Integrating drones into NHS patient diagnostic logistics systems: flight or fantasy?

Using drones to transport patient diagnostics

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ABSTRACT

Healthcare accounts for approximately 5% of emissions in developed nations, and the public healthcare provider in the United Kingdom (UK), the National Health Service (NHS), has set a target to reach net-zero emissions by 2040 without detriment to its quality of patient care. With Uncrewed Aerial Vehicles (UAVs; a.k.a. drones, UAS, or RPAS) starting to be used in health care systems outside the UK, there is increasing interest in how they could be integrated into NHS operations for the more efficient and faster movement of diagnostic specimens. Reflecting on a business-as-usual analysis of current NHS diagnostic specimen logistics across the Solent region of Southern UK, this paper critically evaluates the practical reality of integrating UAV deliveries of this commodity, identifying the benefits and challenges that must be addressed by stakeholders to realise commercial UAV services, including dangerous goods legislation, cargo stability, routing, and weather.

In the exploratory desktop analysis, 14 out of 79 surgeries could be realistically served by a 5m wingspan vertical take-off/landing (VTOL) UAV: seven directly, and seven through ground-based logistics transfers. The results suggested that an average of 1,628 samples could be served by UAV each week, resulting in 42 flights/week with 10 taxi services to cover periods where weather limits flying. This resulted in an approximate total service cost of £2,964/week if regulations develop to relax UAV personnel constraints. Whilst this created a 23% reduction in tailpipe emitted CO2 (excl. taxis) and a 20% reduction in van logistics costs, an overall cost increase of 56% was returned, making any long-term UAV service financially unsustainable. Accounting for greenhouse gas (GHG) emissions, congestion, and air pollution costs, the UAV intervention reduced the marginal external costs of the system by £196 per week (GHG = £81 reduction, congestion = £116 reduction, air pollution – NOx, PM2.5 = <£1 reduction).

INTRODUCTION

Valid use cases for Uncrewed Aerial Vehicles (UAVs; a.k.a. drones, unmanned aircraft systems – UAS, or remotely piloted aircraft systems – RPAS) within healthcare logistics are being increasingly explored (1), with many initial trials undertaken in developing countries (2). The scope for UAVs to overcome the challenges of transporting diagnostic specimens to laboratories from remote rural communities in South Africa as part of tuberculosis and malaria treatment programs was first recognized in 2007 with trials of the e-Juba UAV (electronic pigeon), (3). Commercial UAV operations have since emerged, with Zipline operating a network of UAVs to distribute vaccines, medicines, and blood products to more than a thousand medical facilities across the state of Kaduna in Nigeria and also operating a nationwide service for the distribution of blood products in Rwanda (4,5). UAV healthcare logistics operations are now emerging in developed countries, and there is growing interest in the United Kingdom National Health Service (NHS) as to what benefits might be gained from the introduction of UAVs in terms of (i) improved patient care; and (ii) emissions reductions to help the service become net-zero by 2040 (6). Using a significant data set of historic patient diagnostic sample collections from the 79 surgeries across Southampton UK, this paper investigates the financial and practical realities of integrating UAVs into existing van-based logistics fleets.

LITERATURE REVIEW

Where road infrastructure is poor and topology challenging, UAVs have been shown to offer significant journey time advantages compared to traditional road transport modes (7). Often, airspace is less congested in developing countries and with more sparsely populated areas, UAV operations present fewer safety concerns to regulators which has led to such regions becoming test beds for UAV services (8). The integration of UAVs into medical logistics in more developed countries has been somewhat slower, largely resulting from the strict airspace management legislation which dictates that beyond-visual-line-of-sight (BVLOS) flying requires specific permissions which are often granted to the detriment of other airspace users via temporary restricted flight corridors (Temporary Danger Areas, TDAs in the UK) (9). In November 2020, Matternet announced their intention to implement routine UAV services to support pathology services across a network of hospitals in Berlin (10), but despite aspirations for wider development, very few commercial services exist. Other applications in medical logistics include DHL's parcelcopter, which performed deliveries of medication to remote islands in Germany, 12km from the mainland, using a vertical take-off and landing (VTOL) platform in 2014 (11), while Skyports, using Swoop Aero's VTOL platform, have delivered patient diagnostics from remote Scottish island communities to mainland pathology labs in the UK in 2021 (12,13). To the authors' knowledge, neither service has moved beyond extended trials to the point of commercialisation, suggesting that wider barriers to full implementation of UAV deliveries exist (14).

UAVs operate in many different configurations (electric or fossil-fuelled powered fixed-wing, multi-copter (capable of VTOL), or a hybrid of these arrangements (VTOL with fixed-wing cruise), with a range of options for collecting and delivering cargo such as cable systems, parachute drop, or integral cargo holds within the main fuselage (12,15,16). With respect to performance, fixed-wing platforms are generally more efficient over longer distances compared to VTOL multi-copter UAVs but typically require runways to take-off and land (17). From an NHS perspective, point-to-point UAV services not requiring runways would be essential due to space limitations around medical facilities; thus, VTOL platforms (multi-copter or hybrid) are favoured because of their flexibility.

UAV applications in medical logistics have been primarily based around low weight/volume, time critical items such as patient diagnostics (samples most typically of either blood, urine or stools), pharmacy related products (including chemotherapy), and bloods for transfusion (1). In the case of the latter, Zipline's country-wide blood service in Rwanda is making in excess of 150 flights per day (15), with each catapult-launched, fixed-wing UAV capable of carrying a 1.75kg load up to 120km at 100km/hr BVLOS between distribution centres and hospitals/clinics, where they deliver via parachute (18–20). The speed of service is the key benefit, with Zipline reporting a 95% reduction in blood waste and spoilage (21). This is largely due to the difficult nature of the terrain and the condition of the road infrastructure which can make journey times by land logistics unreliable. It should be noted that the cost-effectiveness of this system has not yet been explored, with the medical improvement being the primary aim so far in its development (22).

Of increasing interest is whether diagnostic specimens (commonly referred to as 'pathology' or 'laboratory samples' or 'specimens') could be more efficiently moved by drone between surgeries and analysis laboratories for the NHS in the UK. Specimens are routinely taken from patients by clinicians with an estimated 80% of treatment plans following on from some form of diagnostic sample analysis (23). After being taken, samples must be stored and transported to the analysis laboratory in a controlled manner, where they must be analysed within a specific time frame (24). The NHS is in the process of implementing a national 'hub-and-spoke' style diagnostic specimen collection system across a series of 29 networks (25,26). Inter-hospital and GP surgery-to-hospital transport is typically handled by multiple vehicle rounds (27) which are subcontracted to third-party logistics providers who provide dedicated collections services for patient diagnostic samples from each surgery on a daily basis along with the replenishment of fresh specimen tubes, associated ancillary packaging and paperwork.

Local area diagnostic specimen collections in the UK are typically undertaken using dedicated logistics providers, operating routine collection services using multiple vehicles linking General Practitioner (GP) surgeries (also known as clinics or doctor's offices in other countries) to pathology laboratories where the samples are analysed (28). As an example, for the catchment area around Southampton, a city on the South coast of the UK with population ~250,000, there are 79 GP surgeries generating some ~3,000 samples each weekday (~70,000 samples/month), which are collected using 10 dedicated van rounds each servicing between 4 to 27 surgeries per day, with many surgeries visited twice daily. Surgeries typically batch samples together for a morning and afternoon collection using standardised packaging approved by the Medicines and Healthcare Products Regulatory Agency (MHRA). A key drawback with this system is that, in most cases, vans do not visit the pathology lab until 11:00 AM at the earliest, which results in significant workload for the analysis teams at specific times of the day (29). One school of thought is that UAVs could be used to target particularly remote surgeries which contribute significantly to the overall carbon footprint of the van round whilst also bringing in batches of samples for earlier analysis.

During the first year of the COVID-19 pandemic, it was identified that samples collected from GPs were turned round significantly slower compared to hospital generated samples with less than a third of community tests being turned around the same day, as opposed to 80% in hospital (30). The implementation of UAVs into existing logistics systems may offer the potential to alleviate some of these issues with trials in the Argyll and Bute region of Scotland by Skyports suggesting that over 12,000 hours of waiting time were saved over a 90 day operation compared to the business-as-usual system involving 14,000 km of BVLOS flight (31). This case study was ideally suited to UAV deployment where island communities could be more effectively served using a point-to-point air bridge as opposed to dual mode van and ferry-based services.

