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Investigating the emissions effect of integrating drones into mixed-mode logistics – A case study of a healthcare setting

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ABSTRACT
Interest is growing in the potential of using Uncrewed Aerial Vehicles (UAVs; known as drones) for logistics applications (i.e. last-mile payload delivery). Based on case studies of pathology specimens taken from patients at community clinics and transported to central laboratories for analysis, the effect on greenhouse gas emissions of using drones alongside more traditional transport modes (i.e. electric vans (e-vans) and bicycle couriers) in mixed-mode logistics systems was investigated for networks in locations with contrasting geographic characteristics. Results suggested that reductions in emissions of up to 83% were possible compared to e-van-only solutions. Notably, bicycle couriers made a considerable contribution to these reductions in some cases. In general, serving clinics that were remote and/or isolated tended to be where drones could offer a beneficial effect. Using drones was also associated with decreases in payload transit times (up to 76%) but increases in costs (up to 134%), raising a question regarding the true value of expedited delivery in a medical context.

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1. Introduction

The emergence of commercial operations utilizing uncrewed aerial vehicles (UAVs; commonly known as drones) in the 2010s has been followed by a period of significant expansion and diversification, with drones now being used successfully in many applications around the world including surveillance, aerial photography, inspection, surveying, monitoring, mapping, and emergency response support. There is also growing interest in the potential of drones for logistics applications (i.e. last-mile payload delivery), where the technology may offer several possible advantages over more traditional surface-based transport modes, such as light goods vehicles (LGVs; commonly known as vans or light-duty trucks) or bicycle couriers (Chung, Sah, & Lee, 2020; Grote, Cherrett et al., 2021; Lin, Shah, Mauntel, & Shah, 2018; Purtell, Hong, & Hiatt, 2024; Rejeb, Rejeb, Simske, & Treiblmaier, 2021).

One suggested advantage is a reduction in energy consumption and the associated detrimental atmospheric emissions, for example, greenhouse gases (GHGs) such as carbon dioxide (CO_2), alongside other potential benefits including reductions in transit times and improved accessibility in hard-to-reach locations, for example, where road networks are poor or where substantial bodies of water must be crossed. Despite these potential advantages, large-scale commercial implementations of drones in the logistics sector still remain scarce, potentially due to barriers such as financial viability and the difficulties inherent in negotiating new and evolving regulatory landscapes associated with an emerging transport mode (Aurambout, Gkoumas, & Ciuffo, 2019; Goodchild & Toy, 2018; Grote, Oakey, Pilko, Krol et al., 2024; Grote, Oakey, Pilko, Smith, & Cherrett, 2023; Meng, Zhou, Li, Peng, & Qiu, 2023; Moshref-Javadi & Winkenbach, 2021; Oakey et al., 2022; Scott & Scott, 2017). Broadly, the potential effects of introducing drones into logistics systems can be conveniently mapped onto the three-pillar concept of sustainability (Purvis, Mao, & Robinson, 2019): environmental (emissions/energy), social (delivery times and access) and economic (costs) (Grote, Oakey, Pilko, Smith et al., 2024), and while the effects on emissions were the main concern of this study, the effects on delivery times and costs were reported as well.

The aims of this study were to make two novel contributions: (i) to explore the effects on GHG emissions from the introduction of drones as an alternative to more traditional surface-based transport modes in mixed-mode, healthcare logistics systems; and (ii) to provide empirical evidence for policy makers and practitioners regarding the potential

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environmental impact of logistics drones in terms of their effects on GHG emissions and the types of locations where they might be best employed. These aims were achieved by applying a novel, mixed-mode logistics planning tool (known as FORSETI—Freight Optimization with RiSk, Energy, and mixed-mode Transport Integration) to analyze a case study of drone applications in real-world healthcare logistics networks with contrasting geographical characteristics.

2. Effects of drones on logistics GHG emissions: a review

The potential for reducing the energy consumption and GHG emissions associated with logistics operations is frequently suggested as an advantage of using drones as a replacement for more traditional transport modes for last-mile delivery (European Environment Agency (EEA), 2020; Meng et al., 2023; Roberts et al., 2023; Stepniak et al., 2024). There are numerous studies of the effects of drone logistics reported in the academic literature, with the majority adopting a theoretical, computational approach, often involving assessment of new or improved optimization algorithms with the objective of minimizing costs, some of which also involve estimates of energy consumption and GHG emissions (Benarbia & Kyamakya, 2022; Chung et al., 2020; Jazairy, Persson, Brho, von Haartman, & Hilletofth, 2025; Moshref-Javadi & Winkenbach, 2021). A recent study by Santiago-Montaño, Silva, and Smith (2024) used a computational approach to investigate the use of drones (payload capacity of two parcels) and electric-assisted bicycle couriers (e-bikes), alongside (conventional Internal Combustion Engine; ICE) trucks, in a logistics system involving parcels transported by drones or trucks from a depot to parcel lockers, from where a proportion of parcels were delivered to homes by e-bikes or trucks and a proportion were self-collected by customers. Based on analysis of a theoretical network minimizing for costs, results suggested the 'greenest' approach was drone (depot-locker) and e-bike (locker-home), with cost increases of as little as 13% generating emissions reductions, on average, of 92% compared to a truck (depot-locker) and e-bike (locker-home) approach. Colajanni, Daniele, and Nagurney (2023) assessed an optimization algorithm for its ability to maximize profit across the theoretical supply chain network for a company that manufactures, stores, and delivers products to customers using a truck fleet, exploring the potential of having drones available (payload capacity of 4 kg) as an alternative transport mode for last-mile parcel deliveries. The effects on GHG emissions were also estimated, with results suggesting reductions of 88% when drones were used as a replacement for trucks.

Chiang, Li, Shang, and Urban (2019) proposed an optimization algorithm to minimize CO_2 emissions from a theoretical logistics network serviced by drone-assisted (payload capacity 2.3 kg) van deliveries (often known as the 'flying sidekick' approach). In contrast to drones and vans operating independently (i.e. both vehicle types operating directly from depots), the 'flying sidekick' approach is where drones and vans operate in combination, with drones launched from delivery vans to make collections/deliveries before returning to the van to land. Results suggested that, on average, reductions in emissions of 22% were possible compared to a traditional van-only approach, assuming that the vans were diesel-fueled. In addition, it was assumed that the drone made its delivery autonomously while the driver continued to drive the van and make other deliveries, an operation that may not be viable in the real-world under current technology and regulatory regimes (Grote, Oakey, Pilko, Krol et al., 2024). Similarly, Meng et al. (2023) assessed a new optimization algorithm for the 'flying sidekick' approach to explore the effects on CO_2 emissions (and costs) of drone-assisted (payload capacity 10 kg) deliveries for a logistics network in Guang'an, China, which also accounted for the influence of the carbon costs of emissions. Results suggested that an emissions reduction of 25% was possible compared to a traditional (gasoline) van-only approach where drones were assumed to deliver autonomously while the driver continued to make other deliveries with the van.

Brown and Bushuev (2024) compared the carbon emissions of four different transport modes for last-mile delivery, which were drones and three types of road vehicle (conventional ICE, all-electric, and plug-in hybrid). In general, based on analysis of a theoretical logistics network, the results suggested that delivery by conventional ICE vehicles generated the most emissions, with plug-in hybrid vehicles next lowest, and all-electric vehicles and drones overlapping as the lowest polluting depending on the number of customers, electric grid pollution rate (i.e. electricity generation grid-mix), ambient temperature, and assumed efficiency of the drones. A systems analysis approach was adopted by Raghunatha, Lindkvist, Thollander, Hansson, and Jonsson (2023) to assess the impact of using logistics drones as an alternative to electric and diesel vans for last-mile delivery. The study found that drones could reduce GHG emissions by up to 26% compared to diesel vans but could increase GHG emissions by over 300% compared to electric vans (e-vans). The analysis was based on a large drone (payload capacity of 544 kg and rotor span of ~20 m), executing multi-drop delivery rounds similar to traditional delivery vans. Such a large drone could pose practical problems in the real-world, such as availability of suitably sized landing sites or unacceptable noise pollution, and is at odds with the trend for utilizing considerably smaller drones for logistics applications (i.e. span <~5 m and payload capacity <~5 kg) (Amazon, 2022; Grote, Oakey, Pilko, Krol et al., 2024; Harding, 2022; Skyports, 2021; Wing, 2023).

Kirschstein (2020) evaluated the effect on GHG emissions of servicing a theoretical set of customers located in Berlin, Germany using drones instead of diesel or electric vans, which included an assessment of the influence of the GHG emissions coefficient (kg/kWh) of a country's electricity generation grid-mix (e.g. nuclear/wind/solar = ~0, natural gas = 0.38, coal = 0.85–1.15). Vans were assumed to be small parcel delivery trucks (empty mass 2500 kg) and drones were assumed to be multi-copter platforms (empty mass 12 kg and payload capacity 2.5 kg). Results suggested that switching to a drone-based parcel delivery system consumed more energy than a van-based system (diesel or electric) in more urban areas with higher customer densities, whereas in more rural areas with lower customer densities, drone delivery consumed comparable (or slightly less) energy. When combined with GHG emissions coefficients, this meant that the only situations where drones produced less emissions tended to be when compared to diesel vans in rural settings, with small coefficient values (<0.3 kg/kWh). Park, Kim, and Suh (2018) investigated the potential for using drones (payload capacity 1.2 kg) instead of (gasoline) motorcycles for pizza delivery in Korea, finding that drones could offer GHG emissions reductions of up to 89%. However, the study was based on a very specific logistics application (i.e. pizza delivery using motorcycles) that is likely to have limited relevance to last-mile parcel delivery in general, where vans traditionally tend to be used, offering economies of scale through multi-drop rounds due to their larger payload capacities.

In general, the finding that drones represent a lower emission option is often based on the assumption that electrically powered drones are replacing conventional (i.e. diesel or gasoline ICE) vans. However, in many cases, the appropriate comparison should be with e-vans because a transition to e-van fleets has already taken place, is underway, or is a committed change for organizations in the near future (European Environment Agency (EEA), 2020; National Health Executive (NHE), 2023; National Health Service (NHS), 2023b). Consequently, a mode-shift to drone delivery may not universally deliver energy and emissions benefits, or benefits may not be as great as expected (Goodchild & Toy, 2018). Drones are also often presumed to have a payload capacity that is better matched to the average size of last-mile deliveries, hence minimizing the inefficiencies (and associated energy consumption and GHG emissions) due to vehicle movements with less-than-full-loads, which are a concern for road-based logistics. This presumption is debatable, with road-based vehicles often able to consolidate multiple deliveries due to their larger payload capacities, improving efficiencies through economies of scale (Goodchild & Toy, 2018; Grote, Cherrett, Oakey, Martinez-Sykora, & Aydemir, 2021; Grote, Cherrett, Whittle, & Tuck, 2021). In reality, the comparatively smaller payload capacities typical of drones could necessitate the fragmentation of larger consignments into smaller, more frequent deliveries, which might negate any potential energy or emissions benefits offered by drone use (Oakey, 2023).

