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The effects of costs on drone uptake in multi-modal logistics systems within a healthcare setting

Matt Grote [a,*], Andrew Oakey [a], Aliaksei Pilko [a], Jakub Krol [b], Alex Blakesley [b], Tom Cherrett [a], James Scanlan [a], Bani Anvari [b], Antonio Martinez-Sykora [c]

[a] Faculty of Engineering and Physical Sciences, University of Southampton, Boldrewood Campus, Southampton S016 7QF, UK
[b] Faculty of Engineering Science, University College London, London WC1E 6BT, UK
[c] Southampton Business School, University of Southampton, Highfield Campus, Southampton S017 1BJ, UK

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ABSTRACT

Uncrewed Aerial Vehicles (UAVs; commonly known as drones) have been gaining interest as a potential transport mode for logistics (i.e., payload delivery), bringing suggested benefits such as reduced transit times and improved access in hard-to-reach locations. However, drones have yet to become widely established in routine logistics systems, with a postulated reason being that the higher costs associated with operating drones relative to traditional surface transport modes (e.g., vans, bicycle couriers) present a barrier to uptake. Based on case studies of two real-world logistics networks transporting patient pathology samples in a healthcare setting in the United Kingdom, this study investigated the effects of the relative costs of drones on mode choice in integrated, multi-modal logistics systems. Results suggested that drones could be a financially viable option if their costs reduced below ~19% of current values, although such a reduction may not be feasible, even in a future involving increased drone automation. Drones reduced sample transit times by up to ~70% compared to vans but benefits to the wider healthcare system were negligible because level of service requirements for transit times could be achieved by all modes.

1. Introduction

The drone industry has seen rapid expansion around the world in recent years, with Uncrewed Aerial Vehicles (UAVs), often referred to as drones, being used by commercial operators for purposes such as inspection, mapping, monitoring, video/photography, humanitarian aid, and emergency response [1–6]. Drones have also been proposed as a potential mode of transport for the logistics industry (i.e., payload delivery), bringing suggested benefits such as reduced payload transit times, reduced emissions, and improved access in locations that are hard to reach via existing surface infrastructure (e.g., poor road networks, across bodies of water) [7–11].

However, there are very few examples of large-scale, commercially successful drone logistics operations in existence. One potential reason why drones have yet to become established as a routine mode in logistics systems is that the higher costs associated with operating drones relative to more traditional surface transport modes, such as Light Goods Vehicles (LGVs; typically known as vans) or bicycle couriers, could present a barrier to uptake [11–13].

The aims of this research were two-fold: (i) to investigate the effects of the relative costs of drones on mode choice within multi-modal logistics systems; and (ii) to produce a quantified estimate of the reduction in costs likely to be necessary for drones to be adopted for routine logistics purposes. These aims were achieved by first developing a novel, multi-modal logistics model (Freight Optimisation with RiSk, Energy, and mixed-mode Transport Integration; FORSETI), and then applying that model to real-world case studies involving logistics within a healthcare setting.

2. Costs of drones for logistics: a review

Much of the previous research reported in the academic literature regarding the costs of drone logistics was found to be centred on studies that investigated the development and/or assessment of new or improved theoretical optimisation algorithms for logistics operations that involve drones [14–18]. In particular, there has been interest

* Corresponding author.
E-mail address: m.j.grote@soton.ac.uk (M. Grote).

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recently in algorithms for optimising the ‘flying sidekick’ approach, whereby drones are launched from vans to make collections/deliveries before returning to the van to land [19–24]. Moreover, a comprehensive review of drone logistics research by Moshref-Javadi and Winkenbach [25] suggested that studies that considered the associated costs were in the minority, with only ~30% of studies including an explicit costs minimisation objective in the algorithmic solution method. Another review of the mathematical models and theoretical algorithmic solution methods for optimisation of drone operations was carried out by Chung et al. [26]. This review included all types of drone operations (i.e., not just logistics), concluding that the effectiveness and efficiency of drone operations can be enhanced (and costs minimised) when drones are used in combination with other vehicles (e.g., vans).

Colajanni et al. [27] evaluated an optimisation algorithm that maximises profit across an entire, theoretical supply chain network for a company producing, storing, and shipping products to customers using a fleet of trucks, with drones (payload capacity 4 kg) also available as an alternative option for transport during the last mile for parcel deliveries. Results suggested that, by utilising drones in the last mile, companies can reduce costs by up to 60%. However, this was based on a prior assumption that drones are cheaper than trucks, which may not be the case in reality. Rave et al. [28] assessed whether a combination of trucks and drones (payload capacity of one customer’s parcel) would be beneficial in reducing the costs of last mile parcel deliveries based on a computational analysis of theoretical logistics networks. The study found that, in 58% of the network scenarios investigated, a combination of launching drones both from dedicated drone depots (i.e., drones serving customers independently of trucks) and from trucks (i.e., the flying sidekick approach) was the best solution, leading to average cost reductions of 33% compared to using only trucks. However, both fixed and variable costs for drones were assumed to be substantially cheaper than those for trucks, which may not be achievable in practice. Meng et al. [29] proposed a new optimisation algorithm to assess the impacts of drone-assisted (payload capacity 10 kg) truck deliveries (i.e., the flying sidekick approach) for a logistics network in Guang’an, China, finding that total costs can be reduced by 22% compared to traditional truck deliveries. The total costs included the truck drivers’ wages and the cost of energy consumption for drones (electric) and trucks (gasoline), along with the carbon costs of emissions associated with energy consumption. However, no costs were allowed for personnel to monitor drones, i.e., drones were assumed to fly autonomously whilst the driver was driving the truck, which may not be feasible under current regulation and technology regimes.

In contrast to the theory-focussed research on algorithmic solution methods, some studies adopted a more practical, real-world emphasis in the analysis. Using high-resolution land-use and population data from across the European Union (EU) and the United Kingdom (UK), Aurambout et al. [9] investigated the optimal locations for delivery drone depots (termed drone-beehives in the study, which are essentially depots where drones are loaded, launched and return to land post-delivery), based on the assumptions that the drones used were similar to those being developed by Amazon Prime Air parcel delivery service (payload capacity ~3 kg) and that 10% of online buyers would choose parcel delivery by drone once per year. An assessment of the costs involved with building and operating beehives versus expected returns from the population within range of beehive locations suggested that drone delivery operations were likely to be most economically viable in Italy, Germany, France and the UK. Dhote and Limbourg [30] modelled the potential for drones (payload capacity 3 kg) to be used in healthcare logistics, transporting biomedical products (e.g., blood for transfusion, pathology samples) between facilities (e.g., hospitals, laboratories, blood transfusion clinics), based on a real-world case study of Brussels, Belgium. Scenario analyses suggested that sharing drones between facilities and the provision of recharging stations for use mid-mission could reduce the costs of operations by ~55% compared to a drone logistics system without these features.

Also in healthcare logistics, Oakey et al. [11] used a real-world case study approach to investigate the potential for drones (payload capacity 5 kg) to be used to transport pathology samples taken from patients at doctors’ surgeries (also known as doctors’ offices) to an analysis laboratory located in Southampton, UK. The study found that, whilst drones offered shorter journey times for samples (average of 88 minutes for vans reduced to 24 minutes for drones), servicing 18% of surgeries by drone instead of van (as used to service all surgeries in business-as-usual) increased total system costs by 56%. Roberts et al. [31] reviewed the evidence for drone delivery of time-critical medical supplies (e.g., automatic external defibrillators (AEDs), naloxone, anti-epileptics, blood products) in out-of-hospital emergency situations, finding several studies in which services were assessed as cost-effective. For example, a study that modelled a service in Germany delivering AEDs using 800 drones to save an additional 1477 life-years, at a cost of ~18 million Euro per year [32]. However, these studies related specifically to the provision of emergency medical services, where rapid interventions (i.e., delivery < ~10 mins) were critical to patient survivability. Raghunatha et al. [33] adopted a systems analysis approach to assess last-mile goods delivery by drones compared to vans, finding that drones could reduce costs by over 50%. However, the drone used in the analysis was assumed to have a payload capacity of 544 kg and to perform multi-drop delivery rounds (i.e., similar to how a logistics van might operate). This is a large drone, with a rotor span of ~20 m, which could present practical challenges (e.g., availability of suitable landing zones, noise pollution), and is not aligned with the prevailing approach being adopted by the burgeoning drone logistics industry in reality, where much smaller drones are preferred (span <~5 m and payload capacity <~5 kg) [34–37].

Instances of the actual implementation of routine drone logistics operations in the real-world often occur in situations where there is a high value attached to rapid payload transit times in locations that are harder to reach due to poor (less direct and often low speed) surface infrastructure [38]. For example, the blood transport service in Rwanda provided by Zipline, which transports blood for transfusion from distribution centres to hospitals/clinics using drones that make deliveries via parachute. An average of ~200 flights per day are performed, with each drone capable of travelling up to 120 km at speeds of ~100 km/h [39–44]. Compared to what would be achievable via land-based modes that are subject to Rwanda’s challenging topology and poor road conditions, the primary benefit of the service is rapid payload transit times, leading to a reported 95% reduction in blood wastage [45]. However, the cost effectiveness has not been demonstrated publicly, and cost estimations of Zipline operations have suggested that drones are considerably more expensive than surface modes and the service is understood to be viable only because it is heavily subsidised by the government [44, 46].

Along with factors such as speed of delivery, reliability of service, accessibility of locations, energy consumption and vehicle emissions, costs are likely to be one of the most important (if not paramount) considerations in organisational decisions regarding appropriate transport modes for logistics. This is true for commercial companies attempting to maximise profits, and for public sector bodies funded by limited taxpayers’ money, such as local government organisations or public healthcare systems (often seen as a promising arena for initiating drone logistics services due to the social benefit involved, e.g., the UK National Health Service; NHS), particularly in the challenging economic circumstances of recent years in many areas around the world.

It has been suggested that higher costs relative to traditional modes mean drones are unlikely to be used routinely for large-scale logistics purposes [11–13]. These higher costs may have been a significant reason (coupled with difficulties in securing regulatory approval from the relevant National Aviation Authorities; NAAs) why test programmes for development of drone deliveries by some high-profile logistics companies (e.g., DHL, Amazon) have been reported in the media as being delayed or abandoned in recent years [47,48].

Conversely, some companies are persisting with the development of (or re-starting) drone delivery services, with self-reported successes. For example: UPS announced in January 2022 completion of 10,000 flights in the USA using a delivery drone manufactured by Matternet; Wing, a subsidiary of Alphabet (the Google parent-company), has completed over 300,000 commercial deliveries in Australia, Finland and the USA (in Texas and Virginia); Amazon is attempting to re-start drone deliveries in Lockeford, a town with ~3500 residents in California, USA; and Walmart, in partnership with Zipline, DroneUp and Flytrex, made over 6000 commercial deliveries during 2022 across seven states in the USA [49,50]. In general, a recent review by Benarbia and Kyamakya [51] suggested that the drone-based parcel delivery industry was still in its infancy, and that more steps (e.g., establishing specific regulatory frameworks around the world to govern use of airspace by civil drones, overcoming the technical and cost challenges of providing infrastructure such as drone ports and recharging stations) were required to achieve the true integration of drones into this logistics sector.

Despite many real-world trials of drone deliveries being reported as successful, few services have advanced beyond exploration of operational issues to the point of emerging as large-scale, commercially viable services, and it is posited that higher relative costs of drones are a significant contributing factor to this situation. Furthermore, the information that would be required to allow verification of whether (or not) any of these drone delivery services are truly cost-effective tends not to be available in the public domain.

