Optimising Product Swaps in Urban Retail Networks

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Abstract: *The Physical Internet (PI) and City Logistics is based on trying to achieve higher levels of consolidation on vehicles that typically requires exchanging loads at intermediate locations. A common problem in urban areas in swapping goods between retail stores where there is a small amount of goods moving between individual stores to satisfy customer requirements where there are stock shortages at some locations. This type of network is also common for deliveries between local post offices or B2B networks particularly with parcel lockers. Such networks are characterised by having multiple common origins and destinations requiring services operating from many to many locations. A number of performance measures can be considered for such networks including number of vehicles operated and distance travelled, service levels/reliability for customers, network efficiency, vehicle load factors and the number of times tasks/consignments are transferred between vehicles.*

This paper describes how networks for exchanging goods between stores can be designed using multi-objective optimisation modelling. A mathematical program has been formulated to include multiple objectives, namely vehicle operating costs, vehicle usage (number of vehicles used), labour costs (proportional to working time) and unreliability costs. Constraints considered include, vehicle capacity, unloading dock capacity and storage capacity. Decision variables are the vehicle routes with loads as well as waiting times at nodes. Coordination of transfers at customer considers vehicle-to-vehicle parcel transfer. Pareto optimal solutions for a small network are presented. A discussion of various solution procedures will be outlined.

Conference Topic(s): *PI network design*

Keywords: *Cross-Docking, Logistics Networks, Multi-objective optimisation, Transshipment*

1 Introduction

Low utilization of urban freight vehicles is contributing to rising costs of urban distribution and increasing levels of urban congestion that is leading to a deterioration in sustainability in many cities. E-commerce is leading to new distribution models with hybrid networks involving deliveries from stores as well as warehouses to homes becoming popular (Arslan et al 2020). However, transfers of goods between stores can provide cost savings and efficiency gains where there is excess stock at some stores and shortages at others. B2B parcel networks have discrete origins such as courier depots and destinations such as parcel lockers (Pan et al, 2021).

There is a growing need to transfer inventory between stores or outlets within retail chains in large metropolitan areas or regions due to growing range of specialty products becoming available, increasing pressure to maintain low stock levels at stores and retailers only a limited number of warehouses within metropolitan areas. Such networks have a discrete number of origins and destinations and a frequent demand for goods to be transferred between them. Similar networks exist for transporting books between libraries within local areas, medicine between hospitals within health care organisations and consignments between urban consolidation centres or hubs in large metropolitan areas.

City Logistics initiatives aim to reduce the economic, social and environmental costs associated with urban freight (Taniguchi and Thompson, 2015). Hyperconnected city logistics based on Physical Internet concepts provides a practical means of integrating urban freight transport systems (Crainic and Montreuil, 2016).

Increasing consolidation levels in vehicles was recognised as the key to achieving sustainable urban goods transport (OECD, 2003). Improved vehicle loading or tonnes moved by km driven has been identified is a key driver of emissions decrease in logistical field (ITF, 2018). This involves increasing the use of available capacity in vehicles and reducing the overall km driven by vehicles while delivering the same amount of goods.

2 Methodology

2.1 Problem description

The problem considers product swaps among retailor shops in an urban network. The aim is to determine the optimal vehicle routes for exchanging goods and identify the best locations for the goods transhipment for a given demand. The left plot of Figure 1 shows an example of a network with five retailor shops when product transhipment is not considered. To deliver 20 delivery tasks from shop $i \in \{1,2,3,4,5\}$ to shop $j \in \{1,2,3,4,5\}\backslash\{i\}$, five vehicles are employed, each from one shop, to deliver products to the other shops. This results in a long total travel distance as well as a lot of travel with empty/low load. On the other hand, if products can be transhipped and exchanged at some shops, fewer vehicles may be needed, and the total travel distance and load factor can be improved. The right plot of Figure 1 gives an example of the network when shop 5 is considered as an exchange point. Products to other nodes can be transhipped at shop 5.