Although UAVs have demonstrated benefits in medical logistics operations in Africa, they have not progressed beyond limited short-term trials in developed countries, and some of the major logistics players have scaled-down their drone service development, suggesting there may be significant challenges which will limit their commercialisation (14,32–34). Some of the key issues that have to be overcome before widespread BVLOS UAV operations are realised include: i) Agreeing and implementing a system of air traffic control such that UAVs and crewed aircraft can operate in shared air space; ii) Understanding the implications on UAV design resulting from the specific carriage regulations related to different medical products (including dangerous goods carriage regulations); iii) Determining routings for UAVs that minimise air and ground risks but do not negatively impact on range, particularly for battery powered UAVs; iv) Satisfying the medical product regulatory agencies (e.g. the MHRA) that the stability of medical products will not be adversely affected through exposure to excessive vibration or temperature during carriage by UAVs; v) Developing reliable contingency strategies for periods when adverse weather prevents UAV flights (32,35,36).

All of these elements add uncertainty when attempting to calculate the true costs of UAV operations in both urban and rural settings, and there have been some attempts to do this for retail UAV operations. Jenkins et al., (2017) attempted to cost business-to-consumer (B2C) package deliveries via a VTOL UAV where the package weighed under 5 pounds (37). Costs were taken from 25 commercial UAV operators and were determined to be:

- *Battery costs* - $100 (to power a UAV carrying 5 pounds (2.26 kg), 10 miles (16km))
- *Battery life* – 250 hours
- *Motor costs* - $60 (for each motor, with 4 being required to fly a 10-pound UAV 6 miles)
- *Motor life* – 750 hours
- *Rotors* - $1 (wholesale price for a set of four commercial grade rotors)
- *Marginal electricity cost* - $0.25 per flight

In terms of hourly operational costs, these were estimated to be $0.94 made up of: Insurance ($0.02/hr); Command and control ($0.02/hr); Communication ($0.02); Labour ($0.02/hr); Maintenance ($0.40/hr batteries, $0.08/hr motors, $0.01/hr rotors, $0.03/hr electrical); Battery charging ($0.24/hr); Airspace charges ($0.10/hr). Jenkins et al., estimated that if an individual UAV platform cost of $2000 was assumed, with each UAV being able to fly a minimum of 50 hourly flights per week, the cost per trip would be $1.74 against $2.50 per typical last-mile delivery using traditional van-based delivery methods (37). This was under the overall assumption that between 86 and 91% of the 86 million packages generated in the U.S. daily were less than 5 pound in weight and could be serviced via UAV. The authors also assumed that operators would replace all components at least once per year due to wear-and-tear.

A key unknown is how much access to airspace for UAV operators will cost, and how this will be managed on a large scale. The concept of UAV Traffic Management (UTM) has been developed as a solution to integrating UAVs and crewed aircraft in low-altitude airspace (under 400 ft) and would be operated by any number of UAS Service Suppliers (USS) (38). The system would require UAV operators to adopt various equipment, conforming to specific standards in relation to UAV tracking and remote identification, UAV-to-UAV communication and detect-and-avoid sensor technology. These would all have a cost associated with them with elements being potentially provided by the USS for a monthly/annual subscription fee. Bohlig (2017) estimated that in the U.S., this could be in the region of $200-$300 per UAV using the system per annum (39).

Weather conditions may also be a limiting factor in the use of UAVs. In Winter 2019/20, the UK experienced seven named storms; a system used to highlight weather of significant severity (40,41). London's Heathrow Airport experiences strong winds on 60 days in a typical year, with strong winds defined as averaging gusts ≥ 28 knots (14.4 m/s); cumulonimbus (CB) cloud warnings, often associated with disruptive weather, on 10 days per year; and snow/ice warnings on 5 days per year (42–44). In such weather, it is likely that UAVs will either not physically be able to achieve their planned flights, due to concerns around flight stability, energy limitations, or regulators limiting their use for safety reasons.

A study by Gao et al. (2021) defined a weather resistant drone as being able to fly in 14 m/s winds and precipitation of up to 50 mm/h. It was highlighted that at latitudes covered by the UK, winds were typically flyable for the majority of the year, with the majority of weather impacts featuring in spring months (Mar-May); however, the positioning of the UK relative to the Atlantic Ocean meant that it is exposed to the North Atlantic Oscillation and stronger winds than other areas of similar latitude as a result (36,45). Jenkins et al., (2017) examined the potential impact of weather on UAV operations using three years' worth of historic weather patterns around Salt Lake City International Airport. The results suggested that over the three-year period, there were only 27 occurrences where the mean wind speed exceeded 30 mph for a 10-minute interval and 138 days where wind speeds were between 15 and 30 mph.

Much interest has been shown in how UAVs might make NHS logistics operations more efficient and timely but the potential costs versus the benefits have not been fully investigated beyond short-term trials. Given the volumes of patient diagnostic samples to be collected on a daily basis, it is unrealistic to expect that such an undertaking could be completed by UAVs alone, particularly given the difficulties of gaining permissions to fly over populated areas where vans or cargo cycles could prove more efficient. More realistic is to think of UAVs serving remote or outlying surgeries that take up considerable van-time to service in the business-as-usual scenario. In this way, UAVs might complement existing van fleets to provide a speedier service to remote outposts.

This paper investigates these issues and attempts to quantify the potential costs and benefits of integrating UAVs into an existing patient diagnostic service serving the area around Southampton and the New Forest compared to the business-as-usual van-based collection rounds.

METHODOLOGY

As part of two funded research projects (E-Drone, (46); Future Transport Zone, (47)), an audit of existing logistics activity related to patient diagnostic collections was undertaken, working with the NHS Trusts in the Solent Region of the UK, and specifically, Southampton General Hospital (SGH) located within the city of Southampton. A historical dataset was obtained of patient diagnostics movements from 79 GP surgeries (also known as 'doctor's offices') in and around Southampton (for November 2018 and March 2021 constituting ~70,000 sample movements/month) to the pathology analysis laboratories at SGH. This dataset was analysed to identify: i) the mean, minimum and maximum flows of products between the various origin and destination points by collection vehicle type; ii) the GP surgery origin locations that impact most on BAU van round time and could be suitable for drone integration; and iii) the implications on UAV carriage requirements resulting from the range, weight and number of products needing to be transported. The typical round schedules from September 2018 were also provided, enabling a comparison to the business-as-usual case.

The audit also involved a series of informal discussions with practice and logistics managers overseeing the day-to-day operations of the patient diagnostic services at SGH to accurately understand the current transportation procedures, data, requirements, and opportunities. The practical experiences gained from undertaking the first BVLOS trial of a fixed-wing drone across the Solent (09/05/20) during the first Covid-19 lockdown (48) and subsequently from mainland UK to the Isles of Scilly (15/12/20) involving the authors (49,50) were also used to reflect on the realities of transitioning UAV services to integrate with land logistics operations in terms of flight permissions, goods carriage legislation and maintaining cargo integrity.

The business-as-usual data collected through the audit were then used in a desktop analysis to quantify the likely numbers, timings and costs of flights that would be needed to provide a UAV collection service for patient diagnostic samples generated by GP surgeries deemed suitable for service by UAV out of the existing 79. The analysis also set out to evaluate the potential benefits to the NHS in terms of improved service times and reduced transport related CO_2.

To understand the flight timetabling requirements, the sample production rates from the historic data were used with a maximum capacity per flight, identifying the time points in each day when either (i) a full load was ready; or (ii) the last sample of the day had been taken at each drone served site.

Units of carriage used in the desktop analysis

In the UK NHS, patient diagnostic samples are typically taken at local GP surgeries and are transported at ambient temperature in specimen containers (Figure 1) within three-layer packaging according to the PI650 packaging instruction under UN3373 (Biological Substance Category B - Diagnostic Specimens) carriage regulations to analysis laboratories which generally reside in major hospitals (25,51). Some smaller hospitals also have facilities for basic pathology analysis and there are also cases where laboratories are operated by private companies such as Viapath in London's Guy's and St Thomas' NHS Foundation Trust (23,52).

In this paper, the medium Versapak (Figure 1, central container) used by the GP surgeries across Southampton was taken as the unit of carriage, with an assumed maximum load of 50 samples per Versapak.