2.1. Summary of review findings

Based on the literature reviewed, it is not clear whether drones are likely to be ruled-out as a viable option in multi-modal logistics systems on the grounds that their costs are too high relative to traditional modes, where costs and economic viability are well-established through years of recorded experience. In general, studies that consider the costs of drone logistics operations tended to be theoretical in nature, primarily concerned with the assessment of algorithm performance in terms of ability to find the optimal solution. Typically, the objective of these algorithms was to minimise the cost of utilising drones, but this was based on an implicit assumption that drones would actually form part (or all) of the solution to a given logistics problem (i.e., assuming drones are utilised for logistics, how best should costs be minimised), and so the question of whether or not drone costs (relative to other modes) would preclude their use in the first place was not addressed. Instances of the implementation of drone logistics services in the real-world do exist, but it is often difficult to verify if these services are commercially viable in the long-term and on a large-scale.

The specific question of the effect of relative costs on the uptake of drones within multi-modal logistics systems that are commercially viable has not yet been explored fully in the literature. Given the general expectation of expanding drone delivery services around the world, this subject matter does not appear to have received due attention, particularly in the context of the practical integration of drones in realistic case study situations based on real-world logistics networks.

The contributions of this research were three-fold: (i) a novel, integrated multi-modal logistics model (FORSETI) was developed to investigate the effect of the relative costs of drones on mode choice to satisfy demand for payload transport within real-world logistics networks in a healthcare setting; (ii) the model generated logistics solutions for case study situations involving a significant historic database of actual movements of patient diagnostics samples from doctors' surgeries to pathology laboratories in the Solent region of the UK; and (iii) guidance for the drone and logistics industries was produced in the form of a quantified estimate of the scale of the reduction in current costs associated with drone operations that are likely to be necessary if drones are to be adopted routinely for logistics purposes.

3. Methodology

A study evaluating the implications of relative costs on the uptake of drones in multi-modal logistics systems in a real-world healthcare setting was a novel undertaking, with no similar studies found in the literature. Fundamentally, the methodological approach adopted was to investigate two testbed logistics networks involving the transport of pathology samples within the UK NHS (Section 3.1). A novel logistics model (FORSETI) was used to conduct the investigation (Section 3.2). Whilst those for vans and bicycle couriers were held constant at current values, the cost parameters for drone operations within FORSETI (Section 3.3) were varied (from current values down to a hypothetical situation where drones were free to use) to assess the effects on drone uptake and estimate the reductions in drone costs likely to be necessary to become a financially viable alternative to traditional surface modes. In essence, this constituted a sensitivity analysis exploring the sensitivity of drone uptake in multi-modal logistics systems to drone costs in two testbed logistics networks.

3.1. Testbeds and scenarios

Across England and Wales, around 300,000 pathology tests are undertaken on each working day [52]. These pathology tests involve samples being taken from patients at doctors' surgeries which are packed into insulated medical containers (brand name Versapak, Fig. 1) by surgery staff, and then collected and transported via networks of daily van rounds to central pathology laboratories (usually located at large hospitals) for analysis. Typically, the accepted target for maximum elapsed time between collection and delivery for samples to remain viable for analysis is 90 minutes (i.e., samples must be delivered to the laboratory within 90 minutes of collection) [53], although there is no universally agreed standard that governs required level of service in terms of maximum transit time, and specific examples of more relaxed requirements do exist in practice (e.g., maximum of 120 minutes [54]). However, the most demanding circumstance (i.e., <90 minutes) was adopted in this study because it was the most favourable for encouraging drone use, with their potential to provide fast transit times.

The two pathology sample collection networks used as testbeds for this study were: (i) the 76 doctors' surgeries sending samples to the pathology laboratory at Southampton General Hospital (SGH), located in Southampton, a city on the South coast of the UK with a population of ~250,000 (Fig. 2); and (ii) the 22 doctors' surgeries sending samples to the pathology laboratory at Saint Mary's Hospital (SMH), located in Newport, a town with a population of ~25,000 on the Isle of Wight (IOW), an island off the South coast of the UK (Fig. 3). Regarding the selection criteria for the case study areas, along with data availability considerations, the two testbeds were chosen to provide contrasting analyses between larger-scale (Southampton) and smaller-scale (IOW) logistics networks. The Southampton testbed was chosen as a typical large surgery network, involving the majority of surgeries concentrated in the urban area of the city itself, with a minority of surgeries in more remote, rural locations outside the city towards the geographic periphery. The IOW testbed was chosen in contrast to Southampton as a smaller surgery network, with no large city and a more even distribution of surgeries across the area.

An assessment was made to determine which surgeries were suitable for service by drone based on two criteria [11]: (i) a suitable landing zone in reasonable proximity to the surgery with sufficient space to allow drones to perform vertical landings and take-offs when making collections of medical containers (assumed drone type was a Vertical Take-Off and Landing (VTOL) and Fixed-Wing (FW) hybrid, Fig. 4 and Section 3.2), i.e., approximately 100 m^2 of open space on-site or on adjacent public land, determined by inspection using Google Maps satellite imagery; and (ii) a suitable flightpath routing available between the pathology laboratory and the landing zone based on acceptable ground risk (maximum threshold of mean risk of a third-party fatality on

Fig. 1. Pathology sample and containers used for transport. Pathology sample (left) and insulated medical containers (right). Medium-sized containers (middle of the three pictured; dimensions 460×255×305 mm; empty mass 2.2 kg; mass when fully loaded with samples ~5 kg; [58]) are typically used to transport pathology samples.

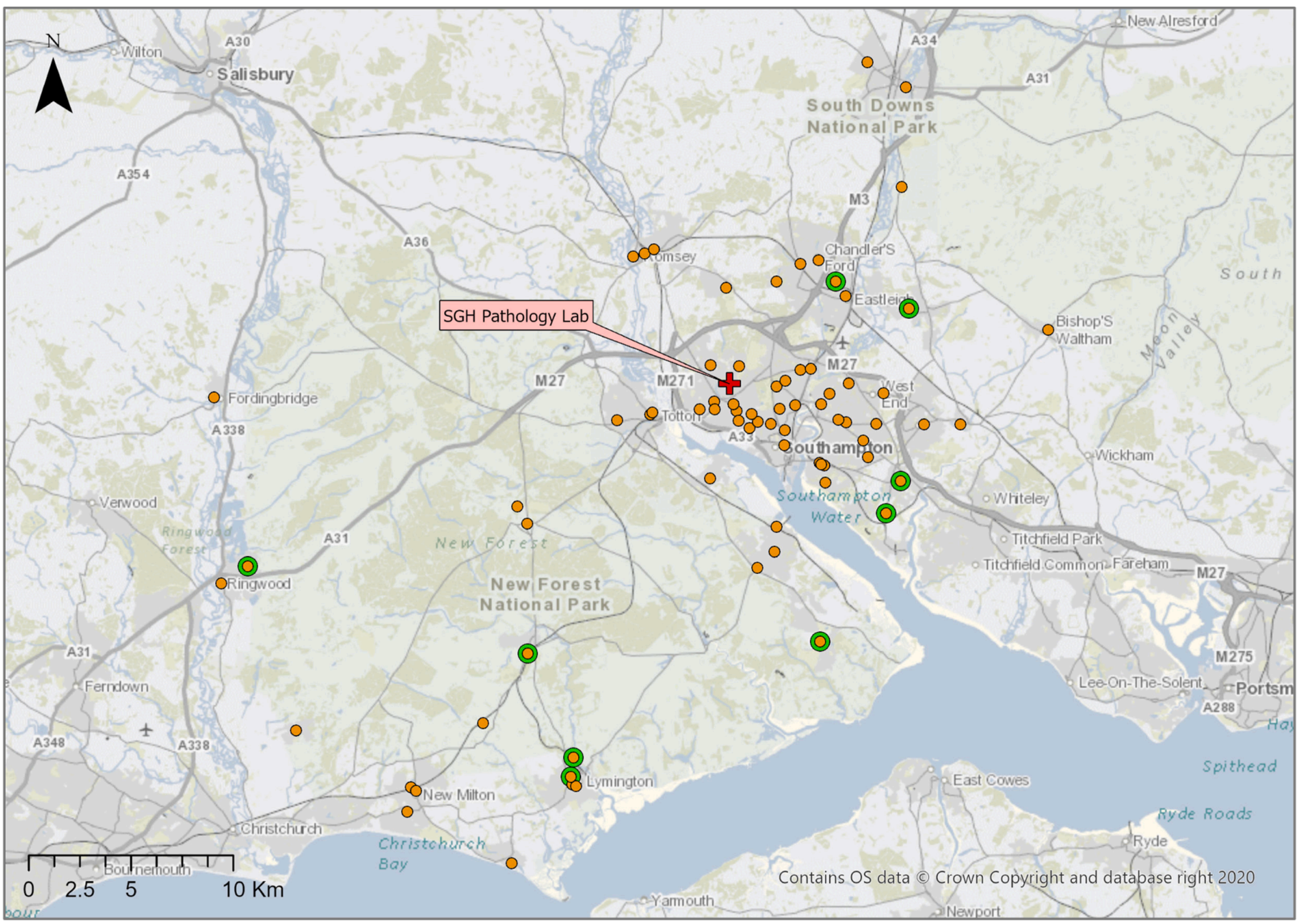

Fig. 2. Map of the Southampton testbed region. Orange circles indicate doctors' surgeries; green ring around an orange circle indicates a surgery is drone suitable. SGH is Southampton General Hospital.

the ground due to a drone crashing along its flightpath of 1×10^{-7} fatalities/flight-hour), assessed using the SEEDPOD drone risk route planning tool [55,56]. As a comparison, the fatality risk for crewed general aviation is $\sim2\times10^{-5}$ fatalities/flight-hour [57]. Drone suitable surgeries (nine for SGH and twelve for SMH) are shown in Fig. 2 and Fig. 3.

The characteristics of the different scenarios investigated in the study are shown in Table 1. Based on real-world historic data regarding the number of samples generated daily by doctors' surgeries, each scenario represented the demand for transport of samples during a four-hour morning shift (09:00–13:00) on a typical weekday, which required every surgery to be visited once for one container of samples (i.e., one medium Versapak) to be collected and transported to the relevant pathology laboratory. The actual production times of samples recorded in the historic data (i.e., the time of day when each sample was taken from a patient) were ignored because these are organised around the extant van collection round schedules (i.e., the time when a van is scheduled to visit a surgery determines when samples are taken from patients at that surgery), and therefore it was assumed that it would be possible to reorganise sample production times around new collection times as scheduled in any logistics solution that might be generated by FORSETI. In accordance with the preferred target for maximum elapsed time

