropical climate and experiences frequent rains in monsoon season, which must be avoided when flying the drone. Because of the terrain's steepness, a drone capable of VTOL was required.

HUMAN RESOURCES

The team required personnel to map the area, maintain and repair the drones, manage operations on the ground and evaluate the project throughout. Expertise to manage the technical aspects of the project, including drone selection, software development and repairs, was also important. It was easy to train health care workers to manage the drone deliveries (such as to secure the payload). However, there was a constraint to the local human resources available on site, since most health care workers were overwhelmed with other health care activities and were often covering multiple villages.

DRONE OPERATION AND NAVIGATION

Flights were monitored by a pilot at the launch site, coordinating with a health worker at the destination via radio communication with an Android phone. The team used raw elevation open-source data to generate their own high-resolution maps of the region where they operated the drones. These maps were very detailed, especially at the landing sites. The maps included information such as the height of trees or slope of the ground, which enabled the team to microprogram the drone to land with very specific instructions.

In addition to the drone (DJI M600) with attached Raspberry Pi, equipment on site included an Android tablet connected to a radio transmitter, a plastic landing platform detected by the drone using optical sensors, and a 3D-printed sample collection container. A user-friendly software application that detects and displays nearby health posts to which the drone can be sent was installed on the tablet.

REGULATIONS AND LEGALITIES

The team pioneered the process of obtaining permissions for the use of drones in a health care context. The process was circuitous and took more than a year. One team member found the legal process less challenging than he had expected because the project stimulated interest and people wanted to facilitate its implementation. Despite the lack of government clarity on how to proceed with regulations, the government was keen to move forward in the best way possible, and the programme was well received.

4.3.
Case study 2: Madagascar

COUNTRY PROFILE

In the Republic of Madagascar, an island country in the Indian Ocean, TB is a prominent public health problem, with an estimated incidence of 238 per 100,000 population. [52] The situation is aggravated by a lack of human resources in health care and a weak health care system [53,54]. The country's insufficient transport networks and the logistical constraints of delivering to remote communities result in poor access to health care. As a result, TB case notification in 2020 was 37,151 people (of an estimated 66,000 incident cases) and treatment coverage was only 55%. [52]

PROJECT OVERVIEW

Location: Ifanadiana district, Vatovavy region

Funding sources: Stop TB Partnership's TB REACH and USAID

Date of deployment: November 2017 – December 2018

Drone type: Hybrid, manufactured by Vertical Technologies

Cost: The Vertical Technologies drone with batteries cost US$ 15,000.

Between November 2017 and December 2018, Stony Brook University (New York, USA) and the Pasteur Institute of Madagascar conducted a pilot project to explore the feasibility of using drones to circumvent poor infrastructure between people with TB and health centers in Madagascar. The aim of the project was to use a drone to transport sputum samples and medicines between a central laboratory in Ifanadiana town and the remote villages in Androrangavola commune of the Ifanadiana district (Vatovavy region, south-central Madagascar). Walking is the only way to travel between these sites and it can take patients several hours or even days to make the trip. Drones can shorten the time it takes for samples to reach the laboratory.

The project was able transport dummy payloads between the villages and health care center, providing a guide for the key considerations that must be made before drone technology is operated in the area at a larger scale.

DRONE TECHNOLOGY

Due to the infrastructure limitations of the villages concerned, the project team selected an autonomous drone capable of bidirectional transport that did not require a launcher or runway to take flight. Initially, the project team selected a hybrid drone manufactured by Vayu; however, the drone was never delivered by the manufacturer. The team then found an alternative manufacturer to provide the drone for the implementation stage: the DeltaQuad drone (Vertical Technologies).

This drone was capable of vertical takeoff and landing, had a flight range of about 60km and could carry a maximum payload of 1.5kg. The drone was partially autonomous, using open-source software (PX4 Professional Autopilot and QGroundControl) for flight control and for pre-planning flight paths. The flight was monitored by a pilot at the takeoff site, who could take over control of the drone if necessary. The drone was met at the destination site by community health workers. The drone had no built-in mechanism to avoid obstacles, but the pilot could execute certain actions, such as return to base, if required.

The team encountered operational issues with this drone and had to make a number of modifications to the hardware and software as problems arose during field testing. Testing and modifications were done at Stony Brook's research center at the project site.

COMMUNITY PERCEPTION

Overall, the project was well received by the village communities. To familiarize local communities with the technology and dispel myths and misconceptions surrounding it, the team made a concerted effort to engage the community throughout the project. In the initial stages, the team met with mayors and officials and disseminated information in each village twice. In the later stages, local health care workers were trained to retrieve the drones and load and unload payloads.

SITE LOCATION

The strongest factor influencing the selection of the Vatovavy region was its proximity to Stony Brook University's Center ValBio research station. This proximity enabled the team to use the research station as a base. The elevation changed rapidly across the flight path, creating thermals that disrupted the drone in flight. The team tried to avoid these areas. The drone was not suitably robust for the rough terrain in the area and changeable weather conditions.

HUMAN RESOURCES

The team required personnel to map the area, maintain and repair the drone, manage operations on the ground and evaluate the project throughout. Expertise to manage the technical aspects of the project, including drone selection, software development and repairs, was also important. It was easy to train health care workers to manage the drone deliveries (such as to secure the payload). However, there was a constraint to the local human resources available on site, since most health care workers were overwhelmed with other health care activities and were often covering multiple villages.

DRONE OPERATION AND NAVIGATION

Flights were monitored by a pilot at the launch site, coordinating with a health worker at the destination via radio communication with an Android phone in this pilot phase.

High resolution and detailed maps were needed to plan the flight path, especially at the landing sites. The maps included information such as the height of trees and slope of the ground, which enabled the team to microprogram the drone to land with very specific instructions. However, the selected flying region was in remote Madagascar where it was challenging to obtain such detailed maps from open-source data such as Google Maps or Bing Maps. A week-long expedition was conducted to manually map out and generate the project's own high-resolution maps of the region where the drone would be operated.

In addition to the drone, the equipment on site included an Android tablet connected to a radio transmitter, a plastic landing platform detected by the drone using optical sensors, and a 3D-printed sample collection container. A user-friendly software application that detected nearby health posts to which the drone could be sent was installed on the tablet.

REGULATIONS AND LEGALITIES

Legal challenges imposed significant delays on the project. At the time of the project, Madagascar had no laws regarding drones and too few legal human resources to keep up with the technological advancements in this field. They had to obtain temporary permits and continue negotiations throughout the project to maintain the permits. The legal authorities had a positive attitude towards the project but were hesitant when it came to signing contracts.

4.4.

Case study 3: Papua New Guinea

COUNTRY PROFILE

Papua New Guinea (PNG) is one of the 30 highest TB burden countries in the world, with an incidence of 441 per 100,000 population [55, 56]. In 2020, 29,959 of an estimated 39,000 total TB cases were notified and treatment coverage was 72%. Access to diagnosis and treatment of the disease is significantly limited by geographical challenges; 87% of the population live in rural areas with limited access to health care facilities. Misconceptions and superstitions around TB remain common. [57] Many people with TB do not complete treatment before they are fully cured, thus exacerbating the emergence of resistant strains of TB.

