A multi-modal and variable-echelon last-mile delivery system

C. Bayliss[a*], T. Bektaş[a], V. Tjon-Soei-Len[b] and R. Rohner[b]

[a] University of Liverpool, Management School, Liverpool, UK
Christopher.Bayliss@liverpool.ac.uk, T.Bektas@liverpool.ac.uk
[b] Darwin Evolution Technologies, UK
vernon@bezos.ai, remo@bezos.ai
[*] Corresponding author

Extended abstract submitted for presentation at the 11th Triennial Symposium on Transportation Analysis conference (TRISTAN XI)
June 19-25, 2022, Mauritius Island

March 28, 2022

Keywords: Open vehicle routing; multi-modal variable-echelon; mobile satellites; cargo bikes

1 INTRODUCTION

Online retail is accounting for an ever increasing of portion of all retail sales. In the UK alone, the volume of the parcel market reached 2.6 billion items in the 2018-19 financial year (Ofcom, 2019). Online sales channels have lead to increased competition with retailers trying to increase their market share by offering lower prices and cheap fast delivery to the customer's doorstep When home delivery demand density is sufficiently high, hiring storage spaces in areas close to points of demand can become cost effective, since it reduces warehouse-to-delivery-zone stem costs. Also, when demand density is sufficiently high and package sizes are small, it can become cost effective to make use of alternative modes of delivery, such as cargo bikes and porters (walkers), which have relatively limited capacity but are environmentally friendly. When the vehicle fleet is highly diversified and some vehicles have limited carrying capacity or range, mobile satellites (kerb side spaces) can be used for transferring parcels between delivery modes en-route.

In this work we address a routing problem that arises within a logistics network composed of multiple localised storage warehouses and a diverse fleet of delivery vehicles. Delivery of an item may be made using a sequence of different transport modes (multi-modal delivery). Parcels can be transferred to and from any pair of vehicle types, hence we consider a pick up and delivery problem with a variable echelon structure.

2 LITERATURE REVIEW

One recent focus in last-mile delivery research is the use of environmentally friendly vehicles such as electric vehicles or porters (walkers). Allen *et al.* (2018) analyse data from delivery routes of two different parcel carriers operating in London, with the aim of evaluating the potential benefits of utilising porters in conjunction with truck deliveries. It was found that, on average, trucks spend 60% of the time stationary, while drivers make deliveries on foot, and that handing over parcels to porters, at relatively few drop off points has the potential to reduce vehicle time by 55% while increasing vehicle utilisation. Martinez-Sykora *et al.* (2020) develop an optimisation model for last-mile delivery in London using a combination of walking and driving. Performing sequences of deliveries on foot, within a vehicle route, can be helpful in densely populated areas where kerbside parking space is hard to find.

When deliveries are outsourced to third party logistics providers or couriers, vehicles need not start from and end at a specific vehicle depot, in such cases the vehicle's routes are referred to as *open routes*. Yu *et al.* (2020) consider a two-echelon open location routing problem for urban delivery. The first echelon consists of (closed) trunk routes from the main depot to kerbside inventory exchange points, where inventory is transferred to third party logistics providers who use motorcycles for (open route) delivery.

Multi-modal delivery concepts which make use of kerbside inventory exchange points require the tours of the vehicles involved to be synchronised. Drexl (2012) provides a classification and review of VRPs with multiple synchronisation constraints. As an archetypal example, the VRP with trailers and transshipments (VRPTT) is used. The main synchronisation issues include determining when must some vehicles be simultaneously present and when some events need to precede others. To the best of our knowledge no other work considers a multi-modal and variable echelon delivery system described in this work.

3 PROBLEM DESCRIPTION

Demand is generated by customers who require home deliveries of products for which inventory can be stored across any number of storage warehouses. Parcel deliveries to customers must be made within specific time windows. A fleet of vehicles consisting of vans, cargo bikes and porters (walkers) are available for making deliveries. Each vehicle type has their own maximum volume, maximum weight, drop times, maximum tour length, maximum tour duration and travel speed. Tours can begin at any warehouse or mobile satellite. Tours end at either a warehouse, customer or mobile satellite. Such tours are called open tours, which are appropriate when deliveries are to be carried out using third party logistics providers.

Deliveries can be made either: (i) directly from a warehouse to a customer using a single vehicle, or (ii) using multi-modal transport, where parcels can be transferred from one vehicle to another by making use of kerb side handover points. For example, a van can meet with a number of cargo bikes and porters at a mobile satellite, who receive inventory which they then deliver. Warehouses can also be used as inventory handover points, which have storage capacity and therefore do not require the vehicles involved to be simultaneously present.

