Universal Locker Systems for urban areas

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Abstract

E-commerce has led to a surge of parcel deliveries owing to the mix of lower price and higher convenience for consumers. This situation has significantly increased parcel shipments, resulting in congestion within the urban metros, leading to worsening traffic and pollution levels. A parcel locker system is a way to optimise deliveries. However, it is ineffective if individual companies take up this initiative in isolation, as customers tend to switch to the most convenient option.

We explore the possibility of a universal locker system facilitated by the New York City government in the Manhattan area. We propose using the city's public facilities as potential locker locations. We assess demand distribution using sample shipment data. The set covering method determines the minimum number of lockers needed for different levels of service. Subsequently, the p-median method recommends the actual locker locations to optimise the weighted average distance to customers.

A solution with 360 lockers would ensure 93% (or 100%) of the population have access to at least one locker within 250m (or 750m). A full roll-out of the system decreases the distribution cost by 75% in comparison to a home delivery model. We recommend an incremental coverage of deliveries over a 3-year time-frame. The financial analysis shows a payback period of around three years (IRR of ~44%), making the project worthwhile. We can extend this study to any large urban area with support from the city government.

Keywords: Universal Locker System, Last-Mile Delivery, Public Locker Locations

1 Introduction

The steady growth of e-commerce and increased customer service expectations have led to a rapid expansion in the number of routes and vehicles going in and out of urban areas. Consequently, we notice an increase in congestion within the city centre, accompanied by an increase in carbon emissions. Many cities are exploring the possibility of setting up parcel lockers to reduce the impact of last-mile delivery.

The introduction of a parcel locker system to enable more efficient delivery is not new. Amazon launched its locker program in September 2011 in New York City, Seattle, and London (The Verge, 2011), and has expanded it to over 900 cities and towns within the U.S. (Amazon, 2019). However, Amazon lockers are proprietary, as in they only address Amazon deliveries. This business model creates an advantage for Amazon (or a similar player) but also implies that customers do not get a consistent delivery experience when we consider other players unless every courier service invests in their locker system, which might be redundant. Also, the substitution from home delivery to parcel lockers by one player in the last-mile delivery sector will not significantly decrease the traffic congestion, since the e-commerce sector involves many last-mile delivery companies.

Several governments (e.g., Singapore and Seoul, South Korea) around the world are implementing nationwide universal parcel locker systems (Logistics Viewpoints, 2019). Such systems allow online retailers and last-mile delivery service providers to deliver to any locker in the network. Locker operators can achieve high utilisation of assets without redundant investment in infrastructure. Simultaneously, the flow of parcels to many households can be consolidated in the parcel locker, thus diminishing traffic flows. However, there is no standardised approach to rationalise the number and locations of lockers in urban areas.

As a case study, we look at New York City, especially Manhattan area, which faces similar challenges as the above-mentioned Asian cities. Moreover, it shares similar geographical and demographical characteristics with a high population density and high traffic congestion. This research explores the feasibility of a universal locker system in Manhattan for all parcel delivery companies and city residents. We propose to have these lockers located in public facilities owned by the city. This approach cuts down on the need to acquire expensive and limited real estate, while also ensuring that we address the parking needs for parcel vehicles better. The primary objective of this research is to establish an estimation of the distribution cost savings as we replace the home delivery system in Manhattan with a universal locker system across the city. Deriving from this analysis, we create a business case for investment in this universal locker system. The analysis and conclusions can be generalised to other urban areas with a similar profile.