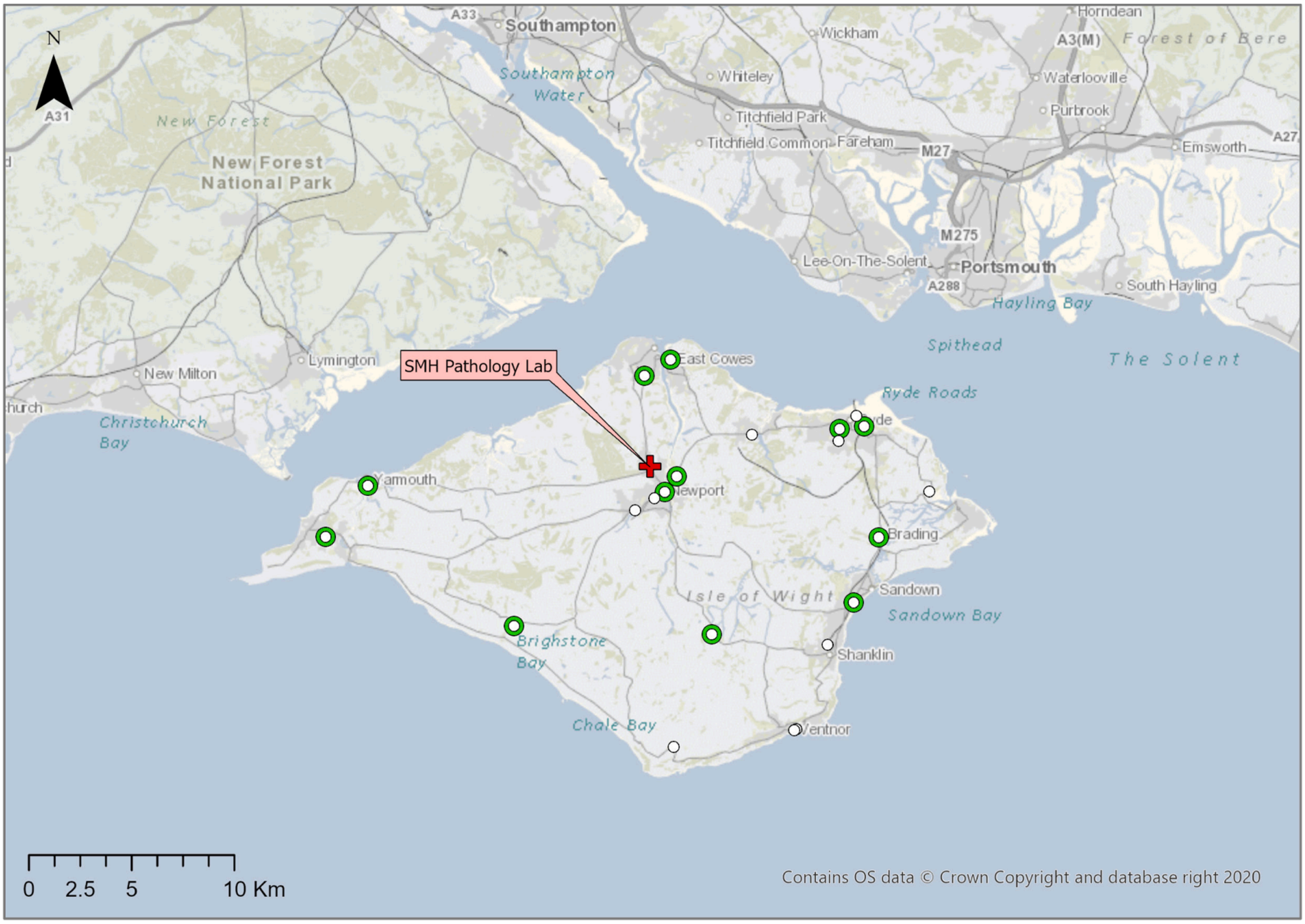

Fig. 3. Map of the IOW testbed region. White circles indicate doctors' surgeries; green ring around a white circle indicates a surgery is drone suitable. SMH is Saint Mary's Hospital.

Fig. 4. Drone type assumed in this study. The drone is an electric VTOL/FW hybrid (5 m wingspan). Cargo bay is sufficient to accommodate one medium-sized medical container.
Source: adapted from Mugin [59].

between collection and delivery for pathology samples, maximum allowable in-transit time (ITT) was assumed to be 90 minutes for all scenarios. Reverse logistics (i.e., delivering empty containers to surgeries) was assumed to be achieved during normal operations (i.e., a vehicle collecting a full container was assumed to drop-off an empty container and sample tubes during the same visit).

Dwell time at each stop (for collections and deliveries by all modes) was assumed to be 2.5 minutes [60]. Electric vans (eVans) were specified because the UK NHS has committed to a complete transition away from using diesel vehicles [61]. Recharging of eVans and van driver breaks were assumed to take place after the end of the four-hour shift. This was a reasonable assumption because all solutions were checked to ensure the maximum distance travelled by any van during any shift was <125 km, which provided a considerable buffer below the typical eVan ranges quoted by manufacturers (e.g., 200+ km), even allowing for these ranges to be somewhat optimistic compared to those that can be achieved in practice. The maximum driving time by any van during any shift was constrained by the four-hour shift period, which complied with European Union (EU) rules on drivers' hours (breaks totalling at least 45 min after no more than 4:30 h driving time).

A battery-swap system was assumed for drones, which involved replacing depleted with fully charged batteries during dwell times at the pathology laboratory. An additional 10 minutes dwell time per drone journey (FORSETI assumes drones only perform out-and-back journeys from the pathology laboratory to a single surgery and return, Section 3.2) was assumed to accommodate these battery-swaps (5 min), and also to allow a check of the drone's continued airworthiness (e.g., damage, malfunctions) to be completed (5 min) at the pathology laboratory [62]. All solutions were checked to ensure the maximum distance travelled by any drone during any shift before landing back at the pathology laboratory was <75 km, which again provided a considerable buffer below the typical range capabilities quoted by manufacturers (e.g., 150+ km) for a drone of the type assumed in this study (i.e., electric VTOL/FW hybrid, Fig. 4 and Section 3.2), including allowing for the energy expended to land/take-off to pick-up samples at a surgery.

In every scenario, all surgeries were specified as available for service by van or bicycle courier. In two scenarios (Soton_Suit and IOW_Suit in Table 1), only those surgeries assessed as drone suitable were specified as available for service by drone. In the other two scenarios (Soton_All and IOW_All in Table 1), all surgeries were specified as available for service by drone, representing an assumed expansion of routine drone logistics; for example, a situation where every surgery has made necessary provisions to create a drone landing zone, or where drone

Table 1
Characteristics of the different scenarios investigated.

Scenario ID	Time	Duration (h:m)	Path Lab	Number of Surgeries	Number of Drone Suitable Surgeries	Maximum ITT (minutes)	Dwell Time (minutes)
Soton_Suit	09:00–13:00	4:00	SGH	76	9 (12%)	90	2.5
Soton_All	09:00–13:00	4:00	SGH	76	76 (100%)	90	2.5
IOW_Suit	09:00–13:00	4:00	SMH	22	12 (55%)	90	2.5
IOW_All	09:00–13:00	4:00	SMH	22	22 (100%)	90	2.5

collections are achieved via a cable and winch system that removes the need for drones to land at surgeries.

3.2. Logistics model description and application

3.2.1. Model structure overview

The FORSETI model is a logistics planning tool designed to analyse the demand for transportation of goods during a particular shift period (e.g., morning, afternoon) and determine how best to deploy and integrate available transport assets to meet that demand (Fig. 5). Transport modes available are vans, drones and bicycle couriers. FORSETI is configured primarily to analyse scenarios involving the transport of pathology samples from doctors' surgeries to central pathology laboratories. However, the underlying framework could be applied to other logistics operations through adaptation of the software.

An overview of the structure of FORSETI is provided in this section (Section 3.2.1), along with a flowchart depicting the modelling process (Fig. 5). Subsequent sections describe the optimisation approach (Section 3.2.2), transport mode elements (Section 3.2.3) and cost parameters (Section 3.3) within FORSETI in more detail, including the underlying assumptions. In addition, citations of references that provide further information about FORSETI are provided throughout Section 3.2 and Section 3.3.

Regarding Fig. 5, the main module of FORSETI (Land-Air Logistics Optimiser; LALO) receives user inputs (Step 1) relating to surgery locations, parameters characterising the transport modes (e.g., costs), and time constraints (e.g., shift start/end times). A matrix of all possible origin-destination (O-D) pairs (i.e., all possible combinations of surgeries and pathology laboratory) is created (Step 2). The support modules then identify the most likely best route between each O-D pair by the different transport modes, and calculate the associated costs, energy, emissions, and travel times/distances data (Step 3 and 4). The complete set of O-D pairs data is then fed back into LALO (Step 5). LALO analyses the optimal combination of vans, drones and bicycle couriers to satisfy the input logistics demand (Step 6), producing solution outputs based on optimising to minimise a (user defined) balance between operating costs, energy consumption, emissions, and maximum in-transit time (Step 7).

3.2.2. Model optimisation approach

Logistics demand inputs to FORSETI consist of a list of surgeries (postcode locations) to be serviced during a shift (one collection from each surgery, Section 3.1), specification of whether (or not) each surgery is suitable for service by drone (Section 3.1), and the location of the destination pathology laboratory. Based on these inputs, FORSETI adopts a novel optimisation approach to solve an extension of the Sustainable Specimen Collection Problem (SSCP), first proposed and described by Oakey et al. [63], with the additional introduction of drones as an available transport mode and scheduling of assets (i.e., a time-constrained mixed-mode two-echelon vehicle routing problem with scheduling). The objective function to minimise the sum of operational costs, energy consumption, carbon dioxide (CO_2) emissions, and maximum ITT is provided in Equation 1.

Equation 1. FORSETI objective function.

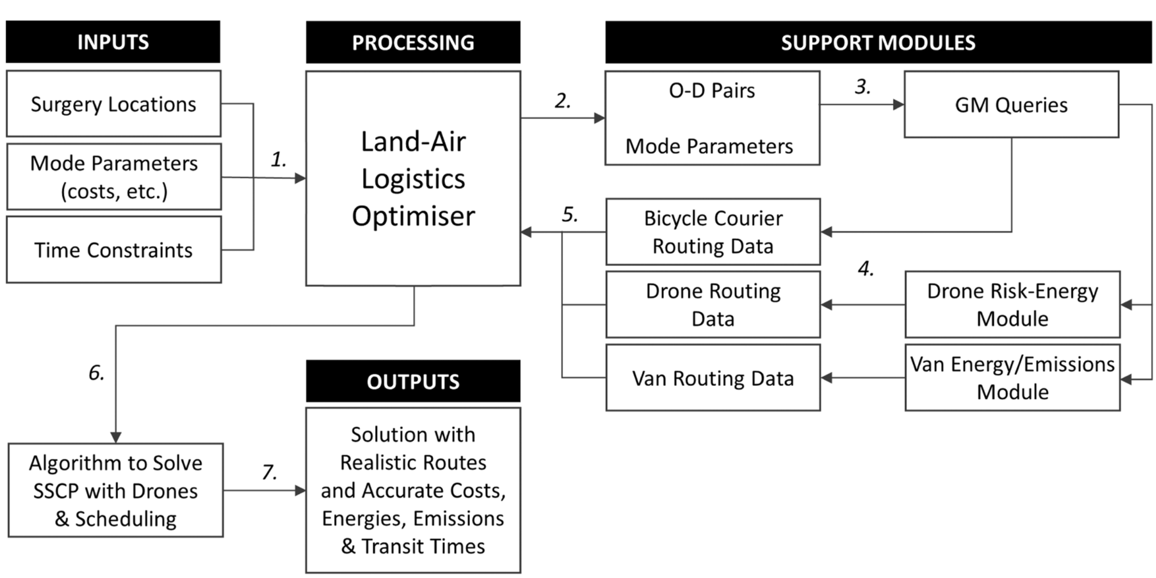

Fig. 5. Flowchart of the FORSETI logistics model. Numbers indicate the sequence of steps within FORSETI. O-D is origin-destination. GM is Google Maps. SSCP is Sustainable Specimen Collection Problem.

$$\min : \sum_{\overline{r}_k \in \overline{R}} \left(x_{\overline{r}_k} \left(\sum_{r_{v,k} \in \overline{r}_k \cap R^V} \theta_1 p_{r_{v,k}} + \sum_{r_{d,k} \in \overline{r}_k \cap R^D} \theta_2 p_{r_{d,k}} + \sum_{r_{c,k} \in \overline{r}_k \cap R^C} \theta_3 p_{r_{c,k}} + \theta_4 \epsilon_{\overline{r}_k} \gamma \right) \right)$$

$$+ \theta_1 W^V A^V_{\max} + \theta_2 \left(W^D A^D_{\max} + W^O A^O_{\max} \right) + \theta_5 u$$

In the optimisation, collection rounds that combine a van or drone route with a set of consolidation bicycle courier routes are created where $\overline{r}_k$ denotes one collection round, and $\overline{R}$ denotes the set of all collection rounds. It should be noted that collection rounds do not necessitate the use of consolidation and can consist of solely one van or one drone route, and bicycle courier routes delivering directly to the pathology lab are also possible. Van, drone and bicycle courier routes are denoted by $r_{v,k}$, $r_{d,k}$ and $r_{c,k}$, respectively; whilst R^V, R^D, and R^C denote the full set of each route type; and $x_{\overline{r}_k}$ denotes a decision variable for whether a given collection is used. The variable costs (e.g., flight-duration/distance-based) of a given route are given by $p_{r_{v,k}}$, $p_{r_{d,k}}$ and $p_{r_{c,k}}$ (van, drone, bicycle courier, respectively). The fixed/standing costs of labour and/or vehicles per shift are denoted by the W values, whilst the $A_{\max}$ values denote a variable defining the number of drivers/operators/drones required in the shift period. The emissions of a collection round are denoted by $\epsilon_{\overline{r}_k} \quad \gamma$ (energy consumed x constant emissions factor), and u denotes maximum ITT. Weighting values for the different constituents of the objective function are used to define the relative importance of: van contribution to total costs (θ_1); drone contribution to total costs (θ_2); bicycle courier contribution to total costs (θ_3); total emissions/energy consumption (θ_4); and maximum ITT (θ_5).