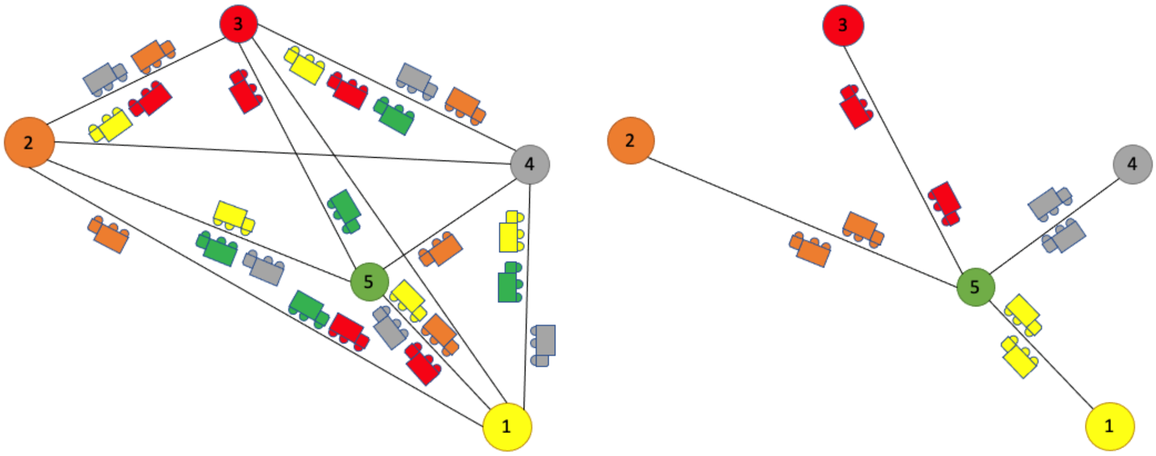

Figure 1: Illustrating product swap networks without (Left) and with (Right) product transhipment.

The objective is to minimise the total delivery cost as well as the reliability of the network, which is measured by the number of product transfers. In the next subsection, we develop a model to determine the vehicle routes and the location of exchange point(s). Key constraints such as vehicle capacity and vehicle coordination (a.k.a. vehicle synchronisation, which requires two vehicles present at the loading area of a shop at the same when transhipment occurs) are taken into account. In addition, vehicles need to occupy loading docks when transhipping goods, and so the dock availability constraint is considered.

2.2 Mathematical model

We consider a set of shops (i.e., nodes) $\mathcal{M}$ in the urban retail network with a set of delivery tasks $\mathcal{N}$; each task n is characterised by its origin and destination nodes (o_n, d_n) and size s_n. There is a set of vehicles $\mathcal{V}$ available to perform delivery; each vehicle is associated with a node, its depot (i.e., start node) f_v, and a capacity c_v. The model needs to decide when a vehicle v is to start from its depot, i.e., $x_v \geq 0$, which route the vehicle takes, which is represented by binary variable $y_{v,ij}$, and what products it picks up/drops off. Binary variable $z_{v,n,ij}$ indicates whether a task n is carried on by vehicle v on path $i \to j$, $i, j \in \mathcal{M}$. Vehicle waiting is allowed at nodes, which is controlled by decision variable $\omega_{v,i} \geq 0$. See Table 1 for the variable notation.

Table 1: Notation for variables

Decision variables	
x_v	Start time of vehicle $v \in \mathcal{V}$ from its depot, $x_v \geq 0, \forall v$
$y_{v,ij}$	$= 1$ if vehicle v traverses route ij; $= 0$ otherwise. $y_{v,ii} = 0$.
$z_{v,n,ij}$	$= 1$ if vehicle v transports task $n \in \mathcal{N}$ through ij; $= 0$ otherwise. $z_{v,n,ii} = 0$.
$\omega_{v,i}$	Additional waiting time of vehicle v at node $i \in \mathcal{M}$
Auxiliary variables	
$\mu_{v,i}$	$= 1$ if vehicle v unloads at node $i \in \mathcal{M}$; $= 0$ otherwise.
$\lambda_{v,i}$	$= 1$ if vehicle v loads at node $i \in \mathcal{M}$; $= 0$ otherwise.
$p\lambda_{v,n,i}$	$= 1$ if vehicle v picks up task $n \in \mathcal{N}$ at node $i \in \mathcal{M}$; $= 0$ otherwise.
$p\mu_{v,n,i}$	$= 1$ if vehicle v drops off task $n \in \mathcal{N}$ at node $i \in \mathcal{M}$; $= 0$ otherwise.
$D_{v,i}$	Departure time of vehicle v at node $i \in \mathcal{M}$
$A_{v,i}$	Arrival time of vehicle v at node $i \in \mathcal{M}$

