Multi-modal multi-echelon logistics optimisation planning for medical interchanges in the Solent region of the UK using drones, cargo bikes, and vans

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The sustainability of urban logistics could be improved by a partial transition of urban freight delivery from ground-based vans and light commercial vehicles to cargo bikes and Uncrewed Aerial Vehicles (UAVs). Due to the benefits of UAVs in terms of transit speed, reduced emissions, and improved access to remote/rural areas, the healthcare sector could particularly benefit from the use of drones, as many medical products could have short shelf lives and therefore require a timely collection/delivery. The Drone Medical Logistics project, which is part of the Solent Future Transport Zone (FTZ) programme funded by the UK Department for Transport (DfT), focuses on developing a simulation environment for optimising and evaluating multi-modal supply chains involving land-to-UAV and UAV-to-land logistics interchanges. This study aims to develop multi-modal logistics planning and optimisation tools that will enable a fleet manager to quantify in what ways drones can be used as part of integrated fleets to efficiently improve deliveries/collections of medical/healthcare products between hospitals and surgeries in the Solent region, whilst reducing emissions and mean receipt times at the pathology labs to improve patient care.

Motivation The healthcare sector is responsible for generating 4-5% of global greenhouse gas emissions in the United Kingdom (UK) (Tennison et al. 2021). Correspondingly, the National Health Service (NHS), the healthcare system of England, has committed to tackle their contributions by reducing their emissions to 'net zero' by 2040 (NHS October 2020). Changes to supply chain and transportation operations have been identified as areas to be addressed.

In the Solent region, many movements of various commodities take place between hospitals and community NHS-operated General Practitioner (GP) surgeries (referred to as clinics or doctor's surgeries), including diagnostic specimens. The accumulated diagnostic specimens, referred to as 'pathology samples', are collected daily from a set of GP surgeries and local hospitals using a set of Light Goods Vehicles (LGVs) to be subsequently delivered to testing laboratories in the central hospital. In this study, we propose to optimise the daily collection problem of patient diagnostic samples in a new topology involving drones and cargo bikes in addition to LGVs to cover the hospitals and surgeries of the Solent region.

Problem Statement To address the aforementioned daily diagnostic sample collection arising in the Solent region, we have proposed the multi-modal multi-echelon routing problem with synchronisation (MMRPS), which is a generalisation of the Sample Collection Problem (SCP, (Yücel et al. 2013)). The MMRPS problem aims to determine the location of consolidation centres, and allocation, routing, and scheduling of drones, cargo bikes, and vans, for the daily medical collections to minimise a weighted sum of fixed, variable and CO_2 emission costs of vans, drones, and cargo bikes, considering patient care. We have proposed a new topology to model the MMRPS problem as shown in Figure 1, where its assumptions are summarised as follows:

- One central hospital (e.g., Southampton General Hospital) is considered to collect all the specimens from the GP surgeries and local hospitals, where split pickups are not allowed.
- Transportation of samples can occur in multiple echelons where a local hospital or consolidation centre can be selected as a stage to dispatch vans/cargo bikes/drones to collect samples. Vans/cargo bikes/drones used between two consecutive stages are called an 'echelon'.
- Vans, cargo bikes, and drones can be dispatched independently from the central and local hospitals. They must return to the same collection point where they have been dispatched from. The cargo bikes can be dispatched independently from the consolidation centres, and they must return to the same collection point where they have been dispatched.
- Samples at one collection point can be collected only once by either a van, a drone or a cargo bike. A drone can be dispatched to visit a collection point with feasible landing spaces only. The collection points with feasible landing spaces are predefined.
- Each van can be dispatched from the central or local hospitals only once in a given period.
- Each drone can be dispatched from the local or central hospitals more than once in a given period.
- To manage the risk of battery failure, drones are assumed to be fully charged when they are dispatched, and the batteries of drones are replaced with fully charged batteries whenever they fly back to their origin destination.
- Vans/drones that arrive early at a consolidation centre/hospital (echelon), are assumed to wait for the collection of all samples to ensure the synchronisation of operations in that echelon.
- Drones are subject to capacity constraints due to their limited payload.

- A hard time constraint to collect all samples is considered to ensure the quality of samples, timely delivery of samples, and a balanced workload. Also, for the gig-economy reasons, a time limit on the travel time of each cargo bike is considered which should not be violated.