3.2.3. *Transport mode elements*

The van element of FORSETI models the costs, emissions/energy consumption and travel time (i.e., the factors related to the objective function constituents) associated with van operations (i.e., LGVs with gross vehicle mass $\leq$3500 kg), with eVans specified in this study because this is a committed change for the UK NHS (Section 3.1). A full description of the estimation of energy consumption is given by Krol et al. [64]. The effects of road traffic congestion on journey times for vans at different times of day are included in FORSETI through querying Google Maps Directions API [65] to obtain driving time and distance between every O-D pair. Journey times are obtained for one-hour intervals across the modelled period (e.g., journey times obtained from a query for 09:00 are assumed to apply 09:00–10:00 until updated by journey times from a query for 10:00). Van rounds are assumed to start/finish at the pathology laboratory. All solutions were checked to ensure the maximum number of medical containers carried by any van during any shift (either loaded with samples or empty for reverse logistics, Section 3.1) was <20, which provided a considerable buffer below the typical payload capacities of vans (~5 m^3 and ~800 kg from manufacturers' specifications).

The drone element of FORSETI models the costs, emissions/energy consumption and travel time associated with drone operations. The drone type assumed in this study was an electric VTOL/FW hybrid drone (similar to the Mugin-5 Pro platform [59]), with a Maximum Take-Off Weight of 60 kg, cruise speed of 65 km/h, and payload capacity for one medium-sized medical container (Fig. 4). A VTOL/FW hybrid drone is a drone that ascends vertically from take-off using copter-style rotors, before transitioning to fixed-wing flight for the cruise, and then transitioning back to the rotors again for a vertical descent to land. Drone flightpaths are planned in FORSETI based on a balance between energy consumption and ground risk, with ground risk estimated as fatalities per journey based on the mean risk of a third-party fatality on the ground due to a drone crashing along its flightpath, taking account of land-use and how population densities vary during the day; a full description is given by Pilko et al. [56]. Energy optimal flightpaths follow direct (i.e., straight line) routes, with such flightpaths often the default assumption in other studies. In contrast, risk optimal flightpaths are not usually straight because they tend to deviate around higher risk areas with higher population densities. In practice, acceptable real-world drone routes are likely to be required to avoid higher risk areas wherever possible, and hence the balance between energy and risk optimal flightpaths planned in FORSETI was viewed as a more realistic approach than the assumption of direct routes.

Drone journeys in FORSETI are assumed to start/finish at the pathology laboratory. Drones only perform out-and-back journeys (from the pathology laboratory to a surgery and return) and have payload capacity for one medical container (either loaded with samples or empty for reverse logistics, Section 3.1). It is expected that if/when drone logistics operations become established, mission commanders will be able to monitor multiple drones simultaneously, and this is included in FORSETI through the operator-to-vehicle ratio. This ratio defines the number of drones that can be operated by a single mission commander, and was assumed to be 1:20 in this study in alignment with recently reported real-world values [66]. The effect of the prevailing en-route wind on drone travel times was assumed to average-out, which was reasonable because all drone routes are out-and-back journeys, and therefore a headwind on the outbound leg would become a tailwind on the inbound leg, and vice versa. The weather conditions during the modelled period (i.e., four-hour morning shifts) were assumed to be acceptable for drone flight, i.e., both precipitation and wind speed were assumed to be within the drone's weather tolerance (typically, 50 mm/h precipitation and 10 m/s wind speed [11]).

The bicycle courier element of FORSETI models the costs and travel time associated with bicycle courier operations. Journey times for bicycle couriers are included in FORSETI in a similar way as for vans, i.e., through Google Maps Directions API queries. Bicycle couriers are limited to a maximum journey distance of 8 km, a typical limit for cyclists completing deliveries as on-demand tasks [67], and therefore predominantly collect samples from surgeries in close proximity to each other, consolidating payloads at one of the surgeries for subsequent collection and onward transport to the pathology laboratory by van or drone; although there is nothing in principle to prevent a bicycle courier delivering directly to the pathology laboratory should this be an optimal deployment of resources. FORSETI can accommodate the issue of precedence generated by consolidation (i.e., consolidation by bicycle courier must be completed prior to collection for onward transport), whilst still maintaining the 90-minute ITT constraint from the first collection in the collection round.

Bicycle courier rounds in FORSETI are assumed to start/finish at the surgery to which collections are consolidated for onward transport by van/drone. For example, a bicycle courier would typically depart from Surgery A, make collections (and deliveries of empty containers) from several nearby surgeries, before returning to Surgery A, where the consolidated load is then collected by van/drone for onward transport to the pathology laboratory. Bicycle couriers are assumed to have capacity for three medical containers.

The application of FORSETI to analyse each scenario (Table 1) consisted of a parameter sweep that varied the drone cost weighting (θ_2) incrementally (0–100 in steps of 0.5 generating 200 solutions for each scenario). Current van and bicycle courier costs are well-established and known with relative certainty, so their weightings ($\theta_1, \quad \theta_3$) were held constant (at 100) to give an effective variation in drone costs from 0% to 100% of current values across the sweep. For example, attaching no relative importance to minimising the contribution of drones to total scenario costs (i.e., $\theta_2 = 0$) is effectively equivalent to making drones free to use (i.e., 0% of current costs).

In this investigation, the emissions/energy consumption and maximum ITT weightings (θ_4 and θ_5, respectively) were set to zero throughout (i.e., no contribution to the objective function) in order to isolate the effect of the cost relationships, which was the focus of this study. In other words, although values for maximum ITT and emissions/energy consumption were calculated for each solution, it was assumed that cost was the driving factor in any organisation's decision to select drones for use in a multi-modal logistics system, a reasonable assumption for profit-driven commercial companies and impecunious public sector organisations alike.

3.3. Cost parameters

The cost parameter values used for the different transport modes in FORSETI were based on current (2022/23) estimates (Table 2). Not all cost parameters are required for each mode. Van cost values were obtained from the Manager's Guide to Distribution Costs published in the UK by the Freight Transport Association (FTA) [68]. Van driver labour costs (GBP 11.93/h, including pay for overtime and productivity) were those for drivers of light rigid vehicles (gross vehicle mass ≤7500 kg). Vehicle running costs (GBP 0.34/mi, including fuel, tyres, and maintenance) and standing costs (GBP 29.33/vehicle/day, including vehicle tax, insurance, depreciation, and overheads) were those for diesel vans with average annual mileage (36,000 miles/year). The FTA do not publish values for eVans, and therefore eVan cost values were assumed to be similar to those for diesel vans, which was reasonable as eVans continue to increase market share and are now competitive on a Total Cost of Ownership basis in Europe [69].

Drone cost values were obtained from a combination of literature sources, commercial information, and the drone expertise possessed by members of the FORSETI research and development team and associated partners (e.g., https://cascadeuav.com/). A detailed breakdown of costs and sources is provided in Appendix A. Drone labour costs (GBP 175.64/h) included: a mission commander in overall command of multiple drones (up to 20 simultaneously in this study, Section 3.2); two safety pilots prepared to take-over manual control should a drone's autopilot malfunction or other safety issues arise (one responsible for departure/arrival operations at the pathology laboratory and the other responsible for arrival/departure operations at GP surgeries); and two loader/technicians at the pathology laboratory (one responsible for receiving, accepting and onward transfer within the building of deliveries, and the other responsible for completing battery swaps and airworthiness checks). Loading of drones at surgeries was assumed to be completed as an additional duty for existing surgery staff, and hence incurred no extra cost.

Vehicle running costs (GBP 32.40/h) included the drone platform itself based on component life expectancies (e.g., airframe, motors, propellers, autopilots, and communications equipment) and electricity consumption. Vehicle standing costs (GBP 8.99/vehicle/day) included operational insurance and UAV Traffic Management (UTM) fees for access to airspace managed by UTM service providers. A profit margin was included for all drone costs based on the assumption that a public sector healthcare organisation (such as the NHS) would be unlikely to operate their own-account fleet of logistics drones (in contrast to own-account van fleets that many public sector organisations do operate), and would instead opt to buy-in drone services from an external drone service provider. The profit margin included was 3% (i.e., costs x 1.03), approximately in accordance with logistics industry standards [70].

Labour costs for both vans and drones were assumed to be paid for the entire modelled period. For example, for the four-hour morning shifts analysed in this study, van drivers and drone personnel were paid for four hours work at their hourly rate. This is how such workers are likely to be paid in practice (particularly in the UK public sector where the work force is ~50% unionised providing greater guarantees for employment terms and conditions [71]), rather than just being paid for the time they are actually engaged in operating a vehicle. In contrast, so-called gig economy workers, such as bicycle couriers, are often paid on a per task basis.

Bicycle courier cost values in FORSETI were based on an analysis of the prices charged for a set of journeys (n=293) in the UK by a real-world courier company (Stuart Couriers [67]), a provider of independent bicycle (and motorcycle/car) couriers in several European countries. Worker costs are charged on a per task basis (GBP 7.07/task), with a task defined as one bicycle courier journey starting at a given surgery, making collections from one (or more) other surgeries in close proximity, before returning to the start surgery to deliver a consolidated load for subsequent collection and onward transport to the pathology laboratory by van or drone (Section 3.2). Additional costs are incurred: for each extra collection stop (GBP 2.78/stop) in addition to the first collection; and for journey distance (GBP 1.01/mi) beyond an initial distance threshold of 0.5 miles. Hence, the cost of a bicycle courier journey (GBP) is given by: $Cost = 7.07 + 2.78(n_c - 1) + 1.01(d - 0.5)$, where n_c is the number of collection stops and d is the journey distance in miles. For example, one courier journey of 2.5 miles involving two collections would cost (1 task x GBP 7.07/task) + (1 additional stop x GBP 2.78/stop) + (2.0 mi x GBP 1.01/mi) = GBP 11.87.

Table 2
Cost parameters required for different modes.

Cost Parameter	Description	Units	Van	Bicycle Courier	Drone
cost_mile	Vehicle running costs per mile	GBP/mi	0.34	1.01[a]	-
cost_ph_lab	Labour costs per hour	GBP/h	11.93	-	175.64
cost_ph_veh	Vehicle running costs per hour	GBP/h	-	-	32.40
cost_task	Costs per task	GBP/task	-	7.07	-
cost_stop	Costs per stop in addition to the first stop	GBP/stop	-	2.78	-
cost_veh_day	Vehicle standing costs per day	GBP/veh./day	29.33	-	8.99

[a]Beyond a threshold distance of 0.5 mi.

4. Results

Through varying the drone cost weighting (θ_2) incrementally, whilst van and bicycle courier costs weightings (θ_1, θ_3) were held constant (Section 3.2), the effect of the relative costs of drones on their uptake in a multi-modal logistics network was analysed. An estimate of the amount by which drone costs would need to be reduced from current values to achieve financial viability was produced for each scenario listed in Table 1.

For the Southampton scenario with only drone suitable surgeries permitted (Soton_Suit in Table 1), drones began to be selected in lower cost solutions when drone costs were reduced to 3.5% of current values (Fig. 6a). Below this tipping point (defined as the price point, as a percentage of current drone costs, at which drones first start to be selected in a given scenario; i.e., 3.5% in this case), two drones were selected (Fig. 6b), servicing all nine drone suitable surgeries and allowing the removal of one van, i.e., number of vans reduced from five to four (Fig. 6c).

