Assignment Q2 2021

Quantitative Methods for Logistics (ME44206)

Group 10

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A delivery company has a number of locations in a region, which consist of pick-up and delivery locations. These locations need to be visited in order to distribute parcels. Delivery will be done using (multiple) vehicles, each with their own capacity limit. The pick-up or delivery of parcels must be done within the time window of a location.

Question a.)

First, only pick-up locations are considered. The vehicle is allowed to start and end at different depots as long as they operate during the hours in which the locations are opened. The following mathematical model will be used to solve this problem.

Indices

i	index for current location (loc_id)		
j	index for destination location (loc_id)		
k	index for vehicle		

Sets

N	set of all locations		$[\ 0\ \ 1\ \ \dots\ \ 12\ \ 13\ ]$
K	set of vehicles		$[\ 0\ ]$
P	set of pick-up locations		$[\ 4\ \ 5\ \ \dots\ \ 12\ \ 13\ ]$
D	set of delivery locations		$[\ 2\ \ 3\ \ \dots\ \ 9\ \ 11\ ]$
S	set of depot locations		$[\ 0\ \ 1\ ]$

Parameters

$xcoord_{i,j}$	x coordinates of the location	[km]	$[\ 40\ \ 10\ \ \dots\ \ 15\ \ 15\ ]$
$ycoord_{i,j}$	y coordinates of the location	[km]	$[\ 50\ \ 90\ \ \dots\ \ 75\ \ 80\ ]$
$demand_i$	parcel volume for the task	[m^3]	$[\ 0\ \ 0\ \ \dots\ \ 20\ \ 10\ ]$
$readytime_i$	earliest time for a task i	[min]	$[\ 0\ \ 0\ \ \dots\ \ 179\ \ 278\ ]$
$duetime_i$	latest time for a task i	[min]	$[\ 1236\ \ 1236\ \ \dots\ \ 254\ \ 345\ ]$
$servicetime_i$	time needed for a task i at the location	[min]	$[\ 0\ \ 0\ \ \dots\ \ 90\ \ 90\ ]$
$pickup\_id_i$	origin location for a delivery	[-]	$[\ 0\ \ 0\ \ \dots\ \ 0\ \ 0\ ]$
$deliver\_id_j$	destination location of a pick-up	[-]	$[\ 0\ \ 0\ \ \dots\ \ 6\ \ 9\ ]$
$capacity_k$	capacity of vehicle k	[m^3]	$[\ 200\ ]$
d_{ij}	distance between location i and j	[km]	$\begin{bmatrix} 0.00 & 50.00 & \cdots & 39.05 \\ 50.00 & 0.00 & \cdots & 11.18 \\ \vdots & \vdots & \ddots & \vdots \\ 39.05 & 11.18 & \cdots & 0.00 \end{bmatrix}$
M	big M	[-]	$[\ 10^8\ ]$

Variables

x_{ijk}	binary variable indicating if vehicle k travels between location i and j	[-]
ta_{ki}	arrival time of truck k at location i or j	[min]

Objective function

$$min \sum_{i \in N} \sum_{j \in N} \sum_{k \in K} x_{ijk} \cdot d_{ij}$$

Constraints

Constraints 1: Only leave from pick-up locations (specifically for question a)

$$\sum_{j \in N} x_{ijk} = 1 \qquad \forall i \in P, \ \ k \in K$$
$$\sum_{j \in N} x_{ijk} = 0 \qquad \forall i \in D, \ \ k \in K$$

Constraints 2: Only visit pick-up locations (specifically for question a)

$$\sum_{i \in N} x_{ijk} = 1 \qquad \forall j \in P, \ \ k \in K$$
$$\sum_{i \in N} x_{ijk} = 0 \qquad \forall j \in D, \ \ k \in K$$

Constraints 3: Arrival time at the next location

$$ta_{kj} \geq ta_{ki} + d_{ij} + servicetime_i - M(1 - x_{ijk}) \qquad \forall i, j \in N, \ \ k \in K$$

Constraints 4: Capacity of vehicle at the next location

$$\sum_{i \in N} \sum_{j \in N} demand_j * x_{ijk} \leq capacity_k \qquad \forall k \in K$$

Constraints 5: A vehicle can not travel to its current location

$$x_{iik} = 0 \qquad \forall i \in N, \ \ k \in K$$

Constraints 6: Binary variable

$$x_{ijk} \in \{0, 1\} \qquad \forall i \in N, \ \ j \in N, \ \ k \in K$$

Constraints 7: Non-negativity

$$ta_{i,j} \geq 0 \qquad \forall i, j \in N$$

Constraints 8: Real-values

$$ta_{i,j} \in R \qquad \forall i, j \in N$$

Question b.)

The implementation of the mathematical model with the data set "data_b.txt" of question a.) in Python can be seen in the attached file "group_10_question_a-b.py".
A single vehicle with a capacity of 200 m^3 is used in this model, which results in the route visible in figure 1. The vehicle passes by the following locations:
1, 7, 12, 13, 10, 5, 4, 0
A cross indicates a location and a dot indicates a depot. As can be seen, the vehicle does not visit every location, this is due to the fact that the vehicle does only visit pick-up locations.

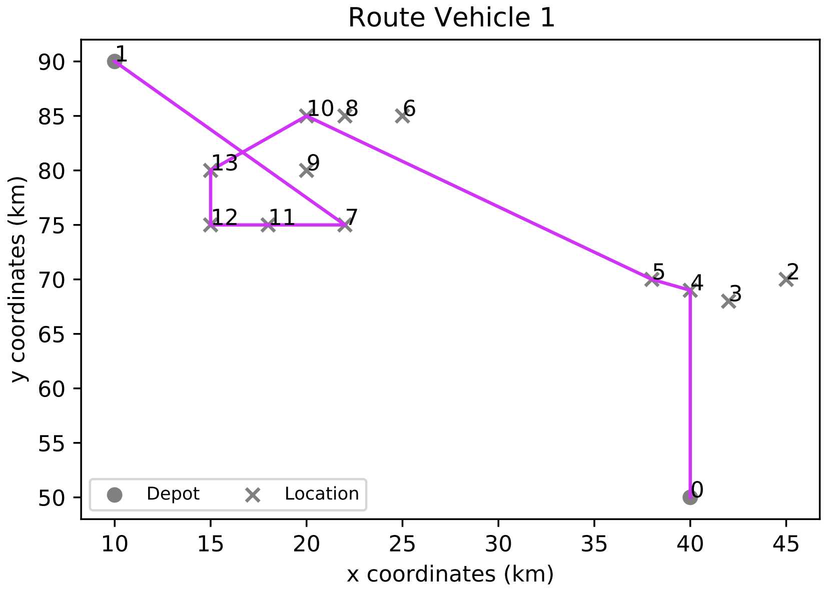


Figure 1: *Vehicle route*

More specific results of this can be seen in Table 1. At every stop, the location index (which results in the route of the vehicle), the new total distance, the travel time and vehicle load are indicated. The last row therefore indicates the total distance traveled, the total travel time and total load. This results respectively in 82.95 km, 790 min and 130 m^3.

Table 1: *Results of mathematical model*

i	j	tot_dist	TD	TA	demand	tot_load
1	7	19	11	30	30	30
7	12	26	120	179	20	50
12	13	31	269	278	10	60
13	10	38	368	475	40	100
10	5	61	565	588	10	110
5	4	63	678	681	20	130
4	0	82	771	790	0	130

Question c.)

The delivery company still has the same locations, each with the same demand values. However, it has now been decided that each vehicle is bound to a depot. This means that a vehicle must return to the depot where it started. This new situation requires the model to be adapted. The adaptations are indicated below.

<u>New Set</u>

PD	set of pick-up and delivery locations	$[\ 2\quad 3\quad \dots\quad 12\quad 13\ ]$

<u>Adapted Parameter</u>

$capacity_k$	capacity of vehicle k	$[\mathrm{m}^3]$	$[\ 200\ ]\ or\ [\ 100\quad 100\ ]\ or\ [\ 75\quad 75\ ]$

<u>New and adapted Constraints</u>

New Constraints: Flow conservation

$$\sum_{j \in N} x_{ijk} = \sum_{j \in N} x_{jik} \qquad \forall i \in N,\ \ k \in K$$

New Constraints: Every vehicle starts at a depot

$$\sum_{i \in S} \sum_{j \in N} x_{ijk} = 1 \qquad \forall k \in K$$

Adapted Constraints 2: Only visit pick-up locations

$$\sum_{i \in N} \sum_{k \in K} x_{ijk} = 1 \qquad \forall j \in P$$
$$\sum_{i \in N} \sum_{k \in K} x_{ijk} = 0 \qquad \forall j \in D$$

Adapted Constraints 4: Arrival time at the next location

$$ta_{kj} \geq ta_{ki} + d_{ij} + servicetime_i - M(1 - x_{ijk}) \qquad \forall i \in N,\ \ j \in PD,\ \ k \in K$$

Removed constraints 1: Only leave from pick-up locations (specifically for question a)

$$\sum_{j \in N} x_{ijk} = 1 \qquad \forall i \in P,\ \ k \in K$$
$$\sum_{j \in N} x_{ijk} = 0 \qquad \forall i \in D,\ \ k \in K$$

Question d.)

The implementation of the mathematical model of question c.) with the data set "data_b.txt" in Python can be seen in the attached file "group_10_question_c-d.py",
Three different situations are investigated in which the capacity differs. In the first case, one vehicle will operate with a capacity of 200 m^3, in the second case two vehicles with a capacity of 100 m^3 each and in the third case two vehicles with a capacity of 75 m^3 each. The results of these three cases will be compared with each other and with the results of question b.).