PROJECT OVERVIEW

Location: Gulf Province, Papua New Guinea

Funding sources: The Nick Simons Foundation

Date of deployment: July 2018

Drone type: Hybrid cargo drone, manufactured by Vayu

Cost: No public information

MSF started a pilot project in PNG in July 2018 to assess whether drones could overcome the country's 'last-mile' problem of transporting TB samples from remote areas to central hospitals. A drone was used to transport sputum samples from remote villages in Malalaua to the central hospital in Kerema for analysis.

The feasibility study was abandoned due to several problems: the weather limited the number of flights it was possible to complete as the drone was not adapted for heavy rains, the drone crashed and was lost in the forest so there was hesitancy about deploying a second, and in general the technology was not developed enough to meet the needs of the MSF team, capable of a limited flying distance. The team is not planning to conduct another study. Rather, the team upgraded lab infrastructure in the project region (providing the necessary equipment to perform microscopy) so TB diagnostic samples no longer had to be transported to the central laboratory for analysis. Local boats were also used to facilitate any necessary transport to the central laboratory. As such, there is no longer a need for drones to assist with the supply chain. However, MSF's feasibility study provides valuable lessons for drone implementation projects going forward.

DRONE TECHNOLOGY

The team requested a drone that was reliable, sustainable and easy to operate. Autonomy was required to supplement the lack of competent human resources in the target health centers. The drone also had to be capable of VTOL since there was a lack of airstrips in the province. They selected a hybrid cargo drone manufactured by Vayu for the project. It could carry a payload of 2kg, had a range of 100km and could fly for one hour. It was partially autonomous and programmed to fly from its origin site to the destination.

COMMUNITY PERCEPTION

According to MSF, the local community was supportive of the project, and health authorities were enthusiastic because they were struggling with the last mile. MSF engaged the local community in Kerema by word-of-mouth one month prior to the project start date, explaining what drones were, how they were operated and why MSF was looking to use them in PNG. More specifically, MSF invited the local community to join them at the local football field in Kerema and demonstrated the technology.

SITE LOCATION

Gulf Province is a remote, hard-to-access, swampy region of PNG. Travel is by boat (if weather permits) or on foot.

HUMAN RESOURCES

MSF Japan coordinated all activities with the vendor and supported the project coordination team to achieve the correct accreditations. One person from MSF Japan joined the vendor and field teams for the field tests. In total, three pilots were used (two from the vendor, one from MSF), though this was not necessary.

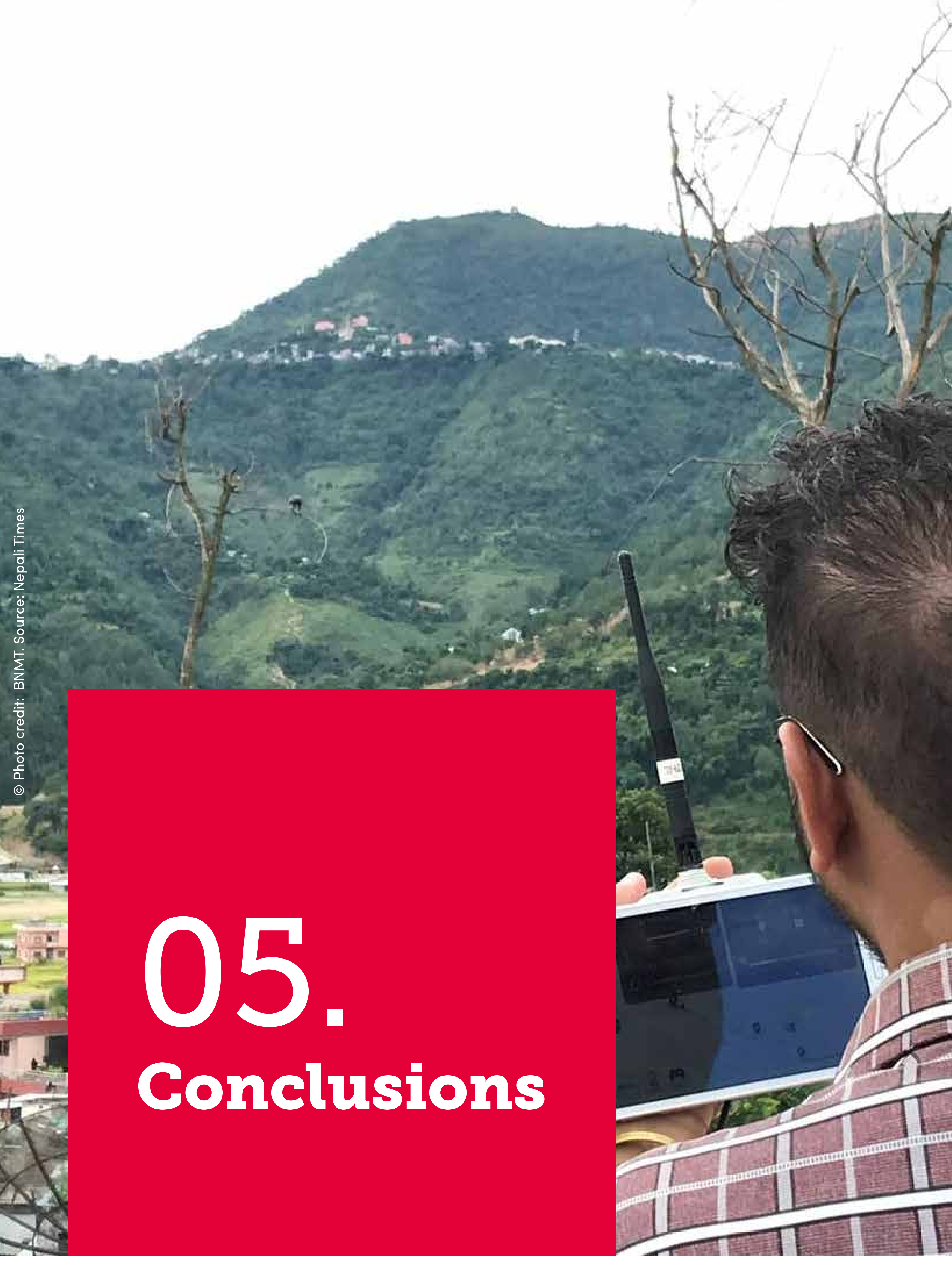
DRONE OPERATION AND NAVIGATION

Two drones were available, but only one was used. During this feasibility study, calibration tests were done on an airstrip at the airport near the central hospital in Kerema. The drone did not go beyond the line of sight, even though it was capable of it. At the destination site in Malalaua, the drone would land using VTOL and a solar power system would be used to recharge its battery. However, the drone did not reach this site during this study.

REGULATIONS AND LEGALITIES

The project imported the drone without problem, but some equipment (particularly batteries) was harder to import. The regulatory approval process was managed by the MSF Head of Mission. Permission for flights was granted by the Civil Aviation Safety Authority (CASA), but it took over six months to obtain. Moreover, permission was needed from the National Airport Corporation to use an airstrip at the airport and from the telecom frequency authority to ensure that the frequency used to communicate with the drone did not interfere with other communications. Both CASA and the Ministry of Health were very supportive of this project.

Papua New Guinea does not have any regulation on the use of drones. Legal authorities faced difficulties in understanding which process to follow for the project and needed to cross-check with New Zealand authorities before giving the green light; the regulation process changed while the team was conducting the feasibility test. The process of acquiring the required permits for the project involved continuous follow-up with the authorities.