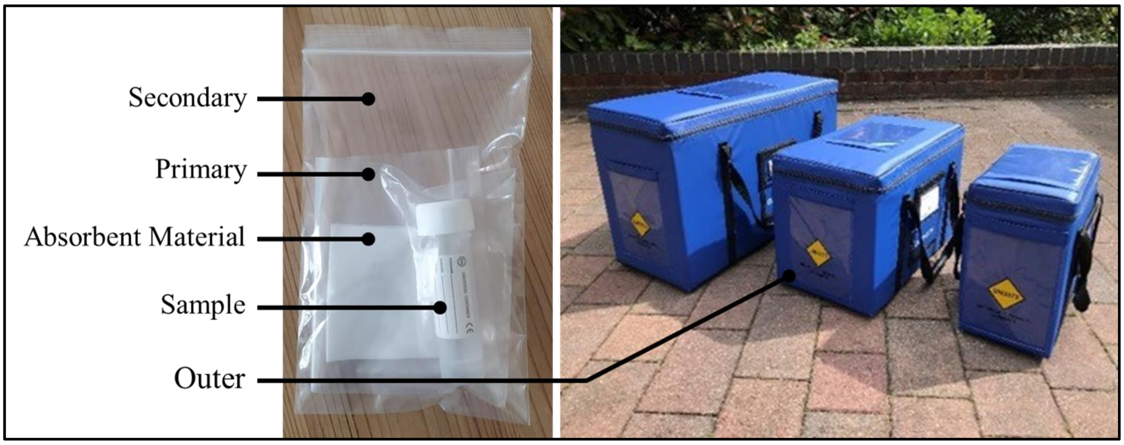

Figure 1: UN3373 PI650 Compliant Packaging. Left – sample, contained in leakproof primary and secondary packaging with absorbent material; right – Versapak insulated outer packaging (centre ('medium') = 460mm (w), 255mm (D), 305mm (H)).

In terms of dangerous goods classification, work by Grote et al., (2021) has highlighted that biological materials considered sufficiently low risk as infectious substances under hazard class 6 (UN3373) can avoid classification as dangerous goods for air transport when packaged in PI650 standard packaging (Figure 1) (53,54), and therefore can be managed in a similar way to when they are transported by ground transportation modes, conforming to the MHRA Good Distribution Practice (GDP) guidelines (55). Civil Aviation Authorities are still developing regulations in this area, and applications for approval are largely handled case-by-case (56). Furthermore, recent trials and research have highlighted medical logistics operators must demonstrate that transport by UAV would not adversely affect the quality and stability of the medical cargo as a result of in-flight conditions experienced during transit (50,54). Current understanding of UAV flown diagnostics suggests that no significant damage is caused (57), though this may vary by platform, packaging, and product.

UAV used in the desktop analysis

The reality of patient diagnostics logistics is that although the individual samples are small in terms of size and weight and ideal for transportation via UAV, they are consolidated into batches such that individual surgeries could be dispatching multiple Versapaks daily, each containing up to approximately 50 samples. In this situation, UAVs would have to have a payload capacity to accommodate at least one medium size Versapak ((460mm (w), 255mm (D), 305mm (H)), estimated capacity of ~50 samples) with an empty weight of approximately 2.4 kg (Figures 2, 3) (58). UAV trials involving such UN3373 cargoes (e.g. Skyports (31)) have been typically undertaken with small numbers of samples contained in bespoke packaging to fit the hold of the UAV. For any long-term commercial service, it would be necessary to carry the existing batch configurations as out-and-back flights using the standard Medicines and Healthcare Products Regulatory Agency (MHRA) approved packaging. An analysis of the sample production data suggested that of the approximate 3000 samples produced for collection each weekday across the 79 surgeries, the scale of production ranged from 1 sample at several surgeries, to 289 samples at the Coastal Medical Partnership (New Milton) surgeries which would have required 4-6 Versapaks, depending on actual sample size (mean per surgery = 41 samples/day, S.D. = 49 samples/day). Dialogue with the pathology lab practice managers highlighted that batches of samples from surgeries cannot currently be mixed into consolidated loads unless undertaken in a controlled environment (e.g., a designated 'primary surgery').

UAV payload capacity has implications for both the planning of operations with aviation regulators in terms of the number of flights necessary and the routing, as well as the type of UAV platform needed. The practicalities of operating UAVs in terms of integration with land logistics systems must also be carefully considered, particularly where surgeries are located in built-up areas. Given the requirement to carry a minimum of one Versapak from each surgery over the distances likely to be involved (~30 km+ one-way), a platform capable of carrying significant volume and weight (approx. 5kg min.) was required. To reduce land-take and infrastructure requirements for take-off and landing, the UAV would also need VTOL functionality, either as a fixed-wing hybrid platform or solely VTOL. Based on the authors' experience of trialling a UAV carrying a Versapak in the Solent Region (59), and considering typical payload-wingspan relationships (60,61), a fixed-wing VTOL platform with a 5m wingspan (Figures 2, 3) was deemed necessary to achieve carriage of such a load over practical distances (e.g., ~30km+) in variable wind conditions. The authors collaborated with Skylift UAV (skyliftuav.co.uk) and identified their adapted Mugin V50 hybrid VTOL platform with a 5m wingspan as being suitable for the task (62).

Figure 2: Skylift Mugin V50, 5m wing-span VTOL fixed-wing UAV

Figure 3: Skylift Mugin V50, with medium sized Versapak (460mm (w), 255mm (D), 305mm (H)) loaded into the hold

GP surgeries used in the desktop analysis

Surgeries were deemed suitable if they: i) had a suitable drone landing site in reasonable proximity (e.g., open space of approx. 100 m^2 within the site grounds or on public land just outside (Figure 4) (note this differs from standard hobby drone practice, but it was assumed rules could be slightly relaxed for trained operators (63,64)); ii) had a low ground risk drone flightpath between the landing site and SGH (mean risk of a fatality on the ground due to a drone crashing along its flightpath = 1e-7 fatalities/flight hour or lower. For comparison, crewed aviation has a fatality risk of ~2e-5 fatalities/flight hour (65)); iii) were not in the flight path of Southampton Airport. Flight paths were planned using SEEDPOD (66), an open-source drone risk route planning tool developed by the authors, so as to minimise ground risk, with assessment based on the risk of fatalities due to a drone crash on the ground under the flightpath. Airspace constraints in the immediate vicinity of Southampton airport were also considered in identifying suitable surgeries.

Figure 4: Example exclusion zone for take-off/landing, as used in flight trials for similar loads **(62)**.

We also considered that secondary ‘satellite’ GP surgeries, in the vicinity of the primary surgeries, could be serviced by UAV, transferring their Versapaks of samples to the primary surgery by ground transport for consolidation and onward flight to SGH. Samples from satellite surgeries were assumed to be transferred by cycle courier to the primary surgeries, with catchment areas defined by the round-trip distance that could be cycled by a typical gig economy worker (e.g. Deliveroo operative) in approximately 20 minutes, plus a further 5 minutes accounting for service time (67).

The desktop analysis utilised the timings and volumes associated with every patient diagnostic collection during March 2021 across all of the 79 surgeries. The dataset recorded the date and time of day for each sample taken from a patient throughout the month. The UAV collection service was assumed to operate Monday-Friday, meaning the occasional samples taken on weekends (27 out of the 9,298 total samples generated at drone serviceable surgeries during the month) continued to be collected as per the existing BAU arrangements (i.e., collection by van). A medium size Versapak (empty mass 2.4 kg) with an assumed maximum capacity of 50 samples was used for collections, whilst the maximum payload of the UAV was assumed to be one full Versapak (up to 20 kg). UAVs were assumed to carry an empty Versapak on outbound journeys from SGH to the surgeries.

UAVs were assumed to make return trips servicing only one primary surgery at a time due to maximum payload constraints (i.e., one medium Versapak containing 50 samples), which ignores the possibility of larger drones with greater payload capacity visiting multiple surgeries per trip. Deliveries of samples to primary surgeries from satellite surgeries were assumed to be instantaneous (i.e., samples were all effectively taken at the primary surgery), ignoring the real-world practicalities of satellite-primary delivery schedules. Flight times were calculated based on a 21 m/s cruise speed.