The three cases result in different routes, which can be seen in figures C.20 - A.5, which can be found in Appendix A. These results are displayed per vehicle. A cross indicates a location and a dot indicates a depot. Each vehicle passes by different locations, which results in the following routes per case:

Case 1: 0, 7, 12, 13, 10, 5, 4, 0;
Case 2: 1, 7, 12, 13, 10, 1 and 0, 5, 4, 0;
Case 3: 1, 12, 13, 10, 1 and 0, 7, 5, 4, 0.

As can be seen, the vehicles do not visit every location, this is because the vehicle only visits pick-up locations.

More specific results of this can be found in the tables next to the plots in appendix A where the route is also displayed per vehicle per case. At every stop, the location index (which results in the route of the vehicle), the new total distance, the travel time and vehicle load are indicated. The last row therefore indicates the total distance traveled, the total travel time and total load.

As can be seen, in all cases the total load is 130. In the second and third case, the vehicle operating from depot 1, takes the most load. This is due to the fact that around this depot, more pick-ups are located. In an ideal situation, in which the travel distance is minimized, one vehicle operates around depot 1 and the other around depot 0. This can be seen in case 2, which results in a total distance traveled of 90.80 km, which is the smallest total distance. This is also the situation in which the travel time is the smallest. In case 3, this way of operating is not possible due to the capacity limit of the vehicles. However, the distribution over the vehicles is more equal than in case 2.
The case of question b results in an even smaller total distance and time, due to the fact that this vehicle is allowed to depart and arrive at different depots. So, this limitation results in more travel kilometers and minutes.

Question e.)

Now a situation in which depot costs are implemented is considered. This means that there is a cost per deport for each vehicle that uses that depot. This situation requires the model to be adapted. The adaptations are indicated below. Some sets and parameters have variable values in them:

α : number of extra vehicles;
β : vehicle capacity;
γ : costs depot 0;
δ : costs depot 1

These will be defined for each different case in question f.).

<u>Adapted set</u>

K	set of vehicles		$[\ 0\ \ 1\ \ \ldots\ \ \alpha\text{-}1\ \ \alpha\ ]$

<u>New and Adapted Parameters</u>

$capacity_k$	capacity of vehicle k	[m^3]	$[\ \beta\ \ \beta\ \ \ldots\ \ \beta\ \ \beta\ ]$
$depotcosts_i$	cost per vehicle for using depot i	[euro]	$[\ \gamma\ \ \delta\ ]$

<u>New Variable</u>

c_k	cost for each vehicle k	[euro]

<u>Extra Objective function</u>

$$min \sum_{k \in K} c_k$$

<u>New Constraints</u>

Constraints: Cost per vehicle leaving from each depot

$$\sum_{i \in S} \sum_{j \in N} x_{ijk} \cdot depotcosts_i = c_k \qquad \forall i \in S, k \in K$$

Constraints 7: Non-negativity

$$ta_{i,j} \geq 0 \qquad \forall i, j \in N$$
$$c_k \geq 0 \qquad \forall k \in K$$

Constraints 8: Real-values

$$ta_{i,j} \in R \qquad \forall i, j \in N$$
$$c_k \in R \qquad \forall k \in K$$

Question f.)

The implementation of the mathematical model of question e.) with the data set "data_f.txt" in Python can be seen in the attached file "group_10_question_e-f.py". More detailed results per route can be found. All parameters have been adapted to the new data file. In these different cases, the values for α, β, γ and δ are altered. The results for each case will be plotted and discussed separately.

Question f.1)

In the first case, 10 vehicles with a capacity of 200 m^3 each are used. There are no depot costs. With this, the variable values are: $\alpha = 9$, $\beta = 200$, $\gamma = 0$, $\delta = 0$. This results in a total travel distance of 701.64 km and total cost of € 0.00. The routes for each vehicle are displayed in Figure 2.

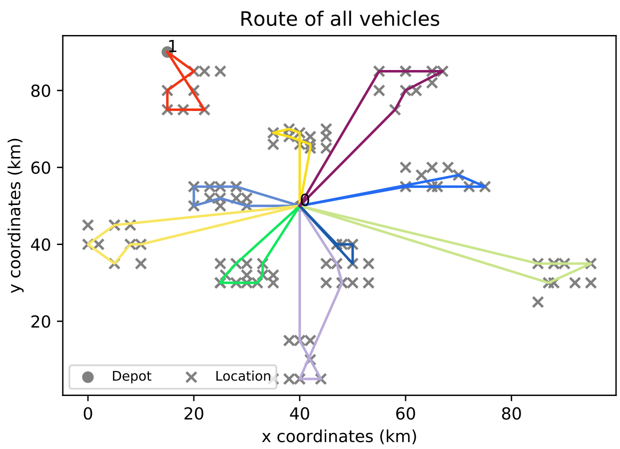


Figure 2: *Routes of all vehicles in Case 1*

Question f.2)

In the second case, 10 vehicles with a capacity of 200 m^3 each are used. Furthermore, depot costs are implemented. With this, the variable values are: $\alpha = 9$, $\beta = 200$, $\gamma = 150 Okido$, $\delta = 100$. This results in a total travel distance of 783.29 km and total cost of € 1300.00. The routes for each vehicle are displayed in Figure 3.

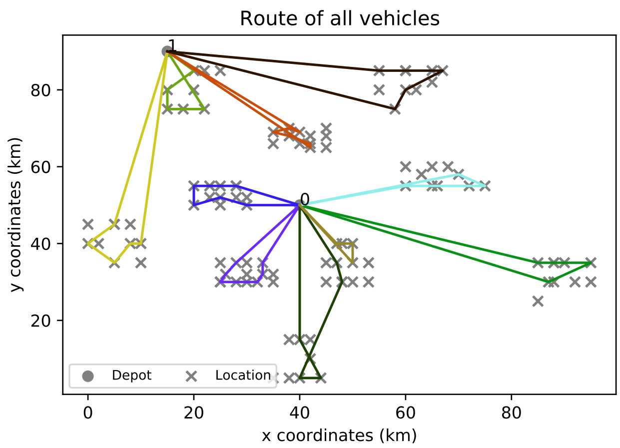


Figure 3: *Routes of all vehicles in Case 2*

When comparing the results of f.1) with f.2), it can be seen that depot costs are implemented. At first, because of the central location of depot 0, almost all vehicles departed from depot 0. In a situation in which depot 0 is more expensive to use than depot 1, some vehicles switch to depot 1. However, still more vehicles depart from depot 0. So, higher depot costs influence the distribution of the vehicles, but a much lower price for depot 1 is needed to create a situation in which all vehicles switch from depot 0 to depot 1.

Question f.3)

In the third case, experiments were done with different depot costs, varying between the values: 100, 200 and 300. The cost for depot 0 is set to be one of these three values. The costs for depot 1 consists of this value for depot 0 multiplied with a factor. These factors vary between the values 0.5, 1.0 and 1.5 for all three different cost levels. The different cases can be seen in Figure 6.

These costs are close to the value given in the assignment. This is because above a specific costs value, the routes are only based on the depot costs. Because of this, the routes will not change; the model will be forced to choose the cheapest depot.

The results show that, with a factor of 1, the model prefers to use depot 0 for all costs. With a factor of 0.5 and costs for depot 0 of 100 euro, a clear difference with the same factor and a costs of 200 euro can be seen. With this factor depot 1 is relatively cheap compared to depot 0. The influence of this increases while increasing the costs for depot 0. With a factor of 1.5, depot 0 is cheaper than depot 1. In this case, the model prefers to use depot 0 for all costs.

In the end, the model does prefer to use depot 0. Even with lower costs for depot 1, depot 0 is used. This is not the case the other way around. A reason for this could be the location of depot 0, compared to depot 1. The total travel distance will be much higher while only using depot 1 compared to depot 0.

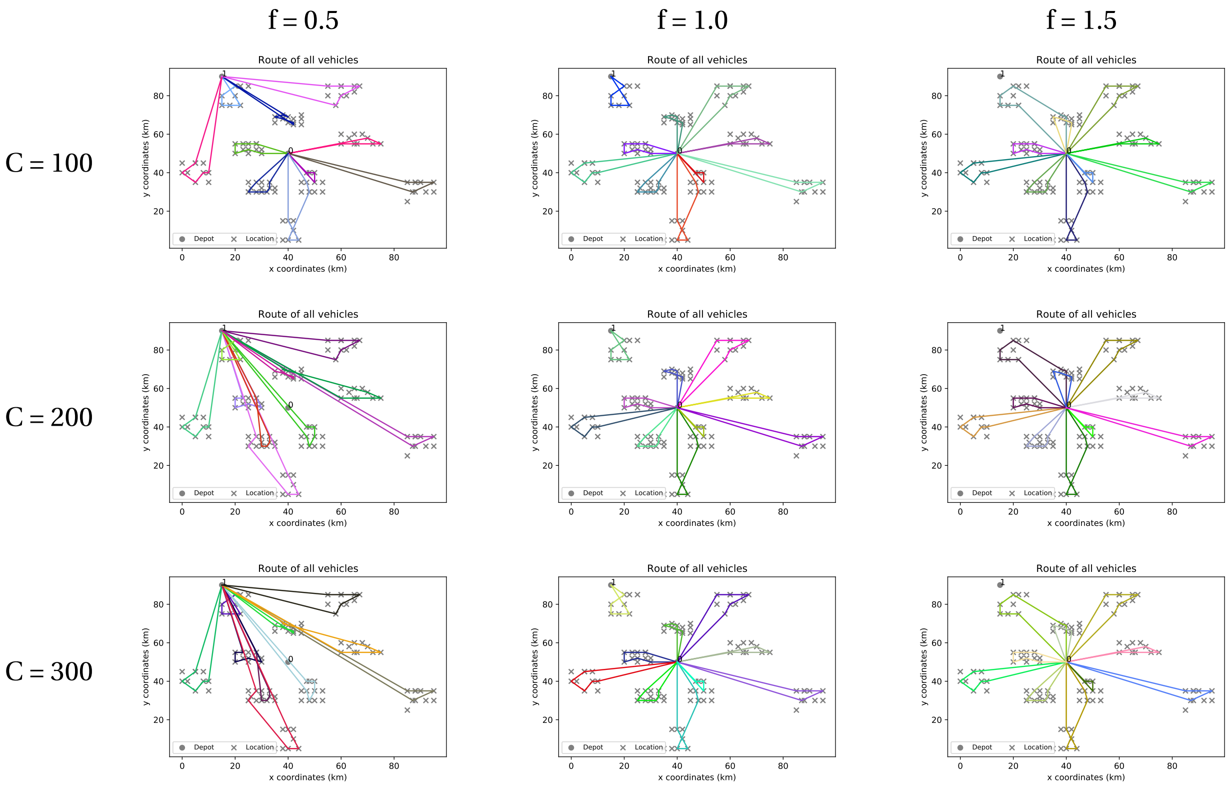


Figure 4: *Variation of factors and costs for the two different depots (depot 0 = C; depot 1 = C*f)*