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05. Conclusions

5.1.
Key considerations and lessons learned

DRONE TECHNOLOGY

- **Drone risk of mechanical failure is high.**

One of the significant challenges to project teams was the unreliability of the drone technologies. **Drones broke down frequently, sometimes requiring parts of the system or the drone itself to be exported back to the manufacturer for repair**, incurring significant costs and delays to the project as a consequence. Case study sites felt that this threatened the sustainability of the projects. Having **technical expertise on site** will help projects to cope with potential mechanical failures, while **a budget should also be set aside for maintenance issues**, including for potential freight and customs charges if new parts are needed and the drone supplier is located overseas.

- **The drone market is immature but developing rapidly.**

Drone technology is still developing. Most drones are not designed for the use cases, contexts, and environments of many public health projects and implementers had to adapt the drones in various ways. Drones may need to be modified to make them better suited to the environment at field sites, **robust enough to handle weather conditions and rough terrain for landing.** Communication systems, ground control software and safety mechanisms might also need to be added to drones for this application. Furthermore, the **range of drones is currently limited** and may prevent the deployment of drones in certain use cases. Drone implementers may also encounter technical challenges in rural environments, including network and satellite navigation issues. Pilot projects may be unsuccessful as a result of technical issues.

Current technological oversight and limitations will likely be remedied as drone application in this field expands and the technology advances. In the meantime, implementers should work with drone manufacturers to ensure their project needs are met and that the manufacturer is transparent about the capabilities of the drones.

COMMUNITY PERCEPTION

- **Perceptions of drones are varied and important to consider and address.**

The perceptions of drones encountered in our literature search were heterogeneous and dependent on cultural context. Negative associations, particularly around the military and surveillance uses of drones, could endanger the success of drone pilot projects. **A thorough assessment of initial and ongoing perceptions** around drones could help project teams better understand the needs of the communities and **tailor engagement strategies** to ensure that drone implementation is well supported.

At present, drone projects are most suitable for remote populations that may be unfamiliar with the technology's application to healthcare. Despite this, our case studies found that **drones were warmly received by communities** because of successful engagement strategies, which fostered an understanding of the projects' benefits. Community engagement can take various forms – from educational workshops to public demonstrations and test flights, as well as directly involving and employing members of the community in the project.

- **Engaging the correct partners is integral to project success.**

To ensure that drone deployment is cognizant to the needs of the beneficiary community, it is important to engage the correct stakeholders. Partnering with individuals and organizations trusted and respected by beneficiary communities can help to improve project perception and gain community trust. Meanwhile, local partners can be invaluable in **recommending how best to engage communities** and **where and when it is appropriate for drone flight** in line with local culture**.** Similarly, local health authorities may be enthusiastic about drone projects, and can be valuable for engaging civil authorities and navigating the regulatory and policy landscape. The successful scale-up project in Rwanda is well integrated with other local institutions and systems.

SITE LOCATION

- **The necessity to import drone equipment can entail financial and regulatory hurdles.**

Project sites are often located in remote areas at a great distance from where the supplier is based. As such, **drones and other necessary equipment must be imported** via international supply chains (air freight and shipping routes). International supply chains should be accounted for in project timelines, and the importation requirements fully scoped in advance. Batteries, for example, cannot arrive via air freight. **Importing materials can incur high customs charges resulting in unexpected project start-up costs and delays to project start dates.** This is also a problem when an unpredictable mechanical failure occurs at project sites, requiring additional parts to be imported into the country or drones to be exported elsewhere for repair.

- **Current drone use is restricted to certain weather conditions.**

Most commercially available drones are **not robust enough to fly in poor weather conditions**, such as heavy rain, wind, or stormy conditions. However, one case study successfully maintained drone operations year-round by implementing simple **pre-flight weather condition checks** at both takeoff and landing sites. Field site climate, how well weather conditions can be predicted, and how often drones can be flown should be carefully considered to assess the suitability of drones for a location. Year-round weather conditions could be a key factor determining the reliability of a drone-based supply chain.

HUMAN RESOURCES

- **Drone projects require a wide range of expertise.**

Projects require a wide range of skillsets on site. In addition to public health, further expertise required could include **pilots to fly the drones, cartographers to map the area, engineers to maintain and repair the drones, and staff on the ground to manage the day-to-day logistics and operations of the drones.** Some teams also reported the need for a **legal expert** to navigate the legal field. Our teams reported positive experiences **training local people** (including health care workers) to take on some of the project roles. User-friendly protocols and systems for managing flights by non-specialist personnel were a key tool for this at case study sites. Involving local communities fosters ownership over the project, while also making the project more sustainable.

DRONE OPERATIONS AND NAVIGATION

- **Safety is a key concern.**

Most drones will break down if they crash into an object, but no case studies reported this being an issue due to the remoteness of the field sites and the ability of drones to avoid obstacles. To reduce the potential risk of harm, flights should **avoid populated areas** and drones should be equipped with obstacle detection sensors that alert ground staff to obstacles so that the drone's flight course can be diverted. Telemetry used to track drones must not interfere with flights in the area.

ITB diagnostic samples are a potential biohazard and drones transporting them should be treated with due precaution. To prevent contact with the biohazard the drone and contents should be clearly labelled, and protocols established for loading and unloading the cargo.

- **Mapping data for drone navigation must be high-resolution**

Publicly available geographic data accessed through internet maps such as Google Maps may not be sufficiently precise for drone navigation programs. As such, **it may be necessary to create a high-resolution map of the area, either using open-source elevation data or by manually mapping regions.** It might be necessary to hire a cartographer for this purpose.

REGULATIONS AND LEGALITIES

- **Legal infrastructure supporting the launch of drone projects is immature.**

As an emerging field, the legal framework for medical cargo drone projects is not sufficiently advanced to keep up with the rapid innovation of drone technology. Countries may not have the human resources to keep up with developments in the technology. The regulatory information available online is also often outdated. Furthermore, bureaucratic processes for obtaining the permits required to run projects are often **inefficient and circuitous,** involving several government departments and requiring time and resources on both sides.

By **scoping these processes in advance**, project teams will reduce the possibility of delays, while ensuring the project is feasible before it is started. It helps to have an administrator dedicated to navigating regulatory processes and negotiating with authorities throughout the project. Buy-in from one department or ministry is helpful in navigating the process and obtaining approvals from others. Project legal teams should **leverage existing contacts with government authorities**, such as the Ministry of Health, in attempts to navigate the in-country regulatory landscape.

© Photo credit: BNMT. Source: Nepali Times

5.2.
Final evaluation going forward

Drones present a novel and innovative solution to the 'last-mile' problem in TB. Drone implementation is most needed in hard-to-reach communities with a high TB burden, but without easy access to diagnosis and treatment. Connecting such communities to centralized health care through drone networks could make the difference between access to TB services or not.

The case studies and literature reviewed in this report provide some important lessons on site selection, human resources, community engagement, drone operation and regulation that should be considered when piloting or scaling up drones to support health care supply chains. Future pilot studies in different sites, communities, and contexts are also likely to encounter new implementation challenges due to the regional or national nature of some key considerations, as well as the ever-changing market and regulatory conditions surrounding drones. Therefore, a concerted effort to conduct further cross-cutting evaluations of pilot and scale-up projects is needed.