Operating strategy during inclement weather

Weather factors were considered in the analysis, with historic wind and precipitation data being used (provided by the MeteoStat Point API (68)). When a flight was calculated to be required, the weather for a 2-hour period following this was checked at the surgery in question, and at SGH. Should either site have wind speeds or precipitation levels outside of the UAV operating range (10 m/s / 19.4knots (69) and 50mm/h (36)), the flight was cancelled and a taxi collection was used as a replacement for that surgery collection. Mean wind speeds at each site, and peak gusts at the hospital were used in the assessment of whether a drone flight was possible. Data availability meant that only the hospital was used for gust analysis. Whilst winds will affect the ground speeds and durations of individual flights, it was assumed that return flights on the same path within a short time window would largely average out variations in travel speeds and times, simplifying calculations.

Due to surgeries continually producing samples even when weather conditions preclude UAV flights, this analysis accounts for contingency plans. Taxis were assumed as the transport mode to be used when weather conditions were deemed such that UAVs could not operate. This assumption was based on information from the discussions with NHS staff, where it was suggested that taxis were often used when other logistics options were not available for collections.

Costings used in the desktop analysis

The cost estimates for the UAV collection service were derived from a combination of UAV development and design expertise within the research team and associated partners (www.cascadeuav.com), literature sources, and commercially available data (70). Key cost elements that were sought related to: i) the life expectancy of specific UAV components (e.g., motors, propellers, servos, autopilots, communications equipment and the airframe itself); ii) the electrical energy consumed during the various stages of flight (take-off, transition, cruise, transition, landing); iii) human resource time for the personnel involved (mission commander, safety pilots, loaders); and iv) operational insurance (full breakdown in Table A1).

There are likely to be additional fees for dangerous goods training, airspace management, etc., though these have not been included. Additionally, prices may be further inflated if a third-party operator is used, as a profit margin will need to be included in cost considerations.

The cost estimates used for collection by van, both in the BAU scenario and for non-drone serviceable surgeries in the intervention scenario, were derived from the ‘Manager’s Guide to Distribution Costs’ (MGDC) published in the UK by the Freight Transport Association (71).

Delivery driver costs (£10.78/hour in Table A1) were assumed to be the stated average value for drivers of light rigid vehicles (≤7.5 tonnes Gross Vehicle Weight; GVW), including overtime and productivity (i.e., bonuses for achieving productivity targets) pay. Vehicle operating costs (£0.46/mile in Table A1) were assumed to be the stated value for a diesel van (≤3.5 tonnes GVW), based on average annual mileage (35,000 miles/year), and including insurance, vehicle tax, depreciation, fuel, tyres, maintenance, and overheads (e.g., salary of the transport manager, running the despatch office, etc.). For consistency, the CO_2 emission factor used in the analysis (0.45 kg/mile for a diesel van ≤3.5 tonnes GVW) was also taken from the same source. Taxis fares were estimated using a local taxi firm quote tool (72).

Marginal External Costs (MECs, often known as society costs) were used to investigate the wider benefits of drones, including greenhouse gas emissions, congestion, and air pollution costs, based on government transport appraisal databook values (73–75). The emissions of the drone's electricity consumption were assumed to be negligible.

RESULTS AND DISCUSSION

The investigated case study was a simplified version of reality, in that the GP surgeries targeted were considered in isolation, ignoring the potential benefits of optimisation with other vehicles and synergies that might be available within the full NHS logistics system. Analyses of the results was based around a comparison against the BAU vehicle-based specimen collections. It should be noted that in this BAU dataset, vehicles also carry out ancillary movements (e.g., internal mail, medical records, etc.) which are being significantly reduced/phased out. As a result, an adapted BAU vehicle round structure is used in the comparisons.

Business-as-usual patient diagnostic collection logistics

In the case of Southampton, part of the 'South 6 Pathology Network' (25), patient samples were collected from 79 GP surgeries on a daily basis (Figure 5) by ten van rounds and transported to SGH for analysis. On a typical day (Monday to Friday), each vehicle (diesel-fuelled Vauxhall Vivaro or Ford Transit, GVW 2.9T, Max. Payload 1.2T, (76)) was making approximately 20 collections from surgeries (310 samples/van) and driving 114 km, taking an average of 4 hours 13 mins. Across the rounds, approximately 3,100 samples were produced on the average weekday, equating to roughly 40 samples per surgery, but considerable differences were observed in the mean sample generation rates by surgery, with 9% producing in excess of 100 samples per day, 47% producing between 20 and 100, and 44% producing under 20 (77) (Figure 6). The rate of sample production was not evenly distributed throughout each day, with a clear peak in patient samples being taken during the mid-morning with maximum production falling between 09:00 and 10:00. The data suggested that 79% of the daily samples taken at GP surgeries had been taken before 12:00, but only 12% of these had reached the pathology lab for analysis by this time (Figure 7). Comparison of sample production between days of the week suggested that Tuesdays had significantly greater numbers of samples produced (23%) compared to 19% on each of the other weekdays (M-F) ($X^2_{(3)}$=19.81, P<0.001).

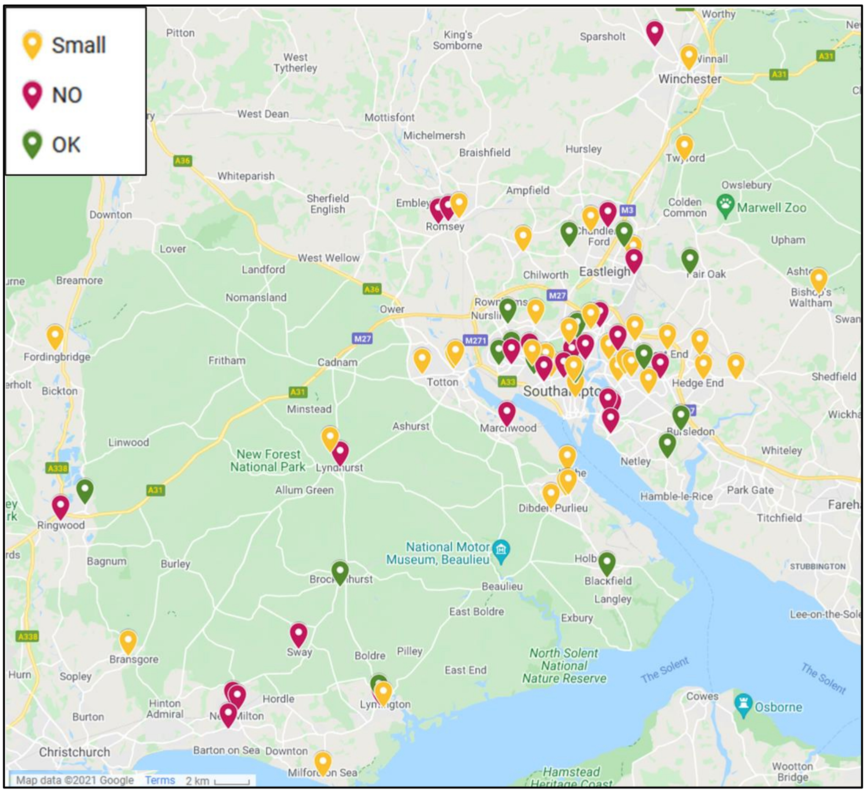

Figure 5: Locations of GP Surgeries in the Southampton area, coloured by landing site suitability. OK = suitable for a craft of approximate 5m VTOL wingspan craft to land with reasonable safety buffer and existing facilities not significantly impacted (e.g., qty. of car park spaces). Small = suitable for 2m VTOL craft. No = not suitable for landing. Only landing site considered, risk of flight to site not considered. Private land not considered due to long term feasibility.