Question f.4)

In the fourth case, 15 vehicles with a capacity of 120 m^3 each were used. Furthermore, depot costs are implemented. With this, the variable values are: $\alpha = 14$, $\beta = 120$, $\gamma = 150$, $\delta = 100$. This results in a total travel distance of 987.05 km and total costs of € 1800.00. The route for each vehicle is displayed in Figure ¯

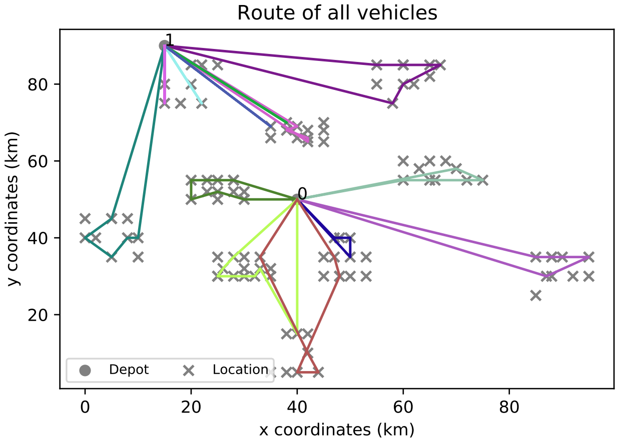


Figure 5: *Routes of all vehicles in Case 4*

Experimenting with different vehicle capacity results in different load distributions over the vehicles. This is visualised in Table 3. As can be seen, the solution is not feasible with a capacity of 100 m^3. Therefore, the first mentioned capacity is 110 m^3. After this, steps of 20 m^3 in the capacity are made while comparing. Furthermore, the load of the vehicles is ordered with ascending values.
Above a capacity of 150 m^3, the distribution does not change anymore. So the optimal solution, in which the capacity is not a limited factor, results in a total distance of 783.29 km. Below this value, the load distribution over the vehicles is more equal, which results in a bit higher total distance value. As can be seen in Figure 6, there is only one different route between a capacity of 120 and 140 m^3. However two vehicles carry different loads, namely vehicle 3 and 10. This can be explained by looking at the coordinates of the locations. Some locations have the same coordinates, which results in comparable routes. The same situation occurs while comparing the capacity of 140 m^3 with the capacity of 180 m^3.

Table 3: *Vehicle load distribution with different capacity limits*

Capacity	v 1	v 2	v 3	v 4	v 5	v 6	v 7	v 8	v 9	v 10	Total distance
100						Not feasible					
110	80	80	90	100	100	100	110	110	110	110	858.45
120	80	80	90	90	100	100	100	110	120	120	819.86
140	80	80	80	90	100	100	100	100	120	140	784.71
160	80	80	80	90	90	100	100	100	120	150	783.29
180	80	80	80	90	90	100	100	100	120	150	783.29

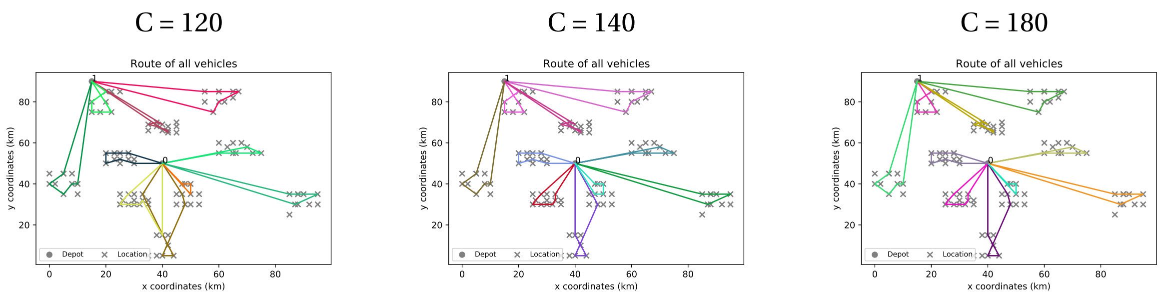


Figure 6: *Routes with various capacities*

Question g.)

In a new situation, deliveries are considered. This means that all parcels must be picked up and delivered at the correct location. No parcels can be stored at the depot, so the vehicles need to be empty at the end of the day. Furthermore, two extra depots are opened, which each have their own depot costs (150, 100, 100, 125). This situation requires the model to be adapted. The adaptations are indicated below.

<u>New index</u>

z	index for locations (loc_id)		

<u>Adapted set</u>

K	set of vehicles		$\begin{bmatrix} 0 & 1 & \dots & 8 & 9 \end{bmatrix} or \begin{bmatrix} 0 & 1 & \dots & 18 & 19 \end{bmatrix}$

<u>New variable</u>

$q_{k,i}$	load for each vehicle k at location i	[-]	

<u>New and Adapted Parameters</u>

$capacity_k$	capacity of vehicle k	[m^3]	$\begin{bmatrix} 200 & 200 & \dots & 200 & 200 \end{bmatrix}$
$depotcosts_i$	cost per vehicle for using depot i	[euro]	$\begin{bmatrix} 150 & 100 & 100 & 125 \end{bmatrix}$

<u>New and adapted constraints</u>

Adapted Constraints 2: Only visit pick-up locations

$$\sum_{i \in N} \sum_{k \in K} x_{ijk} = 1 \qquad \forall j \in P$$
$$\sum_{i \in N} \sum_{k \in K} x_{ijk} = 1 \qquad \forall j \in D$$

New Constraints: Capacity of vehicle at the next location

$$q_{ki} \geq q_{kj} + demand_j - M(1 - x_{ijk}) \qquad \forall k \in K, \;\; i \in N, \;\; j \in PD$$

New Constraints: Capacity of vehicle at the next location

$$q_{ki} \leq q_{kj} + demand_j + M(1 - x_{ijk}) \qquad \forall k \in K, \;\; i \in N, \;\; j \in PD$$

New Constraints: Vehicle must visit specific pickup location before corresponding delivery location

$$\sum_{i \in N} \sum_{z \in N} x_{(pickup\_id_j)zk} \geq \sum_{i \in N} x_{ijk} \qquad \forall k \in K, \;\; j \in D$$

New Constraints: Vehicle must visit specific pickup location before corresponding delivery location

$$\sum_{i\in N}\sum_{z\in N} x_{z(deliver\_id_i)k} \geq \sum_{j\in N} x_{ijk} \qquad \forall k \in K,\ \ i \in P$$

Constraints 7: Non-negativity

$$\begin{aligned} ta_{i,j} &\geq 0 && \forall i,j \in N \\ c_k &\geq 0 && \forall k \in K \\ q_{ki} &\geq 0 && \forall k \in K,\ \ i \in N \end{aligned}$$

Constraints 8: Real-values

$$\begin{aligned} ta_{i,j} &\in R && \forall i,j \in N \\ c_k &\in R && \forall k \in K \\ c_{ki} &\in R && \forall k \in K,\ \ i \in N \end{aligned}$$

Question h.)

The implementation of the mathematical model of question g.) with the data set "data_h.txt" in Python can be seen in the attached file "group_10_question_g-i.py". 10 vehicles with a capacity of 200 m^3 each are used. This model resulted in a computational time of 17.02 seconds. The routs of the different vehicles, and the depots they depart from can be seen in Figure 7. This results in a total distance of 873.42 km and total costs of € 1150.00. More specific results can be found in Appendix B.

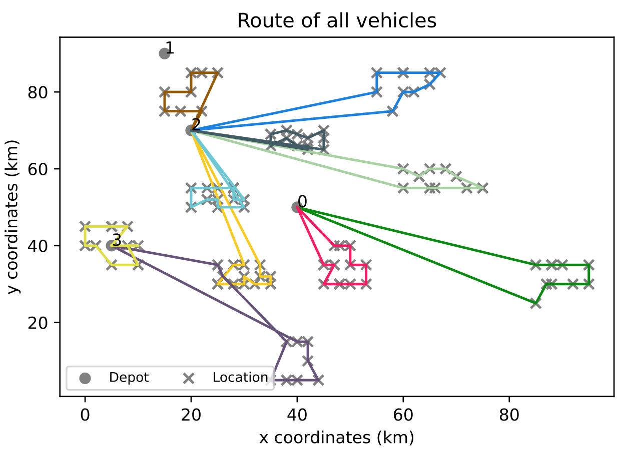


Figure 7: *Routes of vehicles in question h*

Question i.)

The implementation of the mathematical model of question g.) with the data set "data_i.txt" in Python can be seen in the attached file "group_10_question_g-i.py". 20 vehicles with a capacity of 200 m^3 each are used. The routes of the different vehicles, and the depots they depart from can be seen in Figure 8. This results in a total distance of 2349.89 km and total costs of € 2475.00. That is the optimal solution found after 7651.80 seconds. More specific results can be found in Appendix C.

