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Article

Multi-Period Optimization of the Refuelling Infrastructure for Alternative Fuel Vehicles

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Online-Appendix zu

„Multi-Period Optimization of the Refuelling Infrastructure for Alternative Fuel Vehicles “

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A Appendix

A.1 Model Formulations

MP-NC FRLM incl. Minimal Flow Coverage Constraint

$$\max \sum_{t \in T} \sum_{q \in Q} y_q^t \quad (\text{A.1})$$

$$\text{s.t.} \quad \sum_{i \in K_{j,k}^q} z_i^t \geq y_q^t \quad \forall q \in Q, a_{j,k} \in A_q, t \in T \quad (\text{A.2})$$

$$\sum_{q \in Q} f_q^t p_{riq} g_{iq} x_{iq}^t \leq c_i z_i^t \quad \forall i \in N, t \in T \quad (\text{A.3})$$

$$\sum_{i \in K_{j,k}^q} x_{iq}^t = y_q^t \quad \forall q \in Q, a_{j,k} \in A_q, t \in T \quad (\text{A.4})$$

$$\sum_{i \in N} x_{iq}^t = y_q^t l_q \quad \forall q \in Q, t \in T \quad (\text{A.5})$$

$$x_{iq}^t \leq z_i^t \quad \forall i \in N, q \in Q, t \in T \quad (\text{A.6})$$

$$z_i^t \leq z_i^{t+1} \quad \forall i \in N, t \in T \setminus \{n\} \quad (\text{A.7})$$

$$z_i^t - z_i^{t-1} \leq k_i^t \quad \forall i \in N, t \in T \setminus \{1\} \quad (\text{A.8})$$

$$z_i^1 \leq k_i^1 \quad \forall i \in N \quad (\text{A.9})$$

$$\sum_{i \in N} o_i k_i^t \leq b_t \quad \forall t \in T \quad (\text{A.10})$$

$$\frac{\sum_{q \in Q} y_q^t f_q^t}{\sum_{q \in Q} f_q^t} \geq y_q^t, \quad \forall q \in Q \quad (\text{A.11})$$

$$\sum_{t \in T} k_i^t \leq 1 \quad \forall i \in N \quad (\text{A.12})$$

$$z_i^t, k_i^t \in \{0, 1\} \quad \forall i \in N, t \in T \quad (\text{A.13})$$

$$0 \leq x_{iq}^t \leq 1 \quad \forall i \in N, q \in Q, t \in T \quad (\text{A.14})$$

$$0 \leq y_q^t \leq 1 \quad \forall q \in Q, t \in T \quad (\text{A.15})$$

Sets

N	Set of all nodes on the Graph G
Q	Set of all OD pairs
T	Set of all time periods
A_q	Set of all directional arcs on the path $q \in Q$ from origin to destination
$K_{j,k}^q$	Set of all potential station locations, that can refuel the directional arc $a_{j,k} \in A_q$

Variables

z_i^t	Binary Variable that equals to one, if a refuelling facility is open at node i in time period t
k_i^t	Binary Variable that equals to one, if a refuelling facility is constructed at node i in time period t
x_{iq}^t	Semi-Continuous Variable that indicates the proportion of vehicles on path q that are refuelled at node i in time period t
y_q^t	Semi-Continuous Variable that indicates the proportion of flow served on path q in time period t

Parameters

p	Fuel efficiency / fuel consumption per vehicle range
o	Facility opening costs / construction costs
v^t	Fraction of the minimal amount of flow covered in period t
c_i	refuelling capacity at node i
d_q	total distance of path q
θ_q	vehicle range of vehicles on path q
l_q	Number of refuelling occasions on path q depending on the total path distance, $l_q = \text{ceil}\{d_q / \theta_q\}$
b_t	Available budget in period t
f_q^t	Total vehicle flow on the OD path q in time period t
g_{iq}	Binary indicator, that is set to one, if node i is a potential station location on path q
r_{iq}	refuelled driving distance at node i on path q