Drone technology is currently underdeveloped for application in many high-TB-burden countries, as was apparent at case study sites. Existing technology was largely sufficient for medical cargo delivery but lacked the robustness and reliability necessary for such an essential purpose. In the future, growing interest in the use of drones for both commercial and humanitarian purposes will likely advance the technology considerably, making drones better suited for use in the TB context.

Much remains to be learned to ensure the sustainability and long-term impact of drone projects. The specialist nature of the technology and the immaturity of the drone market currently threatens sustainability by producing islands of expertise upon which drone projects are reliant. Taking a bottom-up approach and upskilling community members with the aim of transferring ownership and management of drone projects is a sustainable solution.

This report primarily explored projects implementing drones to support TB care, but drones could reinforce medical supply chains multilaterally for the delivery of medicines, diagnostics, vaccines, and other supplies. The forward-looking approach of Rwanda, for example, provides evidence that drones can be successfully scaled up for some of these purposes. Drones are a versatile tool, and projects could consider diversifying their application beyond TB health care to maximize their impact, generate more value, and better meet the needs of beneficiary communities.

Before using drones to supplement health care supply chains, the alternatives must be considered. Where possible, drones should not replace the development of traditional infrastructure. Although drones may provide a faster solution than infrastructure development in the short term, they are not suitable for the provision of all health care needs. The development of local infrastructure would benefit local communities more comprehensively.

Ultimately, drones are a promising cross-cutting solution to the persistent challenge of the last mile in health care. As the technology matures and its application diversifies, drones could become a game-changer for the provision of TB care in isolated communities not reached by traditional infrastructure.

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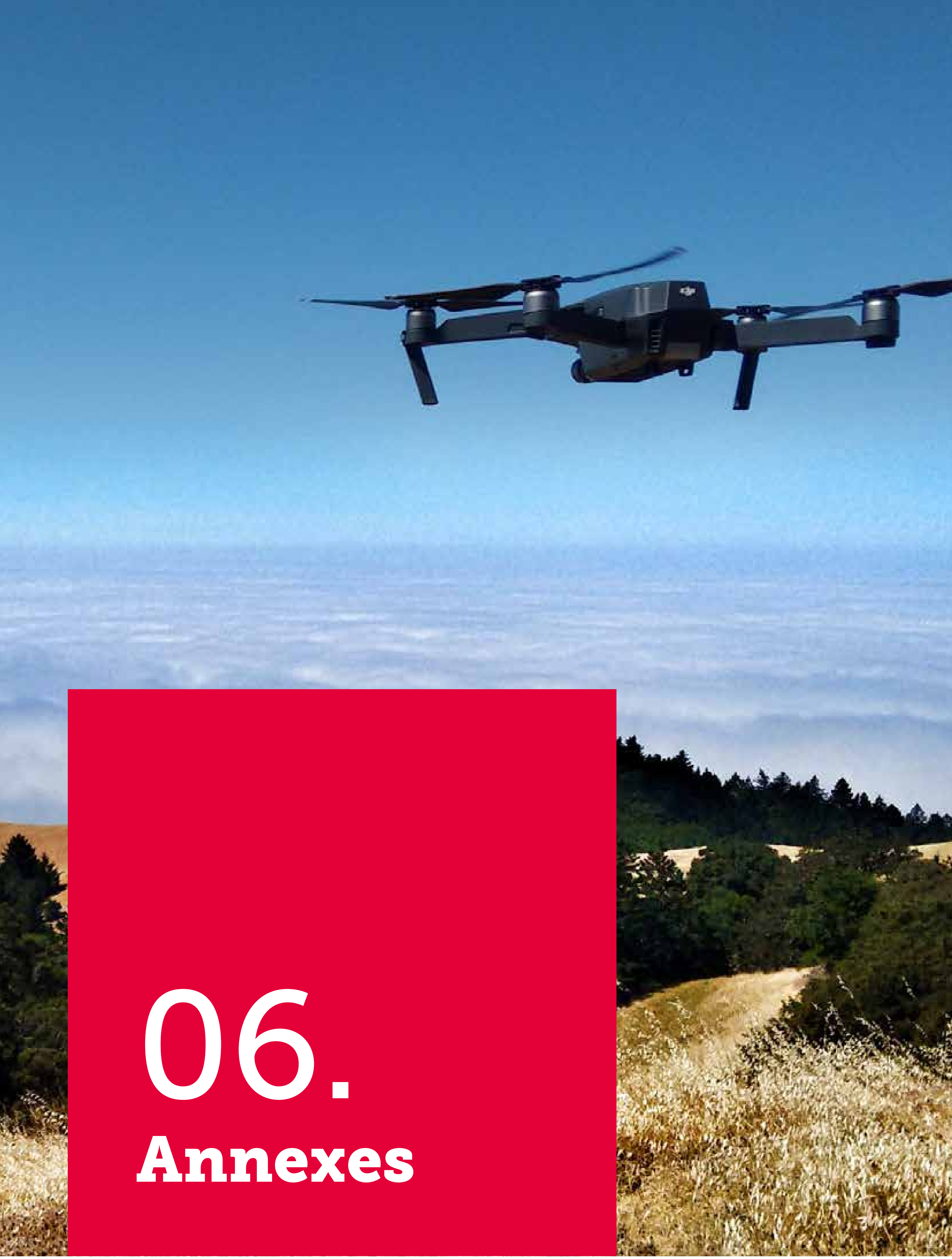

06. Annexes

Annex 1.
Details and transcripts of interviews

Table 1. Exact dates of interviews

Project Member	Institution	Position in Project	Interview Date
Case Study 1: Madagascar			
Simon Grandjean-Pierre	Stony Brook University	Epidemiologist	1 October 2019
Astrid Knoblauch	Stony Brook University	Epidemiologist	1 October 2019
Jesse McKinney	Stony Brook University	Engineer	17 October 2019
Case Study 2: Nepal			
Maxine Caws	Liverpool School of Tropical Medicine	Principal Investigator	21 November 2019
Joseph Brew	Stony Brook University	Project Coordinator	11 October 2019
Jürg Germann	WeRobotics	Engineer	18 November 2019
Case Study 3: PNG			
Massimo Ravasini	Médecins Sans Frontières (MSF)	Project Coordinator	28 October 2019

Table 2. Madagascar transcript (Case study 2)

Madagascar interview responses		
Topic	**Question Asked**	**Response Summary**
PROJECT OVERVIEW		
Funding	As per our records, the project has been funded by USAID and TB REACH. Is the project now being funded by any other sources?	1. The team only received part of the USAID grant because it was tied up with the company that could not deliver operable drones. 2. The project was mostly funded by TB REACH grants, but university grants were also received.
Cost	Drones make it possible to bypass poor roads and transport samples quicker. In the case of this project, is it more cost-effective to use drones? Why not use local transport such as motorcycles or even animals?	1. Cost analysis study is pending.
	How much did this drone project cost to set up and implement?	1. Vertical Technologies – 15k with batteries, Vayu – 25k
DRONE TECHNOLOGY		
Overview	How many drones did you have?	1. The project had two drones – one as a backup in case the first was damaged.
Selection	How did you select a drone manufacturer for the project?	1. The engineer selected the Vayu drone initially after discussion with Vayu. 2. However, the Vayu drone did not work: after one week in the field, they realized the drone would not fly. The interviewee spoke afterwards to other project teams who had the same experience with Vayu. 3. After this initial failure, they switched to another company, Vertical Technologies (VT) based in the Netherlands, and selected a hybrid drone because of its ability to vertically takeoff and land.
Modifications		1. They noted that the VT design did not work reliably because it was hobby-grade and built for western environments. The environment in Madagascar was too rough and the drone could not fly in the rain. 2. The team made some modifications to the company-provided drone to weatherproof it.
Software	Is there anything worth noting about the hardware or material used?	1. There were some hardware issues that called for modification. 2. The company installed the drone with PX4 flight controller (hardware and software for flight control).