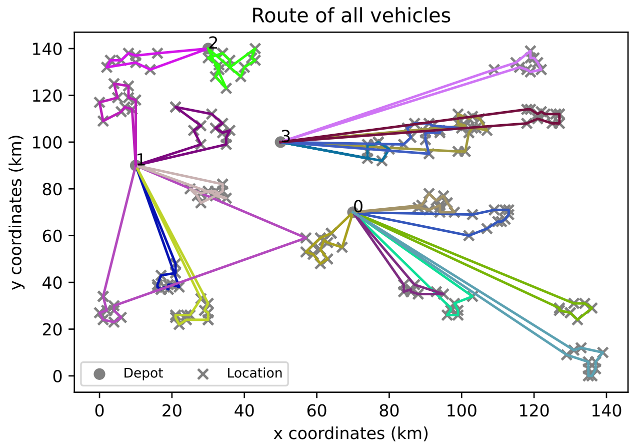


Figure 8: *Routes of vehicles in question i (optimal solution)*

When the computational time is limited to 3600 seconds, no feasible solution is found. Therefore, it was decided to let the model run until an iteration with a gap < 5.00% occurs. The first iteration found has a gap of 1.44%, after a computational time of 5982.24 seconds, with a total distance of 2360.97 km and a total cost of € 2475.00. The routes of the different vehicles, and the depots they depart from can be seen in Figure 9.

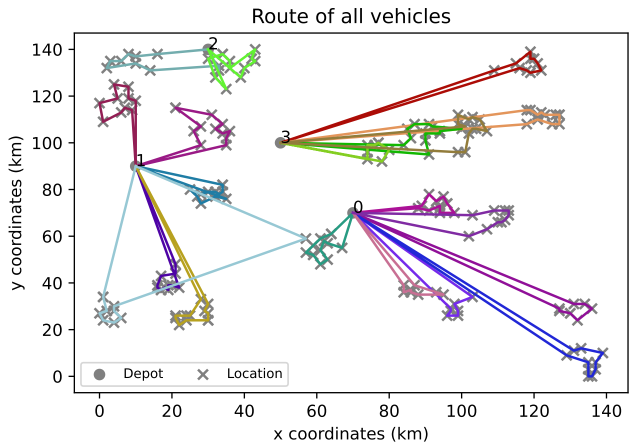
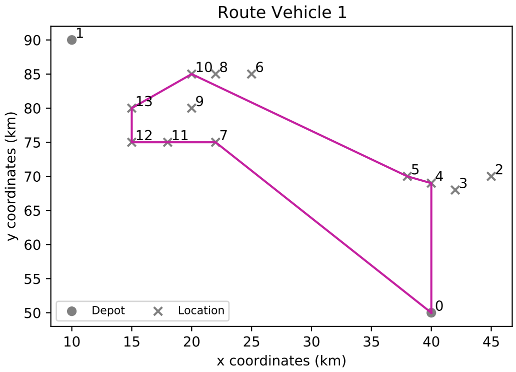


Figure 9: *Routes of vehicles in question i (solution with 1.44% gap)*

As can be seen in this case, this outcome differs little from the optimal solution ultimately found, while the computational time is 1669.56 seconds shorter. In this case, a maximum computational time would therefore not have any major consequences. When the problem becomes bigger, then it could be considered to apply a heuristic evaluation, in order to arrive at an optimum more quickly. This of course also depends on the problem. Does this have to be calculated once, or is it continuously subject to change and is a fast computation crucial?

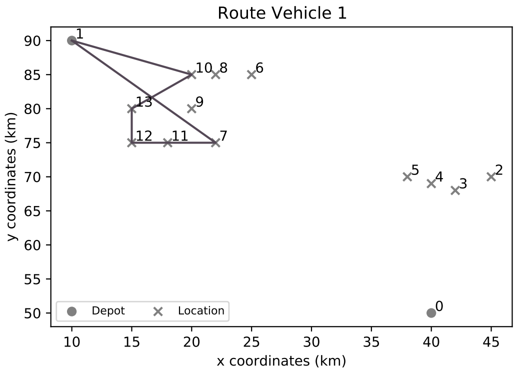
A
Plots

A.1. Question d



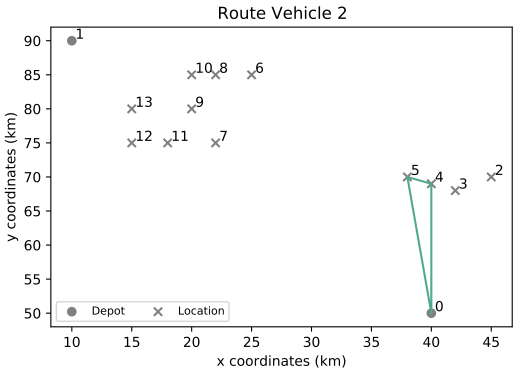
i	j	tot_dist	TD	TA	demand	tot_load
0	7	31	0	30	30	30
7	12	38	120	179	20	50
12	13	43	269	345	10	60
13	10	50	435	475	40	100
10	5	73	565	605	10	110
5	4	75	695	702	20	130
4	0	94	792	886	0	130

Figure A.1: *Results of mathematical model case 1*



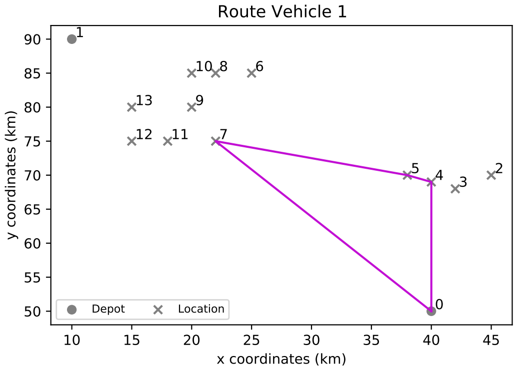
i	j	tot_dist	TD	TA	demand	tot_load
1	7	19	0	30	30	30
7	12	26	120	179	20	50
12	13	31	269	345	10	60
13	10	38	435	475	40	100
10	1	49	565	614	0	100

Figure A.2: *Results of mathematical model case 2 vehicle 1*



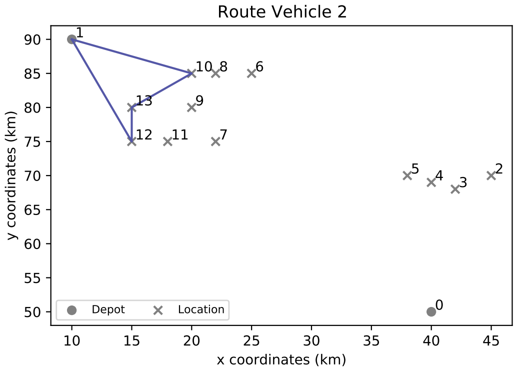
i	j	tot_dist	TD	TA	demand	tot_load
0	5	20	0	605	10	10
5	4	22	695	702	20	30
4	0	41	792	833	0	30

Figure A.3: *Results of mathematical model case 2 vehicle 2*



i	j	tot_dist	TD	TA	demand	tot_load
0	7	31	0	30	30	30
7	5	48	120	605	10	40
5	4	50	695	702	20	60
4	0	69	792	861	0	60

Figure A.4: *Results of mathematical model case 3 vehicle 1*

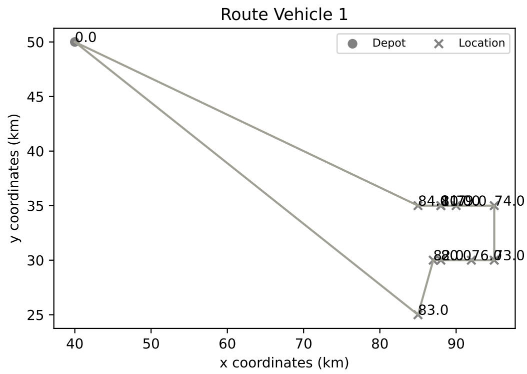


i	j	tot_dist	TD	TA	demand	tot_load
1	12	16	0	179	20	20
12	13	21	269	345	10	30
13	10	28	435	475	40	70
10	1	39	565	604	0	70

Figure A.5: *Results of mathematical model case 3 vehicle 2*

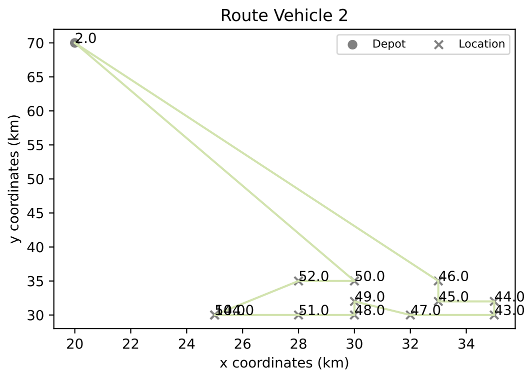
B
Plots

B.1. Question h



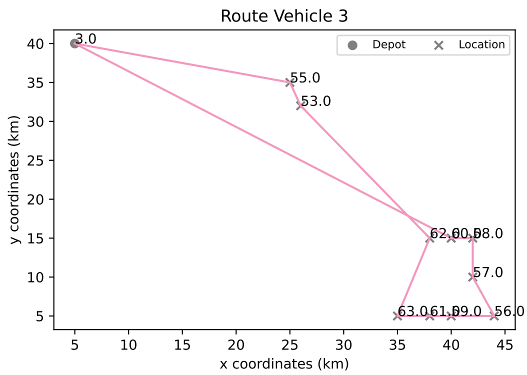
i	j	tot_dist	TD	TA	demand	tot_load
0	84	47.4	0	47.4	30	30
84	81	50.4	137.4	140.4	20	50
81	107	50.4	140.4	140.4	-20	30
107	79	52.4	230.4	232.4	10	40
79	74	57.4	322.4	327.4	20	60
74	73	62.4	417.4	446.6	-30	30
73	76	65.4	536.6	539.6	-10	20
76	80	69.4	629.6	633.6	-20	0
80	82	70.4	723.6	724.6	10	10
82	83	75.8	814.6	820	-10	0
83	0	127.3	910	961.5	0	0