Maximal Flow Covering MP-NC FRLM

$$\max \sum_{t \in T} \sum_{q \in Q} f_q^t y_q^t \quad (\text{A.16})$$

$$\text{s.t.} \quad \sum_{i \in K_{j,k}^q} z_i^t \geq y_q^t \quad \forall q \in Q, a_{j,k} \in A_q, t \in T \quad (\text{A.17})$$

$$\sum_{q \in Q} f_q^t p_{r_{iq}} g_{iq} x_{iq}^t \leq c_i z_i^t \quad \forall i \in N, t \in T \quad (\text{A.18})$$

$$\sum_{i \in K_{j,k}^q} x_{iq}^t = y_q^t \quad \forall q \in Q, a_{j,k} \in A_q, t \in T \quad (\text{A.19})$$

$$\sum_{i \in N} x_{iq}^t = y_q^t l_q \quad \forall q \in Q, t \in T \quad (\text{A.20})$$

$$x_{iq}^t \leq z_i^t \quad \forall i \in N, q \in Q, t \in T \quad (\text{A.21})$$

$$z_i^t \leq z_i^{t+1} \quad \forall i \in N, t \in T \setminus \{n\} \quad (\text{A.22})$$

$$z_i^t - z_i^{t-1} \leq k_i^t \quad \forall i \in N, t \in T \setminus \{1\} \quad (\text{A.23})$$

$$z_i^1 \leq k_i^1 \quad \forall i \in N \quad (\text{A.24})$$

$$\sum_{i \in N} o_i k_i^t \leq b_t \quad \forall t \in T \quad (\text{A.25})$$

$$\sum_{t \in T} k_i^t \leq 1 \quad \forall i \in N \quad (\text{A.26})$$

$$z_i^t, k_i^t \in \{0, 1\} \quad \forall i \in N, t \in T \quad (\text{A.27})$$

$$0 \leq x_{iq}^t \leq 1 \quad \forall i \in N, q \in Q, t \in T \quad (\text{A.28})$$

$$0 \leq y_q^t \leq 1 \quad \forall q \in Q, t \in T \quad (\text{A.29})$$

Sets

N	Set of all nodes on the Graph G
Q	Set of all OD pairs
T	Set of all time periods
A_q	Set of all directional arcs on the path $q \in Q$ from origin to destination
$K_{j,k}^q$	Set of all potential station locations, that can refuel the directional arc $a_{j,k} \in A_q$