When all surgeries were permitted (Soton_All in Table 1), the tipping point occurred at 18.5% of current values (Fig. 6d). Ultimately, as the costs of drones approached 0% of current values (i.e., free to use), drones were the only mode selected, with 12 drones sufficient to service all surgeries during the four-hour shift (Fig. 6e) and the number of vans reduced to zero (Fig. 6 f). Compared to using vans, transporting all samples by drone reduced maximum ITT from 81 to 33 minutes (60% reduction), although the level of service requirement for sample transit times (i.e., <90 minutes) was satisfied in any case. A map of routes for all modes in a solution involving partial uptake of drones when all sites were permitted (i.e., Soton_All scenario) is shown in Fig. 7. A summary of the key results for the Southampton (and IOW) scenarios is presented in Fig. 8.

For the IOW scenario with only drone suitable surgeries permitted (IOW_Suit in Table 1), drones began to be selected in lower cost solutions when costs were reduced to 12.0% of current values (Fig. 9a). After

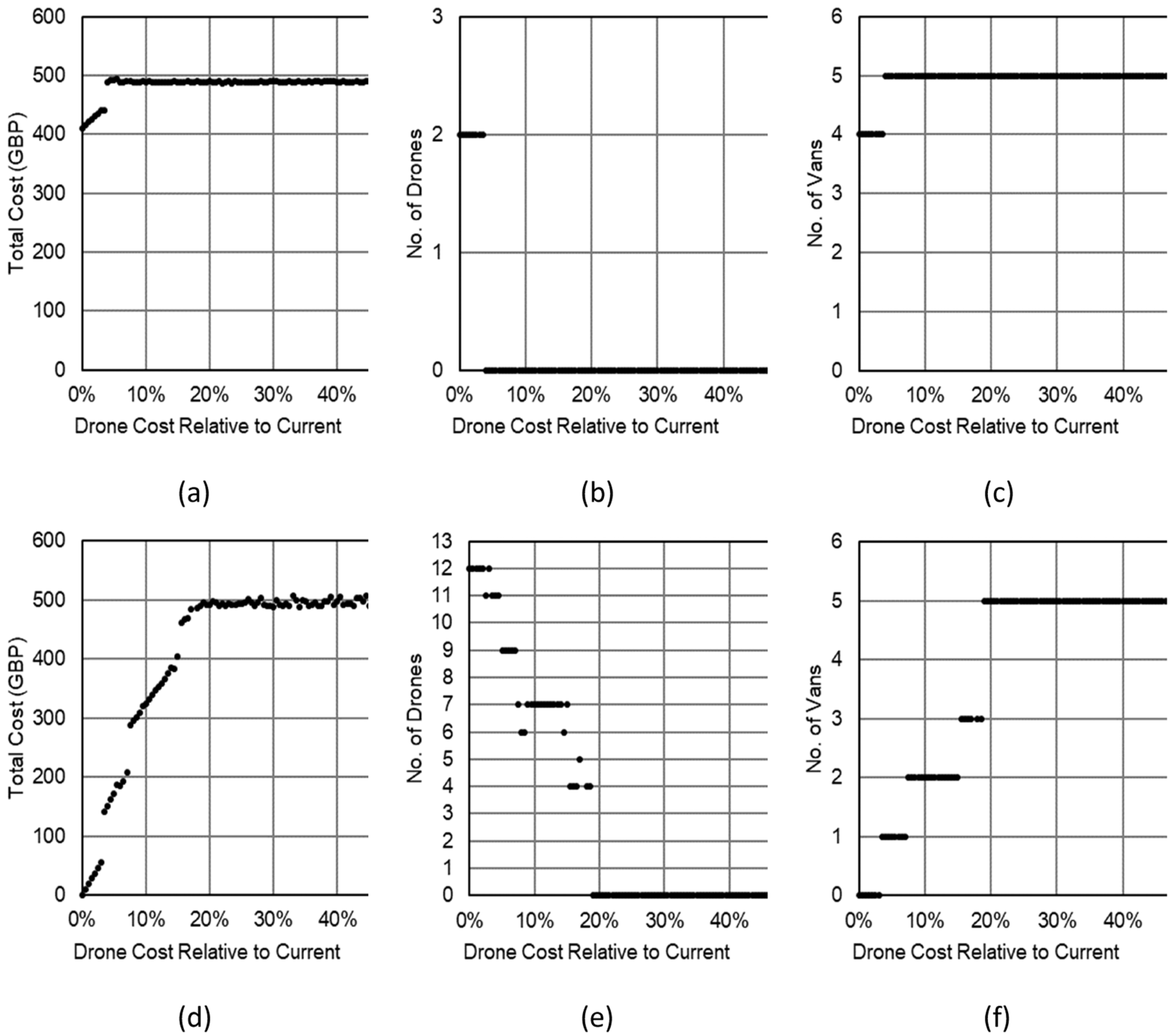

Fig. 6. Southampton cost analysis plotted against drone costs relative to current values. Only drone suitable surgeries permitted: total scenario cost (a), drone uptake (b), and number of vans used (c). All surgeries permitted: total scenario cost (d), drone uptake (e), and number of vans used (f).

this tipping point (i.e., 12.0% and below), one (and eventually two) drone(s) were selected (Fig. 9b), servicing all twelve drone suitable surgeries and allowing the removal of one van, i.e., number of vans reduced from two to one (Fig. 9c).

When all surgeries were permitted (IOW_All in Table 1), the tipping point also occurred at 12.0% of current values (Fig. 9d), i.e., the same percentage as in the IOW_Suit scenario. Again, as the costs of drones approached 0% of current values (i.e., free to use), drones were the only mode selected, with four drones sufficient to service all surgeries (Fig. 9e) and the number of vans reduced to zero (Fig. 9 f). Compared to using vans, transporting all samples by drone reduced maximum ITT from 66 to 19 minutes (71% reduction), although the level of service requirement (i.e., $<$90 minutes) was satisfied in any case. A map of routes for all modes in a solution involving partial uptake of drones when all surgeries were permitted (i.e., IOW_All scenario) is shown in Fig. 10. A summary of the key results for the IOW (and Southampton) scenarios is presented in Fig. 8.

The noise evident in the plots of total scenario costs (Fig. 6a & d for Southampton, Fig. 9a & d for IOW) was due to randomness in the optimisation algorithm, which meant very small route variations were possible between solutions. The discontinuities evident in these same plots are associated with the progressive removal of each van from the solution, leading to a step-change reduction in total scenario costs. An exception to this was the first van removal in the IOW scenarios. This van had relatively low utilisation (operating for only 1 h 40 m during a four-hour shift), and even though the van's fixed (i.e., labour and vehicle standing) costs were saved, the overall effect of its removal on total scenario costs did not produce a large step-change in results.

Bicycle couriers were rarely selected in any of the scenarios. This was because consolidation by bicycle courier was relatively expensive compared to the alternative of vans making additional stops. For example, if a diversion for an extra stop created an additional 2 km of van driving distance (a reasonable approximation of the additional distance required for a van to visit a nearby surgery that might otherwise be consolidated by bicycle courier), this would add GBP 0.42 to total costs (0.34 GBP/mi for vans in Table 2), whilst a bicycle courier journey costs a minimum of GBP 7.07. In fact, bicycle couriers were never selected in any solution for either of the IOW scenarios because the network layout meant that, in any cluster of surgeries that could present an opportunity for consolidation, a van was likely to be passing very close to all surgeries in the cluster anyway, making consolidation by bicycle courier the more costly option. Instead of cost reductions, the main benefit of bicycle couriers tends to be associated with the potential they offer for reduction of CO_2 emissions compared to vans and drones, making their selection more likely if organisations are more concerned with the environmental impacts (rather than costs) of their operations

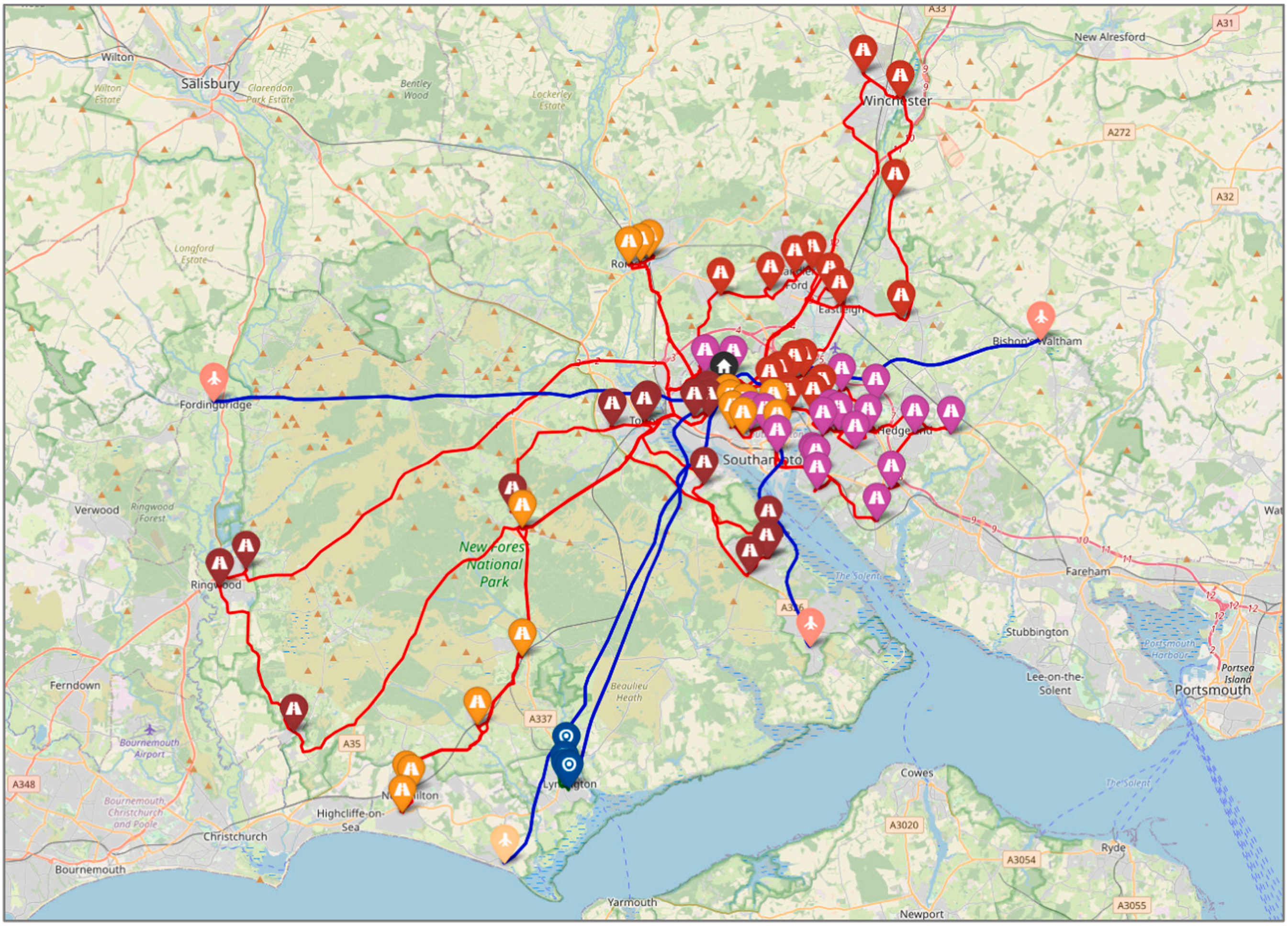

Fig. 7. Map of an example solution for Southampton with all surgeries permitted. Blue, red and green lines indicate drone, van and bicycle courier routes, respectively. Pins indicate surgeries: road symbol is van served; aeroplane symbol is drone served; wheel symbol is consolidated by bicycle courier. Black pin with white house indicates Southampton General Hospital. Base map source: OpenStreetMap.