Madagascar interview responses		
Topic	**Question Asked**	**Response Summary**
REGULATION AND LEGALITIES		
Legal	What can be done to learn the full legal requirements before implementation?	1. The team recommend checking the global database: https://www.droneregulations.info. 2. However, they warn that legislation is not always up to date because the field progresses so rapidly. 3. Madagascar had no laws regarding drones and too few legal human resources in the country to keep up with the technology advancement. 4. The team obtained temporary permits, but they had no reassurance for their continuation. In the end, they were able to obtain three six-month permits with ongoing negotiations with the Civil Aviation Authority.
	What legal work should be in place before starting a drone programme?	1. They advise that flying approval should be obtained prior to programme start. However, they note that starting the programme might speed the process along.
	Were any other administrative issues encountered worth mentioning?	1. Equipment procurement was a significant administrative hurdle, especially for high-value pieces and the customs charges were high for some items. 2. Whilst it was easy to import the Vayu drones into Madagascar for trial purposes, it was much more challenging to import the VT drones since the same regulation did not apply for this import. 3. Furthermore, the team had to obtain insurance, approvals, etc. in two different countries.

Madagascar interview responses		
Topic	**Question Asked**	**Response Summary**
SITE LOCATION		
Site location	What was set up at the site, and would it be useful to have other resources available?	1. There was a drone lab at the research center site (already established by Stony Brook for years), a launching area, a space to practice and tools for drone maintenance.
	What led you to choose the implementation site of the project?	1. They chose the site because Stony Brook had a research center in the district for years and this made it a convenient location. They note that TB prevalence was a secondary consideration.

Madagascar interview responses		
Topic	**Question Asked**	**Response Summary**
DRONE OPERATION AND NAVIGATION		
	How was the drone tracked? Was tracking reliable or does it need to be improved?	1. The drone was tracked via radio communication. 2. Due to regulation, the telemetry range had to be curbed.
Navigation	As noted in the quarterly report, Google and Bing Maps were found to be lacking in high-resolution topography data. Therefore, the team manually mapped and ground-trothed the area the drone was covering. How high of a resolution is needed for topography data on existing mapping services?	1. Google Maps (which averages elevation points for altitude calculation) was not sufficiently precise for the region where the study was conducted, since elevation changes rapidly.
	How could these maps be checked before implementation to determine if they are sufficient for the operations? Should a preliminary study be done to determine if resources need to be attributed to manual mapping?	1. A preliminary study might not help because many problems will not become apparent until a feasibility/pilot project is conducted.
Software	There is open source software available for drone flights; for example, Matternet has used ArduPilot and Elon Musk has planned to open-source Tesla autonomous car software. What software did the drone use?	1. The team used an open-source software called QGroundControl. 2. The software used a hub-and-spoke network approach used within the mapped area without the need for microprogramming.

Madagascar interview responses		
Topic	**Question Asked**	**Response Summary**
Operation	How does it sense obstacles? Does it avoid obstacles directly or require external instructions (e.g., from a pilot after sensing the obstacles)?	1. The drone was semi-autonomous: flights were pre-programmed but monitored by a pilot who could control the drone using a tablet when necessary, e.g., instruct it to go back to base. 2. If the drone encountered an obstacle, it would crash.
Technological limitations	In the quarterly report, some issues regarding design were noted, including component failures, software glitches and problems due to the drone not being designed for industrial use. Were these manufacturer-specific problems, or problems as a result of the market being immature?	1. A mix of both. A lot of companies advertise more than what they can do. True bidirectional and autonomous drones have not yet been achieved. For example, the drone used in Nepal was autonomous, but it had specific chosen landing sites.
Maintenance	How often did the drone break down and what was done to fix it? Did certain problems occur repeatedly and was it easier to correct the problem subsequent times it was encountered?	1. The drone broke down often – attributed to a number of different faults, often because the team needed to upgrade a component. They report an 'iterative' process of breakdown and repair.
	Did it take a long time to repair the drone and can this process be expedited?	1. Importing parts to repair drones was challenging. 2. The team did not have a maintenance budget and so encountered delays in order to obtain additional funding.

Madagascar interview responses		
Topic	**Question Asked**	**Response Summary**
HUMAN RESOURCES		
Personnel required	What personnel was needed at the site and off-site to manage the programme? What is the required skillset for the project team?	1. They had an HR team at the site. 2. The team recommend hiring a tech expert capable of managing the technical side, e.g., choosing the drone, repairing it, etc. They note that it is also possible to work with a drone provider to adapt the technology to the needs of the target community. WeRobotics offers such a service but it comes at a premium. 3. They also recommend hiring a programmer, a drone engineer, a cartographer, someone (from academia) to monitor and evaluate the project, medical staff and people to manage the project on the ground.
Utilizing local expertise	How feasible is it to train local health care workers to implement the tech? Were any such attempts made?	1. They found it useful to have technically trained local people. 2. They did not encounter any problems training health care workers to retrieve the drone and secure the payload. 3. The problem was having local health care workers on site when needed because they were overwhelmed with other health care activities and were often covering many villages.

Madagascar interview responses		
Topic	**Question Asked**	**Response Summary**
COMMUNITY ENGAGEMENT		
Community sensitization	Was the community sensitized to the drone project? What were the communication channels?	1. In Madagascar, there are very few commercial flights and the drone project was a very new concept. The project team had meetings with mayors and officials, visited every village twice to inform local people of how and why the technology was going to be used and to deconstruct myths and stigmas related to drones.
PERCEPTION		
Legal	How did the legal and health authorities view the use of drones for transporting TB samples?	1. They experienced a positive reception from authorities but they were hesitant when it came to signing permits. 2. The team note that support from the Ministry of Health was more valuable than that from academic organizations because it had better connections with the Civil Aviation authorities.
Community	What was the local community's reaction to the programme? Did they think it was helpful and did they want to be engaged? How did the community compare the use of drones with the use of local transport?	1. They felt that the general perception from the community was positive but noted that this is difficult to measure. 2. Since the community had no access to care, there was no comparison to be made in terms of whether or not the drones were helpful in providing a transport link for health care.

Madagascar interview responses		
Topic	**Question Asked**	**Response Summary**
Team	Were there any problems initially thought to be trivial which proved to be significant during implementation?	1. The team stated "Everything." 2. When starting out, they thought that the technology was well-developed, and it would be simple to fly a drone between two points. However, they soon discovered that this was not the case. 3. They noted that the legal field was surprisingly immature, and that navigation was an issue.
	Were the drones and medical equipment secure on site? Were there any issues with theft?	1. The research site was well established and secure and so they encountered no theft. The communities were also safe.
	What kind of logistic activities (emergency or routine) are drones suitable for? What payload?	1. Suitable for remote high-incidence areas and areas where road development is unlikely, e.g., in the Philippines. 2. They think that drones can be used for access to health care more generally, not just for TB or HIV care.
	Could drones replace traditional delivery methods? Or should they be used in conjunction with other means of transport?	1. The team does not think that drones should replace traditional delivery methods, but that they should be used where other delivery methods are lacking and for the 'last mile'. 2. "Drones are a complementary, adaptable solution."
	In your opinion, what are some advantages and disadvantages of using drones for international humanitarian aid?	1. Advantages: Drones have many applications and so can be used as a versatile instrument in remote areas. 2. Disadvantages: Drones discourage the development of other necessary features, e.g., roads.