2 Data Exploration and Analysis

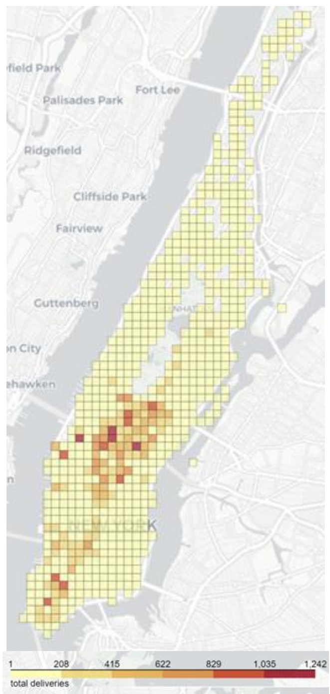

Fig 1. 250m x 250m grid

We start with a sample dataset relevant for this project containing 114,946 courier deliveries within the New York City area in 2014. First, using a grid segmentation approach, we place 250m x 250m segments over the Manhattan area (please refer to Fig 1). Second, we assign 75,094 deliveries and 9,000 points-of-delivery (PoD) for Manhattan (excluding 'heavy items' that are not suitable for lockers) to their corresponding segment. Third, this data is treated as a representative sample of PoDs within the Manhattan region and scaled up to generate a more realistic estimate of e-commerce parcels delivered to Manhattan. The scaling is based on the volumes from Amazon over 2018, considering 5 billion parcels delivered to 120 million households in the USA (Save the Post Office, 2018). Assuming 765,000 households in Manhattan (CUNY, 2019), this represents about 32 million deliveries annually or about 83,000 parcel deliveries per day.

In order to establish a discrete set with possible parcel locker locations, we considered all 3,000 public facilities as provided in the city's Facilities Database (NYC OpenData, 2019). Installing parcel locker boxes in these locations is feasible, convenient and represents the lowest cost option. Moreover, the locations are known to and accessible for the inhabitants. We requested the purchasing and maintenance cost for the parcel lockers from POPstation, the supplier of Singapore Post.

We computed the road network circuity factor and shortest path routing for Manhattan area (please refer to Appendix 1 and 2) using Open Street Map network with Python 3.6 (Boeing, 2017). Lastly, we derived operational and cost parameters for the different vehicle modes (i.e., vans and e-cargo bikes) from the current vehicle fleet of Amazon, UPS and the postal carriers (please refer to Appendix 3).

3 Problem Description

3.1 Research Objective

The objective of this research project is to develop a business case to determine the viability of investing in a universal locker system for an urban area using Manhattan as a case study. As part of this exercise, we will determine the optimal network design for such a system. Specifically, the research questions are:

- What is the return on investment for installing a universal parcel locker system?
- What is the optimal network design for implementing such a delivery system?

3.2 Key Assumptions

- The network consists of one echelon with three potential urban consolidation centre (UCC) locations around the outskirts of the Manhattan area. All parcels going into the city are consolidated at the UCCs, followed by delivery using vans or e-cargo bikes.
- The network only takes parcel delivery into account, not pickup.
- There are no delivery time-window constraints.
- Delivery to parcel lockers takes place twice a day, and a van is estimated to serve up to two parcel lockers per tour.
- A parcel locker has 100 slots with an average of 1.5 "inventory turns" per day.

3.3 Expected Outcomes

- We recommend the optimal number and positioning of the parcel lockers to provide adequate coverage for the population of Manhattan, weighted by the deliveries. This optimisation will consolidate several PoDs to a parcel delivery box, based on the maximum walking distance from the different households to the parcel locker box.
- We provide a total cost estimate and network design after installing the universal locker system in Manhattan. The network design includes a proposal for the optimal number and locations of UCCs in the region and suggests the vehicle fleet mix for the delivery.
- We perform a sensitivity analysis of delivery cost based on the home delivery vs locker delivery ratio. We do not expect that all consumers would transition to the locker system at once. It seems likely from a practical point of view that we should apply a mixed model with part of the inhabitants being served by home delivery, while the rest of the inhabitants pick up their parcel from lockers.
- We propose a business case for the universal locker system investment. We quantify the return on investment based on cost savings, estimated capital investments and

operating expenses. For now, we ignore the monetary value of intangibles, like reduced congestion and emissions.

4 Methodology

For this research, we design a process that goes through the steps illustrated in Fig 2.