$PD_{n,i}$	Departure time of task $n \in \mathcal{N}$ at node $i \in \mathcal{M}$
$PA_{n,i}$	Arrival/Available time of task $n \in \mathcal{N}$ at node $i \in \mathcal{M}$

The objective function consists of three parts: (i) vehicle operating cost (VOC), (ii) labour cost (LC), and (iii) unreliability cost. The VOC is composed of the fixed vehicle cost and the travel cost, which correspond to the two terms in Equation (1).

$$F_{voc} = VC_f \sum_{v\in\mathcal{V}} \sum_{i\in\mathcal{M}} y_{v,if_v} + VC_d \times V \sum_{v\in\mathcal{V}} \sum_{i\in\mathcal{M}} \sum_{j\in\mathcal{M}} y_{v,ij} T_{ij} \quad (1)$$

where VC_f is the fixed rate for employing a vehicle, VC_d is the cost per km, V is the average travel speed, and T_{ij} is the travel time from i to j.

The labour cost includes the salary of vehicle drivers and that of staff working at unloading docks for loading/unloading goods. It is assumed that the salary is proportional to working time. The working time for driving vehicle v is the difference in time between the arrival at and departure from its depot, i.e., $A_{v,f_v} - x_v$. Let binary variables $\mu_{v,i}$ and $\lambda_{v,i}$ indicate whether vehicle v unloads and loads any product at node i. Given the fixed unloading and loading times, U_i and L_i, the working time at node i is $\sum_v (\mu_{v,i} U_i + \lambda_{v,i} L_i)$. So,

$$F_{lc} = LC_d \sum_{v\in\mathcal{V}} (A_{v,f_v} - x_v) + LC_f \sum_{v\in\mathcal{V}} \sum_{i\in\mathcal{M}} (\mu_{v,i} U_i + \lambda_{v,i} L_i). \quad (2)$$

Here LC_d and LC_f are the salary rates for drivers and shop staff respectively.

Generally speaking, the system is more reliable when there are fewer product transfers. Hence the unreliability is measured by the number of transfers made. We let binary variables $p\mu_{v,n,i}$ and $p\lambda_{v,n,i}$ denote if task n is unloaded and loaded, respectively, by vehicle v at node i. Each task needs to be loaded and unloaded at least once. The right-hand side of (3) is the difference between the total number of loading and unloading and $2|\mathcal{N}|$ divided by 2, which gives the additional loading-unloading times, i.e., the number of transfers.

$$F_{ur} = \frac{1}{2} \sum_{i\in\mathcal{M}} \sum_{v\in\mathcal{V}} \sum_{n\in\mathcal{N}} (p\mu_{v,n,i} + p\lambda_{v,n,i}) - |\mathcal{N}| \quad (3)$$

The mathematical formulation of the problem is provided below.

$$\min_{\mathbf{x},\mathbf{y},\mathbf{z},\boldsymbol{\omega}} (F_{\$}, F_{ur}) \text{ s.t.} \quad (4)$$

$$\sum_{j\in\mathcal{M}} y_{v,ij} \le 1 \qquad \forall i \in \mathcal{M}, v \in \mathcal{V} \quad (5)$$

$$\sum_{j\in\mathcal{M}\setminus\{i\}} y_{v,ij} = \sum_{k\in\mathcal{M}\setminus\{i\}} y_{v,ki} \qquad \forall i \in \mathcal{M}, v \in \mathcal{V} \quad (6)$$

$$\sum_{v\in\mathcal{V}} \sum_{j\in\mathcal{M}} z_{v,n,o_n j} = 1 \qquad \forall n \in \mathcal{N} \quad (7)$$

$$\sum_{v\in\mathcal{V}} \sum_{i\in\mathcal{M}} z_{v,n,io_n} = 0 \qquad \forall n \in \mathcal{N} \quad (8)$$