Figure B.1: *Results with pickups and deliveries, vehicle 1*



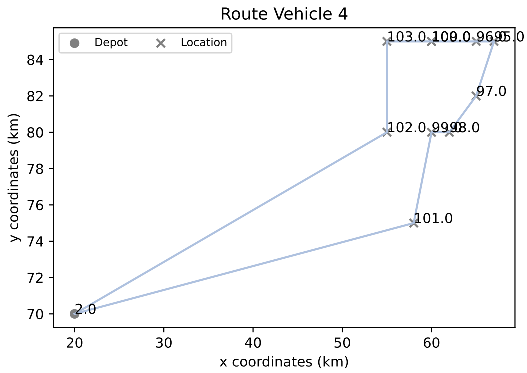
i	j	tot_dist	TD	TA	demand	tot_load
2	46	37.3	0	37.3	10	10
46	45	40.3	127.3	130.3	20	30
45	44	42.3	220.3	222.3	-10	20
44	43	44.3	312.3	314.3	-20	0
43	47	47.3	404.3	407.3	10	10
47	49	50.1	497.3	500.2	-10	0
49	48	52.1	590.2	592.2	10	10
48	51	54.1	682.2	684.2	-10	0
51	54	57.1	774.2	777.2	10	10
54	104	57.1	777.2	777.2	-10	0
104	52	62.9	867.2	1035	10	10
52	50	64.9	1125	1127	-10	0
50	2	101.3	1217	1253.4	0	0

Figure B.2: *Results with pickups and deliveries, vehicle 2*



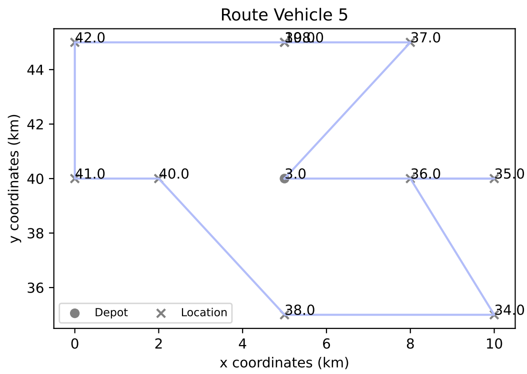
i	j	tot_dist	TD	TA	demand	tot_load
3	60	43	0	43	40	40
60	58	45	133	150.5	-40	0
58	57	50	240.5	245.5	40	40
57	56	55.4	335.5	340.9	20	60
56	59	59.4	430.9	436	30	90
59	61	61.4	526	528	-20	70
61	63	64.4	618	621	-40	30
63	62	74.8	711	721.4	-30	0
62	53	95.6	811.4	848.8	10	10
53	55	98.8	938.8	969	-10	0
55	3	119.4	1059	1079.6	0	0

Figure B.3: *Results with pickups and deliveries, vehicle 3*



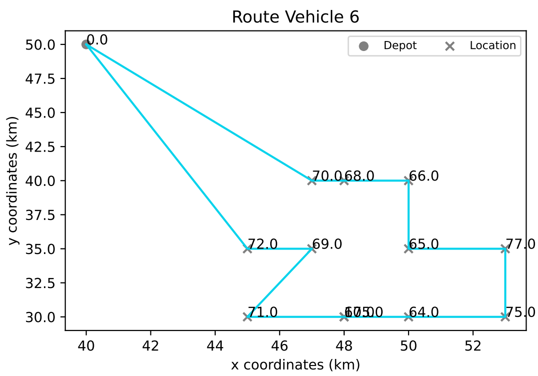
i	j	tot_dist	TD	TA	demand	tot_load
2	101	38.3	0	38.3	20	20
101	99	43.7	128.3	133.7	10	30
99	98	45.7	223.7	225.7	-20	10
98	97	49.3	315.7	319.3	-10	0
97	95	52.9	409.3	412.9	20	20
95	96	54.9	502.9	504.9	-20	0
96	100	59.9	594.9	622	30	30
100	109	59.9	622	622	-30	0
109	103	64.9	712	725	20	20
103	102	69.9	815	820	-20	0
102	2	106.3	910	946.4	0	0

Figure B.4: *Results with pickups and deliveries, vehicle 4*



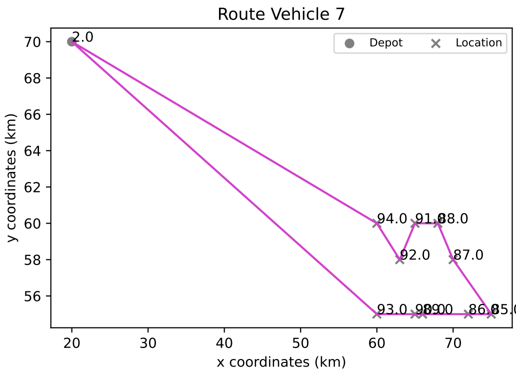
i	j	tot_dist	TD	TA	demand	tot_load
3	35	5	0	31	30	30
35	36	7	121	123	40	70
36	34	12.4	213	218.4	-30	40
34	38	17.4	308.4	313.4	10	50
38	40	23.2	403.4	409.2	-40	10
40	41	25.2	499.2	501.2	30	40
41	42	30.2	591.2	621	-10	30
42	39	35.2	711	716	10	40
39	108	35.2	716	716	-10	30
108	37	38.2	806	816	-30	0
37	3	44	906	911.8	0	0

Figure B.5: *Results with pickups and deliveries, vehicle 5*



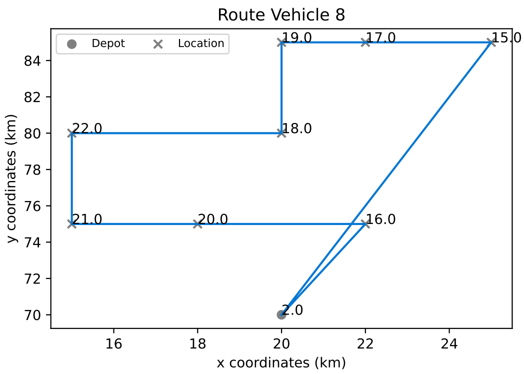
i	j	tot_dist	TD	TA	demand	tot_load
0	70	12.2	0	12.2	10	10
70	68	13.2	102.2	103.2	10	20
68	66	15.2	193.2	195.2	50	70
66	65	20.2	285.2	290.2	20	90
65	77	23.2	380.2	383.2	-50	40
77	75	28.2	473.2	478.2	-10	30
75	64	31.2	568.2	571.2	-10	20
64	67	33.2	661.2	684	10	30
67	105	33.2	684	684	-10	20
105	71	36.2	774	777	-20	0
71	69	41.6	867	875	10	10
69	72	43.6	965	969	-10	0
72	0	59.4	1059	1074.8	0	0

Figure B.6: *Results with pickups and deliveries, vehicle 6*



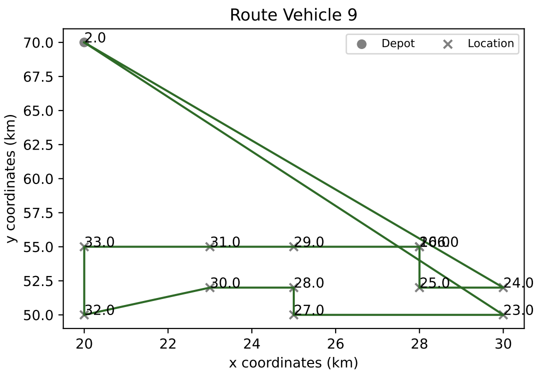
i	j	tot_dist	TD	TA	demand	tot_load
2	93	42.7	0	42.7	10	10
93	90	47.7	132.7	137.7	20	30
90	89	48.7	227.7	228.7	10	40
89	86	54.7	318.7	324.7	-20	20
86	85	57.7	414.7	417.7	20	40
85	87	63.5	507.7	516.7	20	60
87	88	66.3	606.7	609.6	-20	40
88	91	69.3	699.6	702.6	-10	30
91	92	72.1	792.6	795.4	-20	10
92	94	75.7	885.4	889	-10	0
94	2	116.9	979	1020.2	0	0

Figure B.7: *Results with pickups and deliveries, vehicle 7*



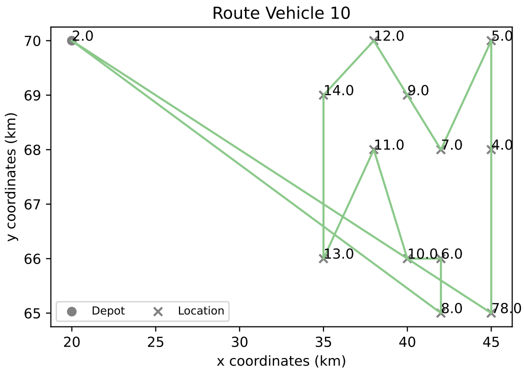
i	j	tot_dist	TD	TA	demand	tot_load
2	16	5.4	0	30	30	30
16	20	9.4	120	124	-30	0
20	21	12.4	214	217	20	20
21	22	17.4	307	312	10	30
22	18	22.4	402	407	-10	20
18	19	27.4	497	528	40	60
19	17	29.4	618	620	-40	20
17	15	32.4	710	721	-20	0
15	2	48.2	811	826.8	0	0