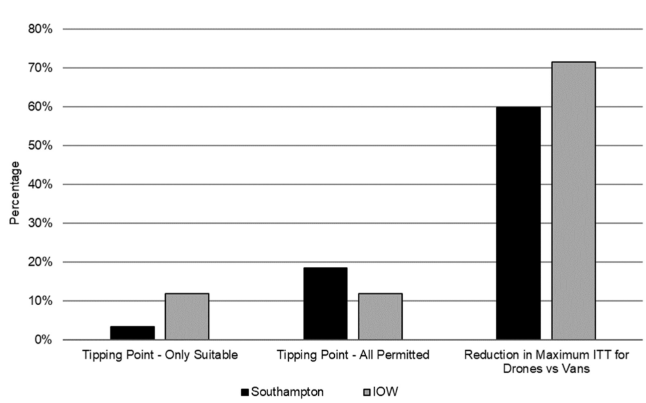

Fig. 8. Tipping points and transit time reductions for Southampton and the IOW. As drone costs were reduced, Tipping Point is the price point at which drones first started to be selected as a percentage of current drone costs. Only Suitable indicates scenarios where only drone suitable surgeries were permitted for service by drone; All Permitted indicates scenarios where all surgeries were permitted for service by drone. Reduction in Maximum ITT for Drones vs Vans is the reduction in maximum ITT when only drones served all surgeries as a percentage of when only vans served all surgeries.

[72–74].

5. Discussion

The key points highlighted in the results of the study have been organised into three sections for convenient discussion: (i) the implications of the scale of the drone cost reductions estimated to be necessary to achieve financial viability (Section 5.1); (ii) the potential effects of network characteristics on necessary drone cost reductions (Section 5.2); and (iii) the other factors that could influence the viability of drone logistics (Section 5.3).

5.1. Implications of necessary drone cost reductions

From the results it was evident that, for the four case study scenarios (Table 1), there were tipping points for reductions in drone costs (price points ranging from 3.5% to 18.5% of current drone costs) below which drones can offer cost advantages in an integrated multi-modal logistics system as an alternative to traditional surface modes (i.e., vans, bicycle couriers). However, these tipping point values represented considerable cost reductions, suggesting drones are unlikely to be financially viable under the cost structures currently prevailing in the logistics and drone industries.

The target for maximum elapsed time between collection and delivery (i.e., ITT) for samples to remain viable for analysis (90 minutes, Section 3.1) was achieved in every scenario solution, and there was

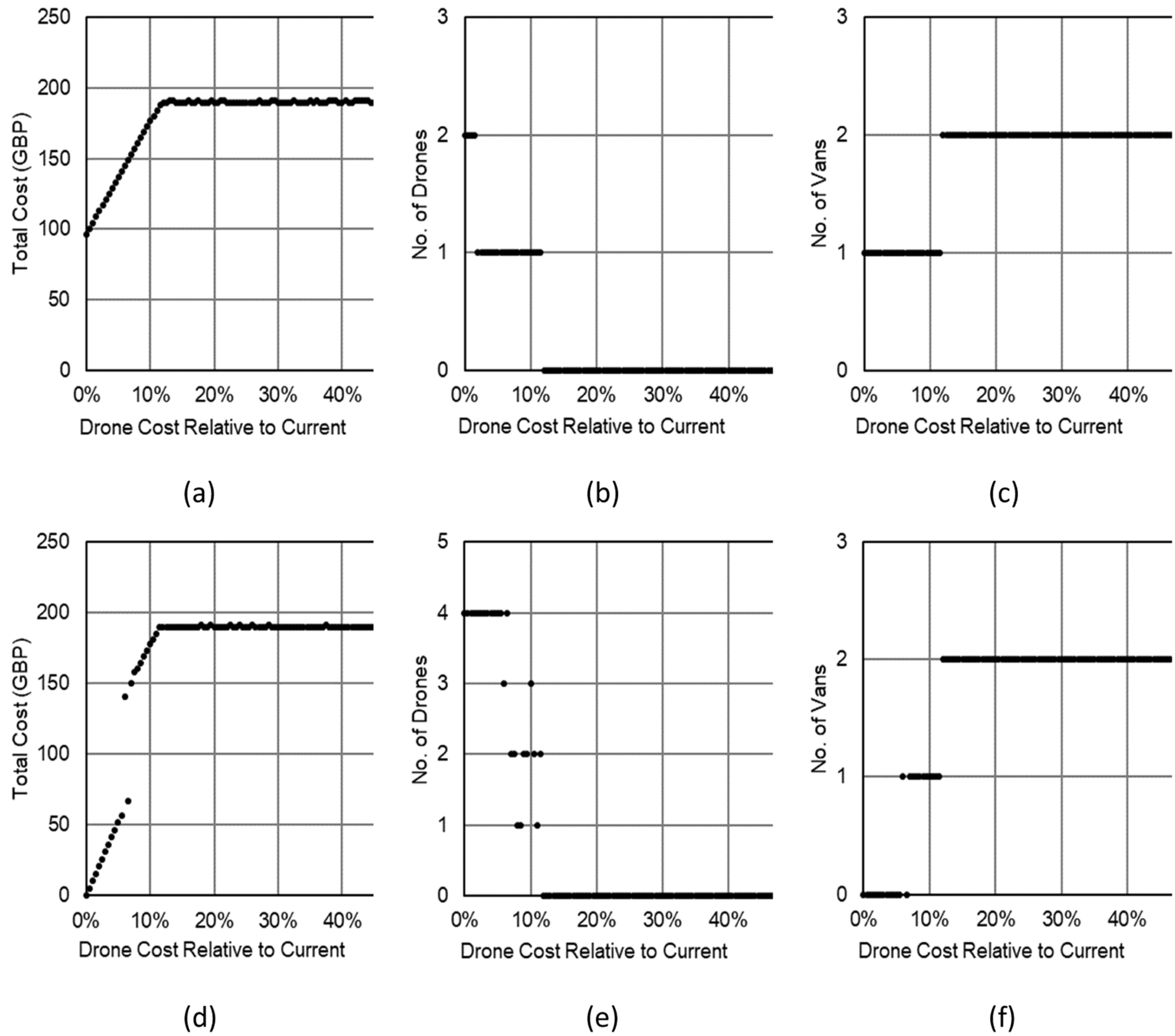

Fig. 9. IOW cost analysis plotted against drone costs relative to current values. Only drone suitable surgeries permitted: total scenario cost (a), drone uptake (b), and number of vans used (c). All surgeries permitted: total scenario cost (d), drone uptake (e), and number of vans used (f).

therefore no meaningful benefit offered by drones in terms of reduced transit times compared to vans and bicycle couriers. In other words, in all solutions (with or without drones) level of service requirements for transit times were met, in large part due to the good accessibility of surgeries via a well-developed and reliable surface network of roads in both testbed areas. Moreover, the assumption in this study of 90 minutes as the maximum ITT represents the “gold standard” from the literature (Section 3.1). In reality, level of service requirements in the NHS in the UK are often more relaxed (e.g., maximum ITT of 120 minutes [54], or even as much as 240 minutes [75]), meaning there is little doubt that level of service requirements could be satisfied comfortably by surface transport modes without any need for the reduced transit times offered by drones.

Discussions with NHS staff suggested that, in terms of the wider patient diagnostic and treatment system as a whole, the benefits of transit time savings in excess of level of service requirements were likely to be negligible due to limitations elsewhere in the system. For example, samples may be delivered more rapidly to the pathology laboratory but then remain unprocessed for a while (e.g., several hours) due to a lack of laboratory processing capacity, or samples may be delivered and processed more rapidly (e.g., diagnosis within several hours rather than a day) but this is unlikely to lead to patients commencing treatments any sooner than under the existing system without considerable investment in the onward patient care process. The typical expectation within the NHS for providing patients with the results of tests on routine pathology samples is that results may be produced after a few days, and usually within a few weeks [76].

Essentially, reducing ITT for transport of routine pathology samples by minutes or hours (as is possible through the use of drones instead of vans and/or bicycle couriers) is likely to be inconsequential in terms of significant beneficial health outcomes for patients when waiting times for treatment in the wider healthcare system are measured in days or often weeks [77]. In these circumstances, it is unlikely there would be any significant value attached to the reduced payload transit times offered by drones from the perspective of improved patient care outcomes through faster diagnostics, meaning there is no additional benefit which could then be used to justify the additional cost of drones. In contrast, for specific use cases involving the delivery of certain time-critical medical items (e.g., AEDs, anti-epileptics) in out-of-hospital emergency situations (as opposed to the delivery of routine pathology samples considered in this study), it is possible that the rapid transit times offered by drones could improve patient outcomes and be cost-effective [31].

In general, it was the relatively expensive labour costs of drones (GBP 175.64/h, Table 2) compared to vans (GBP 11.93/h) and bicycle couriers (equivalent to ~GBP 15.00/h based on completing two tasks per

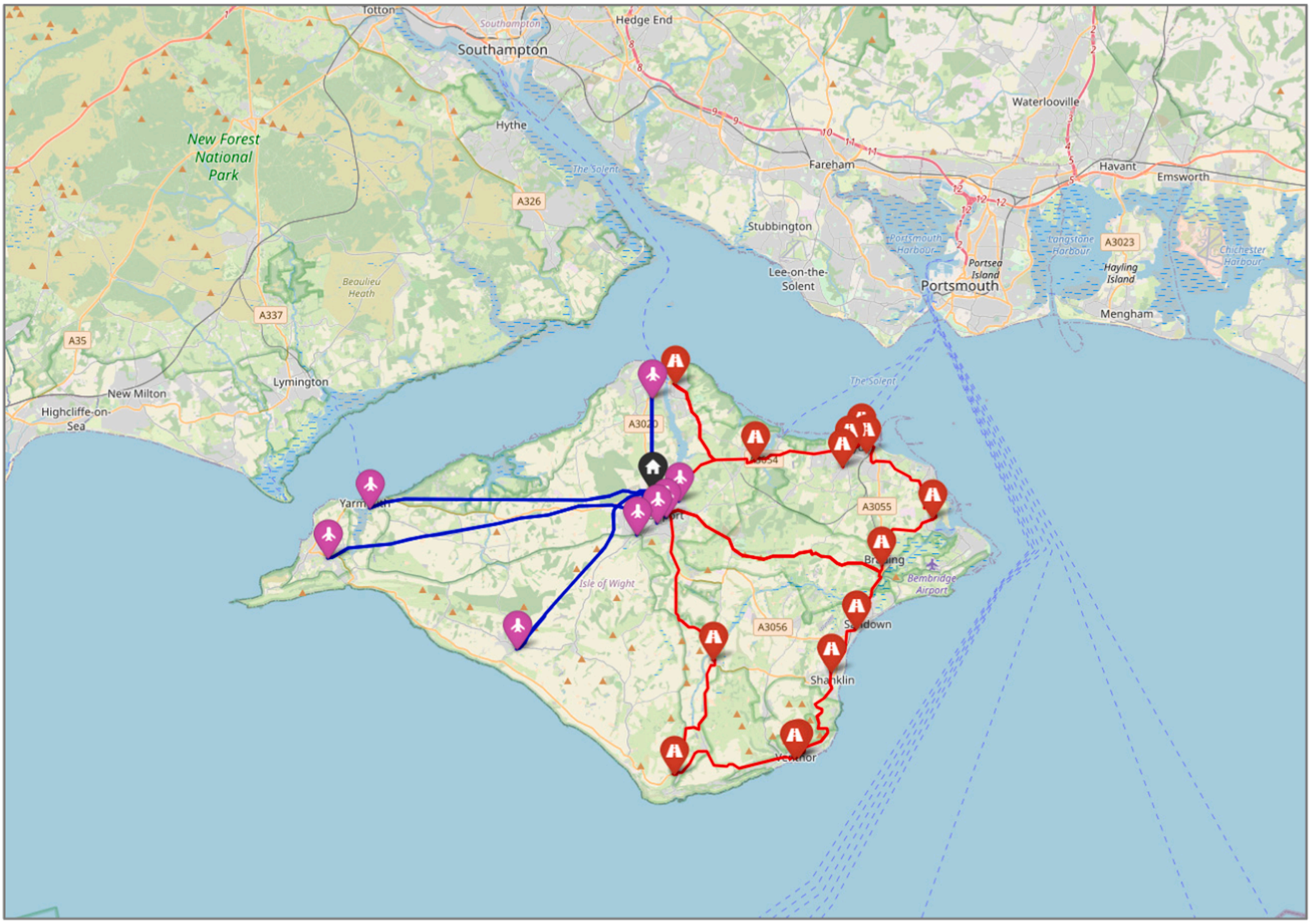

Fig. 10. Map of an example solution for the IOW with all surgeries permitted**.** Blue and red lines indicate drone and van routes, respectively. Pins indicate surgeries: road symbol is van served; aeroplane symbol is drone served. Black pin with white house indicates Saint Mary's Hospital. Base map source: OpenStreetMap.

hour) that had the largest effect on drones' lack of financial viability. It is reasonable to expect that automation of drone logistics operations will increase as technologies advance and regulatory environments mature, and this increased automation is likely to reduce drone labour costs.