The traditional approach to analyzing GHG emissions from transport is based on quantifying direct emissions produced during vehicle operations, that is, tailpipe emissions during the vehicle use stage from in-vehicle fuel combustion (or the equivalent for electric vehicles of emissions from generating the electricity actually used for vehicle propulsion). While the vehicle use stage tends to dominate, a Life-Cycle Analysis (LCA) approach can extend an analysis to include emissions from additional stages such as vehicle manufacture, vehicle maintenance, fuel production and transport (the equivalent for electric vehicles would be emissions associated with extraction, refining and transport of primary fuels before use in electricity generation and with losses in electricity transmission and distribution), and end-of-life vehicle disposal (Figliozzi, 2017; Yowtak, Imiola, Andrews, Cardillo, & Skerlos, 2020).

The approach adopted in this study was closely aligned with the traditional approach to analyzing transport emissions (i.e. direct emissions during the vehicle use stage) because the vehicle use stage tends to dominate, and a full LCA approach was beyond the study's scope, although the emissions factors used in the study did include lifecycle emissions for the electricity consumed (Section 3.1). Some studies that did adopt a LCA approach have suggested that GHG emissions from drones can often exceed those from the more traditional transport modes they are intended to replace (e.g. e-vans), particularly when realistic assumptions are included regarding factors such as typical delivery scenarios, payload capacities, warehousing requirements and vehicle life expectancies (e.g. up to three years for drones and ten years for vans), with drone emissions found to increase on a LCA basis by up to 50% compared to direct emissions alone (Figliozzi, 2017; Stolaroff et al., 2018; Yowtak et al., 2020). Moreover, Wing (the drone delivery subsidiary of Alphabet, the Google parent company) suggests that their logistics drones are regarded as a disposable commodity, having a designed lifetime after which the entire aircraft is retired and removed from the active fleet, which is likely to have a negative effect on life-cycle emissions (Wing, 2021).

Examples of successful implementations of large-scale, routine drone logistics operations in the real-world are rare, which limits opportunities to evaluate what the effects on energy consumption and GHG emissions might be in practice. That said, a few examples do exist, with some self-reported successes. Amazon reported starting drone delivery operations in Lockeford, California and College Station, Texas in the USA, although the Lockeford service was recently reported (in 2024) as being shut down, with the company attempting to implement a new service in Tolleson, Arizona. United Parcel Service (UPS) announced in 2022 completing over 10,000 flights in the USA utilizing drones manufactured by Matternet. Wing reported passing a total of over 300,000 drone deliveries worldwide during 2023, with delivery services in the USA (specifically, Texas and Virginia), Australia, Finland and Ireland. Manna reported in 2024 completing over 170,000 deliveries during the last three years to suburban areas of Dublin, Ireland, with a mean delivery cost and flight time of four Euro and three minutes, respectively, and 30% of deliveries being for cups of coffee. Walmart reported in 2024 completing over 20,000 drone deliveries during the last two years across six states in the USA, working in partnership with DroneUp, Flytrex, Zipline and Wing (Banker, 2022; Douglas-Moran, 2024; Healy, 2024; Link & Dave, 2023; Shakir, 2024). In Rwanda, Zipline has established a drone logistics service that makes ~200 flights per day transporting blood for transfusion from storage depots to clinics and hospitals, overcoming the poor surface infrastructure to provide rapid payload transit times using drones that can fly at ~100 km/h over distances of up to 120 km and make deliveries *via* parachute (Ackerman & Koziol, 2019; Banks & Wyrobek, 2019; Collier, 2020; Ilancheran, 2020; Nisingizwe, Law, & Bimpe, 2022; Walcutt, 2017; Zipline, 2023).

Despite these reported successes, few services (with the possible exception of Zipline's blood delivery service) have progressed much beyond the initial trial stages of exploring operational challenges to become what could be described as commercially viable, routine operations on a large-scale, and it has been suggested that widespread integration of drones into the logistics sector necessitates further development in several areas such as the establishment of regulatory frameworks for governing the use of airspace by drones, and overcoming cost-related and technical challenges associated with provision of necessary infrastructure (e.g. drone ports and recharging stations) (Benarbia & Kyamakya, 2022; Grote, Oakey, Pilko, Krol et al., 2024). Indeed, Swoop Aero (a global drone logistics provider) has recently (2024) got into financial difficulties (Nichols, 2024), highlighting the challenges of sustaining commercial viability. Furthermore, analyses of the effects on GHG emissions of these trials/services are often difficult to achieve because the necessary information tends not to be available in the public domain (e.g. commercially sensitive information). For example, as part of preparations for expansion of Wing's drone delivery service in Dallas-Fort Worth, Texas, USA, the Federal Aviation Administration (the National Aviation Authority for the USA) published its environmental assessment of the proposed operation. While the service is projected to replace (by year five) between 11.2% and 18.7% of delivery miles made by road vehicles, the potential reduction in GHG emissions was one of the environmental impact categories not analyzed in detail in the assessment (Federal Aviation Administration (FAA), 2023).

2.1. Review summary

Based on the review of the literature relating to the introduction of drones for logistics, it was noticeable that, compared to other aspects such as costs and speed of delivery, the potential effects on GHG emissions appeared to have received less attention. While some studies did include the effects on GHG emissions, these were often theoretical in nature, primarily concerned with assessments of algorithm performance instead of emissions effects, and tended to make *ex ante* assumptions that drones would be involved in new logistics systems, rather than assessing whether (or not) drone use would actually deliver emissions benefits compared to other transport modes, and how the geographic characteristics of logistics networks might affect such benefits. When comparisons with other modes were made, these tended to be with conventional ICE vans rather than e-vans, leading to over estimations of the savings that may be possible. Moreover, studies tended to rely on 'broad-brush' assumptions that were not necessarily representative of real-world circumstances, and often considered situations where drones completely replaced (rather than integrated with) existing, traditional modes (i.e. unimodal rather than mixed-mode logistics scenarios).

Regarding drone logistics operations in the real-world (i.e. trials and services that have actually transported payloads by drone) and their effects on GHG emissions, there was a general lack of studies in this area. This was because large-scale, routine drone logistics operations are still scarce in the real-world, and those that do exist tend not to provide empirical evaluations of the effects on GHG emissions (e.g. commercially sensitive information).

No previous studies (theoretical or real-world) were found that explored the specific situation of the effects on GHG emissions of introducing drones as an available transport mode alongside more traditional modes such as e-vans and bicycle couriers in mixed-mode healthcare logistics systems. This lack of evidence was identified as a gap in the existing research, which this study contributed to addressing.

In response to the research gap identified, the novel contributions of this study were two-fold: (i) to perform a comparative analysis of the effect on GHG emissions of the introduction of drones into mixed-mode logistics in three real-world networks in a healthcare setting in areas with contrasting geographic characteristics; and (ii) to produce empirical evidence for policymakers and practitioners regarding the potential effect of introducing logistics drones on emissions and the types of areas where their introduction may offer the greatest benefit.

3. Methodology

The research centered on three case study logistics networks within the UK National Health Service (NHS) for transporting pathology specimens taken from patients at community clinics to central pathology laboratories (often located at large hospitals) for analysis. To conduct this investigation, a novel logistics planning tool (FORSETI) was utilized (Section 3.1). The case study networks were located in three contrasting geographical regions (Section 3.2), which were: (i) a typical, large urban area (city) with surrounding hinterland; (ii) a smaller, more rural area, centered on a small urban area (town); and (iii) a larger, very rural area involving many hard-to-reach locations on islands separated by substantial bodies of water from a small urban area (town) on the mainland. In each case study, three scenarios (benchmark, mixed-mode, and drone-only scenarios, Section 3.2) were analyzed allowing the effect on GHG emissions of introducing logistics drones to be quantified, and the influence of the different geographical characteristics explored. In addition, the research considered the introduction of two different drone platform types: (i) a multi-copter platform; and (ii) a Vertical Take-Off and Landing (VTOL) and Fixed-Wing (FW) hybrid platform (Section 3.1).

3.1. Logistics planning tool

3.1.1. Overview

The FORSETI logistics planning tool was used to analyze the case study. A brief overview of the tool is provided here, with more detailed descriptions available in Grote, Oakey, Pilko, Krol et al. (2024), Oakey (2023) and the references cited throughout Section 3.1. FORSETI is designed to analyze a given situation regarding demand for transport of goods (e.g. during a particular shift period such as a morning, afternoon, or all-day) and determine how best to deploy and integrate transport resources to meet that demand. The logistics transport modes available in FORSETI are vans, bicycle couriers, and drones. Rather than assuming straight-line routings for drones, the tool incorporates more realistic flightpaths that account for ground risk (i.e. the risk of a fatality to a third party on the ground due to a catastrophic failure of the drone in-flight) by detouring away from areas with higher population densities, accounting for land-use and variations in population densities during the day (Pilko, Sóbester, Scanlan, & Ferraro, 2023).

The modeling process within FORSETI is shown by the diagram in Figure 1. The main module of FORSETI is the Land-Air Logistics Optimizer (LALO), which receives inputs from the user (Step 1) regarding clinic locations (e.g. postal codes), transport mode parameters (e.g. costs and dwell time), and time constraints (e.g. shift start/finish times, maximum allowable payload in-transit time). LALO creates a matrix of all possible Origin-Destination (O-D) pairs (i.e. all combinations of clinic-clinic and clinic-laboratory) (Step 2), which is used by the ancillary modules to calculate the costs, energy, emissions, travel times and travel distances associated with the most likely best route between each O-D pair by each mode, including the effects of time-specific traffic congestion *via* Google Maps Directions API queries (Google, 2023) for vans and bicycle couriers (Steps 3 and 4). Based on feedback of the entire set of O-D pairs data (Step 5), LALO then analyses the optimum combination of vans, bicycle couriers and drones to satisfy the logistics demand by solving the Sustainable Specimen Collection Problem (SSCP) with Drones & Scheduling using an algorithm (Step 6), which produces an optimized solution that minimizes a user-defined balance between competing objectives (operating costs, energy consumption, emissions and maximum in-transit time) (Step 7).