Figure B.8: *Results with pickups and deliveries, vehicle 8*



i	j	tot_dist	TD	TA	demand	tot_load
2	23	22.4	0	22.4	10	10
23	27	27.4	112.4	117.4	-10	0
27	28	29.4	207.4	209.4	40	40
28	30	31.4	299.4	301.4	-40	0
30	32	35	391.4	395	10	10
32	33	40	485	490	10	20
33	31	43	580	583	20	40
31	29	45	673	684	-10	30
29	26	48	774	777	10	40
26	106	48	777	777	-10	30
106	25	51	867	873	-20	10
25	24	53	963	965	-10	0
24	2	73.6	1055	1075.6	0	0

Figure B.9: *Results with pickups and deliveries, vehicle 9*

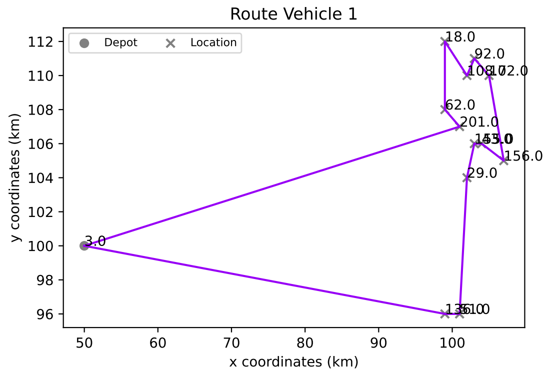


i	j	tot_dist	TD	TA	demand	tot_load
2	8	22.6	0	22.6	10	10
8	6	23.6	112.6	113.6	10	20
6	10	25.6	203.6	205.6	-10	10
10	11	28.4	295.6	298.4	20	30
11	13	32	388.4	392	-20	10
13	14	35	482	498.8	10	20
14	12	38.2	588.8	591.9	10	30
12	9	40.4	681.9	684.2	20	50
9	7	42.6	774.2	776.4	-10	40
7	5	46.2	866.4	870	-20	20
5	4	48.2	960	967	-10	10
4	78	51.2	1057	1068	-10	0
78	2	76.7	1158	1183.5	0	0

Figure B.10: *Results with pickups and deliveries, vehicle 10*

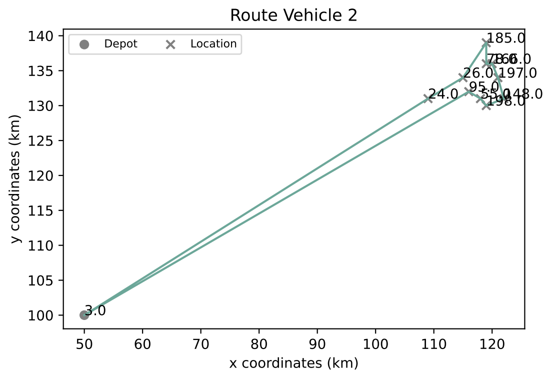
C
Plots

C.1. Question i



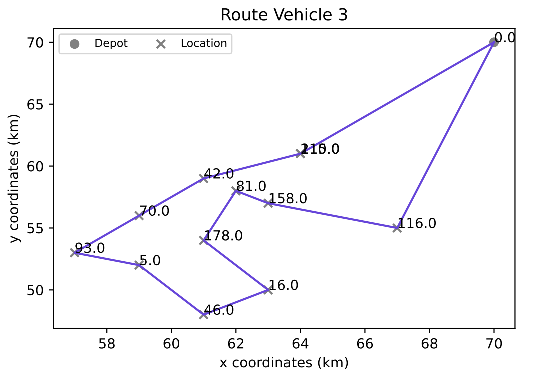
i	j	tot_dist	TD	TA	demand	tot_load
3	136	49.2	0	49.2	10	10
136	51	51.2	139.2	141.2	10	20
51	29	59.3	231.2	239.2	-10	10
29	155	61.5	329.2	331.5	30	40
155	43	62.5	421.5	422.5	20	60
43	156	65.7	512.5	515.6	-10	50
156	172	71.1	605.6	611	-20	30
172	92	73.3	701	703.2	20	50
92	108	74.7	793.2	794.7	-20	30
108	18	78.3	884.7	888.3	20	50
18	62	82.3	978.3	982.3	-20	30
62	201	84.5	1072.3	1090	-30	0
201	3	136	1180	1231.5	0	0

Figure C.1: *Results with pickups and deliveries, vehicle 1*



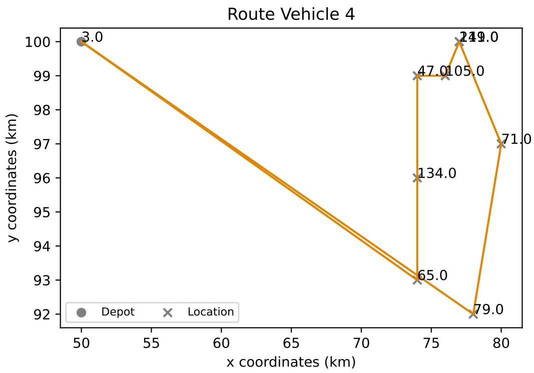
i	j	tot_dist	TD	TA	demand	tot_load
3	24	66.6	0	72	20	20
24	26	73.3	162	168.7	30	50
26	185	79.7	258.7	265.1	20	70
185	78	82.7	355.1	358.1	30	100
78	166	83.7	448.1	449.1	-20	80
166	197	85.9	539.1	541.3	20	100
197	148	89.1	631.3	634.5	-30	70
148	198	92.3	724.5	727.7	-20	50
198	55	93.7	817.7	819.1	-20	30
55	95	95.9	909.1	911.3	-30	0
95	3	169.2	1001.3	1074.6	0	0

Figure C.2: *Results with pickups and deliveries, vehicle 2*



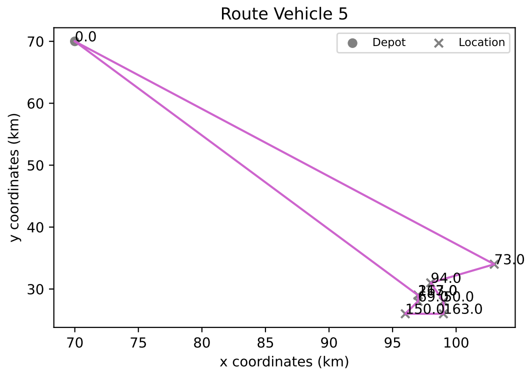
i	j	tot_dist	TD	TA	demand	tot_load
0	116	15.3	0	15.3	10	10
116	158	19.8	105.3	109.8	10	20
158	81	21.2	199.8	201.2	20	40
81	178	25.3	291.2	295.3	-10	30
178	16	29.8	385.3	389.8	10	40
16	46	32.6	479.8	482.6	20	60
46	5	37.1	572.6	577.1	-20	40
5	93	39.3	667.1	669.3	-20	20
93	70	42.9	759.3	762.9	-10	10
70	42	46.5	852.9	931	-10	0
42	110	50.1	1021	1049.1	20	20
110	215	50.1	1049.1	1077	-20	0
215	0	60.9	1167	1177.8	0	0

Figure C.3: *Results with pickups and deliveries, vehicle 3*



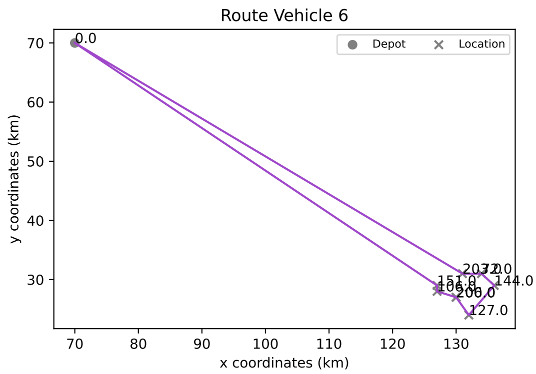
i	j	tot_dist	TD	TA	demand	tot_load
3	65	25	0	25	20	20
65	134	28	115	118	-20	0
134	47	31	208	211	20	20
47	105	33	301	303	20	40
105	149	34.4	393	394.4	20	60
149	211	34.4	394.4	394.4	-20	40
211	71	38.6	484.4	504.5	-20	20
71	79	44	594.5	599.9	-20	0
79	3	73.1	689.9	719	0	0

Figure C.4: *Results with pickups and deliveries, vehicle 4*



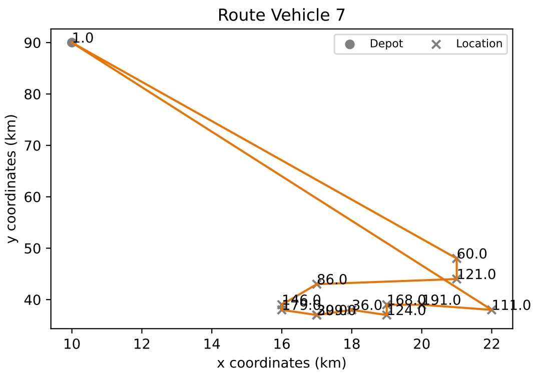
i	j	tot_dist	TD	TA	demand	tot_load
0	167	49.1	0	49.1	30	30
167	213	49.1	49.1	51.7	-30	0
213	69	50.1	141.7	142.7	20	20
69	150	52.3	232.7	235	10	30
150	163	55.3	325	328	-10	20
163	50	57.3	418	420	30	50
50	94	60.5	510	513.1	-20	30
94	73	66.3	603.1	631	-30	0
73	0	115.1	721	769.8	0	0