Table 3. Nepal transcript (Case study 1)

Nepal interview responses		
	Question	**Response**
OVERVIEW		
Funding	How was the project funded?	1. The project was primarily funded by the Nick Simons Foundation but with some funding from WeRobotics.
Cost	How much did this drone project cost to set up and implement?	1. The initial operational costs (including equipment procurement and permissions) were in the range of US$ 350,000. 2. The running cost of the project was much lower.
DRONE TECHNOLOGY		
Drone specification	How did you select a drone manufacturer for the project?	1. The team chose DJI for its large presence and expertise. As such, the team thought they could rely on the company for support if problems occurred. 2. They selected a fairly simple model because they did not want any added complications resulting from more advanced models. 3. The project required a drone that could cover a large vertical distance (as opposed to Madagascar where horizontal distance was required), e.g., horizontally the village was close to the landing site, but it would take three days to walk to the village because of elevation. 4. The landing site in the village was very challenging and so the drone was selected for its ability manoeuvre and takeoff and land vertically
	Is there anything worth noting about the hardware or material used?	1. The off-the-shelf DJI drone is built for mapping or imagery, but user modifications are possible. 2. As such, the team worked with WeRobotics to adapt the drone for cargo transport with the addition of Raspberry Pi, a communication system, ground station software, landing system and safety mechanisms.

Nepal interview responses		
	Question	**Response**
Software	Software – There is open-source software available for drones; for example, Matternet has used ArduPilot and Elon Musk has planned to open-source Tesla autonomous car software. What software did the drone use?	1. The team realized that, despite manufacturers' claims, the off-the-shelf drone could not fly autonomously from point A to point B. Nepal Flying Labs and WeRobotics spent a lot of time developing the software to allow this. 2. The custom-built software allowed detection of the current location of the drone, location of the nearby health posts, the flight path to be set to a selected post, and automatic takeoff, flight and landing. 3. Drone is controlled via Android application.
	Did you make any modifications?	1. Additional features were added to the off-the-shelf drone. 2. Communication system: To increase the range of the drone from 5km to 15km (for 1kg payload), they added a communication system, including a radio-frequency module, 4G connection to the Internet and satellite communication unit, which enabled the drone to exchange signals to and from different ground stations. 3. Ground station software: The team linked the drone to an Android app to select the drone's takeoff and landing location and monitor its flight. 4. Landing system: The team added ground-detection sensors, which became activated in the last 10m of flight to enable greater precision than GPS-based landing (which has an inaccuracy of 10–15m). 5. Safety mechanisms: To prevent damage to the drone, the drone was set to land at one of the pre-defined safe-to-land spots when the battery was low.

Nepal interview responses		
	Question	Response
REGULATION AND LEGALITIES		
Legal	What permissions (from government ministries) were obtained before implementation?	1. Written permission was obtained from every government agency and local authority with a potential interest to ensure comprehensive awareness and inclusion. 2. The process of obtaining permissions was circuitous and took more than a year. 3. Despite the lack of government clarity over how to proceed with regulations, the government was supportive to develop an approval framework and keen to move forward in the best way possible.
	Were any other administrative issues encountered worth mentioning?	1. There was no consensus classification for importing medical drones and the corresponding tariffs associated. 2. There was a lack of clarity over project ownership due to multiple international stakeholders. 3. The team relied on a Chinese drone manufacturer and a team of experts to program the software. Long-term sustainability of the project needs to be developed. Delays were introduced into the project because of the need to import hardware after the project had started.
	Any additional comments?	1. Obtaining permissions was a major obstacle, since many permissions had never been requested in Nepal before this project. The process was even more challenging because there were also government changes during the time. 2. The BNMT chief investigator found the legal process less challenging than expected because the project stimulated interest and people wanted to facilitate its implementation.
Permissions	How did you obtain permission?	1. By the time the team had permissions for flights, it was the beginning of the rainy season, so they were starting implementation at the hardest time. 2. It was difficult to get staff to the site particularly in the rainy season due to poor transport links. 3. The drone was not waterproof; they did not fly the drone in bad weather. It hails in the hills in Nepal, but it rarely rains continuously in the region, so the team established a protocol to check if the weather was suitable for flights. This system was feasible because flight time is only five minutes.

Nepal interview responses		
	Question	Response
SITE LOCATION		
Equipment on site	What was set up at the site, and would it be useful to have other resources available?	1. Drone with Raspberry Pi and optical sensors attached, Android tablet connected to radio transmitter, plastic platform for landing, 3D-printed specimen collection box.
Site selection	What led you to choose the implementation site of the project?	1. The Stony Brook team went to Nepal looking for a site for a drone project. They were looking at a different district based on geography. BNMT suggested the team consider the Pyuthan district because they had strong ties with the government health network there, and if there were problems, the authorities would work together to solve challenges rather than shut down the project. The area also had a high prevalence of TB.
DRONE OPERATION AND NAVIGATION		
Maintenance	How many drones were used?	1. Two on site, third in Swiss WeRobotics office for testing.
	How often did the drone break down and what was done to fix it? Did certain problems occur repeatedly and was it easier to correct the problem subsequent times it was encountered?	1. On a single occasion mechanical breakdown occurred. Replacement parts were procured from Switzerland, but the parts were small and simple to import.
Operations	How was the drone operated?	1. The drone was semi-autonomous with the pilot on standby and able to command the drone to return to base or hover in place via radio signal.
Obstacle detection	How does it sense obstacles; does it avoid obstacles directly or require external instructions (e.g., from a pilot after sensing the obstacles)?	1. The drone used in the project did not have obstacle detectors because they were not necessary for the typical flight conditions: the drone stayed 100m above the ground – at this elevation there are no other flights (ensured by Civil Aviation Authority [CAA]) and there should be no other activity (or trees). However, the team had to liaise with the CAA to ensure that the airspace was free. 2. Area not heavily populated and quiet, so in an event of collision and drone crash, very unlikely that the drone would harm anyone on the ground. Cannot guarantee zero risk, but this is true for any system, even motorcycles. No issues have been encountered to date.