The optimization process within FORSETI solves an extension of the SSCP to include scheduling of assets and logistics drones as an available mode (i.e. a time-constrained mixed-mode two-echelon vehicle routing problem with scheduling) (Oakey, Martinez-Sykora, & Cherrett, 2023, 2024), based on an objective function (1) that minimizes the sum of operating costs, energy consumption, emissions and maximum In-Transit Time (ITT).

$$\min: \sum_{\bar{r}_k \in \bar{R}} \left(x_{\bar{r}_k} \left(\sum_{r_{v,k} \in \bar{r}_k \cap R^V} \theta_1 p_{r_{v,k}} + \sum_{r_{d,k} \in \bar{r}_k \cap R^D} \theta_2 p_{r_{d,k}} + \sum_{r_{c,k} \in \bar{r}_k \cap R^C} \theta_3 p_{r_{c,k}} + \theta_4 \epsilon_{\bar{r}_k} \gamma \right) \right) + \theta_1 W^V A^V_{\max} + \theta_2 \left(W^D A^D_{\max} + W^O A^O_{\max} \right) + \theta_5 u \quad (1)$$

The optimization process involves the creation of collection rounds that combine a van route ($r_{v,k}$) or a drone route ($r_{d,k}$) with bicycle courier routes ($r_{c,k}$) providing payload consolidation. Collection rounds do not necessarily involve consolidation, and can consist only of a van, a drone, or even a bicycle courier route delivering directly to the pathology laboratory. The full set of routes by van, drone and bicycle courier are denoted by R^V, R^D, and R^C, respectively. The full set of all collection rounds is denoted by $\bar{R}$, while a single collection round is denoted by $\bar{r}_k$, and a decision variable ($x_{\bar{r}_k}$) indicates whether a particular collection round is used.

The fixed costs of labor and/or vehicles per shift are denoted by W^V for a van and driver combined, and by W^D for a drone and W^O for a drone operator; while the number of vans, drones, and drone operators required in a shift period is given by $A^V_{\max}$, $A^D_{\max}$, and $A^O_{\max}$, respectively. Bicycle couriers are assumed to be paid on a per-task basis (related to route distance and number of collections) typical of gig-economy workers, and therefore do not have any fixed costs. This is unlike van drivers and drone operators, who are assumed to be paid for the entire shift period

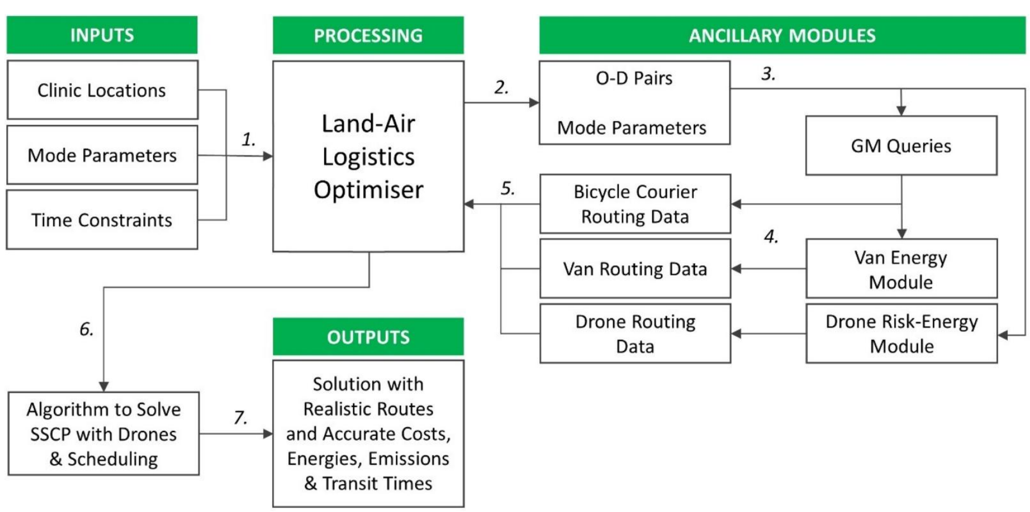

Figure 1. Diagram of the FORSETI logistics planning tool. Numbers indicate step sequence. O-D is origin-destination. GM is google maps. SSCP is sustainable specimen collection problem.

because this is how such workers are likely to be paid in reality, regardless of time spent actually operating the vehicle, particularly in the UK public sector where strong union representation (∼50%) helps to guarantee better employment terms and conditions (Department for Business & Trade (DBT), 2023). The variable costs (e.g. based on flight-duration for drones or distance traveled for ground vehicles) of each route are denoted by $p_{r_{v,k}}$, $p_{r_{d,k}}$, and $p_{r_{c,k}}$ for van, drone, and bicycle courier, respectively.

The emissions of a collection round are given by the energy consumed on the round ($\epsilon_{\bar{r}_k}$) multiplied by an emissions factor (γ), while maximum ITT is denoted by u. The GHG emissions factors used in FORSETI have constant values (Section 3.1.2), which means emissions are directly proportional to energy consumed, i.e. optimization to minimize energy consumption or emissions produces the same solution.

The relative importance of the different constituents of the objective function are defined by weighting values as follows: van costs (θ_1); drone costs (θ_2); bicycle courier costs (θ_3); total emissions/energy consumption (θ_4); and maximum ITT (θ_5). The constraints implemented in FORSETI were as follows:

- decision variable ($x_{\bar{r}_k}$) must be binary (i.e. 1 or 0);
- maximum ITT for any specimen of 90 minutes (Section 3.2);
- vehicle journeys must finish where they started;
- maximum vehicle ranges of: 125 km between recharging stops for e-vans, sufficient to complete all out-and-back journeys for drones, and 8 km for bicycle couriers (Section 3.1.3);
- numbers of drivers/operators and vehicles are unconstrained;
- all clinics must be served by at least one route (see Oakey et al. (2024) for the complete formulation of these constraints).

While the effects on costs and transit times are obviously important factors for organizations considering the introduction of logistics drones, the focus of this study was to explore the effects on GHG emissions. For this reason, the costs and maximum ITT weightings ($\theta_1, \theta_2, \theta_3$, and θ_5) were all set to zero throughout in order to isolate the effects on emissions and energy consumption, where the weighting (θ_4) was set to 100. The objective function (1) within FORSETI was originally designed to support multi-objective optimization, but within the scope of this study only one objective was used (i.e. emissions/energy consumption). Nevertheless, full model functionality was described in the interests of completeness and transparency (and because cost and transit time values were reported as part of the results, Section 4).

3.1.2. Emissions factors

Emissions of GHGs are calculated within FORSETI as a combined total for all types emitted (the vast majority of ∼99% is constituted by CO_2) in terms of CO_2-equivalent

Table 1. Emission factors for CO_2-eq based on energy (and diesel) consumption.

Emissions	EF (energy) (kg CO_2-eq/kWh)	EF (diesel) (kg CO_2-eq/liter)
WTT-eq	0.0505	0.6099
TTW-eq	0.1934	2.5578

Source: Department for Business Energy & Industrial Strategy (BEIS) and Department for Environment Food & Rural Affairs (DEFRA) (2022).

(CO_2-eq) based on energy consumed multiplied by Emissions Factors (EFs) published by the UK government (Department for Business Energy & Industrial Strategy (BEIS) and Department for Environment Food & Rural Affairs (DEFRA), 2022) (Table 1), where CO_2-eq is defined as the amount of CO_2 emitted that would cause the same time-integrated radiative forcing, over a given time-horizon, as an emitted amount of other GHGs. When desired, FORSETI can also model diesel vans (e-vans were assumed in this study, Section 3.1.3) and therefore includes UK government EFs for diesel combustion as well. These EFs are included in Table 1, but only because they were used in this study for the manual estimation of emissions from ferries (Section 3.2).

The two components of total (i.e. Well-To-Wheel; WTW) lifecycle CO_2-eq emissions are calculated in FORSETI: i) Well-To-Tank (WTT) emissions associated with fuel production, processing and distribution; and ii) Tank-To-Wheel (TTW) emissions associated with fuel used in-vehicle. The terms WTW, WTT, and TTW more properly describe liquid fuels (e.g. diesel), and so WTW-equivalent (WTW-equivalent), WTT-equivalent (WTT-eq), and TTW-equivalent (TTW-eq) were adopted as the equivalent terms for the electric vehicles in this study. Hence, WTT-eq describes emissions associated with extraction, refining and transport of primary fuels before use in electricity generation and with losses in electricity transmission and distribution, and TTW-eq describes emissions from generating the electricity actually used for vehicle propulsion.

The EFs published by the UK government used in this study are representative of the national electricity generation grid-mix in the UK. If the grid-mix were to change (e.g. future increase in electricity generated from renewable sources), then the EFs would be likely to change as well.

3.1.3. Transport mode settings

The van type in FORSETI was set as an e-van (i.e. electric LGV with gross vehicle mass ≤4250 kg) because the switch from diesel to electric vehicle fleets is a committed change within the NHS (National Health Executive (NHE), 2023; National Health Service (NHS), 2023b). Energy consumption for an e-van is estimated within FORSETI using a physics-based, instantaneous energy consumption model (i.e. varying with an e-van's speed-time profile), with characteristics based on commercially available e-vans, and a full description of this model is given by Krol, Anvari, Blakesley, and Cherrett (2023). As an approximate guide to the magnitude of values, overall average energy consumption estimated by the model for e-vans is typically ∼0.69 MJ/km, which equates to WTW-eq emissions of ∼0.046 kg CO_2-eq/km based on the UK government EFs used in the study (Table 1).

Figure 2. Multi-copter drone platform (left) and VTOL/FW hybrid drone platform (right). Both drones are shown loaded with one medical container (dimensions $460 \times 255 \times 305$ mm, Figure 3), which is underslung for the multi-copter drone and contained within the cargo compartment located in the forward fuselage for the VTOL/FW hybrid drone (wingspan of $\sim$5 m).

In FORSETI, e-van collection rounds are assumed to start and finish at the pathology laboratory. Payload capacity was set to 4 m^3/600 kg and maximum range between stops for recharging to 125 km, ensuring all operations were conducted well within the constraints of typical e-vans (i.e. $\sim$5 m^3/800 kg payload capacity and 200+ km range quoted in manufacturers' specifications). FORSETI cost parameter values for e-vans (2022/23 values) were obtained from the Manager's Guide to Distribution Costs published in the UK by the Freight Transport Association (Freight Transport Association (FTA), 2022), with values assumed to be the same as those for diesel vans because the FTA do not publish e-van-specific values, which was a reasonable assumption given that e-vans are now competitive for Total Cost of Ownership (Noll, del Val, Schmidt, & Steffen, 2022). Labor costs for drivers (GBP 11.93/h) included pay for overtime and productivity; vehicle running costs (GBP 0.34/mi) included fuel, tires, and maintenance; and vehicle standing costs (GBP 29.33/vehicle/day) included vehicle tax, insurance, depreciation, and overheads.