$$\sum_{v\in\mathcal{V}} \sum_{j\in\mathcal{M}} z_{v,n,id_n} = 1 \qquad \forall n \in \mathcal{N} \quad (9)$$

$$\sum_{v\in\mathcal{V}} \sum_{i\in\mathcal{M}} z_{z_{v,n,d_n j}} = 0 \qquad \forall n \in \mathcal{N} \quad (10)$$

$$\sum_{v\in\mathcal{V}} \sum_{j\in\mathcal{M}} z_{v,n,ij} \le 1 \qquad \forall i \in \mathcal{M}\setminus\{o_n, d_n\}, n \in \mathcal{N} \quad (11)$$

$$\sum_{v\in\mathcal{V}} \sum_{j\in\mathcal{M}} z_{v,n,ij} = \sum_{v\in\mathcal{V}} \sum_{k\in\mathcal{M}} z_{v,n,ki} \qquad \forall i \in \mathcal{M}\setminus\{o_n, d_n\}, n \in \mathcal{N} \quad (12)$$

$$z_{v,n,ij} \le y_{v,ij} \qquad \forall i,j \in \mathcal{M}, n \in \mathcal{N}, v \in \mathcal{V} \quad (12)$$

$$p\mu_{v,n,i} \ge \sum_{k\in\mathcal{M}} z_{v,n,ki} - \sum_{j\in\mathcal{M}} z_{v,n,ij} \qquad \forall i \in \mathcal{M}, n \in \mathcal{N}, v \in \mathcal{V} \quad (13)$$

$$p\lambda_{v,n,i} \ge \sum_{j\in\mathcal{M}} z_{v,n,ij} - \sum_{k\in\mathcal{M}} z_{v,n,ki} \qquad \forall i \in \mathcal{M}, n \in \mathcal{N}, v \in \mathcal{V} \quad (14)$$

$$M\mu_{v,i} \geq \sum_{n\in\mathcal{N}} p\mu_{v,n,i} - 1 \qquad \forall i \in \mathcal{M}, v \in \mathcal{V} \qquad (15)$$
$$M\lambda_{v,i} \geq \sum_{n\in\mathcal{N}} p\lambda_{v,n,i} - 1 \qquad \forall i \in \mathcal{M}, v \in \mathcal{V} \qquad (16)$$
$$A_{v,i} = \sum_{j\in\mathcal{M}} y_{v,ji}\left(D_{v,j} + T_{ij}\right) \qquad \forall i \in \mathcal{M}, v \in \mathcal{V} \qquad (17)$$
$$D_{v,f_v} = x_v + \lambda_{v,f_v} L_{f_v} + \omega_{v,f_v} \qquad \forall\, v \in \mathcal{V} \qquad (18)$$
$$D_{v,i} = A_{v,i} + \mu_{v,i} U_i + \lambda_{v,i} L_i + \omega_{v,i} \qquad \forall i \in \mathcal{M}\backslash\{f_v\}, v \in \mathcal{V} \qquad (19)$$
$$A_{v,f_v} \leq T \qquad \forall v \in \mathcal{V} \qquad (20)$$
$$\omega_{v,i} \leq w \qquad \forall i \in \mathcal{M}, v \in \mathcal{V} \qquad (21)$$
$$PA_{n,i} = \sum_{v\in\mathcal{V}} \sum_{k\in\mathcal{M}} z_{v,n,ki}(A_{v,i} + U_i) \qquad \forall i \in \mathcal{M}, n \in \mathcal{N} \qquad (22)$$
$$PD_{n,i} = \sum_{v\in\mathcal{V}} \sum_{j\in\mathcal{M}} z_{v,n,ij}(D_{v,i} - \omega_{v,i} - L_i) \ \forall i \in \mathcal{M}, n \in \mathcal{N} \qquad (23)$$
$$PA_{n,i} \leq PD_{n,i} \qquad \forall i \in \mathcal{M}\backslash\{o_n, d_n\}, n \in \mathcal{N} \qquad (24)$$
$$PD_{n,i} - D_{v,i} \leq \left(1 - p\mu_{v,n,i}\right)M \qquad \forall i \in \mathcal{M}, n \in \mathcal{N}, v \in \mathcal{V} \qquad (25)$$
$$PA_{n,i} - D_{v,i} \leq \left(1 - z_{v,n,ij}\right)M \qquad \forall i,j \in \mathcal{M}, n \in \mathcal{N}, v \in \mathcal{V} \qquad (26)$$
$$\sum_{n\in\mathcal{N}} s_n z_{v,n,ij} \leq c_v \qquad \forall v \in \mathcal{V} \qquad (27)$$
$$\max_{v\in\mathcal{V}} \sum_{u\in\mathcal{V}\backslash\{v\}} \mathbf{1}\left(A_{u,i} < D_{v,i} \& A_{v,i} < D_{u,i}\right) + 1 \leq l_i \quad \forall i \in \mathcal{M} \qquad (28)$$
$$x_v, \omega_{v,i} \geq 0 \qquad \forall i \in \mathcal{M}, v \in \mathcal{V} \qquad (29)$$
$$y_{v,ij}, z_{v,n,ij} \in \{0,1\} \qquad \forall i,j \in \mathcal{M}, n \in \mathcal{N}, v \in \mathcal{V} \qquad (30)$$