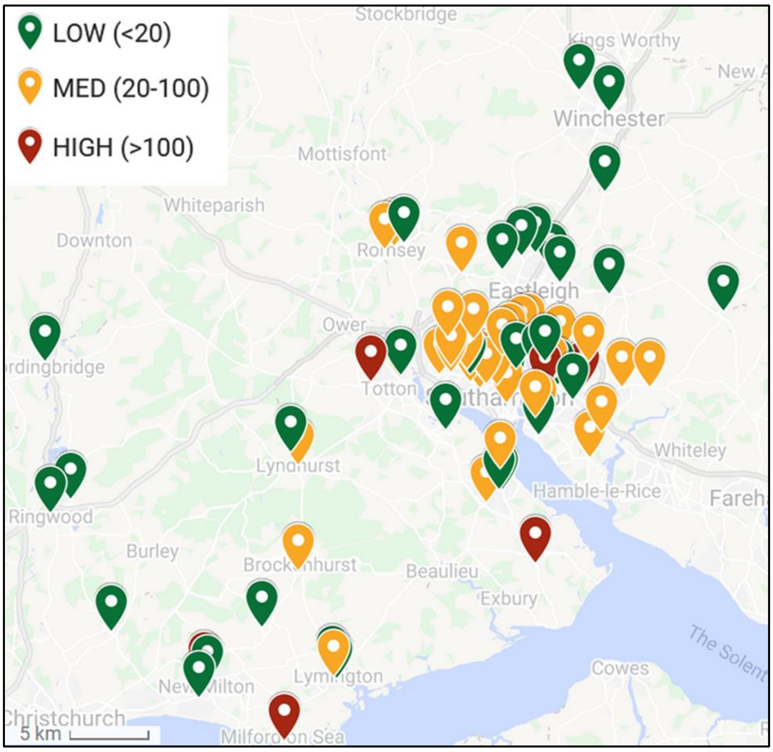

Figure 6. Surgery locations – coloured by daily sample production rate.

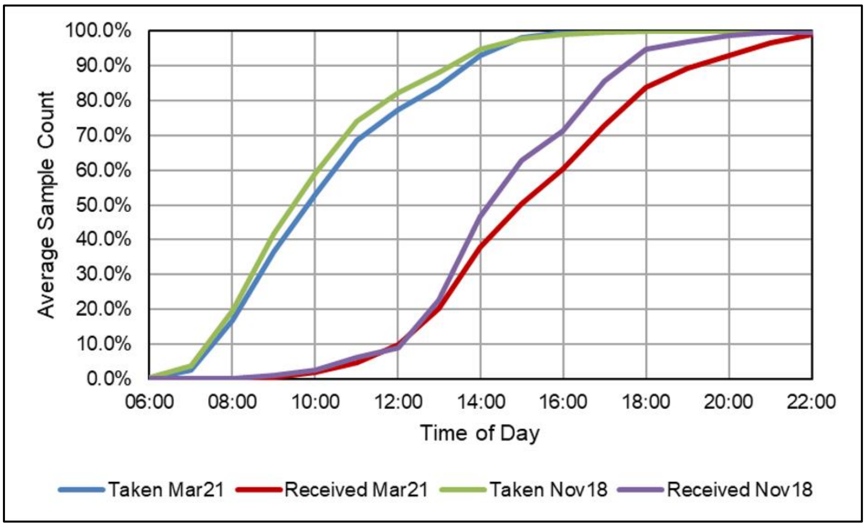

Figure 7: Plot of GP Sample Records for Southampton - "Bleed Time" (Time Taken) vs. Time Received at SGH Laboratory. March 2021 and November 2018 datasets shown to demonstrate minimal long-term change.

Determining GP surgeries appropriate for service via UAV

Following an audit of possible landing locations at the 79 GP surgeries in the Southampton area, it was found that only 20% of sites could feasibly support landing a UAV at a practical distance from surgeries, assuming a VTOL fixed-wing platform with a 5m wingspan (Figure 8), capable of carrying a medium sized Versapak. This audit involved visually inspecting each surgery via Google Earth and quantifying the size of nearby areas that could be suitable for landing without significantly affecting the existing purpose (e.g., a public park should still be able to function as one, even after cordoning a landing site), subject to landowners' permission. The results suggested that 49% of surgeries were suitable for smaller VTOL-only platforms (assumed UAV footprint of 2m). Under UK aviation regulations, set out by the Civil Aviation Authority (CAA), UAVs must be 50m from people or property not in the operator's control, though reasonable exceptions are negotiable, which would be required in some circumstances (63,64). Other mechanisms, such as cables and parachutes, can enable collection without landing, though CAA regulations explicitly state that items should not be dropped from UAVs during flight (78), whilst underslung loads may also limit aerodynamic performance, increasing energy use and limiting range.

Further to the practicality of landing locations is the flight path which is followed. Flight paths must account for a variety of factors, such as other airspace restrictions (e.g., airport control zones) to ensure safety for other users, overflight ground risk (e.g., flying over populous areas may be riskier in the event of crash landing), nature reserves, and noise. These considerations can be addressed using planning tools and UAV Traffic Management (UTM) systems, though if a surgery is located in an area which is not accessible without infringing regulations or bylaws (79), it may not be possible to serve it. As a result, the number of possible surgeries which can be served is likely to be even more limited.

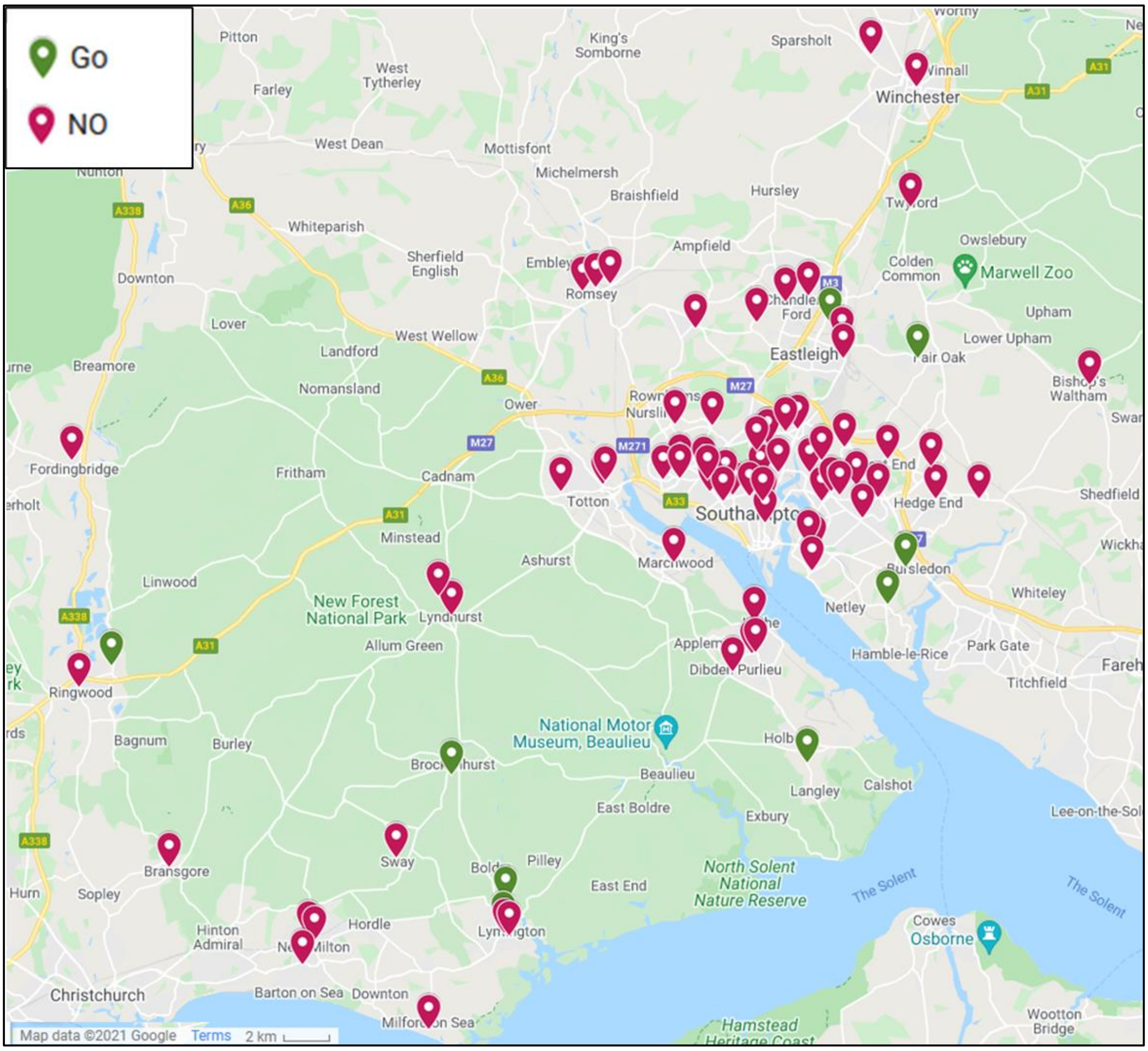

Figure 8. GP Surgeries in the Southampton area coloured by GO/NO-GO Status. GO = suitable for a craft of approximate 5m VTOL wingspan craft to land without excessive ground overflight risk (mean risk of a fatality on the ground due to a drone crashing along its flightpath = 1e-7 or lower). Airspace restrictions are not considered.