The drone type was set as an electrically powered multi-copter platform (Figure 2) with Maximum Take-Off Mass (MTOM) of 25 kg, payload capacity for one medical container (Section 3.2), and a cruise speed of 65 km/h. Energy consumption for a multi-copter drone is estimated within FORSETI using a physics-based, instantaneous energy consumption model (i.e. varying with a drone's phase of flight such as take-off, climb, cruise, descent, landing), with characteristics based on commercially available drones, and a full description of this model is given by Blakesley, Anvari, Krol, and Bell (2022). As an approximate guide to the magnitude of values, overall average energy consumption estimated by the model for multi-copter drones is typically $\sim$0.36 MJ/km, which equates to WTW-eq emissions of $\sim$0.024 kg CO_2-eq/km based on the UK government EFs used in the study (Table 1).

In FORSETI, drones are assumed to perform out-and-back journeys, starting and finishing at the pathology laboratory and collecting from a single clinic, departing on each journey with a fully charged battery based on a battery-swap system at the pathology laboratory. An additional 10 min dwell time per drone journey was allowed at the pathology laboratory to complete: (i) a battery-swap (5 min); and (ii) a pre-departure safety check (5 min) of the drone's continued airworthiness (e.g. damage and malfunctions) (Civil Aviation Authority (CAA), 2022). Drones were assumed to have sufficient range to complete all out-and-back journeys without needing a battery-swap (or re-charge) anywhere other than the pathology laboratory. This was because drones were the new technology under investigation in the study and where possible, the desire was to enable (rather than constrain) the uptake of this new technology to allow the fullest exploration of their potential effect on GHG emissions. The implications of this assumption are discussed in Section 4. The effects of the prevailing enroute wind were ignored because they were assumed to average-out over out-and-back journeys (i.e. outbound headwinds became inbound tailwinds, or vice versa).

The entire analysis was repeated with the drone type changed to an electrically powered VTOL/FW hybrid platform (Figure 2), with a MTOM of 60 kg, payload capacity for one medical container, cruise speed of 65 km/h and wingspan of 5 m, to assess sensitivity to drone energy consumption. This platform type uses rotors for vertical take-off and landing, but transitions to fixed-wing flight for cruising, making it more efficient than a multi-copter platform. Energy consumption of the VTOL/FW hybrid drone was approximated as half that of the multi-copter drone because multi-copter drones are known to have flight endurances that are typically shorter by a factor <0.5 (Thielicke, Hübert, Müller, Eggert, & Wilhelm, 2021). The choice of drone was based on practical trials undertaken with both platform types by the authors as part of the UK government funded E-Drone[1] and Future Transport Zone[2] projects.

FORSETI cost parameter values for drones were obtained from Grote, Oakey, Pilko, Krol et al. (2024), based on a plausible future situation where drone logistics services have become well established, involving increased automation and improved techniques and economies of scale in drone manufacturing (values were in terms of 2022/23 currency values, i.e. no inflation effects to enable like-for-like comparisons with other modes). Labor costs (GBP 31.44/h) included a mission commander in overall command of multiple drones (operator-to-vehicle ratio for drones was set at 1:20 in accordance with recently reported real-world values for simultaneous monitoring (Crosby, 2023)) and a loader/technician at the pathology laboratory; vehicle running costs (GBP 20.33/h) included the drone platform (based on component costs and life expectancies) and electricity consumption; and

[1] http://www.e-drone.org/.
[2] https://solent-transport.com/solent-future-transport-zone/.

Figure 3. Insulated medical container (left) and typical pathology specimen (right). Insulated medical container (brand name versapak) has dimensions 460 × 255 × 305 mm, empty mass 2.2 kg, mass when fully loaded with specimens ~5 kg (Versapak, 2021).

vehicle standing costs (GBP 8.99/vehicle/day) included operational insurance and fees for access to shared airspace managed by UAV Traffic Management (UTM) service providers (Grote et al., 2022). These costs were for a VTOL/FW hybrid drone and were assumed to be the same for a multicopter drone, which was reasonable given that the only variations were reasonably minor changes to platform component costs and electricity consumption, affecting only one constituent of overall drone costs (i.e. vehicle running costs).

For bicycle couriers (assumed to be classical pedal bicycles rather than e-bikes), energy consumption and emissions were assumed to be zero in FORSETI. Bicycle couriers had capacity for three medical containers (Section 3.2) and were limited to a maximum journey distance of 8 km, a typical maximum for this transport mode in the real-world (Stuart Couriers, 2023). Hence, bicycle couriers predominantly carried out consolidation rounds, starting at a given clinic, making collections from one (or more) other nearby clinics, before returning to the start clinic to deliver a consolidated payload for subsequent onward transport by e-van or drone to the pathology laboratory; although bicycle couriers could deliver directly to the pathology laboratory if this was found to be an optimal use of resources. FORSETI cost parameter values for bicycle couriers (2022/23 values) were obtained from data on prices charged by a real-world courier company in the UK (Stuart Couriers, 2023). Costs were on a per task basis (GBP 7.07/task), where a task was defined as one consolidation round. Each extra collection on a round in addition to the first collection incurred an extra cost (GBP 2.78/stop), as did round distance beyond an initial threshold of 0.8 km (GBP 0.63/km).

3.2. Testbed regions and scenarios

Over 300,000 pathology specimens are taken from patients on each working day at community clinics across the UK (Royal College of Pathologists (RCPath), 2023). These specimens are packed by clinic staff into insulated medical containers (brand name Versapak; Figure 3) for collection and transportation to central pathology laboratories for analysis (typically situated at large hospitals) *via* networks of daily van rounds. The 'gold standard' for the maximum elapsed time between specimen collection and delivery to the laboratory for quality assurance is 90 min (McDonald, 1972). However, no universally ratified standard governs the required service level in terms of maximum transit time, and in practice, instances of more relaxed constraints do exist, for example, maximum of 120 min (Southern Health NHS Foundation Trust (SHFT), 2019) or even 240 min (Hull University Teaching Hospitals NHS Trust (HUTHT), 2021). Nevertheless, this study adopted the most stringent constraint (i.e. <90 min) because of its tendency to encourage drone use, with their potential to offer rapid transit times.

Three logistics networks with contrasting geographical characteristics were used as testbeds: (i) the network of 76 community clinics (Figure 4) across the city of Southampton (population ~250,000 on the South coast of the UK) and its surrounding hinterland, which send specimens to the pathology laboratory located at Southampton General Hospital (SGH) in Southampton; (ii) the network of 22 community clinics (Figure 5) across a smaller, more rural area centered on the town of Newport (population ~25,000 on the Isle of Wight off the South coast of the UK), which send specimens to the pathology laboratory located at Saint Mary's Hospital (SMH) in Newport; and (iii) the network of 23 community clinics (Figure 6) across the much larger, very rural area centered on the town of Oban (population of ~8500 in the Highlands on the West coast of Scotland in the UK), which send specimens to the pathology laboratory located at Lorn and Islands Hospital (LIH) in Oban. This network included many hard-to-reach island locations separated from Oban on the mainland by substantial bodies of water that required two additional, location-specific transport modes, which were locally arranged e-vans and ferries, where local e-vans were assumed to be based at island clinics for transporting specimens from the clinic to the ferry port.

Three scenarios were investigated in each of the three testbed regions (Table 2). First, a benchmark scenario was used to represent Business-As-Usual (BAU) operations (i.e. pseudo-BAU scenario), where all clinics were serviced by e-van rounds, with the addition of the two location-specific modes for island clinics in the Highlands testbed (i.e. local e-van and ferry). A benchmark scenario was used (rather than true BAU) because it was not possible to obtain all the details of actual ground truth about existing specimen collection operations from the logistics providers involved. This was particularly true in the Highlands testbed for the island clinics, where discussions with local NHS staff revealed that

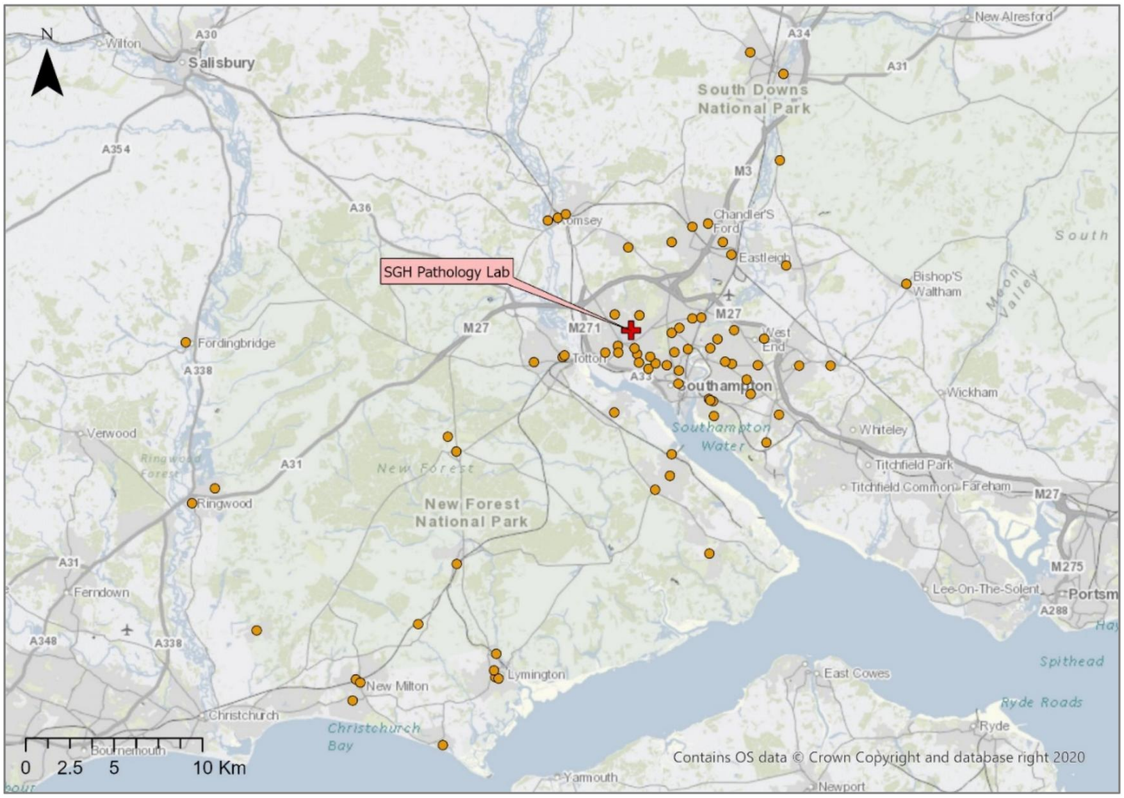

Figure 4. Map of the Southampton testbed region. SGH is Southampton general hospital. Orange circles indicate community clinics.

Figure 5. Map of the isle of wight testbed region. SMH is Saint Mary's hospital. Orange circles indicate community clinics.