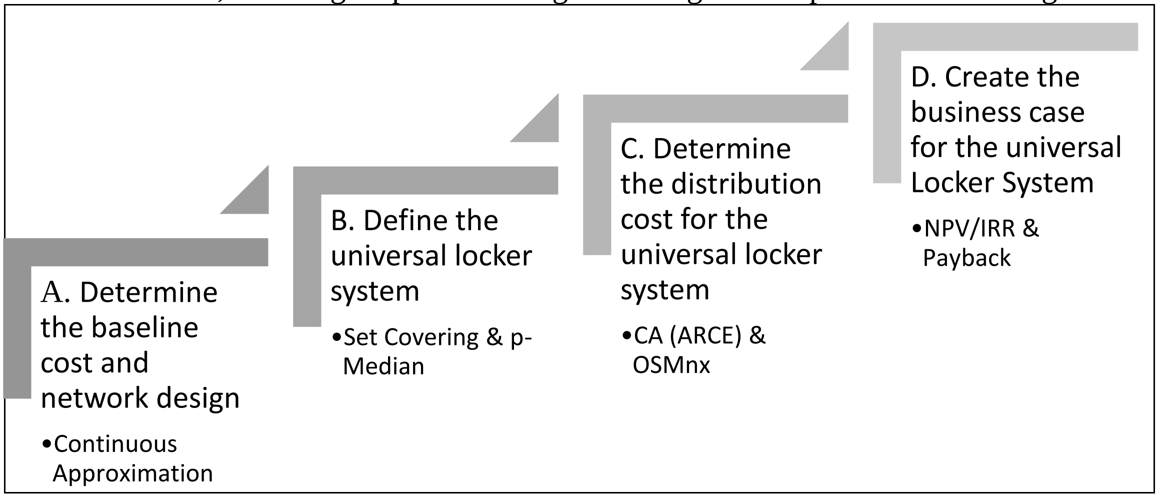

Fig 2. Methodology and process flowchart

A. *Determine the baseline cost and network design.* We estimate the distribution cost to provide home deliveries to the Manhattan region using Augmented Routing Cost Estimation (ARCE) method (Winkenbach, Kleindorfer & Spinner, 2016). We split the Manhattan area into 250m x 250m segments, and the demand distribution is constructed by scaling up the sample shipment data using the approach described in Section 2. We assume UCCs are located in uptown, midtown and downtown areas of Manhattan and use a mix of vans and e-cargo bikes for delivery. The distribution model for ARCE was implemented using Python & Gurobi. All distances were computed based on Euclidean distances.

B. *Define the optimal number and positions of lockers.* Given the candidate locker locations, we take the approach proposed by Lee, Chen, Pham & Choo (2019) and formulate a set covering problem to obtain the minimum number of lockers to meet maximum walking distances of 250m, 500m, 750m, and 1km (Appendix 4). Next, a p-median model is formulated to select the optimal locations of "p" lockers that minimises the total demand-weighted distance (Appendix 5). From the minimum number of lockers given by the set covering problem, we gradually increase the "p" value input to the p-median model until at least 95% of all the PoDs can meet the maximum walking distance criteria to the nearest locker.

C. *Calculate the distribution cost for the universal locker system.* Similar to baseline costing, ARCE method is applied to estimate the distribution cost for lockers. Also, we use the number of parcel lockers in each segment as the delivery density and the number of deliveries assigned to the parcel lockers as the number of items per drop. Next, to validate the results produced by the ARCE method, we also create dedicated tours using the OSMnx module for all the parcel lockers using shortest-path-distance to determine the real driving distance. Lastly, we conduct a sensitivity analysis for varying percentages of home deliveries (0%, 25%, 50%, 75%, and 100%).

D. *Create a business case for the universal locker system.* Finally, we evaluate the investment proposal for implementing the lockers in Manhattan. We assume that in the first year, we will deliver 25% of the packages through the lockers. This percentage then increases in subsequent years to 50% and 75% and levels off at that point. To assess the financial viability of the project, we use NPV, IRR and payback period metrics.

5 Results and Discussions

5.1 Baseline Delivery Cost of Home Deliveries

Vehicle	Volume
Van	265
e-Cargo bike	82,948
Total	*83,213*

Table 1. Delivery split

Parameter	Value
Active UCCs	2
Total PoDs	9458
Total Cost	$80,479
Total Parcels	83213
Cost per Parcel	$ 0.97

Table 2. Network cost

The baseline model is home deliveries only has been created using three possible UCC locations and the vehicle parameters (please refer to Appendix 3). The total daily distribution cost for about 83,000 parcels is $80,479 (or $0.97 per parcel). We recommend two UCCs for serving the entire region. We perform around 99% of all deliveries by an e-cargo bike. As the UCC is near the city area leading to shorter linehaul distances and the intra-stop distances in these dense areas are short, e-cargo bikes are preferable to vans. The baseline assumes the usage of UCCs, as it seems likely that large parcel carriers like UPS or Amazon would place hubs near the city areas to enable the usage of light vehicles to overcome congestion and reduce the linehaul.