To enable UAV service at some of these otherwise unsuitable GP surgery sites, transfer to an appropriate collection site by land logistics may be possible. This would maintain some of the environmental and speed benefits of UAVs, but potentially inflate the costs of operation. Additionally, contracting and coordinating the multi-leg journeys presents new challenges in terms of optimisation, with secure handovers and well aligned timings being critical for such a model to succeed.

Based on the given assumptions regarding landing space and ground risk (Figure 8), and airspace restrictions around Southampton Airport, nine surgeries were identified for UAV service (out of the 79 in/around Southampton in total). Two of these nine were within the catchment areas of neighbouring surgeries also classified as suitable, and therefore assumed to be serviced as satellite surgeries by drones landing at the nearby primary surgery, resulting in seven primary surgeries being used in the analysis. The planned flight path routes from SGH to these seven surgeries are shown in Figure 9, using a shared path over the urban area around the hospital before splitting in different directions. Seven additional surgeries (i.e., satellite surgeries, including the two classified as suitable themselves) were included in the investigation (smaller points in Figure 9) through being within the catchment areas of the seven primary surgeries.

Characteristics of a Drone Collection Service

Results suggested that 13% of the ~70,000 samples generated across the area in March 2021 (9,298 – 27 generated at weekends = 9,271) had the potential to be served by a UAV collection service using multiple V50 UAVs involving 194 return flights and 46 taxi trips (i.e., 46 flights which had to be replaced by taxis due to poor weather) at a total cost of £13,633. This equates to average weekly values of 1,628 flown samples/week (387 by contingency taxi), 42 flights/week (10 contingency taxis) at a cost of £2,964/week (Table 2). These cost estimates were based on a foreseeable future situation where automated UAV operations have been established, allowing a mission commander to manage multiple UAVs simultaneously (two per operator), removing the need for safety pilots for take-off and landing (80). The number of drones required for long-term operations has not been identified as this would depend on the demand faced and the wider UAV and air operations in the area.

A further analysis of potential costs based on present day (2021) personnel requirements in the UK, where commercial BVLOS drone operations are still in their infancy (i.e., one mission commander per drone, safety pilots for take-off and landing), resulted in much higher costs for a drone collection service (£8,676 /week) shown by Cost 2 in Table 1 (personnel making up 86% of costs currently, reducing to 56% in the future situation). This emphasises how a drone collection service is unlikely to be financially viable on a commercial basis until the technology matures, highlighting the importance of efforts to advance the technology.

An analysis of historical weather data for the flight routes in question suggested that of an original 240 monthly flights, 46 (19%) would not be possible under the weather conditions experienced at either the hospital, surgery or both locations. The modelled alternative (a direct taxi service to the hospital) would result in performance reductions (slower delivery times) and potential additions to tailpipe emissions (dependent on the type of taxi modelled), however, they did introduce cost savings over the planned UAV service (e.g., Blackfield surgery return flight = £60 vs. taxi one-way = £33.11) which calls into question the financial value of a UAV service in this case. The weather data also suggested that the distribution of cancelled UAV flights was not even, with only a few days seeing the majority of cancellations (10th-12th March 2021 in Figure 10). The wind tolerance of the V50 UAV used in this desktop analysis was assumed to be 10 m/s (19.4 knots); a level that is less than the weather-resistant UAVs described by Gao et al. (36) (27 knots, 14 m/s).

Table 2 shows an example of a typical daily flight schedule (Friday 19th March 2021), indicating how some surgeries generate far more samples and therefore UAV flights compared to others which was a consistent observation throughout the month, as shown in the chart of the daily number of flights generated by each surgery (Figure 10).

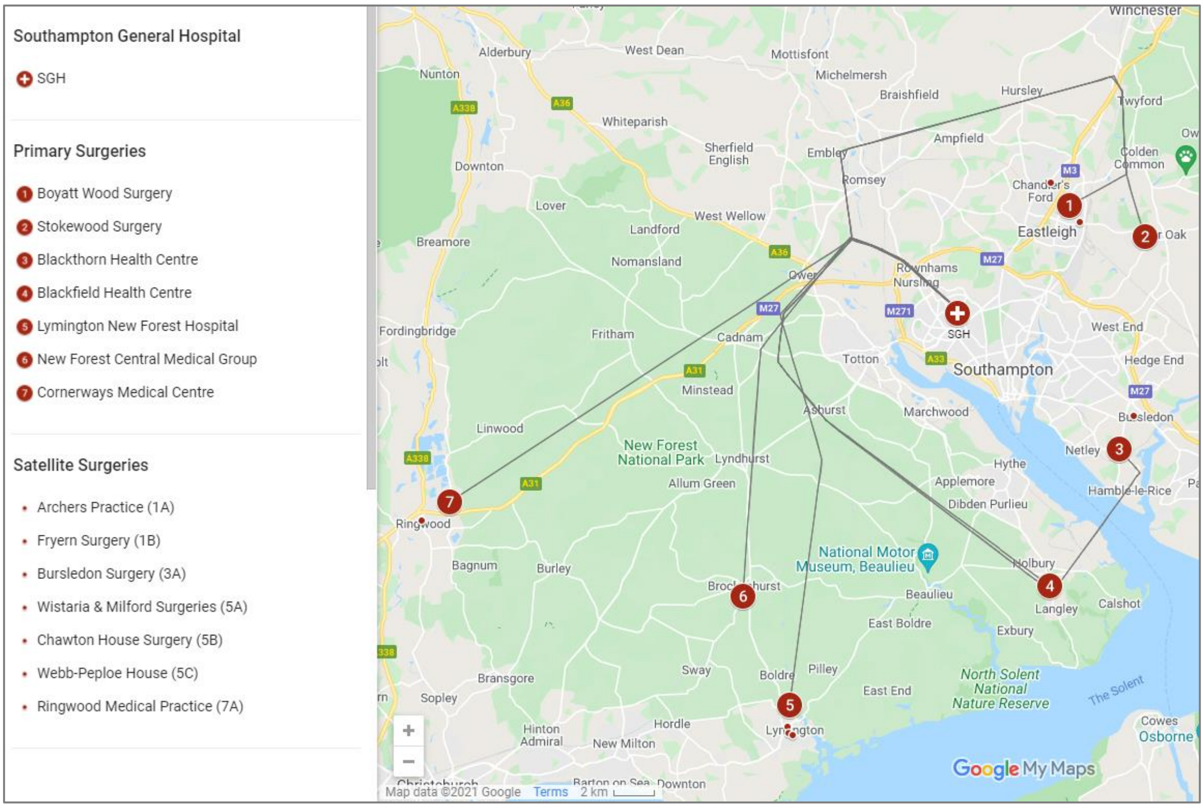

Figure 9: Locations of Doctors' surgeries included in the investigation. Grey lines indicate drone flightpaths.

Table 1: Summary of flights, samples and costs for the UAV collection service.

Statistic		B'field	B'thorn	Boyatt Wood	S'wood	C'ways	New F'st Central	Lym. Hosp.	All Surgeries
Monthly Totals	Flights	32	40	4	3	1	19	95	194
	Flown Samples	1,060	1,589	10	8	1	519	4,302	7,489
	Taxis	3	10	1	1	1	4	26	46
	Samples by taxi	105	392	2	3	1	67	1,212	1,782
	Cost 1	£2,034	£3,189	£269	£209	£101	£1,108	£6,724	£13,633
	Cost 2	£6,218	£9,651	£813	£618	£228	£3,239	£19,146	£39,912
Daily Avg.	Flights	1.4	1.7	0.2	0.1	0.0	0.8	4.1	8.4
	Flown Samples	46.1	69.1	0.4	0.3	0.0	22.6	187.0	325.6
	Taxis	0.1	0.4	0.0	0.0	0.0	0.2	1.1	2.0
	Samples by taxi	4.6	17.0	0.1	0.1	0.0	2.9	52.7	77.5
	Cost 1	£88	£139	£12	£9	£4	£48	£292	£593
	Cost 2	£270	£420	£35	£27	£10	£141	£832	£1,735
Weekly Avg.	Flights	7.0	8.7	0.9	0.7	0.2	4.1	20.7	42.2
	Flown Samples	230.4	345.4	2.2	1.7	0.2	112.8	935.2	1628.0
	Taxis	0.7	2.2	0.2	0.2	0.2	0.9	5.7	10.0
	Samples by taxi	22.8	85.2	0.4	0.7	0.2	14.6	263.5	387.4
	Cost 1	£442	£693	£58	£46	£22	£241	£1,462	£2,964
	Cost 2	£1,352	£2,098	£177	£134	£50	£704	£4,162	£8,676

Cost 1 is for the reasonably foreseeable future situation; Cost 2 is for the current situation.