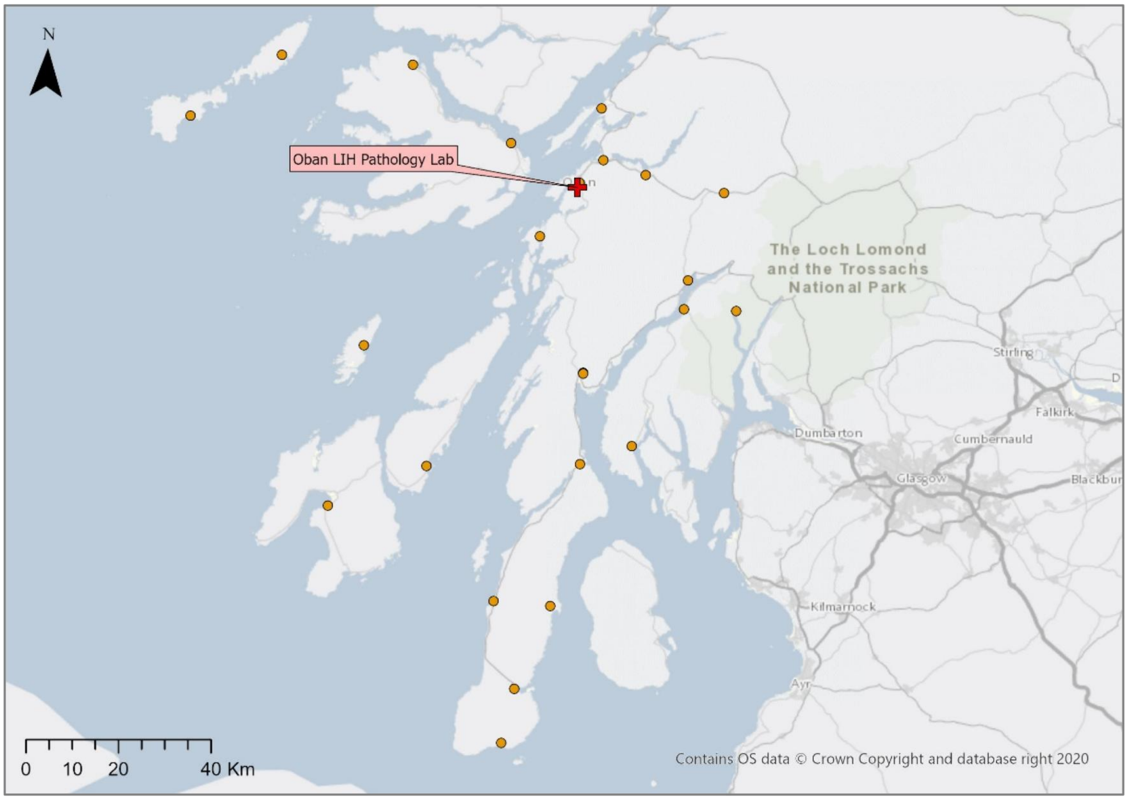

Figure 6. Map of the highlands testbed region. LIH is lorn and islands hospital. Orange circles indicate community clinics.

Table 2. Scenario characteristics.

Testbed	Scenarios	Shift time	Shift duration (h:m)	Pathology laboratory[a]	Number of clinics	Maximum ITT allowed (min)
Southampton	Benchmark MixedMode DroneOnly	09:00-13:00	4:00	SGH	76	90
Isle of Wight	Benchmark MixedMode DroneOnly	09:00-13:00	4:00	SMH	22	90
Highlands	Benchmark MixedMode DroneOnly	09:00-17:00	8:00	LIH	23	300

[a]SGH is Southampton General Hospital; SMH is St Mary's Hospital; LIH is Lorn and Islands Hospital.

specimens were transported through a patchwork of various local, often unofficial arrangements involving clinic staff or other means (e.g. arrangements with members of the public). Second, a mixed-mode scenario involved the introduction of drones and bicycle couriers as available modes, offering potential alternatives to servicing clinics by e-van (or local e-van/ferry); and thirdly, a drone-only scenario represented the situation where the entire network of clinics was served only by drone.

Based on historical data relating to the typical number of specimens generated daily at community clinics, each scenario represented the realistic demand for specimen transport during a four-hour morning shift (09:00–13:00), which required each clinic to be visited once to collect one container (i.e. Versapak) of specimens. Dwell time was assumed to be 2.5 min for all collections and deliveries (Allen et al., 2018). Reverse logistics (i.e. replenishing supplies of empty containers and specimen tubes at clinics) was assumed to be done during normal operations (i.e. when vehicles made collections, empty replacements were dropped-off at the same time).

The Highlands testbed was a less typical geographic region and had a number of anomalies compared to the Southampton and Isle of Wight (IOW) testbeds. Total shift length and maximum allowable ITT had to be extended (to 8 h and 300 min, respectively, Table 2) so that it was possible to collect all specimens in the benchmark scenario due to the distances and modes involved, that is, long duration ferry (mean = 156 min, maximum = 283 min) and e-van (mean = 148 min, maximum = 437 min) journeys. While the actual specifics of ground-truth BAU were unknown, it seems likely that these extended timescales must exist in the real-world for the system to be workable in practice.

In addition, no waiting time was allowed for ferry connections, meaning the ferry was assumed to depart from an island as soon as specimens were delivered to the ferry port by a local e-van. In reality, ferry connections are likely to involve some waiting time, even if the arrival of local e-vans at ferry ports were scheduled to coincide with ferry departure times. Therefore, transit times from island clinics are likely to be longer in the real-world. The Highlands testbed was too rural for a realistic assumption that routine bicycle courier services would be reliably available throughout the region, with service providers tending to offer bicycle couriers only in more urban settings due to the shorter distances they can cover compared to other modes (e.g. maximum of 8 km, Section 3.1). Therefore, bicycle couriers were switched off as an available mode in FORSETI for the Highlands scenarios.

The two modes specific to the Highlands testbed (i.e. local e-van and ferry) were not available in FORSETI, and so emissions, energy consumption, costs, and transit times for these modes were calculated and incorporated into FORSETI outputs manually. Route distances (and travel times) were obtained from Google Maps and energy consumptions were calculated using energy consumption factors assumed to be: (i) 0.6 MJ/km for a local e-van obtained from the manufacturer's specification (Vauxhall Combo Electric van); and (ii) 161.0 MJ/km for a modern diesel-electric ferry obtained from Kortsari, Mitropoulos, Heinemann, and Hagbarth Mikkelsen (2020). Regarding the ferries, these are scheduled public transport services that would be making their journeys (and consuming energy) anyway, regardless of whether or not there were specimens that required transport. Therefore, the proportion of total ferry energy consumed due to transporting a container of specimens (in addition to usual payloads) was allocated according to the mass of a container (5 kg) as a fraction of the total payload mass (assumed to be 50% laden giving a total payload mass of 100,850 kg for passengers, cars and trucks combined), i.e. $(5/100{,}850 \times 161.0 \;=)\; 0.008$ MJ/km for a container transported by ferry.

For local e-vans, emissions were calculated based on energy consumed using the EFs (kg CO_2-eq/kWh) from FORSETI (Table 1). For ferries, energy consumed was converted to the volume of diesel required to generate that energy using the on-board diesel generators based on diesel's net calorific value (42.7 MJ/kg) and density (840 kg/m^3), before emissions were calculated using the EFs (kg CO_2-eq/liter) from FORSETI (Table 1). Costs for the two modes were based on cost factors assumed to be (i) 0.28 GBP/km for a local e-van based on the tax-free milage allowance claimable as expenses for using an e-van for work purposes in the UK (HMG, 2024); and (ii) 2.40 GBP/journey based on the price charged by the local ferry operator for freight up to 25 kg (Calmac Ferries, 2024).

4. Results and discussion

4.1. Individual testbeds

Results for the Southampton testbed (Table 3) suggested that introducing logistics drones as part of a mixed-mode solution alongside e-vans and bicycle couriers could reduce energy consumption and emissions of GHGs from the benchmark scenario by 23% when the multi-copter drone was available (MixedMode_Multi) and 53% when the (more energy-efficient) VTOL/FW hybrid drone was available (MixedMode_Hybrid); although these reductions were associated with considerable cost increases of 65% and 88%, respectively, and the majority of the reductions were contributed by the introduction of a large number of bicycle couriers ($B = 18$ and $B = 33$ in Table 3 for MixedMode_Multi and MixedMode_Hybrid scenarios, respectively) with their zero emissions/energy. The optimum combination of modes (i.e. vehicle fleet mix) to minimize emissions in the Southampton testbed (assuming no weather or vehicle serviceability issues that could require back-up vehicles to be added to the fleet to ensure service reliability, Section 4.3) was found to be 2 e-vans, 3 drones and 18 bicycle couriers when the multi-copter platform was available, and 1 e-van, 4 drones and 33 bicycle couriers when the VTOL/FW hybrid platform was available (Table 3).

The situation where all clinics were served only by drones resulted in increases in emissions/energy from the benchmark scenario of 175% for the multi-copter (DroneOnly_Multi) and 37% for the hybrid (DroneOnly_Hybrid), and also a cost increase of 80%; although maximum transit time was reduced by 63%. Maps of the vehicle routes in the different scenario solutions are shown in Figure 7.

Results for the IOW testbed (Table 4) showed that a mixed-mode solution could also reduce energy consumption and emissions in a smaller, more rural network, with reductions from the benchmark scenario of 24% when the multi-copter drone was available (MixedMode_Multi) and 37% when the hybrid drone was available (MixedMode_Hybrid). However, drones were not selected to service any clinics in the MixedMode_Multi solution ($D = 0$ in Table 4), and all the emissions/energy savings were the result of using bicycle couriers. Drones are relatively expensive compared to e-vans and bicycle couriers (Grote, Oakey, Pilko, Krol et al., 2024), and avoiding their use in the MixedMode_Multi solution

Table 3. Summary results for Southampton.

Scenario	Fleet composition	WTW CO_2-eq Emissions (kg)	Energy (MJ)	Cost (GBP)	Maximum ITT (min)
Benchmark	V = 5; D = 0; B = 0	24	348	489	88
MixedMode_Multi	V = 2; D = 3; B = 18	18	268	807	90
MixedMode_Hybrid	V = 1; D = 4; B = 33	11	162	919	90
DroneOnly_Multi	V = 0; D = 12; B = 0	65	955	882	33
DroneOnly_Hybrid	V = 0; D = 12; B = 0	32	478	882	33

Note: V is e-van, D is drone, B is bicycle courier.