The multi-objective function is given in (4), where F_1, F_2 are converted to the total financial cost $F_{\$}$. For vehicle routing, Constraint (5) ensures that each vehicle visits a node at most once, and (6) is the flow balance constraint. For performing delivery tasks, Constraints (7)-(10) guarantee that goods of each task are picked up from its origin and dropped off at its destination. For other nodes, Constraint (11) ensures that the goods can visit each of them at most once, and the product flow balance constraint is (12). Constraint (13) connects the decision variable for vehicle flow with that for product flow.

Equations (13) and (14) define the auxiliary variables for product unloading and loading respectively. Take (13) as an example. The term $\sum_{k\in\mathcal{M}} z_{v,n,ki} - \sum_{j\in\mathcal{M}} z_{v,n,ij}$ compares the incoming path to and the outgoing path from node i of v with task n. Task n must be unloaded at node i by v if it is positive. Likewise, Equations (15) and (16) define the variables for vehicle unloading and loading, respectively, through the corresponding variables for delivery tasks. Equations (17)-(19) define the vehicle arrival and departure times at nodes. The arrival time is defined through departure and travel times, while the departure time is the sum of arrival, loading/unloading and waiting times. Constraint (20) ensures all vehicles return to their depots by the end of delivery time period T. Constraint (21) imposes the waiting time limit.

The arrival and departure times for tasks are defined in (22) and (23). Product transfers are guaranteed by constraints (24)-(26). More precisely, (24) ensures that product's pick-up must be after its arrival, and furthermore, (25) requires that the corresponding vehicle's departure time cannot be earlier than that of the product. The vehicle v can transport product(s) of task n on route ij if the product's arrival time at i is not less than the vehicle departure time. The vehicle capacity constraint is respected by (27).

Loading dock capacity is respected by (28), where the left-hand side, including an indicator function $\mathbf{1}(\cdot)$ and a maximum function, calculates the maximum number of docks used at node i at any time and l_i is the number of available docks. Clearly, (28) is not a linear constraint. To linearise it, we define additional binary variables $AD^1_{v,u,i}$ ($DA^1_{v,u,i}$) to indicate whether vehicle v departs from node i before u arrives (v arrives at node i before vehicle u departs), and binary variable $l^1_{v,u,i}$ to indicate whether vehicles u, v are at node i at the same time. That is,

$$AD^1_{v,u,i}M \geq D_{v,i} - A_{u,i} \qquad \forall i \in \mathcal{M}, \forall u \neq v \in \mathcal{V} \qquad (31)$$
$$DA^1_{v,u,i}M \geq D_{u,i} - A_{v,i} \qquad \forall i \in \mathcal{M}, \forall u \neq v \in \mathcal{V} \qquad (32)$$
$$l^1_{v,u,i} + 1 \geq AD^1_{v,u,i} + DA^1_{v,u,i}, \qquad \forall i \in \mathcal{M}, \forall u \neq v \in \mathcal{V} \qquad (33)$$
$$l^1_{v,u,i} \leq AD^1_{v,u,i}, l^1_{v,u,i} \leq DA^1_{v,u,i}, \qquad \forall i \in \mathcal{M}, \forall u \neq v \in \mathcal{V} \qquad (34)$$
$$AD^1_{v,u,i}, DA^1_{v,u,i}, l^1_{v,u,i} \in \{0,1\} \qquad \forall i \in \mathcal{M}, \forall u \neq v \in \mathcal{V} \qquad (35)$$