5.2 Minimum Number of Lockers for an Acceptable Walking Distance

Max Distance	Min Lockers
≤ 1000m	24
≤ 750m	39
≤ 500m	85
≤ 250m	318

Table 3. Summary of set covering results

An obvious trade-off exists between the number of lockers and the maximum distance for a consumer to walk to the nearest parcel locker. First, the minimum number of lockers for a maximum walking distance of 1 km is computed using a set covering method. Assuming a walking speed of 5 kmph, we limit the maximum walking time to 12 minutes. Next, the same process is repeated to determine the minimum number of lockers required for a variety of acceptable distances. As shown in Table 3, the required number of lockers increases exponentially as the maximum walking distance decreases.

5.3 Locker Location Selection to Minimize Weighted Distance to Recipients

The p-median method is applied to determine the optimal location of the suggested number of lockers. The p-value is derived from the set covering result and gradually adjusted by a multiple of ten until we reach an acceptable service level. Fig 3 shows the results for the recommended locker locations positioned in their corresponding segment.

Table 4 shows the resulting service levels for different scenarios. A network of 360 lockers assures that 92.7% of PoDs have access to a locker within 250m, and 99.7% of the PODs have access to a locker within a 500m range. The worst-case scenario is for 0.3% of the PoDs covering 0.1% of deliveries that have access to a locker within 750m, representing about three blocks and a 10-minute walk.

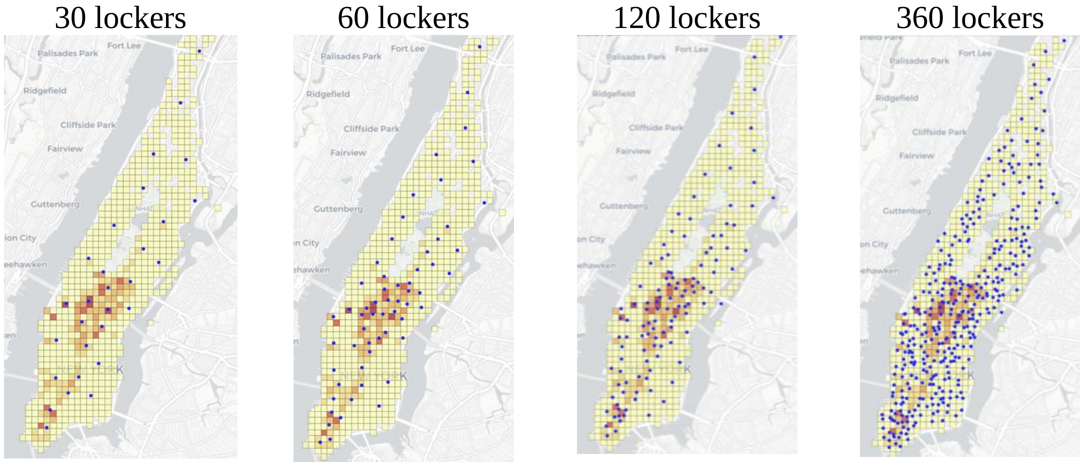

Fig 3. Recommended locker locations using p-median method (for different p-values)

Service Level	30 lockers	60 lockers	120 lockers	360 lockers
% PoDs ≤ 250m	20.0%	37.9%	63.9%	92.7%
% PoDs ≤ 500m	65.3%	86.2%	96.3%	99.7%
% PoDs ≤ 750m	91.1%	98.1%	100%	100%
% PoDs ≤ 1000m	98.7%	100%	100%	100%
% PoDs > 1000m	1.3%	-	-	-
Avg Distance to PoD	449m	325m	236m	144m
% Demand ≤ 250m	31.7%	60.3%	83.2%	96.3%
% Demand ≤ 500m	79.6%	94.3%	98.7%	99.9%
% Demand ≤ 750m	95.7%	99.3%	100%	100%
% Demand ≤ 1000m	99.5%	100%	100%	100%
% Demand > 1000m	0.5%	-	-	-
Wgt Distance to PoD	377m	257m	191m	137m