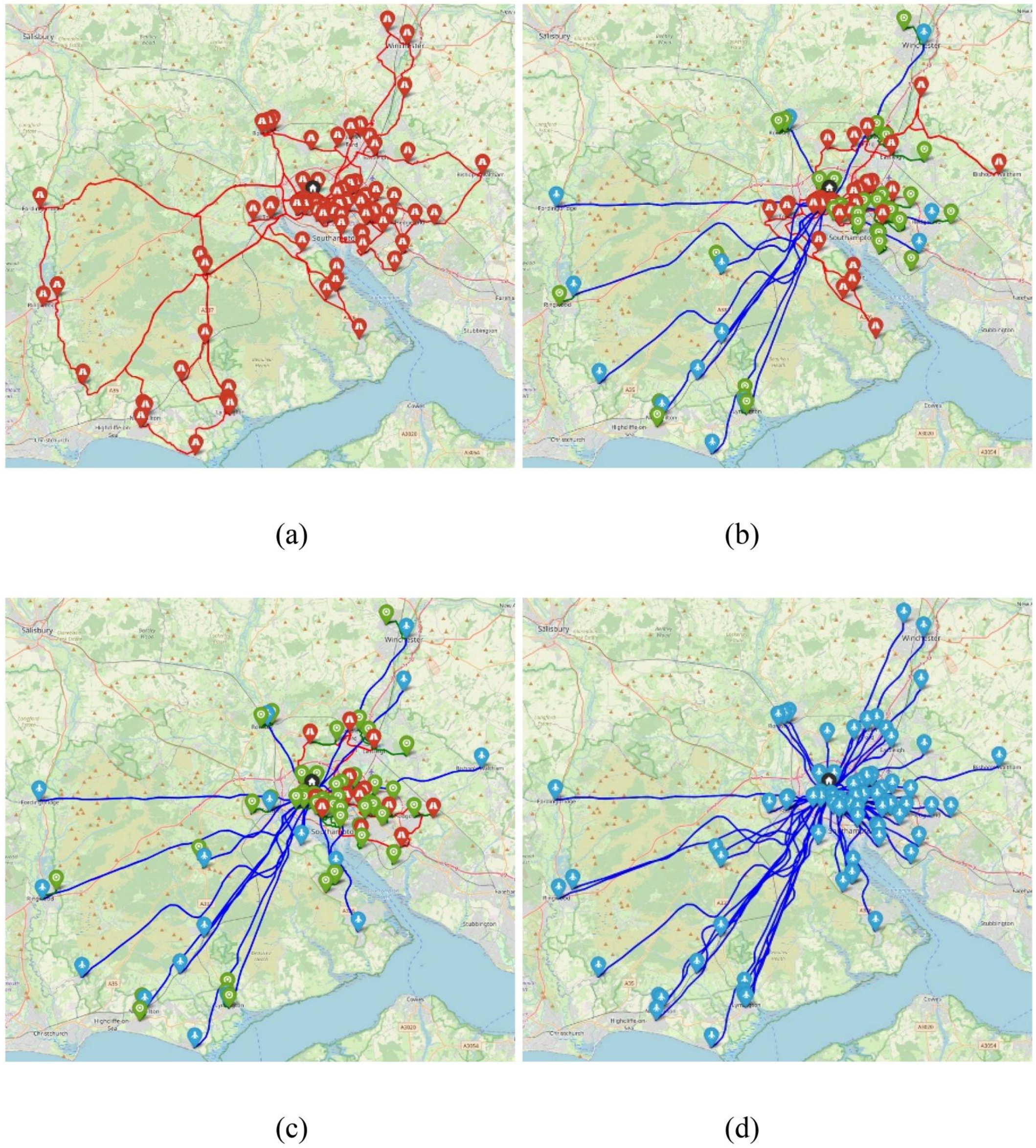

Figure 7. Maps of scenario solutions for Southampton. (a) Benchmark; (b) MixedMode_multi; (c) MixedMode_hybrid; (d) DroneOnly (both multi and hybrid). Blue, red and green lines/pins indicate drone, e-van and bicycle courier routes/clinics, respectively. Black pin indicates Southampton general hospital. Base map source: © OpenStreetMap.

Table 4. Summary results for Isle of Wight.

Scenario	Fleet composition	WTW CO_2-eq Emissions (kg)	Energy (MJ)	Cost (GBP)	Maximum ITT (min)
Benchmark	V = 2; D = 0; B = 0	8	119	190	79
MixedMode_Multi	V = 1; D = 0; B = 6	6	90	188	90
MixedMode_Hybrid	V = 0; D = 2; B = 7	5	75	368	90
DroneOnly_Multi	V = 0; D = 4; B = 0	19	276	345	19
DroneOnly_Hybrid	V = 0; D = 4; B = 0	9	138	345	19

Note: V is e-van, D is drone, B is bicycle courier.

meant that this gave a small (1%) cost reduction compared to the benchmark scenario, with the costs of using bicycle couriers completely offset by the elimination of one e-van (Benchmark $V = 2$ reduced to MixedMode_Multi $V = 1$ in Table 4), making this solution an attractive option overall. In contrast, the better energy-efficiency of the hybrid drone meant that drones were selected in the MixedMode_Hybrid solution ($D = 2$ in Table 4), but this also meant that costs increased by 94% due to the use of drones. The optimum fleet mix to minimize emissions in the IOW testbed (again assuming no requirement for additional back-up vehicles) was found to be 1 e-van, 0 drones and 6 bicycle couriers when the multi-copter platform was available, and 0 e-vans, 2 drones and 7 bicycle couriers when the VTOL/FW hybrid platform was available (Table 4).

The situation where all clinics were served only by drones resulted in increases in emissions/energy from the benchmark scenario of 132% for the multi-copter (DroneOnly_

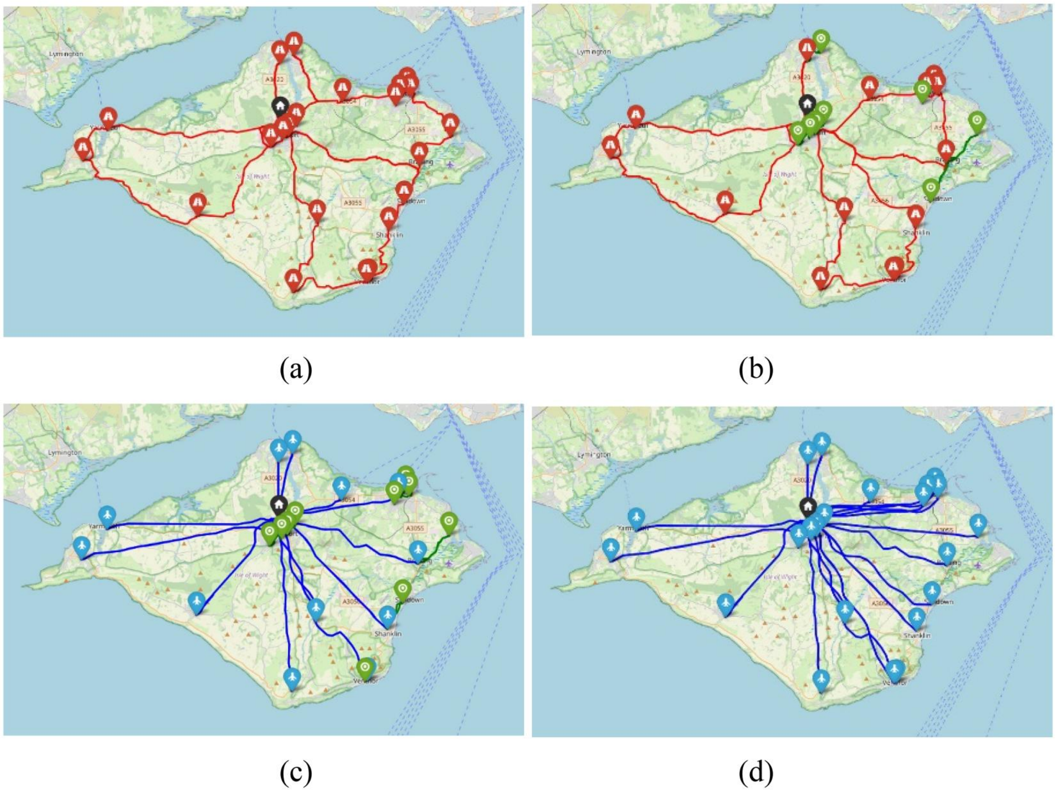

Figure 8. Maps of scenario solutions for isle of wight. (a) Benchmark; (b) MixedMode_multi; (c) MixedMode_hybrid; (d) DroneOnly (both multi and hybrid scenarios). Blue, red and green lines/pins indicate drone, e-van and bicycle courier routes/clinics, respectively. Black pin indicates St mary's hospital. Base map source: © OpenStreetMap.

Table 5. Summary results for highlands.

Scenario	Fleet composition	WTW CO_2-eq Emissions (kg)	Energy (MJ)	Cost (GBP)	Maximum ITT (min)
Benchmark	V = 2; D = 0; B = 0; (F = 4; LV = 6)	47	698	476	297
MixedMode_Multi	V = 0; D = 5; B = 0; (F = 3; LV = 5)	16	229	962	297
MixedMode_Hybrid	V = 0; D = 5; B = 0; (F = 3; LV = 5)	8	121	962	297
DroneOnly_Multi	V = 0; D = 6; B = 0; (F = 0; LV = 0)	19	277	1,113	117
DroneOnly_Hybrid	V = 0; D = 6; B = 0; (F = 0; LV = 0)	9	138	1,113	117

Note: V is e-van, D is drone, B is bicycle courier, F is ferry, LV is local e-van. LV = 5 for the mixed-mode scenarios includes one local e-van on the mainland to collect all specimens that have arrived at Oban ferry port and transport them to Oban hospital (4.2 km return trip). For reasons of efficiency, this local e-van was assumed also to collect specimens from the clinic that it passed on the journey to/from the ferry port.

Multi) and 16% for the hybrid (DroneOnly_Hybrid), and also a cost increase of 82%; although maximum transit time was reduced by 76%. Maps of the vehicle routes in the different scenario solutions are shown in Figure 8.

Results for the Highlands testbed (Table 5) suggested that a mixed-mode solution could reduce energy consumption and emissions in a much larger, very rural network as well, with reductions from the benchmark scenario of 67% when the multi-copter drone was available (MixedMode_Multi) and 83% when the hybrid drone was available (MixedMode_Hybrid); although both these reductions were associated with a considerable cost increase of 102%. The optimum fleet mix to minimize emissions in the Highlands testbed (once again assuming no requirement for additional back-up vehicles) was found to be 0 e-vans, 5 drones, 0 bicycle couriers, 3 ferries and 5 local e-vans both when the multi-copter platform was available and when the VTOL/FW hybrid platform was available (Table 5).