Then (28) is replaced with

$$\sum_{u \in \mathcal{V} \setminus \{v\}} l^1_{v,u,i} + 1 \leq l_i \qquad \forall i \in \mathcal{M}, \forall v \in \mathcal{V} \qquad (36)$$

Finally, Equations (28) and (29) define the decision variables.

3 Model Application

3.1 Experiment settings

In this section, we perform a numerical experiment on a small network with five nodes. The locations of the nodes are selected to represent shops in southeast (node 1), western (node 2), northern, eastern (node 4) and CBD (node 5) areas of Melbourne. See Figure 1. The parameters used in the experiment is given in Table 2. There are two loading docks at each node for transhipment. All vehicles have the same capacity of 300 items, corresponding to a rigid truck, and the delivery distances and demand are provided in Table 3. We analyse the delivery efficiency in terms of total vehicle travel time (VKT), load factor (LF) as well as the delivery reliability in terms of product transfer times. The program is coded in Python and uses Gurobi 9.1.2 to find optimal solutions.

Table 2: Parameters

Labour cost		Vehicle cost		Travel speed	Max wait
LC_d =\$35/hr	LC_f =\$45/hr	VC_d =\$5/km	VC_f =\$10/veh	V =50km/hr	w =1hr

Table 3: Delivery distances ($dist_{ij}$ in km) and demand (s_{ij} in items)

From\To	Node 1		Node 2		Node 3		Node 4		Node 5	
	$dist_{ij}$	s_{ij}	$dist_{ij}$	s_{ij}	$dist_{ij}$	s_{ij}	$dist_{ij}$	s_{ij}	$dist_{ij}$	s_{ij}
Node 1	0	0	53	137	69	20	26	25	18.7	35
Node 2	53	154	0	0	30.2	35	53.4	43	38.8	39
Node 3	69	0	30.2	0	0	0	51	0	54	0
Node 4	26	0	53.4	0	51	0	0	0	18	0
Node 5	18.7	20	38.8	39	54	22	18	22	0	0

3.2 Impacts of product transhipment

We examine the results for three cases (i) dedicated vehicles are employed for shops (i.e., A vehicle only ships products originated from its own depot. See the left plot of Figure 1 for example), (ii) vehicles can transport products from any shop and product swap is forbidden, and (iii) a limit B is imposed on the number of product swaps. For Case (i), given there are three source nodes, 1, 2, 5, each dispatches one vehicle to transport products to other nodes. For example, the vehicle starting from node 1 carries goods for four tasks and drops off them at nodes 3, 4, 1, 5 in order. This results in a total financial cost of $2902.6 ($30 for vehicle cost, $2470.5 for travel cost, $402.1 for labour cost), VKT of 494.1km and LF of 0.326.

Figure 2 depicts the optimal routes for Case (ii) and Case (iii). Vehicle colours match their depot colours, and each rectangle with two coloured squares represents a delivery task for which the colours indicate its origin and destination. For Case (ii), two vehicles from nodes 2 and 5 are employed. The vehicle from node 5 is responsible for transporting products from node 5 to nodes 1 and 4 whilst the other transports the rest of the products. Relaxing the dedicated-vehicle constraint and keeping the no-product-swap condition, the VKT reduces to 227.4km and the total cost decreases to $1390 ($20 for vehicle cost, $1137 for travel cost, $240 for labour cost), saving more than 50% compared to Case (i). In Case (iii), we set the limit of swapping times to $B = 6$. The optimal solution uses two vehicles from nodes 1 and 2 and has four products swapped at intermediate node 5. Compared to Case (ii), the product swap helps improve the delivery efficiency; reducing the VKT by about 18% to 185.7km and the cost by 18% to $1139.3 ($20 for vehicle cost, $928.5 for travel cost, $192.8 for labour cost). Furthermore, Case (iii) raises the LF from 0.519 by Case (ii) to 0.754, which is a significant improvement compared with Case (i).