Table 2: Example daily flight schedule for the UAV collection service.

B'field Time (Smp.) Cost 1 Cost 2	**B'thorn** Time (Smp.) Cost 1 Cost 2	**Boyatt Wood** Time (Smp.) Cost 1 Cost 2	**S'wood** Time (Smp.) Cost 1 Cost 2	**C'ways** Time (Smp.) Cost 1 Cost 2	**New F'st C'tral** Time (Smp.) Cost 1 Cost 2	**Lym. Hosp.** Time (Smp.) Cost 1 Cost 2	**All Surgeries Total**
						09:10 (50) £60 £191	
	10:30 (50) £75 £236						
						11:45 (50) £60 £191	
						14:20 (50) £60 £191	
	14:45 (47) £75 £236						
15:05 (50) £60 £191							
					15:20 (26) £52 £164		
16:25 (5) £60 £191							
						17:30 (13) £60 £191	
Totals	Flts. (Smp.) Cost 1 Cost 2						
2 (55) £121 £382	2 (97) £149 £472	0 (0) £0 £0	0 (0) £0 £0	0 (0) £0 £0	1 (26) £52 £164	4 (163) £242 £765	12 (440) £746 £2,359

Time is UAV departure time; Smp. is number of samples on-board; Cost 1 is for the reasonably foreseeable future situation where multiple UAVs are overseen by one ground controller; Cost 2 is for the current situation involving safety pilots. Shaded cells indicate UAV flights.

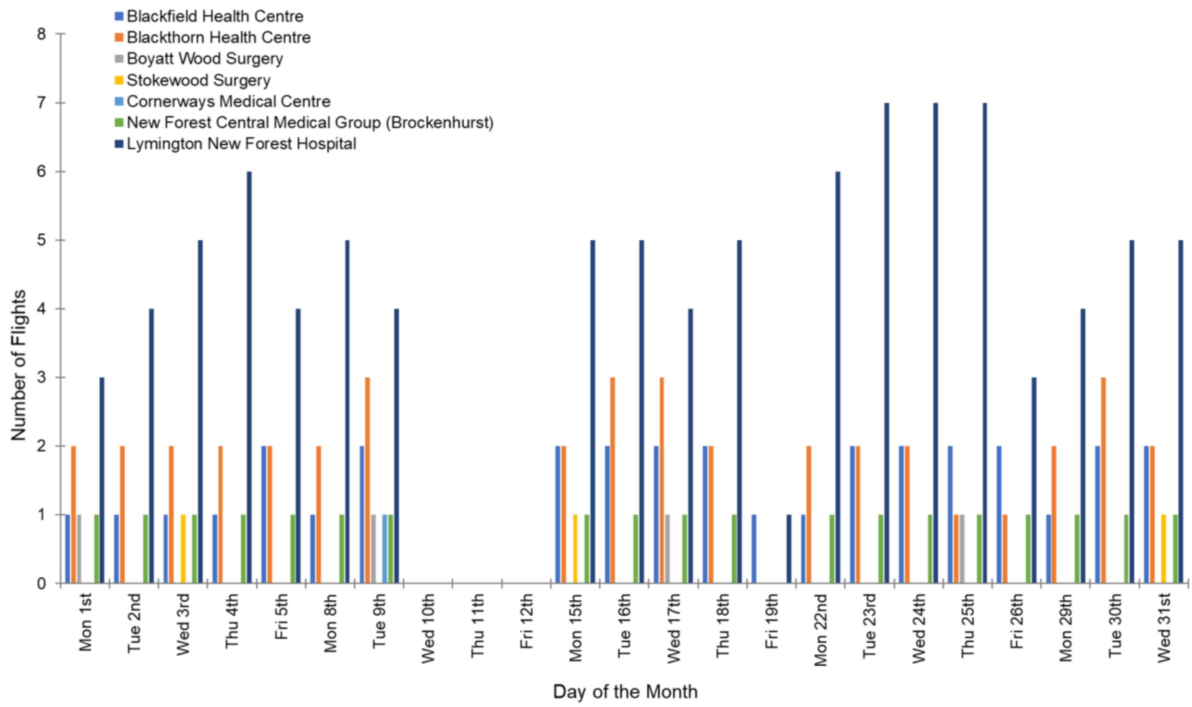

Figure 10: Number of flights per day for the UAV collection service during March 2021.

Comparison of BAU and Intervention Scenarios

The results (Table 3) suggested that replacing two vans with multiple drones serving 14 different surgeries (7 primary, direct by drone; and 7 satellite, by connecting ground cycle transportation) would reduce overall BAU van round time by 17.6% (37:05 hours) and distance travelled by 23.0% (1,306 vehicle-kilometres; vkm) per week. In terms of emissions benefits, the daily removal of two diesel vans would reduce tailpipe CO_2 emissions by 23.0% (365 kg) per week. Meanwhile, the use of drone service contingency taxis adds a further 49kg of CO_2 each week, resulting in a net emissions reduction of the system of 19.9% (317kg).

Offsetting the cost reduction resulting from fewer van collections (-£776/week, Table 3) against the cost of introducing multiple UAVs (£2,964/week, Table 1) produces a net cost increase of (£2,964-£776=) £2,188/week for drones to service the 14 surgeries. In terms of the overall cost for providing a sample collection service to all 79 surgeries, this represents a 56% increase from the BAU scenario which costs £3,911/week based on van-only collections (Table 3) to the intervention scenario costing £6,099/week based on a combination of collection by UAV (and taxi) (£2,964/week in Table 1) and van (£3,135/week in Table 3). It should be noted that UAV costs in this analysis do not match those given by Jenkins et al. (2017), particularly in terms of the cost of labour and the platform itself (37). This deviation is, in part, due to the larger craft being used, and the assumptions made around drone management by staff.

In comparison to existing collections by van, a drone collection service for the 14 surgeries featured in this investigation represents a considerable increase in cost (i.e., £2,964/week for UAVs *cf.* £776/week for vans) for a relatively small gain in terms of reduced transit time (37 hours/week). The results (Table 1) suggested that a UAV integrated collection service is less cost effective for some surgeries because they generate far fewer samples than others, resulting in inefficient transport with less than full payloads, although ultimately all samples must be collected.

For example, values for average payload and cost per sample (including collections by replacement taxi when necessary) range from: Lymington New Forest Hospital with (5,514/121=) 45.6 samples/collection and (£6,792/5,514=) £1.23/sample, respectively; to Cornerways Medical Centre with (2/2=) 1 sample/collection and (£117/2=) £58.50/sample, respectively. This disparity in cost effectiveness between surgeries suggested that, when further optimisation of the collection service is conducted in future research, some form of mixed-mode (i.e., van-drone) hybrid collection service involving localised consolidation of samples by vans performing routine timetabled collections for onward transport of consolidated payloads by drone might represent a less expensive solution. For example, drone flights to the relatively inefficient surgeries (i.e., low samples/flight and high costs/sample) at New Forest Central Medical Group and Cornerways Medical Centre (surgeries 6 and 7 in Figure 9, respectively) could be eliminated using scheduled van collections instead, consolidating samples at the nearby (and already efficient) Lymington New Forest Hospital (Surgery 5 in Figure 9) for onward transport to SGH.

Investigating the Marginal External Costs (MECs, often referred to as society costs) associated with the reduction in road vehicle mileage can demonstrate some further benefits of the drone service. Accounting for greenhouse gas (GHG) emissions, congestion, and air pollution costs, the intervention presented reduces the MECs of the system by £196 per week (GHG = £81 reduction, congestion = £116 reduction, air pollution – NO_x <£1 reduction, $PM_{2.5}$ = <£1 reduction) (73–75). Whilst these cost reductions will not directly benefit the operators, they highlight the possibility of benefits to drones beyond commercial costs. For example, this use case may help the health service operate more efficiently, though quantifying this is considerably more difficult.