In contrast to the Southampton and IOW testbeds, the situation where all clinics were served only by drones produced savings (rather than increases) in emissions/energy from the benchmark scenario, with reductions of 60% for the multi-copter (DroneOnly_Multi) and 80% for the hybrid (DroneOnly_Hybrid), and also a reduction in maximum transit time of 61%; although costs were increased by 134%. Maps of the vehicle routes in the different scenario solutions are shown in Figure 9.

4.2. Testbed comparisons

Results from each individual testbed suggested that the introduction of drones into mixed-mode logistics systems alongside e-vans and bicycle couriers can lead to reductions in energy consumption and GHG emissions, albeit with associated cost increases in most cases and with much of the reductions often due to the use of bicycle couriers (Tables 3–5 for the Southampton, IOW and Highlands testbeds, respectively). Furthermore, comparing the results from the three testbeds with each other suggested that different logistics networks with contrasting geographical characteristics

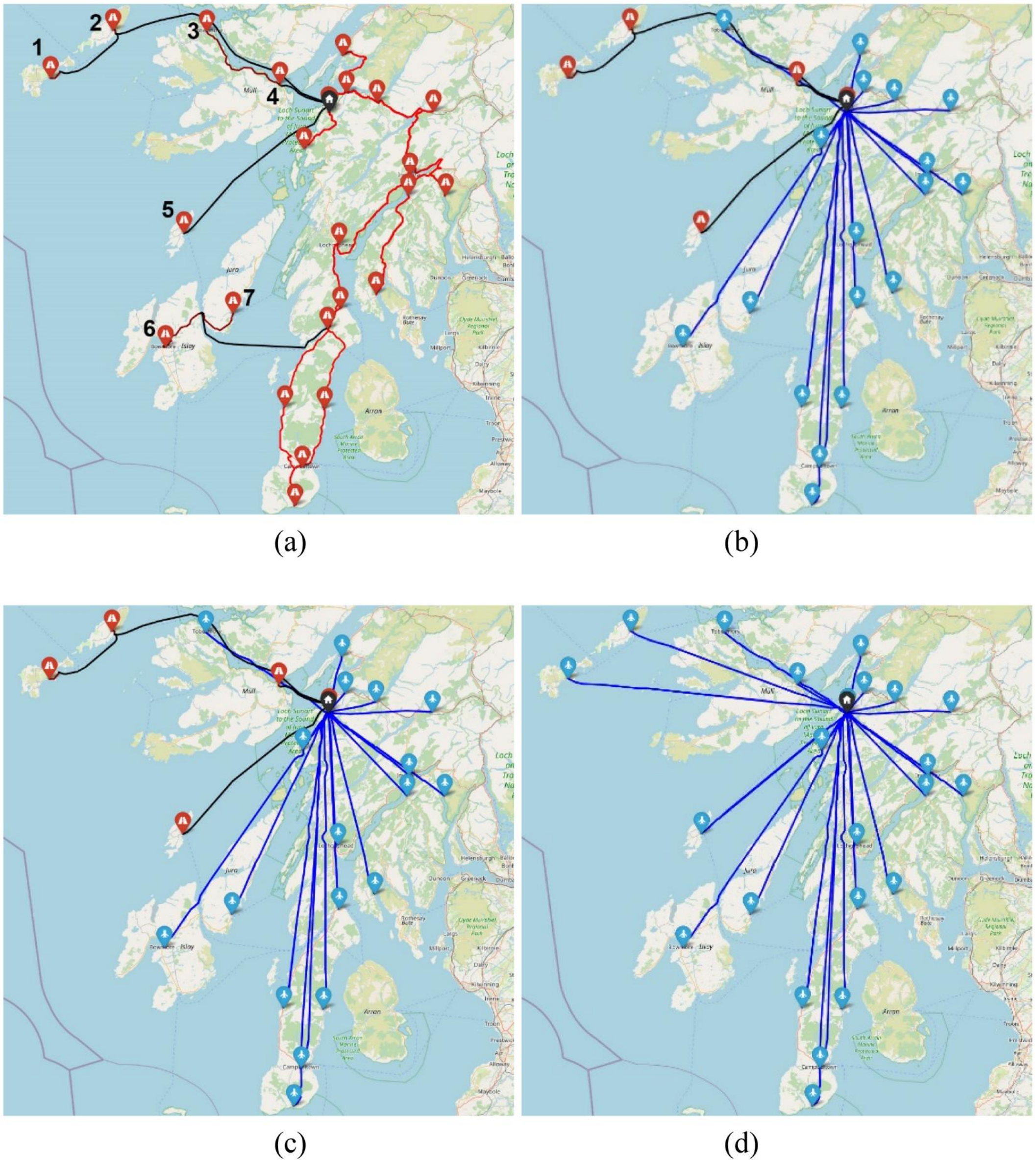

Figure 9. Maps of scenario solutions for highlands. (a) Benchmark; (b) MixedMode_multi; (c) MixedMode_hybrid; (d) DroneOnly (both multi and hybrid scenarios). Blue, red, black and dark red lines/pins indicate drone, e-van, ferry and local e-van routes/clinics, respectively. Black pin indicates Lorn and Islands Hospital. Numbers identify community clinics in island locations. Base map source: © OpenStreetMap.

can influence the potential of drones to offer emissions/energy reductions.

Comparison of the results for the benchmark and mixed-mode scenarios across the different testbeds highlighted the influence of network characteristics in terms of the type of clinic location most likely to be selected for service by drone when optimizing to minimize emissions. In the Southampton testbed, it tended to be the more remote (i.e. further from the pathology laboratory) and/or isolated (i.e. further from each other) clinics that were served by drone, while urban locations where clinic densities were high and the pathology laboratory was closer (i.e. clustered/proximate clinics) were served by e-vans and bicycle couriers (Figure 7(b) and (c)).

Compared to Southampton, the IOW testbed had a more even distribution of clinic locations surrounding a pathology laboratory that was reasonably central, i.e. it had fewer clinics that were particularly remote/isolated or clustered/proximate. This network layout appeared to be at the point where drones became an environmentally favorable alternative to e-vans from an emissions/energy perspective, with no drones being selected in the mixed-mode scenario when the multi-copter drone was available (Figure 8(b)), but when the more energy-efficient hybrid drone was available, e-vans were eliminated completely (Figure 8(c)).

Compared to both Southampton and the IOW, the Highlands testbed was much larger and more rural, meaning almost all clinics were remote/isolated, which led to a substantial replacement of e-vans by drones in both mixed-mode scenarios, particularly for the clinics located on the mainland (Figure 9(b) and (c)). Of the seven clinics located on islands (which are all remote/isolated, numbered 1–7 in Figure 9(a)), there were four (numbers 1, 2, 4 and 5) that continued to be served by e-van/ferry in the mixed-mode scenarios. This was because the existing benchmark journey from these clinics yielded relatively low emissions/energy due to the e-van proportion of the total journey distance being very short (i.e. low emissions/energy) and the ferry proportion having virtually zero emissions/energy, that is, the ferry was making the journey anyway regardless of whether or not specimens were carried, and carriage of a container of specimens (5 kg) causes very little additional emissions/energy to a half-laden ferry with an existing payload of 100,850 kg (Section 3.2). For the remaining three island clinics (numbers 3, 6 and 7), the e-van proportion of the total journey distance was much longer (i.e. higher emissions/energy), resulting in service by drone being the favorable alternative in the mixed-mode scenarios despite the ferry proportion having virtually zero emissions/energy.

In general, clinic locations that were remote/isolated in all three testbeds tended to be where drones could offer a beneficial effect on emissions/energy compared to e-vans. This was because these locations (in contrast to locations in urban areas, where clinic density is higher and the pathology laboratory is closer) involved higher stem mileages for e-vans and restricted e-vans' ability to utilize their larger payload capacity to generate economies of scale by collecting from multiple clinics clustered together (i.e. e-vans traveling long distances to make few collections were inefficient). Moreover, when clinics were isolated, the ability to use bicycle couriers for consolidation was limited due to their maximum range constraints (i.e. <8 km, Section 3.1), and bicycle couriers were not available at all in the Highlands testbed due to the very rural nature of the area (Section 3.2). In more urban locations, particularly in the city of Southampton itself, e-vans and bicycle couriers tended to be the preferred transport mode, with bicycle couriers in particular recognized for their far lower (i.e. zero) emissions compared to e-vans and drones (Conway, Cheng, Kamga, & Wan, 2017; Gruber & Narayanan, 2019; Marujo et al., 2018).

Comparison of the results for the benchmark and drone-only scenarios across the different testbeds supported the finding that remote/isolated clinics were where drones could offer the most potential for emissions/energy benefits. Results showed emissions/energy increases due to drones in Southampton (175% for the multi-copter and 37% for the hybrid, Table 3) and the IOW (132% for the multi-copter and 16% for the hybrid, Table 4) compared to e-van-only solutions, whereas emissions/energy decreases were shown in the Highlands (−60% for the multi-copter and −80% for the hybrid, Table 5) because this testbed had far more clinics that were remote/isolated compared to Southampton and the IOW.

4.3. Practicalities and wider considerations

In reality, while the environmental (i.e. emissions/energy) performance of their logistics operations are likely to be important to organizations, the effects of drones on costs and payload transit times may be more important concerns. In particular, the cost effects may be of paramount importance to both profit-driven commercial companies and public sector organizations with limited budgets funded by the taxpayer (e.g. the NHS). The clearest examples of the potential effects of drones on costs and transit times from the case study analysis were provided by comparison of the benchmark with the drone-only scenarios, where drones generated cost increases and maximum transit time reductions of +80% and −63%, +82% and −76%, and +134% and −61% in the Southampton, IOW, and Highlands testbeds, respectively, compared to e-van-only (or e-van/ferry-only) solutions. The transit time reductions generated by drones may be seen as a positive outcome, but the associated cost increases were considerable, even when using parameter values based on plausible future drone costs that are ∼55% less expensive than current (2022/23) costs (Grote, Oakey, Pilko, Krol et al., 2024), as was the case in this study (Section 3.1). Such cost increases are likely to be a significant barrier to drone up-take.

If FORSETI is set to optimize to minimize transit times (rather than to minimize emissions, as was the case in this study), this tends to result in drones being selected to service the more remote clinic locations because of their potential for faster transit times, whereas e-vans and bicycle couriers are selected for any less remote clinics that they can service in less time than it takes drones to service the more remote clinics because they are relatively less expensive modes (Oakey, 2023). This pattern of drones servicing more remote clinics is similar to that found when optimizing to minimize emissions (i.e. the results of this study), where clinic locations that were remote/isolated tended to be where drones could offer the most beneficial effect (Section 4.2).