Table 4. Service levels for relevant locker scenarios

5.4 Estimated Delivery Cost with Parcel Lockers

Firstly, we estimate the distribution cost for 100% locker deliveries for 30, 60, 120, and 360 lockers using the ARCE method. We cap the number of parcels that we can place in a locker at 150 per day. In cases when we assign more deliveries to a locker, the density value of that specific segment is increased. For example, if a segment has a total 300 deliveries, we set the items per drop to 150 and the density to 2. Table 5 gives an overview of the estimated cost for each scenario.

Recommendations	30 lockers	60 lockers	120 lockers	360 lockers
Deliveries by e-cargo bike	0	0	0	0
Deliveries by van	83,213	83,213	83,213	83,213
Active UCCs	1	1	1	1
Total Cost	$22,138	$22,246	$22,237	$29,846
Cost per parcel	$0.27	$0.27	$0.27	$0.36

Table 5. Network cost estimates for relevant locker scenarios

The usage of lockers implies that linehaul cost and handling cost (i.e. placing each parcel in the locker) covers most of the delivery cost. Therefore, the distribution cost is relatively insensitive to the proposed small changes in the number of lockers. However, two changes occur in the network design: a full migration to van delivery and the closure of a UCC. Since each route now comprises of linehaul with a high number of items per drop, vans with a larger payload and higher speed are a better option in this network.

An alternative approach is applied to validate the usage of the ARCE method. Based on the van payload and locker capacity, we expect a van to serve two parcel lockers per route. Assuming we perform deliveries twice a day, a van still seems more suitable than a larger trailer. Shortest path distances from the UCC to all parcel lockers are retrieved from OSMnx and compared with the intra-stop and linehaul time calculated by the ARCE method. A resulting difference of only 5% gives us enough confidence to use results from ARCE method for further analysis.

Finally, a sensitivity analysis is performed to evaluate the 360 lockers scenario with varying levels of adoption. We acknowledge that while the option for 100% parcel locker usage is most cost-effective, it may not be a practical one. Therefore, we assume a mixed model in which a portion of the consumers still receives home delivery. Table 6 shows the total distribution cost for different scenarios.

Scenario	A	B	C	D	E
Locker Adoption	0%	25%	50%	75%	100%
Home Delivery Statistics					
> Ratio of deliveries	100%	75%	50%	25%	0%
> Deliveries by e-cargo bike	82,948	62,149	40,681	20,010	0
> Deliveries by Van	265	260	926	793	0
> Active Depots	2	2	1	1	0
> Distribution Cost	$80,479	$62,580	$44,082	$24,657	0
> Cost per Parcel	$0.97	$1.00	$1.08	$1.19	0
Locker Delivery Statistics					
> Ratio of deliveries	0%	25%	50%	75%	100%
> Deliveries by e-cargo bike	0	0	0	0	0
> Deliveries by Van	0	20,804	41,606	62,410	83,213
> Active Depots	0	1	1	1	1
> Distribution Cost	0	$8,954	$15,918	$22,882	$29,846
> Cost per Parcel	0	$0.43	$0.38	$0.37	$0.36
Overall					
> Distribution Cost	$80,479	$71,534	$60,000	$47,539	$29,846
> Cost per Parcel	$0.97	$0.86	$0.72	$0.57	$0.36

Table 6. Sensitivity analysis for distribution cost based on adoption level

5.5 Business Case for Universal Locker System

For the business case, a phased approach regarding the adoption is applied, considering locker adoption to grow to 25%, 50% and 75% of the total deliveries over three years. This approach allows us to spread our investment needs as well as iron out issues with each rollout and cascade learnings across phases.

We assume a lifespan of 8 years for the lockers, with a straight-line depreciation rate of 12.5%. The locker cost of $20,000 per unit and maintenance cost of $200 per month for each locker is estimated based on data from SingPost. Reasonable rent of $500 per month for a locker is assumed, considering the city of New York would facilitate the project to use existing public facilities. We also budget for supervision assuming one full-time employee to handle 25 lockers, at $5,000 per month. An economic evaluation of the project indicates an NPV of $9.9M based on hurdle rate of 10%, an IRR of 44%, and a payback period of 3.15 years. Table 7 shows the financial evaluation of this project.