For the purposes of discussing financial viability under a regime of increased automation, an estimate of potential future drone costs was calculated (Table 3). These future drone costs were estimated in terms of current (2022/23) currency (GBP) values (i.e., they are not true future drone costs taking in to account an estimate of inflation in the logistics sector during the intervening years), which allowed direct, like-for-like comparisons to be made with the current costs used elsewhere throughout the study. As an emerging technology and potential new mode for logistics, drones are more likely to experience considerable cost reductions as/when the drone logistics market matures and becomes routine, compared to vans and bicycle couriers where the logistics market is already well-established and cost trends known with relative certainty through years of recorded experience. One caveat to this is that van costs may also experience cost reductions in the future due to factors such as the maturing of the eVan market and the potential introduction of autonomous vehicles. Such cost reductions for competing transport modes would negatively affect the financial viability of drones as a potential alternative, meaning the drone cost reductions required may be even greater than they were when compared to current van and bicycle courier costs.

Table 3
Current and future values for drone cost parameters.

Cost Parameter	Units	Current Values[a]	Potential Future Values
cost_ph_lab	GBP/h	175.64	31.44
cost_ph_veh	GBP/h	32.40	20.33
cost_veh_day	GBP/veh./day	8.99	8.99

[a]Current values are reproduced from Table 2.

Increased automation was assumed to result in employment as a mission commander becoming a less skilled (and therefore lower paid) occupation (revised cost GBP 20.26/h [78]), and for the requirements for safety pilots and loader/technicians to be reduced or removed completely. Future labour costs (GBP 31.44/h in Table 3) included one mission commander (revised cost) and one loader/technician (same cost as current; Appendix A). A linearly decreasing (from 3% per annum to 0% per annum over a 30-year period), compound annual rate of reduction (equivalent to 0.626 x current cost) was applied to the drone platform (revised cost GBP 19.60/h) to account for the evolution of technology and new manufacturing methods/processes, and for economies of scale in manufacturing due to the forecast expansion of the global drone industry [79–81]. Future vehicle running costs (GBP 20.33/h in Table 3) included the drone platform (revised cost) and electricity consumption (same cost as current; Appendix A). Vehicle standing costs (GBP 8.99/vehicle/day in Table 3) were assumed to remain as current. Additionally, as was the case for the original estimation of current drone costs (Section 3.3), all future costs included a 3% profit margin.

The combined effect of the future reductions in the individual drone cost parameters (cost_ph_lab, cost_ph_veh and cost_veh_day in Table 3) was to reduce overall drone operating costs to an estimated 43% of

Table 4
Comparison of future and current drone operating costs.

	Soton Testbed	IOW Testbed	Combined Overall	Combined Overall (Future Shared-Capacity Regime)
Current Cost (GBP)	1843.66	1030.54	2874.20	2874.20
Future Cost (GBP)	881.96	344.96	1226.92	1143.45
Max Simultaneous Drones	12	4	16	16
Mission Commander Capacity	20	20	40	20
Future as % of Current Cost	48%	33%	43%	40%

current values (Table 4). This estimate was produced using FORSETI to calculate total scenario costs in the Southampton and IOW testbeds with only drones available to service all surgeries (i.e., vans and bicycle couriers switched off as possible transport modes), firstly with current cost parameter values, and then with estimated future values, giving: (Soton_Future + IOW_Future)/(Soton_Current + IOW_Current) = (GBP 881.96 + 344.96)/(GBP 1843.66 + 1030.54) = 43% (Table 4). In contrast, even in the scenario most favourable to drone uptake (Soton_All in Table 1), the tipping point did not occur until drone costs were reduced to 18.5% of current values. In other words, the estimated possible reduction in future drone costs (100% - 43% = 57% reduction) was still some way short of the reduction necessary for drones to become financially viable in multi-modal logistics systems (100% - 18.5% = 82.5% reduction).

If the maturing and expansion of the drone logistics market leads to a sufficiently high level of consistent demand, one other possible way to reduce drone labour costs in the future would be to improve utilisation of mission commanders. In this study, the operator-to-vehicle ratio for drones was set at 1:20 (Section 3.2; and this could conceivably increase further in a future involving more drone automation), but the maximum number of drones monitored simultaneously in any scenario solution was 12. Hence, spare monitoring capacity existed, which suggested there was potential to combine monitoring workloads (i.e., sharing mission commander capacity across multiple applications) to reduce the number of mission commanders required, and therefore reduce the fixed costs associated with labour.

The potential for a shared-capacity regime to reduce future drone costs was explored in relation to the case study by assuming one mission commander could monitor both testbeds simultaneously (i.e., the required number of mission commanders reduced from two to one), which increased utilisation to 80% of capacity (i.e., a maximum of 16 drones (12 in Southampton plus 4 in the IOW) monitored simultaneously out of a capacity of 20) and produced a reduction in overall drone operating costs to an estimated 40% of current values (Table 4). This estimate was calculated in the same way as for the non-shared-capacity regime, but with the (revised future) cost of one mission commander over a four-hour shift (GBP 20.26/h x 4 x 1.03 profit margin = GBP 83.47) deducted from the future costs, giving: (GBP 881.96 + 344.96 – 83.47)/(GBP 1843.66 + 1030.54) = 40% (Table 4). Again, the estimated reduction in future drone costs in a shared-capacity regime (100% - 40% = 60% reduction) was still some way short of the reduction necessary for drones to become financially viable, even in the scenario most favourable to drone uptake (100% - 18.5% = 82.5% reduction in Soton_All).

5.2. Effects of network characteristics

The effect of the proportion of drone suitable surgeries in the network can be seen by comparing the two Southampton scenarios. Here, the tipping point occurred at a higher value when all surgeries were permitted compared to when only drone suitable surgeries were permitted (Soton_Suit = 3.5% vs. Soton_All = 18.5%). When drones were limited to only suitable surgeries (12% of surgeries in Soton_Suit, Table 1), vans were still required to service the remaining surgeries. This increased the likelihood that a van round would be passing close to any given drone suitable surgery, meaning it tended to be cost advantageous for the van to service that surgery instead of using a drone; i.e., one extra stop on a van round tended to be a less expensive alternative to sending a drone (this was true as well for potential consolidation by bicycle courier, which was also relatively expensive compared to the alternative of a van making an additional stop, Section 4). Hence, drone costs had to reach a lower tipping point before drones started to be selected.

When the proportion of drone suitable surgeries was increased to all surgeries (100% of surgeries in Soton_All, Table 1), the necessity for vans to be used anyway was removed, meaning drones could offer cost advantages at a higher tipping point by eliminating vans from entire regions of the testbed area. The first surgeries adopted for drone service tended to be those in more remote regions on the far South and West of the area (on the far side of the New Forest National Park region), followed by surgeries located in other geographical extremities, which can be seen in the example solution involving partial uptake of drones shown in Fig. 7.

Stem mileage and cost-per-collection is higher for van rounds in more remote regions compared to the city region (where surgery density is higher and the pathology laboratory is less distant), and therefore surgeries in these regions offered the greatest benefits from a cost perspective. In addition, due to the interaction of the operator-to-vehicle ratio (1:20) with drone labour costs (Section 3.3), the marginal cost of an extra drone (up to 20) was relatively small compared to the initial cost of the first drone, and having all surgeries permitted provided greater scope for using extra drones at these marginal costs compared to when only drone suitable surgeries were permitted (ultimately, a maximum of 12 drones were used (Fig. 6e) compared to a maximum of 2 when only drone suitable surgeries were permitted (Fig. 6b)).

In contrast, comparing the two IOW scenarios, the tipping point occurred at the same value in both scenarios (IOW_Suit and IOW_All = 12.0%). This was due to a combination of two factors. Firstly, the IOW had a relatively high proportion of drone suitable surgeries to start with (55% of surgeries were drone suitable compared to only 12% in Southampton, Table 1), which meant that there was little difference in how the progressive uptake of drones occurred in both IOW scenarios (i.e., similar pattern of surgeries transferring from van to drone service) as drone costs were incrementally reduced; and secondly, the first van to be removed had low utilisation, which meant it could be fairly easily transferred to drone service at the same price point in both scenarios (Section 4).

Considering further comparisons between Southampton and the IOW suggested that other network characteristics (as well as proportion of drone suitable surgeries) must also influence tipping point values; for example, characteristics such as geographic scale, total number of surgeries, surgery clustering, road types, road layout, etc. Comparing the two scenarios where the proportion of drone suitable surgeries was the same (i.e., 100% of surgeries permitted in both Soton_All and IOW_All), the tipping points were found to be different (Soton_All = 18.5% vs. IOW_All = 12.0%). Typically, due to its larger geographic scale and road layout, the network in Southampton had more van rounds involving high stem mileages than there were in the IOW network (e.g., van routes to service surgeries located in geographically remote regions, a long distance from the SGH pathology laboratory, such as the New Forest National Park). Such routes were relatively costly for vans due to the time and distance associated with travelling the high stem mileage, which meant drones became financially viable at higher costs in Southampton than in the IOW.

The influence of different network characteristics on the financial viability of drone logistics is an area that requires further research.

Ideally, this research should aim to produce generalisable findings, so that they can be applied to any logistics network where the introduction of drones is under consideration. In essence, such work would constitute sensitivity analyses exploring the sensitivity of the financial viability threshold (i.e., tipping point) to varying network characteristics (e.g., network size, clustering of surgeries, centrality of pathology laboratory).

5.3. Other influential factors

There are a number of other factors (other than costs) that could influence the viability of drone logistics, and these are discussed in this section (Section 5.3). The closest that drones came to being financially viable in this study was in scenarios where all surgeries were assumed to be suitable for servicing by drones (i.e., Soton_All at 18.5% of current costs); although this would still require a large reduction in current costs that may well not be achievable, even with reduced costs due to automation in the future (future drone costs estimated to be ~43% of current costs, or 40% of current costs in a shared-capacity regime). This assumption may be an overly optimistic prediction for the expansion of drone landing zones. In reality, it could prove difficult for all surgeries to find suitable open space (~100 m^2, Section 3.1) and gain the appropriate permissions from regulatory authorities (e.g., land-use planning authority, National Aviation Authority), particularly in dense urban areas, that would be required to enable safe drone collections, which in turn would limit the financial viability of logistics drones.

The alternative of drone collections via cable/winch systems (i.e., avoiding the need for landing zones) may prove impractical for reasons such as the difficulties of safely connecting medical containers via a cable during collection below a hovering drone in all weather conditions. Wing (the Alphabet subsidiary) has developed an automated cable/winch system that requires minimum human intervention [82], but this involves much smaller packages (<1.5 kg) in purpose-built packaging and does not need to allow for the issues associated with carrying payloads that could be classified as dangerous goods when carried by air (e.g., pathology samples), requiring movement in a certified crash-protected container [5,83,84].