<table>
<tr><th colspan="3">Nepal interview responses</th></tr>
<tr><th></th><th>Question</th><th>Response</th></tr>
<tr><td>Navigation and tracking</td><td>How was the flight path set?</td><td>1. The drone had a pre-planned route and its distance to destination and elevation were monitored.
2. The team generated their own high-resolution maps with raw elevation raster data (open-source).
3. They also created high-resolution landing maps – including the elevation of trees and slope of the ground – and programmed the drone to descend a certain number of meters in order to land.</td></tr>
<tr><th colspan="3">HUMAN RESOURCES</th></tr>
<tr><td>Personnel required</td><td>What personnel was needed at the site and off-site to manage the programme? What was the required skillset for the project team?</td><td>1. The Stony Brook PI was the main external project member. He recruited local partners who can continue the programme when he leaves. Partners – ground operations: Birat Nepal Medical Trust; air operations: Nepal Flying Labs – part of WeRobotics, Drone Nepal (private company that provides drone services).
2. Diverse skillset required: engineers, drone pilots, medical staff, laboratory staff and community health workers, public health professionals experienced in integration with government system.
3. It is better to search for existing infrastructure rather than bring in an external drone team; project goal is to supplement and give the country the opportunity to implement the technology.
4. For legal work, the Nepal team used organizational expertise and personal connections to interact with different ministries.</td></tr>
<tr><td>Local expertise</td><td>How feasible is it to train local health care workers to implement the tech? Were any such attempts made?</td><td>1. Health care workers were trained to control the drone in emergency situations – make emergency landings.
2. They are in the process of transitioning piloting drones from Nepal Flying Labs to local health care workers.</td></tr>
<tr><th colspan="3">COMMUNITY ENGAGEMENT</th></tr>
<tr><td>Community sensitization</td><td>Was the community sensitized to the drone project? What were the communication channels?</td><td>1. 16 sites (villages where drones landed), currently flying to eight of them. Communication channel: radio, demos were presented to students and mayors, community engagement meetings, talking to schools, groups, word of mouth, etc.</td></tr>
</table>

Nepal interview responses		
	Question	Response
PERCEPTION		
Community	What was the local community's reaction to the programme? Did they think it was helpful and did they want to be engaged? How did the community compare the use of drones with the use of local transport?	1. The team emphasize the importance of the community feeling a shared ownership of the project. 2. The team describe a "very positive reaction, very tech friendly community...community members and healthcare workers asked constructive questions about the technology, e.g., 'maybe we can use this to transport blood'." 3. Despite it being a remote location in Nepal with a very traditional community, there was no resistance to the technology, and they understood and embraced the purpose of the technology. 4. Current transport via jeeps – drive off-road, walking-time-consuming 5. There is a sense of pride in the district that they are the ones implementing the new technology. 6. Local tailors made the cloth with the QR code for landing.
Legal and health authorities	How did the legal and health authorities view the use of drones for transporting TB samples?	1. The technology was received positively by the health authorities and they were a useful ally because the civil authorities were more willing to engage if approached by the Ministry of Health.

<table>
<tr><th colspan="3">Nepal interview responses</th></tr>
<tr><th></th><th>Question</th><th>Response</th></tr>
<tr><td rowspan="3">Project team</td><td>What kind of logistic activities (emergency or routine) are drones suitable for? What payload?</td><td>1. The team suggests drones are used for transport to remote areas in critical situations that need to be addressed within a few hours (e.g., anti-venom [difficult to store] for lethal snake bites, oxytocin for women in labour, post-hemorrhage medicines that prevent blood loss).
2. They also suggest drones are used to transport diagnostic devices, e.g., portable ultrasound.</td></tr>
<tr><td>Drones make it possible to bypass poor roads and transport samples quicker. In the case of this project, is it more cost-effective to use drones? Why not use local transport such as motorcycles or even animals?</td><td>1. The team said that cost-effectiveness is not a useful metric at this stage because in the future the situation will be different (tech more developed, possibly cheaper). Whilst the technology is probably less cost-effective than motorcycles at the present time, this may not be the case in the future. Moreover, currently Nepal has very underdeveloped local transport networks and so it is almost impossible to compare drone transport with other forms of transport.
2. The team will conduct a health economic evaluation in the near future.
3. The team hopes to scale up the project when further funding can be secured. In preparation for this, the team wants to establish clearer legal and regulatory frameworks with the government and partners.
4. The drones save a lot of time compared to current reliance on local health care workers walking to local villages to deliver treatment. The cost-effectiveness of time savings is difficult to quantify.
5. The team said that the cost-effectiveness of using drone technology can be improved by utilizing drones for multiple applications.</td></tr>
<tr><td>Were there any problems initially thought to be trivial which proved to be significant during implementation?</td><td>1. Obtaining permissions was more time-consuming and challenging than expected.
2. Community understanding was also more significant: helpful to have local partners because they suggested good ways to introduce the project to the community, e.g., to set up demos for students and mayors.</td></tr>
<tr><th colspan="3">OTHER</th></tr>
<tr><td>Additional comments</td><td>Any additional comments?</td><td>1. The project has established that drones are useful to the community, and drone delivery has been active for over one year.</td></tr>
</table>

Table 4. Papua New Guinea transcript (Case study 3)

<table>
<tr><th colspan="3">Papua New Guinea interview responses</th></tr>
<tr><th></th><th>Question</th><th>Response</th></tr>
<tr><th colspan="3">OVERVIEW</th></tr>
<tr><td>Funding</td><td>How was the project funded?</td><td>1. The project was funded by MSF. The project was a feasibility test carried out in July 2018 to see if drones were a possible solution to the poor infrastructure and resulting problem of transporting samples from remote areas to the central hospital in PNG.</td></tr>
<tr><th colspan="3">DRONE TECHNOLOGY</th></tr>
<tr><td>Selection</td><td>How did you select a drone manufacturer for the project?</td><td>1. A team member did a market analysis and visited company sites before selecting a drone manufactured by Vayu.</td></tr>
<tr><td>Drone technology</td><td>Is there anything worth noting about the hardware or material used?</td><td>1. A hybrid cargo drone used with payload of 2.5kg, range of 50km (flies for one hour).</td></tr>
<tr><th colspan="3">REGULATION AND LEGALITIES</th></tr>
<tr><td rowspan="3">Legal</td><td>What permissions (from government ministries) were obtained before implementation?</td><td>1. The team needed to obtain permission from many authorities: they needed certification from the Civil Aviation Authority, from ASL (a flight control authority) and from the telecom frequency authority to ensure the frequency with which the drone was operating would not interfere.
2. The authorities needed to be notified for each flight.
3. Since it was a feasibility study, the respective authorities wanted more control. It took six months to get permission from the Civil Aviation Authority and they requested specifications of the device from the manufacturer.
4. The process did not progress without the team continuously following up with the authorities.</td></tr>
<tr><td>Were any other administrative issues encountered worth mentioning?</td><td>1. Importing the drone was alright. The issue was bringing in batteries (cannot be part of air cargo). The batteries needed to be shipped before the drone to arrive on time.</td></tr>
<tr><td>Any additional comments?</td><td>1. A major obstacle was establishing pathways for obtaining permissions because the team was requesting permissions, e.g., permission to fly beyond line of sight, permission for medical cargo flights, for the first time. There were also government changes during the time. Their strategy was to get permission from every government agency possible.
2. One team member found the legal process less challenging than expected because it stimulated interest and people wanted to facilitate its implementation.</td></tr>
</table>