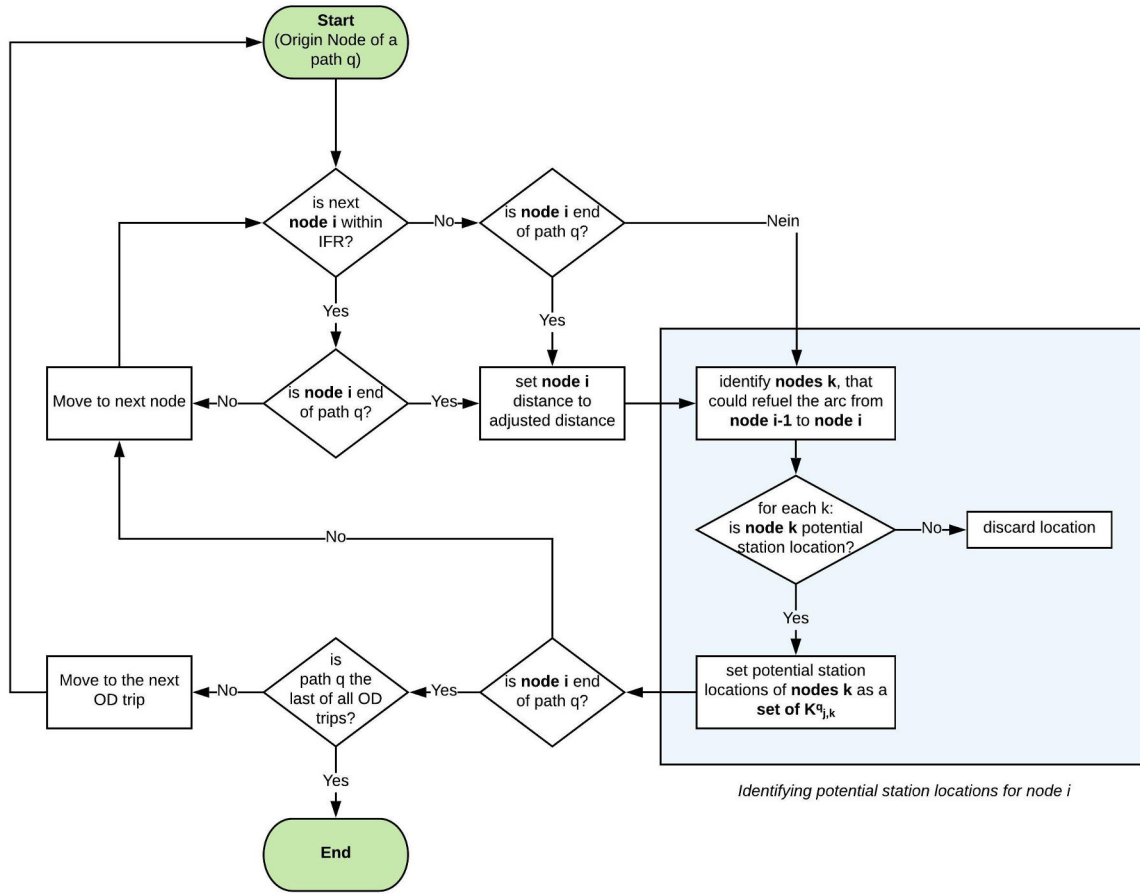
Variables

z_i^t	Binary Variable that equals to one, if a refuelling facility is open at node i in time period t
k_i^t	Binary Variable that equals to one, if a refuelling facility is constructed at node i in time period t
x_{iq}^t	Semi-Continuous Variable that indicates the proportion of vehicles on path q that are refuelled at node i in time period t
y_q^t	Semi-Continuous Variable that indicates the proportion of flow served on path q in time period t

Parameters

p	Fuel efficiency / fuel consumption per vehicle range
o	Facility opening costs / construction costs
c_i	refuelling capacity at node i
d_q	total distance of path q
θ_q	vehicle range of vehicles on path q
l_q	Number of refuelling occasions on path q depending on the total path distance, $l_q = \text{ceil}\{d_q / \theta_q\}$
b_t	Available budget in period t
f_q^t	Total vehicle flow on the OD path q in time period t
g_{iq}	Binary indicator, that is set to one, if node i is a potential station location on path q
r_{iq}	refuelled driving distance at node i on path q

A.2 Graphs and Charts

Figure 22: Flowchart to determine the Set $K_{j,k}^q$ in the NC-FRLM.