Typically, logistics systems aim for certainty of delivery based on reliable modes of transport. In comparison to established logistics modes such as vans and bicycle couriers, current limitations of emerging drone technology could affect their reliability. The study assumed that drone flights were never precluded by weather conditions exceeding a drone's weather tolerance (typically, 50 mm/h precipitation and 10 m/s wind speed, Section 3.2). However, recent analyses of historical weather data in the Southampton region by Oakey et al. [11] and Oakey and Cherrett [85] found that ~20% of drone flights would not be possible due to poor weather involving strong winds (assuming typical drone weather tolerance, Fig. 11). Therefore, back-up arrangements to make collections when drones cannot fly would be needed, and these would be likely to incur additional costs. For example, discussions with NHS staff suggested that commercial taxi operators were often used on an ad-hoc basis for pathology sample collections when other options were not available. Drone weather tolerance needs to improve to increase service reliability levels and minimise the costs associated with implementing back-up arrangements; although it will be challenging for drones to match the reliability of vans and bicycle couriers that can operate in all but the most extreme weather conditions.

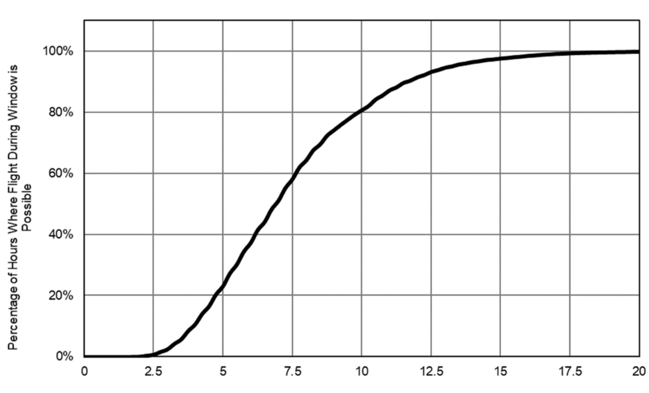

Fig. 11. Ability to fly at different platform wind tolerances for a VTOL/FW hybrid drone. The data are based on a weather window of 08:00–17:00 from Mar 2019 to Feb 2020 in the Solent region on the South coast of the UK. Source: adapted from Oakey and Cherrett [85].

Being commercial aircraft, logistics drones are likely to be subject to more stringent and/or frequent serviceability testing regimes (e.g., airworthiness checks prior to every departure, Section 3.1) compared to vans or bicycles, with vans typically subject only to annual serviceability testing (e.g., the annual test of roadworthiness known as the MOT required in the UK) and bicycles typically not subject to any serviceability testing requirements at all. Hence, vans and bicycle couriers are more likely to be able to continue operating whilst carrying minor malfunctions, i.e., drones are more likely to be prevented from operating due to unserviceability than vans or bicycles. Again, this would require back-up transport arrangements to be in-place to make collections when drones cannot fly, incurring additional costs. The associated safety issue of drones suffering in-flight failures (even after passing pre-departure airworthiness checks) leading to crashes was addressed in this study through FORSETI producing drone trajectories balanced between energy and risk optimal flightpaths, which tended to deviate around higher risk areas with higher population densities (Section 3.2.3).

The study assumed that only pathology samples were transported within the testbed logistics networks. In practice, other payloads such as paper records, bulky medical supplies or equipment (e.g., clean linen, cleaning equipment/products), and internal post may also need to be transported alongside the samples. In this situation, drones are unlikely to be a suitable option for carrying these heavy and/or bulky items, and vans and/or bicycle couriers with their greater payload capacities would become more attractive options. The cost composition of the drone platform (Section 3.3 and Appendix A) was based on the drone type assumed in FORSETI, which has sufficient payload capacity for one medium-sized medical container (Section 3.2.3). If drones were required to carry payloads of larger volumes/masses, then the cost composition of the drone platform would be likely to change, which limits the universal applicability of model results, although the majority of drone costs were associated with labour rather than the vehicle itself (Table 2). A drone of the type assumed in this study had a range of ~150+ km (Section 3.1) which, although less than the range of a typical eVan (~200+ km, Section 3.1), was sufficient to service all locations in the testbed logistics networks. However, reaching all desired locations in geographically larger networks may be challenging without the use of intermediate battery-swap and/or charging stations, particularly if drones are required to carry larger payloads over longer distances.

The expansion of routine drone logistics operations still faces many regulatory and technological challenges. For example, viable drone logistics is likely to require drones to be flown longer distances beyond visual line of sight (BVLOS) of operators, integrated in shared airspace alongside existing crewed air traffic [10]. Typically, the way in which BVLOS flights are achieved currently is by drone operators applying to the relevant NAA to activate a temporary Segregated Airspace Volume (SAV) that excludes all other air traffic from the vicinity of the drone operations. However, SAVs are inconvenient for other airspace users and are not a scalable solution [6]. Aviation regulators around the world are aware of these challenges, and work to develop and implement fully integrated, shared airspace solutions is on-going under the generic over-arching concept of UAV Traffic Management (UTM), but all such solutions are likely to require reliable Detect-And-Avoid systems to be established to provide inflight de-confliction between aircraft, based on fitting standardised electronic conspicuity equipment to all aircraft involved [6,10].

The effects on drone flightpaths of any airspace constraints were ignored in the study. For example, zones of low-level controlled airspace that typically surround airports (e.g., Southampton airport) for the protection of crewed aircraft where it may be difficult to obtain crossing clearances for drones, or zones of designated UTM airspace involving pre-specified locations of corridors for drone operations. These airspace constraints could extend route distances for drones; although UTM drone corridors are likely to follow routings with low ground risk where possible, so there would be some alignment expected with the drone routes used in this study.

The scope of this study was limited to exploring the financial viability of drones (i.e., a focus on the effects of drone costs). Whilst costs are undoubtedly an important driver of organisational decision-making, consideration of the environmental impacts of using drones for logistics compared to more traditional transport modes may also become an increasingly important driver given the current global focus on climate change and reducing carbon footprints. It has been suggested that drones could have the potential to reduce the carbon emissions associated with logistics operations, and this potential may start to receive similar attention to costs from some organisations, particularly when influenced by carbon pricing schemes [29,86].

Drones' potential to reduce carbon emissions should be treated with caution, however. For example, the typical perception is that logistics drones are electrically powered, leading to the assumption that they offer a low-emission alternative to existing diesel van fleets. This assumption may be somewhat questionable, given that the transition to eVan fleets is a committed change in many cases [61,86]. In addition, drones are assumed to be more appropriately sized with respect to their payloads, thereby reducing the energy consumption and emissions associated with inefficient less-than-truckload operations. Again, this assumption may be somewhat questionable, given the opportunities to improve efficiency through consolidating payloads for transport by ground vehicles with larger payload capacities (i.e., vans), producing economies of scale [8]. This study was focussed on isolating the effects of drone costs on the uptake of drones in multi-modal logistics systems, but investigation of the effects of environmental factors (e.g., energy consumption, carbon emissions, air pollutant emissions, noise pollution) is important as well and is suggested as an area for further research.

6. Conclusions

Drones could be a financially viable option in some multi-modal logistics systems integrated with traditional surface modes, but only in circumstances where their costs were considerably less expensive than current values, i.e., a reduction below ~19% of current values would be necessary. Reduced payload transit times are often suggested as a potential benefit of drone logistics, but in the case study scenarios analysed, the level of service requirement for pathology sample transit times (<90 minutes elapsed time between collection and delivery) was met in all solutions (with or without drones), which meant it was unlikely there would be any value attached to faster delivery by drone in the wider patient diagnostic and treatment system as a whole (e.g., improved patient care outcomes through faster diagnostics) that could be used to off-set their additional costs.

In general, it was the relatively expensive labour costs of drones compared to vans and bicycle couriers that had the largest effect on drones' lack of financial viability. In the future, drone labour costs could be reduced by automation and drone platform costs could be reduced by evolution of technology and economies of manufacturing scale. However, in combination, these reductions only achieved a reduction in overall drone costs to ~43% (or 40% in a shared-capacity regime) of current values, which suggested that necessary reductions to ~19% of current values may not be feasible at all.

Financial viability of drones also relied on several other factors that may be difficult to achieve in practice. These factors included: that all sites in the logistics network were suitable for service by drones; that the weather tolerance of drones was sufficient to allow them to operate in most weather conditions; that there was little or no demand to transport bulky and/or heavy items, where vans and/or bicycle couriers with their greater payload capacities would be more attractive options; and that drone flightpaths were not significantly extended due to airspace constraints.

Network characteristics effected the financial viability of logistics drones. However, it is not possible to generalise these effects based solely on the results of the four case study scenarios analysed in this study. Further research is required to investigate the effect of varying network characteristics on financial viability, with the aim of establishing general relationships that can be applied by any organisation considering the potential for drone logistics operations.

The scope of this study was the financial viability of drones (i.e., a focus on drone costs). However, organisations may also place importance on other factors (alongside costs) such as energy consumption, air pollutant emissions, or transit times (or some weighted combination of all these factors), and further research is required to investigate the interaction of these different objectives.

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Declaration of Competing Interest

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

Data Availability

The data that have been used are confidential.

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Appendix A

Table A1
Drone cost values.

Item	Cost (GBP)	Cost Basis
Mission Commander	50.00	Per Hour
Safety Pilot	50.00	Per Hour
Loader/Drone Technician	10.26	Per Hour

(*continued on next page*)

Table A1 (*continued*)

Item	Cost (GBP)	Cost Basis
Operational Insurance and UTM Fees (including: third party liability, noise liability, invasion of privacy liability, product liability, employer's liability, and professional indemnity)	2200.00	Per Year
Electricity	0.17	Per kWh
Forward Motor (e.g., Dualsky XM6360EA-19 220KV, assumed life 1000 flight-hours)	0.10	Per Flight-Hour
Forward Electronic Speed Controller (ESC) (e.g., Hobbywing 100 A 12 s HV, assumed life 100 flight-hours)	1.00	Per Flight-Hour
Forward Propeller (e.g., 21" pusher propeller, assumed life 100 flight-hours)	0.50	Per Flight-Hour
VTOL Motor (e.g., 4x Eaglepower UA90 150KV, assumed life 1000 flight-hours)	0.32	Per Flight-Hour
VTOL ESC (e.g., 4x Hobbywing 80 A 12 S ESC, assumed life 100 flight-hours)	3.20	Per Flight-Hour
VTOL Propeller (e.g., 4x Eaglepower UC2480L 24″ propeller, assumed life 100 flight-hours)	1.60	Per Flight-Hour
Servo (e.g., 2x Savox SC-1256 TG, 2x Savox SC-1251MG, 2x Savox SH-0263MG, assumed life 250 flight-hours)	1.20	Per Flight-Hour
Li-Po Battery (e.g., 2x Tattu HV 32,000mAh 6 S 10 C, assumed life 500 flight-hours)	1.20	Per Flight-Hour
Airframe Base Platform (e.g., Mugin-5 Pro, assumed life 1000 flight-hours)	10.00	Per Flight-Hour
Autopilot (e.g., Distributed Avionics Masterless, assumed life 1000 flight-hours)	10.00	Per Flight-Hour
Satellite Receiver (e.g., Honeywell Satcom, assumed life 1000 flight-hours)	0.50	Per Flight-Hour
Terrestrial Mobile Network Receiver (LTE) (assumed life 1000 flight-hours)	0.20	Per Flight-Hour
Radio Communications (assumed life 1000 flight-hours)	0.20	Per Flight-Hour
Radio Control Unit (x2) (assumed life 1000 flight-hours)	0.30	Per Flight-Hour
Ground Control System (assumed life 1000 flight-hours)	1.00	Per Flight-Hour

Values were obtained from a combination of literature sources, commercial information, and the drone expertise possessed by members of the FORSETI research and development team and associated partners (e.g., https://cascadeuav.com/). Specific sources were: Lin *et al.* [87]; NHS [88]; BEIS [89]; Distributed Avionics [90]; Honeywell [91]; and Mugin [59]. Example aircraft components are shown to provide an indication of how the costs for a drone were estimated. The generic drone modelled within FORSETI was not necessarily fitted with these specific components.

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