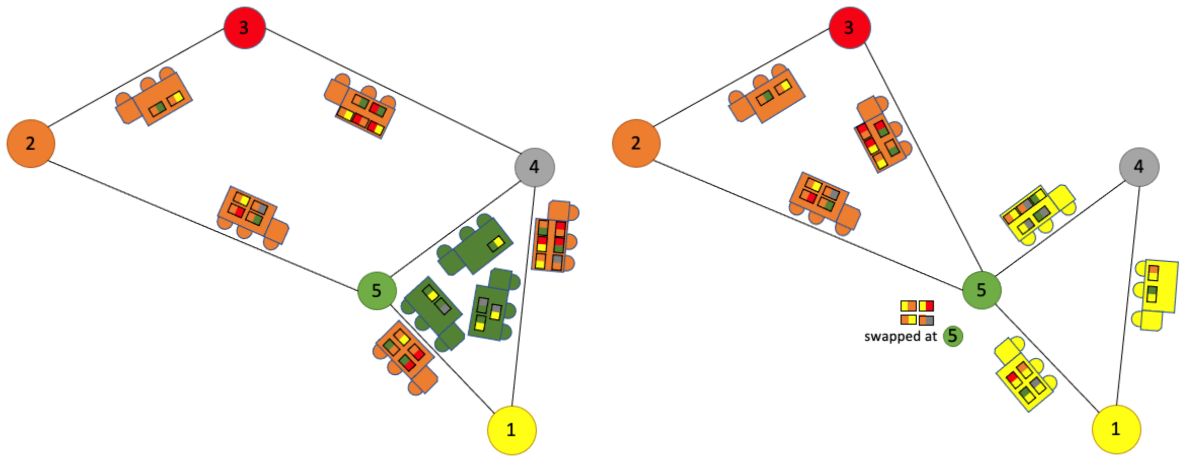

Figure 2: Vehicle and product routes without (Left) and with (Right) product transhipment.

We plot the space-time diagram for vehicles employed for Cases (ii) and (iii) in Figure 3, where x-axis is time and y-axis the index of node. A flat segment represents vehicle loading/unloading at a node. For both cases, the vehicle originated from node 2 starts at time 0, and it returns at time 233min in Case (ii) and 168min in Case (iii). That is to say, compared to Case (ii), Case (iii) has all product delivery complete 65min earlier. Case (i) has all vehicles return to their depots by time 223min. The second vehicle for both Cases (ii) and (iii) has a delayed start. In Case (iii), the vehicle originated from node 1 starts at time 14min so that it arrives at node 5 at the same time as the vehicle from node 2 for synchronisation and transhipment purposes. For Case (ii), since unnecessary delayed start is not penalised, the solution has the vehicle from node 5 start at 47min, which results in the same objective as the solution having it start at time 0. We remark that because the model allows flexible start times (through variable x_v), vehicle waiting at nodes is absent in both solutions for Cases (ii) and (iii). It is important to have flexible start times. Otherwise, the cost for vehicle waiting may jeopardize the benefit derived from product swapping. In that case, the transfer type of vehicle-to-storage-to-vehicle can be considered provided that the cost for temporary storage is reasonable.