Routes incur travel costs dependent upon tour length (fuel) and duration (wages), and each vehicle used invokes a fixed cost. The objective is to determine a fleet configuration, i.e., numbers of van, cargo bike and porters, and plan a set of routes which are feasible and transport all parcels to the required locations, at a minimum total cost.

As an example to highlight the flexibility of the approach, a feasible solution may include a van, a cargo bike and a porter. The van may start from a warehouse, visit a mobile satellite and transfer inventory to the cargo bike, before making some customer deliveries. The cargo bike may then visit another mobile satellite where inventory is transferred to the porter, who then makes some customer deliveries. The cargo bike may then meet with the van a second time at another mobile satellite to restock, before both carry on to perform the remaining deliveries.

4 HEURISTIC ALGORITHM

We propose a two-phase heuristic solution methodology. First a constructive phase, followed by an improvement phase. While time remains, this procedure is repeated and the algorithm generates more solutions, always keeping track of the lowest cost solution generated overall.

The constructive phase is based on building a solution, one step at a time, where in each step, we find a way to modify the current solution such that a another customer's delivery is fulfilled, and continue until all customer orders are fulfilled. The 6 ways (referred to as operations) in which another customer's order can be included in the current solution are as follows: 1) Add a customer to an already utilised vehicle's route; 2) Change the type of an already utilised vehicle and visit another customer; 3) Use an existing vehicle rendezvous to generate extra opportunities to visit another customer; 4) Change the type of an already utilised vehicle and use an existing vehicle rendezvous to generate extra opportunities to visit another customer; 5) Visit another customer by using a new vehicle directly or in conjunction with an existing or a new vehicle rendezvous; and 6) Add new vehicle rendezvous in the hope that applying the above operations again generates a way to add another customer to the current solution. These 6 operations are considered in this order, and we stop when we find the first operation that provides a feasible way to include another customer in the current solution. Lower cost operations have a higher probability of selection. The logic behind the ordering of operations is that the earlier ones are simpler and cheaper and the latter ones are more expensive and generally redundant if earlier ones return feasible decisions. For example, there is no need to swap a porter to a van (Operation 3) if the porter can still visit more customers, since the porter is generally cheaper.

While the constructive heuristic provides a diversification mechanism, a local search provides an intensification mechanism. The local search improvement phase focuses on improving the route efficiency of sub-routes, which consist of customer sequences without vehicle rendezvous in between, thereby leaving the logistic backbone of the solution, including any vehicle rendezvous and warehouse visits, intact. The local search procedure uses two neighbourhood structures: i) *two-opt*, which removes unnecessary cross-overs in routes; and ii) *cut-and-insert*, which finds more efficient alternative positions for each customer.

5 COMPUTATIONAL RESULTS

Experiments were conducted on an instance based on real sales data within London that includes demand information for 340 customers. A customer order comprises a delivery location and a set of parcels, each of which has a size (scalar volume) and a weight. A depot is located on the outskirts of London, and five mobile satellite locations are distributed across the city. Vans, cargo bikes and porters are available for making deliveries, and there relative characteristics are designed to reflect reality. In general, larger vehicle types are more expensive but have higher capacity and range. Smaller vehicle have shorter customer service times. Prior to the main experiments, the proposed heuristic was first benchmarked against an integer linear programming formulation developed for the problem and was able to find optimal solutions for all instances with up to 20 customers. Further tests were run on existing benchmark instances of the open vehicle routing problem (Ruiz *et al.*, 2019), on which the heuristic achieved an average gap of 3.73% in comparison to best known solutions reported in the literature.

The experiment compares three scenarios, which differ in the way that vehicles can be used to make deliveries, namely Scenario S) Only vans are allowed to make deliveries and no rendezvous are allowed at mobile satellite locations; Scenario M) Vans, cargo bikes and porters are allowed to make deliveries, but no rendezvous are allowed at mobile satellite locations; and Scenario MM) Vans, cargo bikes and porters are allowed to make deliveries, and rendezvous are allowed at mobile satellite locations. Each instance is solved using the proposed heuristic method.