An advantage of a drone collection service is more frequent and expeditious (i.e., shorter travel times) collections and deliveries compared to the existing van collection service, particularly if a mixed-mode consolidation approach were to be utilised because drones would reach full capacity (i.e., 50 samples) in shorter timescales and be ready to depart from surgeries earlier in the day. The existing van collection service for all 79 surgeries in/around Southampton involves 10 collection-rounds/day in BAU (Table 3), with each round including between one and three delivery stops at the SGH pathology laboratory, generating 21 deliveries/day, generally concentrated during the period from mid-morning to early afternoon. In contrast, the drone collection service for just the 14 surgeries investigated generates an average of 10.4 deliveries/day (Table 1), with deliveries spread throughout the day from ~09:00 to ~17:00 (Table 2). Van travel times from the investigated surgeries to SGH ranged from 20 to 265 minutes with an average of 88 minutes, whereas drone flight times ranged from 19 to 30 minutes with an average of 24 minutes. The contingency taxi services range from 24-60 minutes, meaning any cancelled flights will experience much slower delivery.

Table 3: Weekly road vehicle total costs, round times, van vkm, and CO_2 emissions (inc. contingency taxis).

Scenario	Number of Rounds/Day	Van Costs (£)	Van Round Time (h:m)	Van Vkm (km)	CO_2 (kg)
BAU	10	£3,911	210:50	5,686	1,589
Intervention	8	£3,135	173:45	4,380	1,272
Reduction	2	£776 (+£196 MECs)	37:05	1,306	317

Reduction costs show Marginal External Cost reductions in brackets.

A more frequent and expeditious service has the potential to provide three benefits: (i) better workflow management and control for laboratory staff and/or equipment of samples arriving for analysis; (ii) samples spend less time subjected to uncontrolled in-vehicle conditions, which may be harmful to samples (e.g., excessive temperature or vibration conditions) and affect the integrity of analysis results (50,81,82); and (iii) reduced time periods from sample extraction to laboratory arrival (and subsequent diagnosis), which would be advantageous for any time-critical samples. For example, blood samples taken from cancer patients to inform the prescription of chemotherapy treatments, a significant proportion of which are bespoke manufactured for their specific needs a few hours prior to administration. Emerging evidence from discussions with NHS practitioners suggest that there may be further advantages in providing for separation of some samples for fast-tracking analysis and improving the flexibility of collection services. A potential avenue for future research therefore could be to investigate the life-enhancing benefits to patients of fast-track sample analysis, and then to relate those benefits to a monetary value as a way to justify the additional expense of drones compared to vans. This could be based on the Quality Adjusted Life Year (QALY), a metric commonly used for economic evaluation of medical interventions (83).

CONCLUSIONS

Trials and applications for medical logistics drones are becoming more prevalent throughout the world, though, very few have translated into commercial services. This research used a series of real-world datasets to investigate the true practicality and feasibility for UAV service of NHS diagnostic specimens. An audit of activity in the Solent region of the UK highlighted demands for earlier and more frequent delivery of samples to the analysis laboratory, in addition to shorter transit durations, and faster times to diagnosis. Furthermore, medical regulators require that goods are carried in industry approved packaging (e.g., a Versapak sample carrier) to protect their contents, and that the carriage environment does not cause damage to specimens due to matters such as temperature range exceedance.

Combined with a subsequent investigation of the constraints relating to aviation, such as weather and energy, it was identified that a large (c. 5m) wingspan drone would be required to service the collection needs of a typical GP surgery. Additionally, UN3373 dangerous goods certification would be required, and vibration/temperature validation of any platform would be recommended. Under these assumptions, it is evident that very few GP surgery sites (20%) would be practically capable of receiving such a craft, and even fewer (11%) would be able to receive it after ground risk considerations, with airspace limitations potentially reducing this still further.

In an exploratory desktop analysis, 14 out of 79 surgeries could be served by UAV: seven directly, and seven through ground-based logistics transfers. The results suggested that an average of 1,628 samples could be served by UAV each week, resulting in 42 flights/week with 10 taxi services to cover periods where weather limits flying. This resulted in an approximate total service cost of £2,964/week if regulations develop to relax UAV personnel constraints. Whilst this does create a 20% reduction in tailpipe emitted CO_2 (excl. taxis) and 20% reduction in van logistics costs, an overall cost increase of 56% was returned, making any long-term UAV service financially unsustainable. Some sites were more cost effective than others, with per sample operating costs ranging from £1.23 to £58.50; however, the existing methods were still more affordable in all cases. Furthermore, other costs, such as airspace management and dangerous goods training costs, weren't considered in this analysis; should they be included, operations would be made even more difficult to justify.

Drone service does offer other potential benefits which have indirect value, such as faster diagnosis and treatment plan development, although quantifying their true value to the health service is slightly ambiguous. It should also be noted that some surgeries are significantly more cost efficient than others, meaning for any operation to be closer to cost neutral, further analysis of the benefits needs to be undertaken on a case-by-case basis.

When all of the challenges of UAV delivery are considered together, the somewhat competitive operating costs presented by past studies of UAV operations are put into context (28). A previous investigation into the practicality of UAV delivery services by McKinnon (84) highlighted that widespread services are unlikely due to operating costs not being worth the limited added value. In the context of NHS diagnostics, under existing infrastructure, there is not likely to be significant value added in the Solent region. Should changes to regulations enable load consolidation, there may be a point at which UAVs can effectively integrate into existing fleets and eliminate the need for one or more vans to visit the more remote surgeries.

AUTHOR CONTRIBUTIONS

Conceptualization: AO, TC, MG, AS
Ideas: AO, TC, MG
Data Curation: AO, MG, TC, AP
Formal Analysis: AO, MG, AP
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Writing – Review & Editing AO, MG, AS, TC, AP, JD, LABO

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Appendix

Table A1. Cost assumptions used in the desktop analysis. Costs and life expectancy based on Cascade UAV research consortium development experience (www.cascadeuav.com). **Example components are shown to demonstrate possible options, the craft described in this paper was not necessarily fitted with these <u>exact</u> components.**

Item (Qty)	**Assumed Life (flight hours)**	**Cost Per Flight Hour**
Forward Motor (e.g. Dualsky XM6360EA-19 220KV (85))	1,000	£0.10
Forward Electronic Speed Controller (ESC) (e.g. Hobbywing 100A 12s HV (85))	100	£1.00
Forward Propeller (e.g. 21” (85))	100	£0.50
VTOL Motor (e.g. 4x Eaglepower UA90 150KV (85))	1,000	£0.32
VTOL ESC (e.g. 4x Hobbywing 80A 12S ESC (85))	100	£3.20
VTOL Propeller (e.g. 4x Eaglepower UC2480L 24” Propeller (85))	100	£1.60
Servo (e.g. 2x Savox SC-1256TG, 2x Savox SC-1251MG, 2x Savox SH-0263MG (85))	250	£1.20
Li-Po Battery (e.g. 2x Tattu HV 32000mAh 6S 10C (85))	500	£1.20
Base Platform (e.g. Mugin V50)	1,000	£5.00
Autopilot (e.g. Distributed Avionics Masterless (86))	1,000	£10.00
Satellite Receiver (e.g. Honeywell Satcom (87))	1,000	£0.50
Terrestrial Mobile Network Receiver (LTE) (88)	1,000	£0.20
Radio Comms	1,000	£0.20
Radio Control Units (x2)	1,000	£0.30
Ground Control System	1,000	£1.00
Item	**Cost**	**Cost Basis**
Insurance - Legal liability to 3rd parties (bodily Injury and/or Property Damage GBP 10,000,000 each occurrence) - Noise liability (GBP 2,500 – any one occurrence and in the annual aggregate) - Invasion of privacy (GBP 2,500 – any one occurrence and in the annual aggregate) 1. Product Liability - £10 million 2. Employers’ Liability - £10 million	£2,000	Per Year

3. Professional Indemnity - £2 million		
Electricity (89)	£0.17	Per kWh
Safety Pilot	£50	Per Hour
Mission Commander	£50	Per Hour
Loader/Unloader (90)	£10.26	Per Hour
Delivery Driver (71)	£10.78	Per Hour
Van Mileage (71)	£0.46	Per Mile