Figure C.5: *Results with pickups and deliveries, vehicle 5*



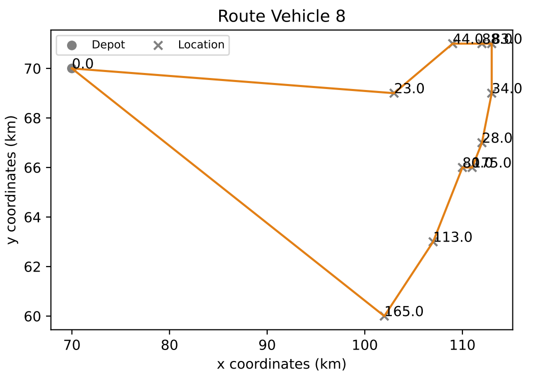
i	j	tot_dist	TD	TA	demand	tot_load
0	151	70.2	0	70.2	20	20
151	106	71.2	160.2	161.2	-20	0
106	200	74.4	251.2	254.4	30	30
200	206	74.4	254.4	254.4	-30	0
206	127	78	344.4	348	10	10
127	144	84.4	438	444.4	10	20
144	72	87.2	534.4	537.2	-10	10
72	203	90.2	627.2	655.8	-10	0
203	0	162.6	745.8	818.2	0	0

Figure C.6: *Results with pickups and deliveries, vehicle 6*



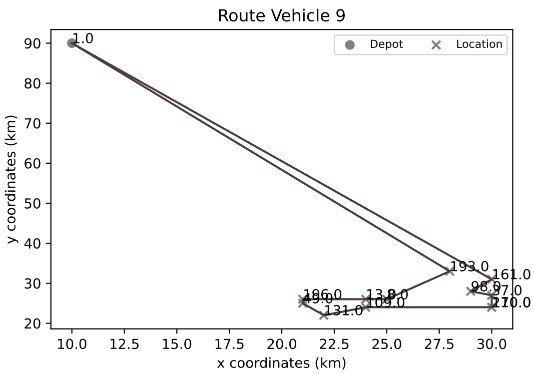
i	j	tot_dist	TD	TA	demand	tot_load
1	60	43.4	0	53	10	10
60	121	47.4	143	147	-10	0
121	86	51.5	237	241.1	10	10
86	146	55.6	331.1	348.7	20	30
146	179	56.6	438.7	439.7	-10	20
179	39	58	529.7	531.1	30	50
39	209	58	531.1	531.1	-30	20
209	36	59.4	621.1	622.5	30	50
36	124	60.8	712.5	713.9	20	70
124	168	62.8	803.9	808.4	-20	50
168	191	63.8	898.4	899.4	-20	30
191	111	66	989.4	1003	-30	0
111	1	119.4	1093	1146.4	0	0

Figure C.7: *Results with pickups and deliveries, vehicle 7*



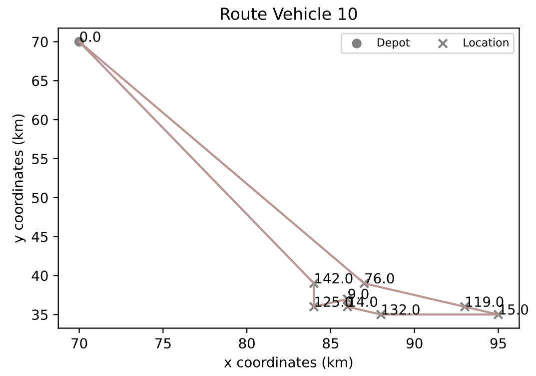
i	j	tot_dist	TD	TA	demand	tot_load
0	23	33	0	33	30	30
23	44	39.3	123	129.3	20	50
44	88	42.3	219.3	222.3	20	70
88	83	43.3	312.3	313.3	10	80
83	34	45.3	403.3	405.3	-20	60
34	28	47.5	495.3	497.6	10	70
28	175	48.9	587.6	589	-20	50
175	80	49.9	679	680	-30	20
80	113	54.1	770	774.2	-10	10
113	165	59.9	864.2	892	-10	0
165	0	93.4	982	1015.5	0	0

Figure C.8: *Results with pickups and deliveries, vehicle 8*



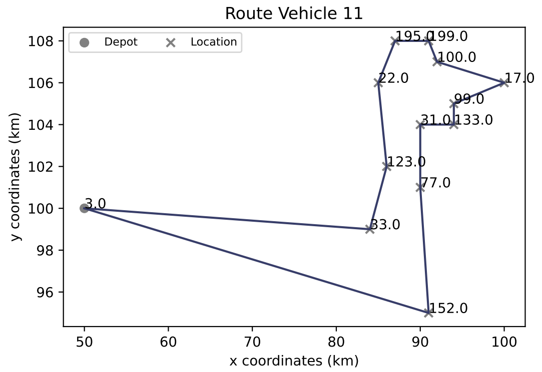
i	j	tot_dist	TD	TA	demand	tot_load
1	193	59.8	0	59.8	20	20
193	8	67.4	149.8	157.4	20	40
8	13	68.4	247.4	248.4	20	60
13	196	71.4	338.4	341.4	20	80
196	49	72.4	431.4	432.4	-20	60
49	131	75.6	522.4	525.6	-20	40
131	109	78.4	615.6	618.4	-20	20
109	170	84.4	708.4	714.4	20	40
170	210	84.4	714.4	714.4	-20	20
210	37	87.4	804.4	807.4	10	30
37	98	88.8	897.4	898.8	-20	10
98	161	92	988.8	1016	-10	0
161	1	154.3	1106	1168.3	0	0

Figure C.9: *Results with pickups and deliveries, vehicle 9*



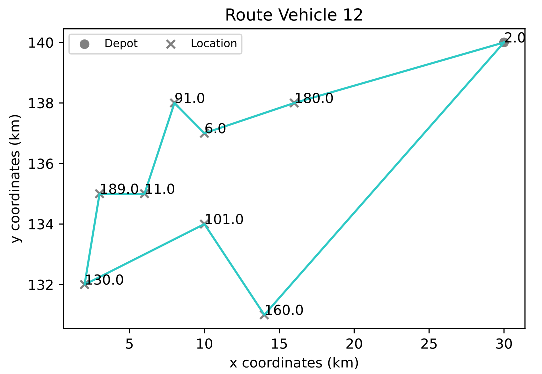
i	j	tot_dist	TD	TA	demand	tot_load
0	76	35.4	0	35.4	20	20
76	119	42.1	125.4	132.1	20	40
119	15	44.3	222.1	224.3	10	50
15	132	51.3	314.3	321.3	-20	30
132	14	53.5	411.3	413.5	-10	20
14	9	54.5	503.5	510.7	10	30
9	125	56.7	600.7	602.9	-20	10
125	142	59.7	692.9	695.9	-10	0
142	0	93.7	785.9	819.9	0	0

Figure C.10: *Results with pickups and deliveries, vehicle 10*



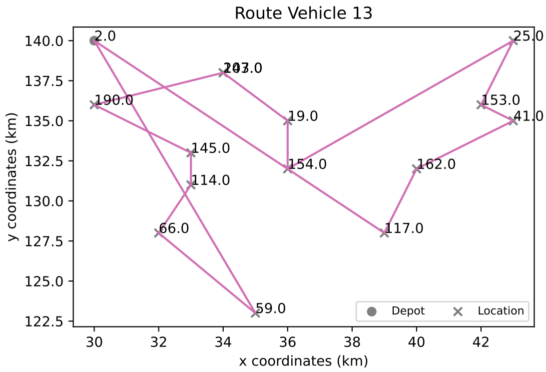
i	j	tot_dist	TD	TA	demand	tot_load
3	33	34	0	34	20	20
33	123	37.6	124	127.6	10	30
123	22	41.7	217.6	221.7	-10	20
22	195	44.5	311.7	314.6	20	40
195	199	48.5	404.6	408.6	-20	20
199	100	49.9	498.6	500	30	50
100	17	58	590	598	10	60
17	99	64.1	688	694.1	-30	30
99	133	65.1	784.1	785.1	10	40
133	31	69.1	875.1	879.1	-20	20
31	77	72.1	969.1	972.1	-10	10
77	152	78.2	1062.1	1097	-10	0
152	3	119.5	1187	1228.3	0	0

Figure C.11: *Results with pickups and deliveries, vehicle 11*



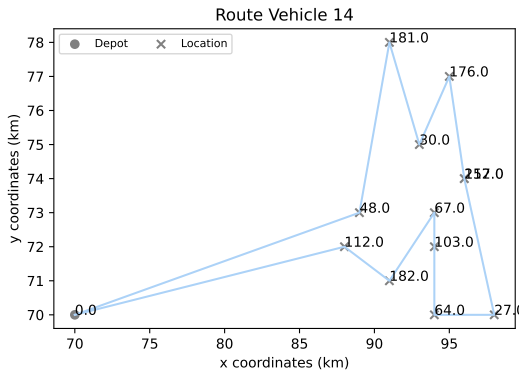
i	j	tot_dist	TD	TA	demand	tot_load
2	180	14.1	0	86	10	10
180	6	20.2	176	182.1	30	40
6	91	22.4	272.1	274.3	30	70
91	11	26	364.3	367.9	40	110
11	189	29	457.9	460.9	-40	70
189	130	32.2	550.9	554.1	-30	40
130	101	40.4	644.1	652.3	-30	10
101	160	45.4	742.3	763.2	-10	0
160	2	63.8	853.2	871.6	0	0