The faster transit times and higher costs associated with drones highlighted the question of the true value to organizations of expedited delivery when it is perfectly possible to meet the requirements of existing level of service agreements using traditional surface transport modes. The patient diagnosis and treatment process in the NHS is usually measured in days and weeks due to the timescales inherent in the wider healthcare system (National Health Service (NHS), 2023a), so there is likely to be no (or very little) material benefit to the organization in reducing transit times by minutes or hours, while incurring extra costs.

In this study, drones were assumed to have sufficient range to complete all out-and-back journeys without needing a battery-swap (or re-charge) anywhere other than at the pathology laboratory (Section 3.1). It has been suggested that multi-copter drone platforms have a typical maximum range of ∼32 km (Rez, 2018), and this range would be insufficient to cover the distances required to service many of the clinics without intermediate stops for re-charging or battery-swaps, particularly in the Highlands testbed where the maximum out-and-back drone journey was 246 km (maximum out-and-back journeys in the Southampton and IOW testbeds were 63 km and 33 km, respectively). Any such requirement for intermediate stops would be likely to have a negative effect on emissions/energy due to the need to perform extra landings and take-offs, which consume disproportionately greater amounts of energy compared to the cruise; and also on costs due to the need to provide and staff the infrastructure at intermediate stop locations and on transit times due to the extra time taken during intermediate stops.

VTOL/FW hybrid drone platforms offer a more feasible solution because they typically tend to have a greater maximum range due to using a fixed-wing to generate lift during the horizontal cruise flight stage, which is more energy-efficient (Thielicke et al., 2021), for example, typical range capabilities quoted by drone manufacturers of 150+ km (Grote, Oakey, Pilko, Krol et al., 2024). If a VTOL/FW hybrid platform was used, in conjunction with provision for battery-swaps (or re-charging) at the community clinic locations (as well as at the pathology laboratory) while the drone was on-site anyway for a collection, drone ranges would be sufficient to cover even the most distant clinic in the Highlands testbed (i.e. maximum one-way drone journey of 123 km vs range of 150+ km), avoiding the need for any intermediate stops and their associated negative effects.

Comparison of typical ranges for multi-copter and VTOL/FW hybrid drones (i.e. 32 km vs 150 km) indicated that the assumption used in this study that the energy consumption of a VTOL/FW hybrid drone was approximately half that of a multi-copter drone (Section 3.1) was quite conservative. Therefore, it is possible that VTOL/FW hybrid drones could be able to generate greater emissions/energy savings than those estimated in this study.

In the Highlands testbed, due to its larger geographic size, the journey distances of e-vans exceeded the maximum range between stops for recharging (125 km, Section 3.1), with the longest distance traveled by an e-van being over 400 km and taking nearly 8 h to complete (including dwell time). Such situations necessitated intermediate stops for e-vans to be recharged, and also for driver breaks. For example, European Union (EU) rules on drivers' hours require breaks totaling at least 45 min after no more than 4:30 h driving time, which would not be an issue in the Southampton and IOW testbeds with four-hour shift periods, but would require a break during the longer shift period (8 h, Section 3.2) in the Highlands testbed. Intermediate stops for e-vans were assumed to be unlikely to affect emissions/energy significantly in the real-world, but would be likely to affect costs and transit times negatively (due to the extra time taken during intermediate stops, and the associated drivers' extra pay). Also in the Highlands testbed, bicycle couriers were assumed to be unavailable (i.e. switched off as a potential mode in FORSETI) because it was too rural for routine bicycle courier services (with their limited range of <8 km, Section 3.1) to be reliably available throughout the region (Section 3.2). That said, it may be possible in the real-world to use ad-hoc local arrangements for transport by bicycle rather than e-van or drone where distances are short enough, and this would generate additional savings in emissions/energy.

This study estimated lifecycle GHG emissions from electricity consumed (i.e. WTT-eq + TTW-eq, Section 3.1) but did not adopt a full LCA approach including emissions from vehicle manufacturing, maintenance, and end-of-life disposal as well, i.e. the study's approach was closely aligned to the traditional approach to analyzing transport emissions (Section 2). Evidence from previous studies has suggested that the situation regarding GHG emissions may be less favorable for drones compared to traditional modes (e.g. e-vans) if a full LCA approach was adopted for the vehicle as a whole (i.e. not just electricity used) (Section 2). The effect of a full LCA approach was beyond the scope of this study but is an area recommended for further research.

A key requirement of logistics services is reliability, providing certainty of delivery to customers, which can be affected by weather conditions and the technical reliability of vehicles. In developed nations, traditional logistics modes such as e-vans and bicycle couriers have close to 100% reliability in most weather conditions, with only severe local events likely to cause disruption (e.g. local flooding, storm conditions) (Hampson, 2022; Post & Parcel, 2010; Rudland, 2022). In contrast, typical weather tolerances for drones, e.g. 10 m/s wind speed and 50 mm/h precipitation (Oakey et al., 2022), tend to make them more susceptible to disruption by weather conditions that are not particularly uncommon. Analysis of historic weather conditions in the regions of the case study testbeds suggested that drones would be prevented from flying due to strong winds in the Southampton and IOW testbeds on up to ~20% of occasions and in the Highlands region on up to ~50% of occasions (Oakey & Cherrett, 2023; Oakey et al., 2022). Regarding the technical reliability of vehicles, drones (as commercial aircraft) are likely to be subject to more stringent serviceability inspection regimes (i.e. airworthiness checks prior to every departure, similar to those in crewed aviation, Section 3.1) compared to the inspection regimes for e-vans and bicycle couriers (e.g. annual roadworthiness check required for e-vans by the UK government and no checks at all required for bicycles), which means drones are more likely to be prevented from flying in the event of a minor malfunction, whereas e-vans and bicycle couriers are likely to be able to continue to operate. In this study, it was assumed that drone flights were never prevented by weather conditions or vehicle serviceability issues. In the real-world there is likely to be a need for back-up arrangements to be in-place to transport payloads when drones are grounded (e.g. the NHS often uses taxis on an ad-hoc basis as a back-up), which could have negative implications for emissions/energy, as well as costs and transit times.

All the community clinics were assumed to have a landing site available that was large enough to accommodate the drone types used in the study. Based on the requirements of the larger of the two drone platforms considered (i.e. VTOL/FW hybrid drone with wingspan 5 m, Section 3.1), this corresponded to a requirement for ~100 m^2 of accessible open space in close proximity to every clinic (Oakey et al., 2022). Creating and maintaining these landing sites would involve investment by the NHS and may be difficult to achieve in practice in some areas, such as densely populated urban areas (e.g. Southampton city) where open space is at a premium. Alternative systems of collection and delivery such as cable/winch systems could eliminate the need for landing sites at clinics, but these may be impractical due to safety concerns over attaching a medical container to a cable from a hovering drone in all weather conditions

(Grote, Oakey, Pilko, Krol et al., 2024). Wing has recently (2023) developed an automated cable/winch system for their delivery drones (Shankland, 2023), but the system relies on using Wing's bespoke packaging design, which is relatively small (<1.5 kg) and may be difficult to adapt for use with medical containers (or any other packaging designs).

Regulations restricting the use of airspace by drones could lead to drone journeys being extended, and therefore increased emissions/energy (and costs and transit times). For example, Southampton Airport is a small international airport located just to the North of the city of Southampton within the testbed area, which is surrounded by a zone of controlled airspace to protect air traffic landing and taking-off at the airport. Drones are likely to need to divert around (or negotiate permission for a route across) this control zone, potentially increasing journey distances. Furthermore, UAV Traffic Management (UTM) is a burgeoning concept under development around the world to facilitate drone operations by creating zones of airspace where drones can be integrated harmoniously alongside existing crewed aircraft in shared airspace. As UTM zones start to become established, any necessity to route *via* such zones may also cause drone journeys to be extended (Grote, Oakey, Pilko, Smith et al., 2024; Grote, Pilko et al., 2021; Grote et al., 2022).

The findings of the research were broadly consistent with other research studies in the domain of drone logistics, in that the use of drones can produce GHG emissions reductions (Section 2). However, logistics systems need to be modeled with reasonable fidelity (e.g. realistic payload capacities, delivery scenarios, comparisons to e-vans not diesel vans) to avoid over optimistic assessments of potential benefits, and the benefits of drone logistics are not universal, being available only in certain circumstances. For example, drones offered the greatest emissions/energy benefit when servicing locations that were remote/isolated, while e-vans and bicycle couriers were more favorable when locations were clustered/proximate (Section 4.2). This finding is similar to Kirschstein (2020), who found that logistics drones consumed comparable (or slightly less) energy to e-vans in more rural areas where customer densities are lower, but consumed more energy in urban areas where customer densities are higher, although this was not specifically a study of healthcare logistics and considered drones entirely replacing, rather than integrating alongside, e-vans (i.e. unimodal rather than mixed-mode logistics).

A case study approach was the method adopted in this study, and while networks with different geographic characteristics were analyzed, the results of the study are not necessarily generalizable. The study was UK-focused, and it is possible that the geographic characteristics may not be common in other countries, although it seems likely that similar characteristics will be found in networks in other developed nations similar to the UK. Furthermore, geographic characteristics may not be the most important factor influencing the emissions effect of drone logistics and other factors (e.g. drone platform type, payload capacities) may have a more important role. Nevertheless, further research is necessary to establish generalizable relationships between network geographic characteristics (e.g. clinic clustering, pathology laboratory centrality, network size) and the likelihood that introducing drones to mixed-mode logistics systems would have a positive influence on overall energy consumption and GHG emissions. Such relationships would provide a useful tool to guide practitioners considering the suitability of drones for their logistics needs, and this is suggested as an area for future research.

5. Conclusions

The findings of the study suggested that the introduction of drones (and bicycle couriers) into mixed-mode logistics systems alongside e-vans could lead to reductions in energy consumption and GHG emissions compared to e-van-only solutions. In general, community clinic locations that were remote (i.e. far from the pathology laboratory) and/or isolated (i.e. far from each other) tended to be where drones could offer a beneficial effect, while urban locations where clinic densities were higher and the pathology laboratory was closer were better served by e-vans and bicycle couriers, with bicycle couriers (assumed to have zero energy consumption and emissions) making a considerable contribution to savings in some cases. The introduction of drones also tended to be associated with increases in overall costs and decreases in maximum payload in-transit times (i.e. elapsed time between specimen collection and delivery at the laboratory), raising a question regarding the true value of expedited delivery to the organizations involved.

Drones may play a role in improving the emissions/energy performance of mixed-mode logistics systems, particularly where nodes in the network are isolated/remote, but this would have to be balanced against any associated cost increases, offset by the value of expedited delivery. Moreover, there are a number of practical challenges and wider considerations still to be overcome that may limit the ability of drones to generate their full potential emissions/energy benefits in the real-world, such as range constraints, LCA emissions performance, service reliability, landing site availability, and airspace restrictions.

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Data availability statement

The data that have been used are confidential and cannot be shared publicly.

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