Year	0	1	2	3	4	.	8
Distribution Cost $/d	80,479	71,534	60,000	47,539	47,539		47,539
Locker Locations	0	137	277	416	416		416
Locker Additions	0	137	140	139	0		0
Savings $/d	0	8,945	20,479	32,940	32,940		32,940
Savings M$/y	0	2.68	6.14	9.88	9.88		9.88
CapEx M$	2.74	2.80	2.78	0	0		0
Cum. Investment M$	2.74	5.54	8.32	8.32	8.32		8.32
Depreciation M$/y	0	0.34	0.69	1.04	1.04		1.04
Rental $/mo	0	68,500	138,500	208,000	208,000		208,000
Maintenance $/mo	0	27,400	55,400	83,200	83,200		83,200
Supervision $/mo	0	27,400	55,400	83,200	83,200		83,200
OpEx $/mo	0	123,300	249,300	374,400	374,400		374,400
OpEx M$/y	0	1.48	2.99	4.49	4.49		4.49
Net Savings M$/y	0	0.86	2.46	4.35	4.35		4.35
Cum. Savings M$	0	0.86	3.32	7.67	12.02		29.42
Cashflow M$	-2.74	-1.94	-0.32	4.35	4.35		4.35
Cum. Cashflow M$	-2.74	-4.68	-5.00	-0.65	3.70		21.10

Table 7. Financial analysis of the project for implementing universal locker system

6 Conclusion

This research demonstrates the financial benefits of adopting a universal locker system in an urban area, using Manhattan as a case study. Using a combination of the set covering and p-median methods, the target number of lockers and their optimal locations are determined, while ensuring that the majority of the inhabitants are within 250m walking distance. We strategically place the locations within the city's existing public facilities infrastructure, in order to ensure that the locker location is feasible, and it is accessible to the recipients. Since shifting from home delivery to a locker pickup system might be a significant change for some people, a mixed model is proposed to gradually migrate them to the new locker system over several years. Whereas the current home delivery distribution network is strongly dependent on e-cargo bikes for delivery and UCC in geographical proximity, the vans alone serve the network design for the locker system. It is optimal for serving a large urban area like Manhattan from one UCC. The business case assumes that we increase the adoption rate of the universal parcel locker system to 75% of all shipments over a 3-year timeframe. This approach results in a network with two urban consolidation centres, each dedicated to locker deliveries and door deliveries respectively. The overall distribution cost per parcel drops from $0.97 to $0.57, a savings of over 40%. After accounting for CapEx and OpEx of the locker operations, the project seems financially attractive with a payback period of three years and IRR of ~44%.

We recommend that the New York City officials initiate a dialogue with the delivery companies and secure the management and financial commitment to this project. We can incentivise the early adopters with discounts and rewards. Over time, we can switch to a reward/penalty scheme that ensures that the target number of shipments move through the locker network. For high-density areas where residential buildings have a significant share of packages, we can further work with the building management to install parcel lockers within their premises, thus reducing the need for real estate while also securing support from building residents. In parallel, we should initiate a study into the congestion level and pollution level in the city road network to evaluate the non-tangible benefits. We realise that in the locker model, we distribute most of the packages via vans. We can re-assess the city policies about allowing larger delivery vehicles within city neighbourhoods during off-hours, as this would allow us to reduce transportation cost and miles driven on account of increased loads handled per trip.

Future research in this area may focus on extrapolating the model for cities with varying density of PoDs and package volumes. In such cases, the optimal walking distance might vary significantly across the network, and the solution might yield varying levels of benefit depending on the location of the universal lockers. Some of the drawbacks of set-covering and p-median models are the lack of locker capacity constraint and expectation of deterministic delivery volumes. Incorporating these features into these models by extending this research may improve its practical applicability. The locker-based solution does tend to ignore the potential issues with abandoned deliveries, which may reduce the locker capacity over time. There might be a need to evolve regulations around maximum pickup timelines to make it fair to all parties.

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Appendix 1.