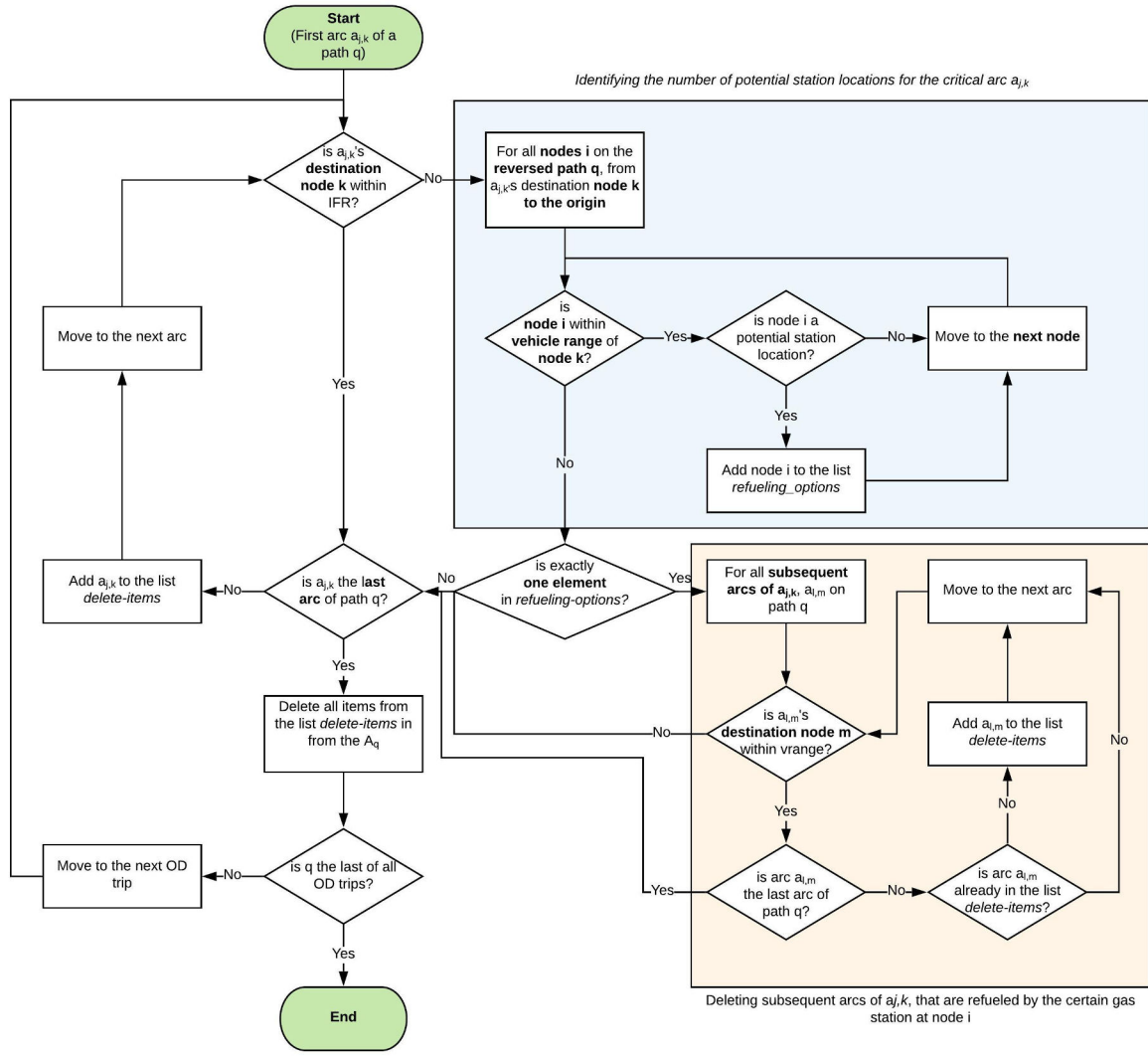


Figure 23: Flowchart to remove the non-critical arcs from A_q in the MP-NC FRLM.