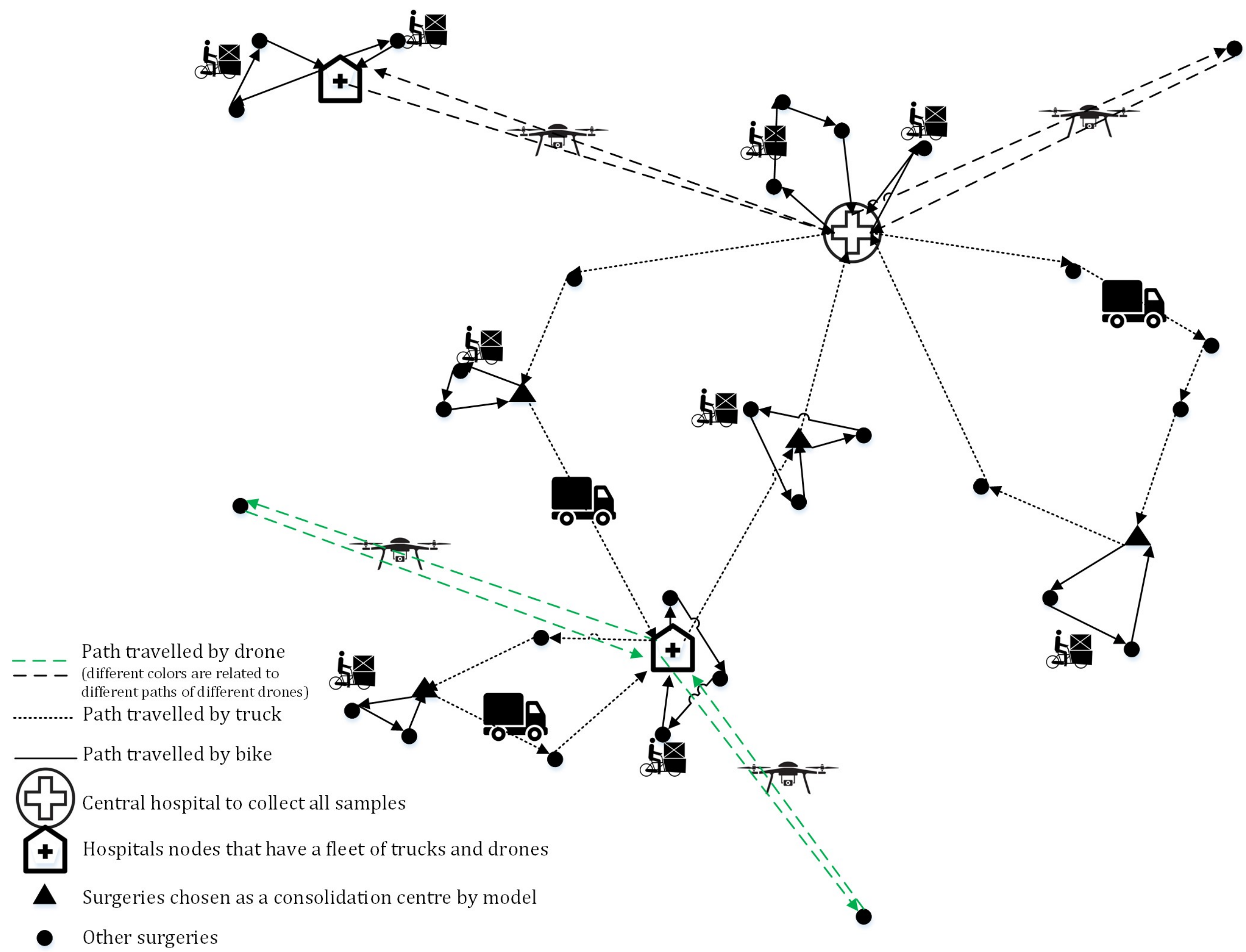

Figure 1 A representative example of the proposed topology.

Approach For the MMRPS, we have developed an optimisation model to locate consolidation centres, and allocate, route, and schedule vans, drones, and cargo bikes. The objective function of the MMRPS is to minimise a weighted sum of fixed, variable and CO_2 emission costs of vans, drones, and cargo bikes. To efficiently solve the optimisation model, we have implemented an ALNS-based meta-heuristic method in C++, which solves the problem in seconds.

Results Computational experiments have been conducted using the diagnostic samples data for the Southampton area in the Solent region to demonstrate the performance of the proposed topology, optimisation model and solution method. The Key Performance Indicators (KPIs) considered in the evaluation are patient care, emission, and costs. The key results are shown in the following:

(i) Significant improvement of patient care as diagnostic samples are collected within 90 minutes after their ready times (with an average sample receipt time of 56 minutes) rather than 253 minutes in the business as usual,

(ii) Emissions are significantly reduced from a daily 782 kg to 484 kg per day, and

(iii) The number of vans needed to service GP surgeries/ local hospitals was reduced from 10 vans per day to a maximum of 4 vans, 2 drones and 19 cargo bikes per day.

Conclusions The research work proposed in this paper has addressed the daily diagnostic sample collection problem arising in the Solent region by developing a new topology for the multi-modal multi-echelon routing problem with synchronisation, an optimisation model and an ALNS-based meta-heuristic solution method. The MMRPS aims to minimise a weighted sum of fixed, variable and CO_2 emission costs of vans, drones, and cargo bikes for the allocation, routing and scheduling of vans, drones, and cargo bikes, along with the location of consolidation centres. The performance evaluation results have shown significant improvements in the KPIs of patient care and emissions.

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