Sample code for retrieving circuity factor for Manhattan from OSMnx

```
stats = ox.basic_stats(ox.graph_from_place('Manhattan, NY'))
stats['circuity_avg']
```

Appendix 2.

Sample code for calculating and plotting the shortest path between two locations

Fig 4. Shortest path using OSMnx

```
G = ox.graph_from_place('Manhattan, NY',
   network_type = 'drive')
ox.plot_graph(G, fig_height=10, fig_width=10,
   edge_color='black')
orig_node = ox.get_nearest_node(G,
   (float(input_loc.iloc[i,1]),
   float(input_loc.iloc[i,2])),
   method='euclidean')
dest_node = ox.get_nearest_node(G,
   (float(input_loc.iloc[i,4]),
   float(input_loc.iloc[i,5])),
   method='euclidean')
route = nx.shortest_path(G, orig_node, dest_node)
route_length = nx.shortest_path_length(G,
   orig_node, dest_node,weight = 'length')
ox.plot_graph_route(G, route, fig_height=10,
   fig_width=10)
```

Appendix 3.

Operational parameters for heterogeneous vehicle fleet

Parameter	Van	eCargo bike
Payload (volume)	7 m^3	2.7 m^3
Payload (parcels)	200	55
Linehaul speed	30 km/h	15 km/h
Intra-stop speed	20 km/h	12 km/h
Driver wages	$25/h	$25/h
Operating cost	$5.00/h	$2.50/h
Loading time per trip	30 min	15 min
Serving time per PoD	1 min	1 min
Parking time	60 sec	10 sec
Maximum service duration	8 h	8 h
Circuity Factor	1.044	1.044

Table 8. Operational parameters (applicable for ARCE method)

Appendix 4.

Mathematical formulation for set covering problem

Indices

i = Points of Delivery (PoDs)

j = Potential Universal Locker Location

Parameters

M = Maximum distance from any PoD to nearest Universal Locker Location

In this research, we use different values: 250m, 500m, 750m and 1000m.

d_{ij} = Distance from PoD *i* to Locker Location *j*

Decision variables

X_j = 1 if Locker Location *j* is activated, 0 otherwise

Y_{ij} = 1 if PoD *i* is assigned to Locker Location *j*, 0 otherwise

Model SetCover

Minimise $\sum_{j \in J} X_j$

(1) $\sum_{j \in J} Y_{ij} \geq 1, \forall \text{ i} \in I$

(2) $Y_{ij} \leq \text{X}_j, \forall \text{ i} \in \text{I, j} \in \text{J}$

(3) $\sum_{j \in J} \text{d}_{\text{ij}} * \text{Y}_{\text{ij}} \leq \text{M}, \forall \text{ i } \in \text{I}$

Explanation

The objective is to minimise the total number of lockers to we need to open. Constraint (1) ensures that at least one locker serves each PoD. Constraint (2) ensures that a locker must be open so that we can use it. Constraint (3) ensures that the distance to the closest locker is within the maximum limit set for all PoDs.

Appendix 5.

Mathematical formulation for p-median

Indices

i = Points of Delivery (PoDs)

j = Potential Universal Locker Location

Parameters

N = Target number of Locker Locations

In this research, we use different values: 30, 60, 120 and 360.

These numbers come from the values derived from the set covering method.

d_{ij} = Distance from PoD *i* to Locker Location *j*

P_i = Total parcel deliveries for PoD *i*

Decision variables

X_j = 1 if Locker Location *j* is activated, 0 otherwise

Y_{ij} = 1 if PoD *i* is assigned to Locker Location *j*, 0 otherwise

Model SetCover

Minimise $\sum_{j \in J} \sum_{i \in \text{I}} P_i * d_{ij} * Y_{ij}$

(1) $\sum_{j \in J} Y_{ij} \geq 1, \forall \text{ i} \in I$

(2) $Y_{ij} \leq \text{X}_j, \forall \text{ i} \in \text{I, j} \in \text{J}$

(3) $\sum_{j \in J} X_j = \text{P}$

Explanation

The objective is to minimise the total distance between PoDs and assigned lockers weighted by the number of deliveries. Constraint (1) ensures that at least one locker serves each PoD. Constraint (2) ensures that a locker must be open so that we can use it. Constraint (3) ensures that the total number of open lockers is P.