Instance	Solution cost (£)	Solution time (s)	Vehicles used	Total miles	Van miles	Cargo bike miles	Iterations
S	985.01	2678.42	(7)	241.38	241.38	0	4000
M	943.20	2760.22	(5 2 0)	245.43	190.03	55.40	4000
MM	898.51	4207.03	(5 2 0)	223.78	165.20	58.58	4000

Table 1 – *Three scenario experiment results*

Table 1 provides solution costs, solution times, the numbers of vehicles of each type used in each solution, total miles, van miles and cargo bike miles and the number of iterations completed. The results show that scenario 3, where multiple vehicle types and vehicle rendezvous at mobile

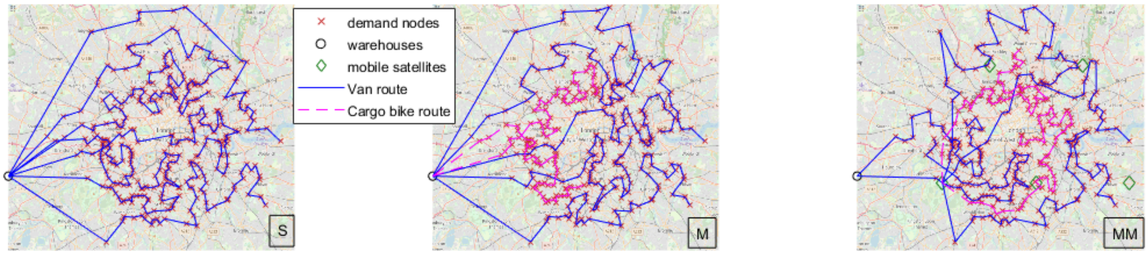

Figure 1 – *Vehicle route solutions for instances S, M and MM.*

satellites are allowed, leads to the lowest solution costs. Similarly, scenario 2, always provides lower cost solutions than scenario 1, thus highlighting the potential benefits of utilising smaller vehicles with lower fixed and variable costs. Table 1 shows how the relative savings, between the three scenarios, were made. Scenarios 2 and 3 both exploits vehicle types with lower fixed and variable costs, and as a result reduces van miles, and therefore tailpipe emissions. Scenario 3 can also significantly reduce the total distance that must be travelled, which can be attributed to reduced warehouse stem costs. Figure 1 depicts the differences between the three scenarios. Porters are only used when the spatial scale of the instance is reduced and parcel sizes reduced.

6 CONCLUSIONS

The multi-modal and variable-echelon last-mile delivery system described in this work is designed to take advantage of cost and externality savings brought about through the use of distributed inventory storage, coordinated use of alternative vehicle types and use of mobile satellites for transporting inventory between vehicle during delivery routes. Experiments conducted on real data showed that allowing the use of alternative vehicle types, such as cargo bikes, and making use of vehicle rendezvous at mobile satellites, both introduce cost reducing degrees of freedom into the routing optimisation problem.

ACKNOWLEDGEMENTS

We thank InnovateUK (Project No: 45624) for funding this work.

References

Allen, Julian, Bektaş, Tolga, Cherrett, Tom, Bates, Oliver, Friday, Adrian, McLeod, Fraser, Piecyk, Maja, Piotrowska, Marzena, Nguyen, ThuBa, & Wise, Sarah. 2018. The Scope for Pavement Porters: Addressing the Challenges of Last-Mile Parcel Delivery in London. *Transportation Research Record*, **2672(9)**, 184–193.

Drexl, Michael. 2012. Synchronization in vehicle routing—A survey of VRPs with multiple synchronization constraints. *Transportation Science*, **46**, 297–316.

Martinez-Sykora, Antonio, McLeod, Fraser, Lamas-Fernandez, Carlos, Bektaş, Tolga, Cherrett, Tom, & Allen, Julian. 2020. Optimised solutions to the last-mile delivery problem in London using a combination of walking and driving. *Annals of Operations Research*, **295**, 645–693.

Ofcom. 2019. *Annual monitoring update on the postal market. Financial year 2018-19. Technical Report.* Available at https://www.ofcom.org.uk/__data/assets/pdf_file/0028/186139/annual-monitoring-update-postal-market-18-19.pdf.

Ruiz, Efrain, Soto-Mendoza, Valeria, Barbosa, Alvaro Ernesto Ruiz, & Reyes, Ricardo. 2019. Solving the open vehicle routing problem with capacity and distance constraints with a biased random key genetic algorithm. *Computers & Industrial Engineering*, **133**, 207–219.

Yu, Vincent F., Winarno, Lin, Shih-Wei, & Gunawan, Aldy. 2020. Design of a two-echelon freight distribution system in an urban area considering third-party logistics and loading–unloading zones. *Applied Soft Computing Journal*, **97**, 106707.