Papua New Guinea interview responses		
	Question	**Response**
SITE LOCATION		
Equipment on site	What was set up at the site, and would it be useful to have other resources available?	1. On site there was a solar panel system to charge the drone battery and a 10m strip to secure landing. An assistant would oversee landing.
Site selection	What led you to choose the implementation site of the project?	1. The site was selected based on a 2014 pilot project in the same area – with a flight path from the central hospital in Kerema to a remote village in Malalaua. 2. At the central hospital, the takeoff point was the airstrip (near the hospital).
DRONE OPERATION AND NAVIGATION		
Operation	Documentation states that the drone operated autonomously, but what was the level of autonomy? How did it sense obstacles; did it avoid obstacles directly or require external instructions (e.g., from a pilot after sensing the obstacles)?	1. The drone could fly beyond line of sight. In theory, it could autonomously fly from origin to destination given coordinates. 2. Two pilots, one at origin and the other at the destination, monitored the flight and safety during landing. 3. The team chose a flight path which avoided villages to reduce the safety risk.
	The need to swap batteries was noted as a major disadvantage in the 2014 project. Was it a problem for this project? Did other aspects of the design of the drone lead to any problems?	1. The plan was to recharge the batteries at the destination, but in this feasibility test, the drone did not make it that far. 2. Calibration tests were done on the airstrip during the feasibility test. Drone did not go beyond line of sight.
Navigation and tracking	How was the drone tracked? Was tracking reliable or does it need to be improved?	1. GPS was used for tracking. They could not assess the reliability because the feasibility test was too short, and the drone never reached its destination.
	Which maps did the team use (e.g., Google Maps)? Did existing maps of the region have a high enough resolution? Was any manual mapping done?	1. The team used Google Maps at the beginning to pinpoint points A and B (origin and destination), but the precision was insufficient. 2. They were able to use Google Maps for fixing the flight path but needed to use more specific GPS coordinates for landing.
Software	What software did the team use?	1. MSF worked with a start-up software company.

Papua New Guinea interview responses		
	Question	**Response**
Maintenance	How many drones were used?	1. The project had two drones, but only one was used.
	How often did the drone break down and what was done to fix it? Did certain problems occur repeatedly and was it easier to correct the problem subsequent times it was encountered?	1. The drone encountered an electrical issue: connection between the battery and motor broke down, preventing the drone from reaching its destination.
	Did it take a long time to repair the drone and can this process be expedited?	1. To fix the electrical problem, the supplier needed to ship it back to the United States and see why the problem occurred. This could not be completed given the time constraint.
HUMAN RESOURCES		
Required expertise	Human resources: What personnel was needed at the site and off-site to manage the programme? What was the required skillset for the project team?	1. MSF Japan coordinated all activities. 2. An MSF member pilot was in charge of the execution of field tests and there were an additional two pilots on the vendor side (but this was not necessary). 3. The team also had an MSF mission-level coordinator for legal requirements and a local person at the site.
Local expertise	How feasible is it to train local health care workers to implement the tech? Were any such attempts made?	1. The plan was to train local health care workers to load samples, change the battery and perform easy maintenance activities like cleaning. This stage was not reached in this feasibility study.
COMMUNITY ENGAGEMENT		
Community sensitization	Was the community sensitized to the drone project? What were the communication channels?	1. Local community health care workers explained the project to communities, used megaphones and answered questions. The message was spread one month before, two weeks before and one week before in Kerema and Malalaua.
PERCEPTION		
Community	What was the local community's reaction to the programme? Did they think it was helpful and did they want to be engaged? How did the community compare the use of drones with the use of local transport?	1. There was positive perception among the community.

Papua New Guinea interview responses		
	Question	**Response**
Legal and health authorities	How did the legal and health authorities view the use of drones for transporting TB samples?	1. Health authorities were enthusiastic because they were struggling with the last mile. Legal authorities did not have negative perception of the project, but they faced difficulties in understanding which process to follow. The regulation process changed whilst the project was ongoing.
Team	Were there any problems initially thought to be trivial which proved to be significant during implementation?	1. Solving problems related to drone laws and regulations took more time than expected.
OTHER		
Future plans	This was a feasibility study. Are there any plans to conduct another study using drones?	1. For the moment there are no plans to conduct another study. They learned a lot from the July 2018 project, but the infrastructure in the region is better now and there is not as much of a need for drones to assist with the supply chain.
Additional comments	Any additional comments?	1. Drones can be a solution, but certain points need to be brought into consideration: 1) who is managing the drone on the ground – team needs a pilot; 2) the reliability of the technology – robust drones are more expensive; consider the supply chain of the aircraft – reliable aircrafts need certification at each and every step; motor and components used in hobby-grade drones are not certified or standard resulting in less robust devices. 2. Drones are still in development; technology is not quite there yet.

Annex 2.

Public health drone projects identified in literature review

Country	Involved Organizations	Use Population	Cargo	Drone Manufacturer	Drone Type	Reported Distance and Payload	Reference
Bhutan	WHO, Government of Bhutan	Remote mountain communities	Medicines	Matternet	Quadcopter	20km ~2kg	4
Democratic Republic of the Congo (DRC)	Gavi, Village Reach, WeRobotics, Ministry of Health DRC	Remote riverine communities	Vaccines, medicines, samples, test results	Swoop Aero	Fixed-wing with VTOL (Hybrid)	80km 2kg	58
Dominican Republic	Inter-American Development Bank	Rural community	Blood and urine samples, medicines	Matternet Vertical Technologies	M2 Quadcopter Hybrid	1kg	59
Ghana	Gavi, UPS, Government of Ghana	General population	Vaccines (COVID-19, yellow fever, polio, measles, etc.), blood products, critical medicines	Zipline	Fixed-wing ('Zips')	150km 1.5kg	25
Madagascar	Stony Brook University, Stop TB Partnership, Government of Madagascar	Rural mountainous community	TB diagnostics and medicines	Vertical Technologies	Hybrid	60km 1.5kg	48
Malawi	UNICEF, USAID	Rural communities on Lake Malawi	Diagnostic samples, vaccines, medication, blood, small medical instruments	Swoop Aero	VTOL Fixed-wing (Hybrid)	45km 1.5kg	19,60
Mozambique	VillageReach, Ministry of Health Mozambique, Instituto Nacional de Saúde	Rural communities around Maputo	TB sputum samples (planned for HIV and COVID-19)	Swoop Aero	VTOL Fixed-wing (Hybrid)	7km 0.8kg	20

Country	Involved Organizations	Use Population	Cargo	Drone Manufacturer	Drone Type	Reported Distance and Payload	Reference
Nepal	Birat Nepal Medical Trust, Stony Brook University, WeRobotics, Liverpool School of Tropical Medicine, DroNepal, Nepal Flying Labs, and The Nick Simons Institute	Mountain communities	Sputum samples for TB	DJI	Hexarotor drone	15km 6kg	51
Papua New Guinea	MSF	Remote communities in Gulf Province	Sputum samples for TB	Matternet	Quadcopter	28km 200–500g	3
Peru	WeRobotics, Becton, Dickson and Company (BD), Peruvian Ministry of Health, UAV del Peru, Peru Flying Labs	Amazonian communities	Diagnostic test supplies (alongside food and other supplies)	Event 38 Unmanned Systems Oriol	Fixed-wing VTOL quad plane	10–120km	45
Rwanda	Gavi, UPS, Government of Rwanda	General population	Blood for transfusions, medicines. COVID-19 vaccines.	Zipline	Fixed-wing ('Zips')	150km 1.5kg	24,34
South Africa	South African National Blood Service (SANBS) and Western Cape Blood Service	Rural communities	Blood	Quantum Systems SANBS	Fixed-wing with VTOL (hybrid) Own drone (TRON)	20km 1.2kg 100km 2kg	61
United Republic of Tanzania	Tanzanian Ministry of Health	General population	Blood	Zipline	Fixed-wing ('Zips')	150km 1.5kg	23,27
Vanuatu	Vanuatu Ministry of Health and UNICEF	Island population	Vaccines	Wingcopter	Quadcopter	83km, 3.3kg	62

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