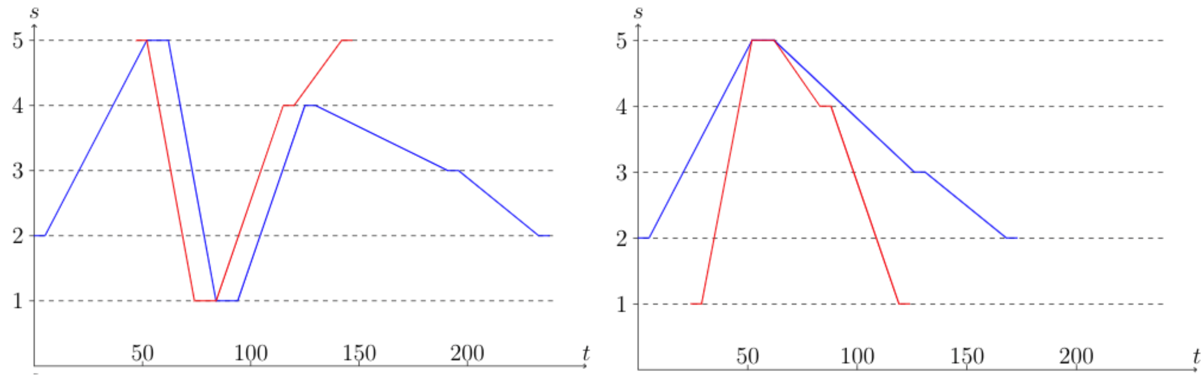

Figure 3: Time-space diagram for vehicle routing without (Left) and with (Right) product transhipment.

3.3 Pareto front

Through imposing a constraint on the number of product transfers, we can transform the multi-objective problem to a problem which minimises the financial cost. We plot the pareto front for this multi-objective problem and the resulting VKT and LF in Figure 4. We observe that the financial cost decreases with the number of transfers allowed. Allowing one task to be transhipped can result in a cost decrease of approximately 5%. For this small network, swapping four delivery tasks can achieve the best financial performance. In addition, product swaps benefit VKT as well as the LF; the VKT decreases with the number of transfers. The LF slightly drops when one swap is implemented, which is due to an empty-running leg. It increases to 0.745 when three swaps are allowed, very close to the largest LF 0.754 observed.

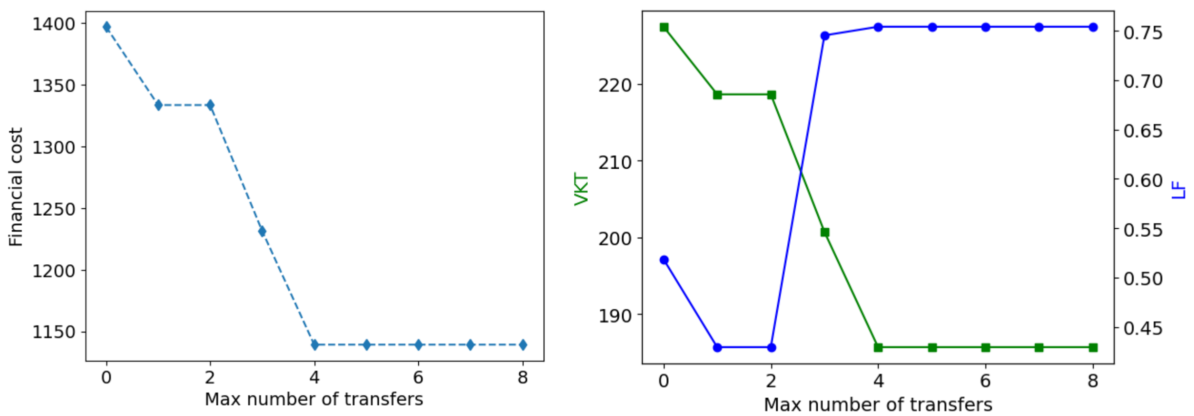

Figure 3: Left: Pareto front; Right: VKT and LF against the maximum number of transfers.

4 Conclusions

Designing more efficient goods transfer networks in urban areas requires consideration of origin and destination patterns as well exploring opportunities for transferring goods at intermediate shops. We analysed delivery efficiency in terms of total vehicle travel time (VKT), load factor (LF) as well as the delivery reliability in terms of number of product transfers. The model presented in this paper allows improved goods transfer networks to be designed and allows trade-offs between transport costs and reliability to be explored.

When product swaps at stores are allowed significant financial cost savings were estimated compared to networks where dedicated vehicles are employed for shops. Swap networks were found to have substantially increased load factors leading to savings in VKT that would lead to reduced emissions.

It is planned to enhance the model in several ways, including incorporating stochastic travel times between shops to allow reliability levels to be investigated in more detail, allowing short term storage of goods being transferred to increase opportunities for efficient transfers and developing heuristics based solution procedures to allow larger networks to be designed.

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