Figure C.12: *Results with pickups and deliveries, vehicle 12*



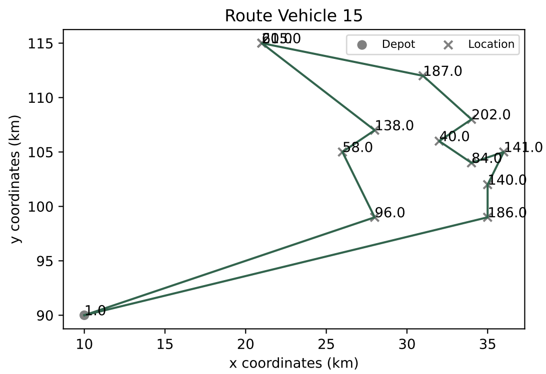
i	j	tot_dist	TD	TA	demand	tot_load
2	117	15	0	65	10	10
117	162	19.1	155	159.1	20	30
162	41	23.3	249.1	253.4	-20	10
41	153	24.7	343.4	344.8	-10	0
153	25	28.8	434.8	438.9	10	10
25	154	39.4	528.9	539.5	10	20
154	19	42.4	629.5	632.5	10	30
19	143	46	722.5	726.1	20	50
143	207	46	726.1	728.3	-20	30
207	190	50.5	818.3	822.8	-10	20
190	145	54.7	912.8	917	20	40
145	114	56.7	1007	1009	-20	20
114	66	59.9	1099	1102.2	-10	10
66	59	65.7	1192.2	1198	-10	0
59	2	83.4	1288	1305.7	0	0

Figure C.13: *Results with pickups and deliveries, vehicle 13*



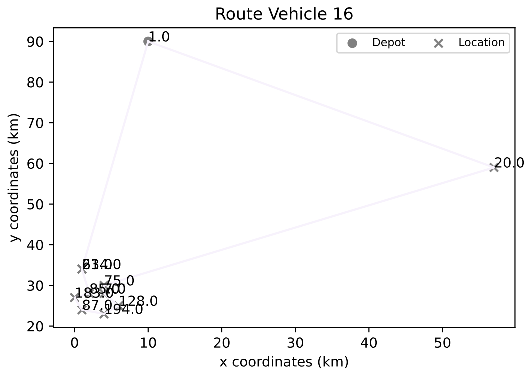
i	j	tot_dist	TD	TA	demand	tot_load
0	48	19.2	0	19.2	10	10
48	181	24.6	109.2	114.6	10	20
181	30	28.2	204.6	208.2	30	50
30	176	31	298.2	301.1	10	60
176	157	34.2	391.1	394.2	10	70
157	212	34.2	394.2	394.2	-10	60
212	27	38.7	484.2	488.7	-10	50
27	64	42.7	578.7	582.7	-30	20
64	103	44.7	672.7	674.7	-10	10
103	67	45.7	764.7	765.7	10	20
67	182	49.3	855.7	859.3	-10	10
182	112	52.5	949.3	952.5	-10	0
112	0	70.6	1042.5	1060.6	0	0

Figure C.14: *Results with pickups and deliveries, vehicle 14*



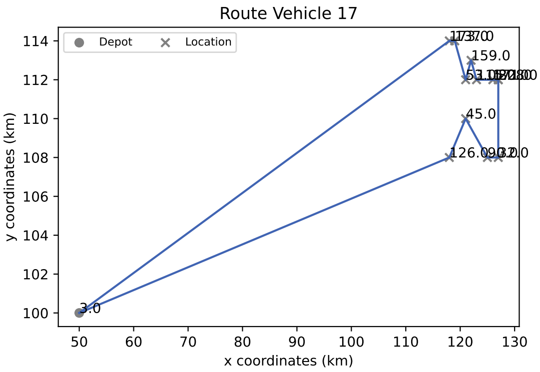
i	j	tot_dist	TD	TA	demand	tot_load
1	96	20.1	0	51	10	10
96	58	26.4	141	147.3	40	50
58	138	29.2	237.3	240.2	-40	10
138	61	39.8	330.2	340.8	10	20
61	205	39.8	340.8	340.8	-10	10
205	187	50.2	430.8	441.2	-10	0
187	202	55.2	531.2	536.2	10	10
202	40	58	626.2	629.1	10	20
40	84	60.8	719.1	721.9	-10	10
84	141	63	811.9	814.1	-10	0
141	140	66.2	904.1	907.3	10	10
140	186	69.2	997.3	1000.3	-10	0
186	1	95.8	1090.3	1116.9	0	0

Figure C.15: *Results with pickups and deliveries, vehicle 15*



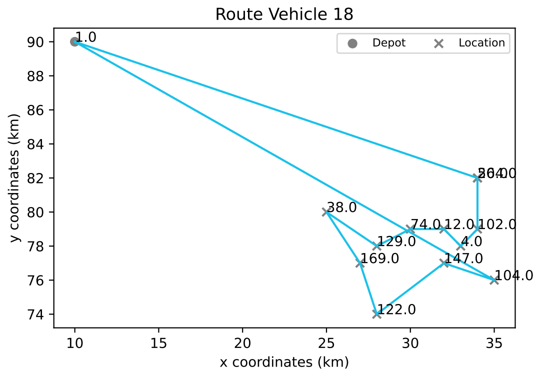
i	j	tot_dist	TD	TA	demand	tot_load
1	63	56.7	0	77	20	20
63	214	56.7	77	77	-20	0
214	85	62.8	167	173.1	10	10
85	183	65	263.1	265.3	-10	0
183	87	68.2	355.3	358.5	10	10
87	194	71.4	448.5	451.6	10	20
194	128	74.2	541.6	544.5	-10	10
128	7	77.8	634.5	638.1	10	20
7	75	79.8	728.1	739.6	-10	10
75	20	140.2	829.6	890	-10	0
20	1	196.5	980	1036.3	0	0

Figure C.16: *Results with pickups and deliveries, vehicle 16*



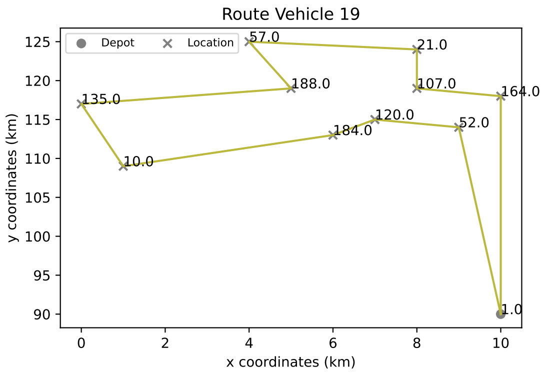
i	j	tot_dist	TD	TA	demand	tot_load
3	173	69.4	0	69.4	10	10
173	137	70.4	159.4	160.4	20	30
137	53	73.2	250.4	253.3	20	50
53	159	74.6	343.3	344.7	20	70
159	115	76	434.7	436.1	-20	50
115	171	79	526.1	529.1	10	60
171	82	80	619.1	620.1	20	80
82	208	80	620.1	620.1	-20	60
208	32	84	710.1	714.1	-10	50
32	90	86	804.1	806.1	-10	40
90	45	90.5	896.1	900.6	-20	20
45	126	94.1	990.6	994.2	-20	0
126	3	162.6	1084.2	1152.7	0	0

Figure C.17: *Results with pickups and deliveries, vehicle 17*



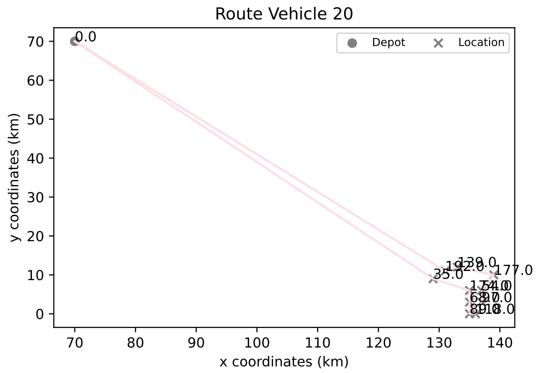
i	j	tot_dist	TD	TA	demand	tot_load
1	104	28.7	0	35	10	10
104	147	31.9	125	128.2	20	30
147	122	36.9	218.2	223.2	-20	10
122	169	40.1	313.2	316.3	10	20
169	38	43.7	406.3	409.9	-10	10
38	129	47.3	499.9	503.5	-10	0
129	74	49.5	593.5	595.8	20	20
74	12	51.5	685.8	687.8	20	40
12	4	52.9	777.8	779.2	-20	20
4	102	54.3	869.2	870.6	-20	0
102	56	57.3	960.6	963.6	10	10
56	204	57.3	963.6	963.6	-10	0
204	1	82.6	1053.6	1078.9	0	0

Figure C.18: *Results with pickups and deliveries, vehicle 18*



i	j	tot_dist	TD	TA	demand	tot_load
1	164	28	0	76	10	10
164	107	30.2	166	168.2	20	30
107	21	35.2	258.2	272.1	10	40
21	57	39.3	362.1	366.2	-10	30
57	188	45.4	456.2	472.7	-10	20
188	135	50.8	562.7	568.1	30	50
135	10	58.9	658.1	667.4	-20	30
10	184	65.3	757.4	763.8	20	50
184	120	67.5	853.8	860.2	-20	30
120	52	69.7	950.2	952.5	-30	0
52	1	93.7	1042.5	1066.5	0	0

Figure C.19: *Results with pickups and deliveries, vehicle 19*



i	j	tot_dist	TD	TA	demand	tot_load
0	35	84.9	0	84.9	10	10
35	174	91.6	174.9	190.8	30	40
174	68	94.6	280.8	283.8	20	60
68	89	97.6	373.8	376.8	10	70
89	118	98.6	466.8	469.4	30	100
118	97	101.8	559.4	562.5	-10	90
97	54	104.8	652.5	655.5	-10	80
54	177	109.3	745.5	750	-20	60
177	139	115.6	840	852.3	-30	30
139	192	117.8	942.3	944.6	-30	0
192	0	202.7	1034.6	1119.5	0	0

Figure C.20: *Results with pickups and deliveries, vehicle 20*