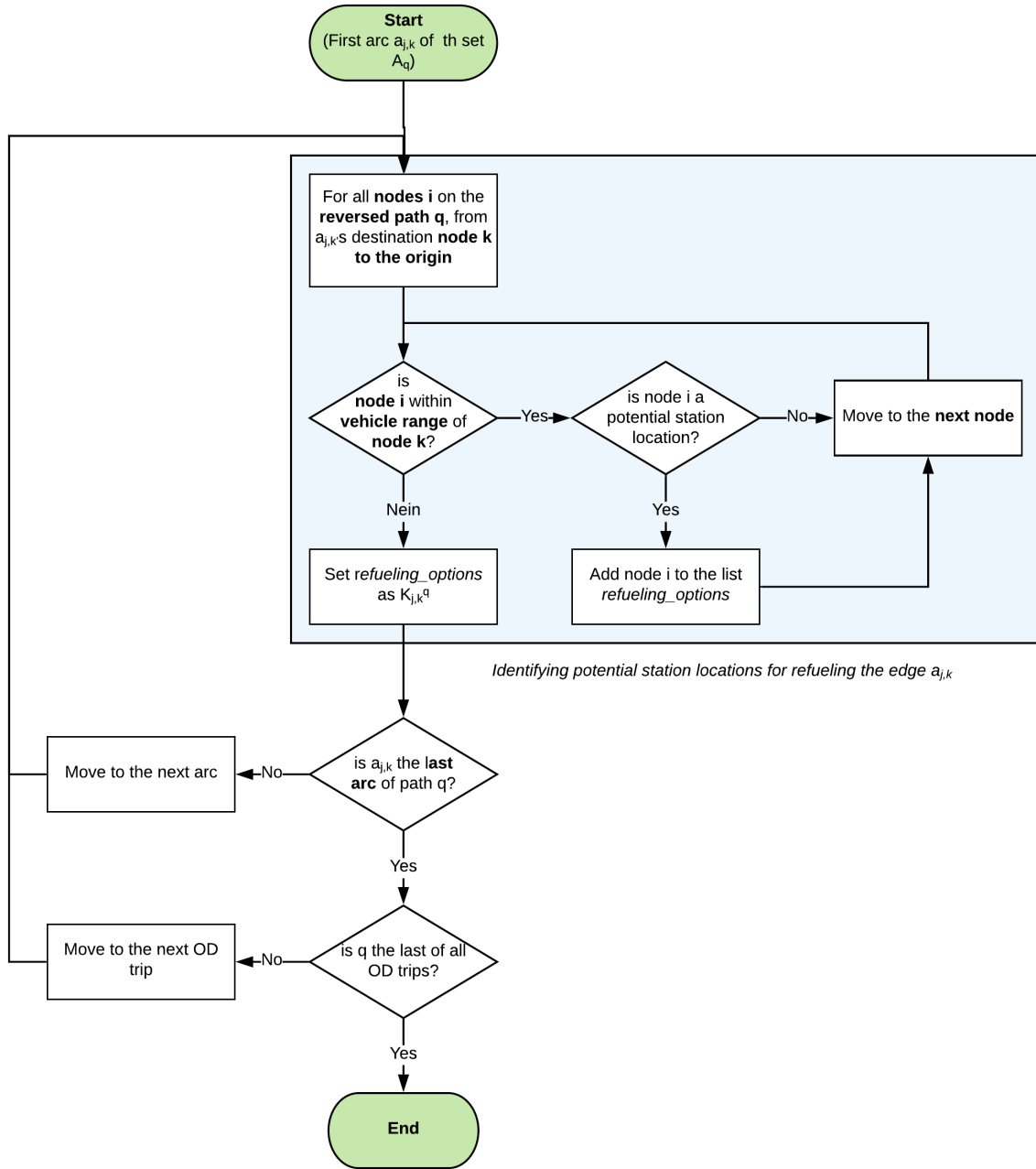


Figure 24: Flowchart to determine the Set $K_{j,k}^q$ in the MP-NC FRLM.

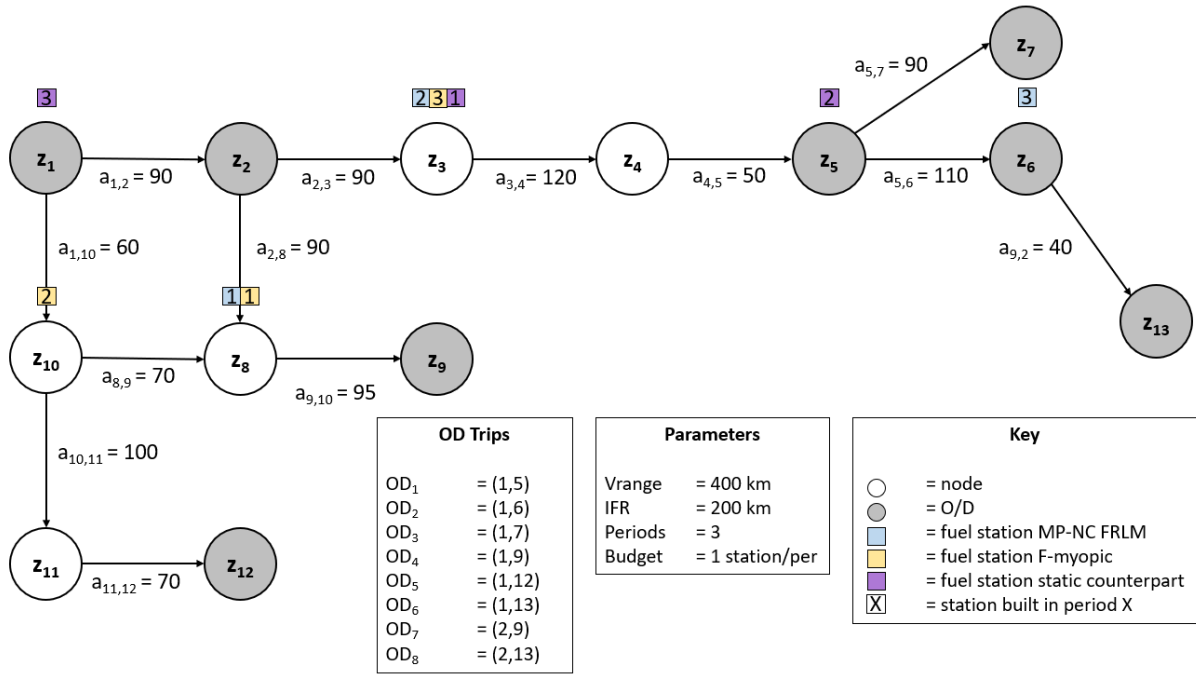


Figure 25: Exemplary problem in the numerical experiment with both $VMPP > 0$ and $VMPS > 0$

A.3 Tables

OD Trip	Flow in t=1	Flow in t=2	Flow in t=3
(1,5)	5	10	12
(1,6)	5	10	12
(1,7)	5	10	15
(1,9)	5	10	15
(1,12)	5	10	15
(1,13)	5	10	15
(2,9)	5	10	15
(2,13)	5	10	15

Table 12: OD flows of the VMPS, VMPP > 0 problem in figure 25

		Period t=1	Period t=2	Period t=3
MP-NC FRLM	Operating Stations Paths Covered	z_8 (1,9), (2,9)	z_8, z_3 (1,9), (2,9), (1,5)	z_8, z_3, z_6 (1,9), (2,9), (1,5), (1,6), (2,13)
Static Counterpart	Operating Stations Paths Covered	z_8 (1,9), (2,9)	z_8, z_1 (1,9), (2,9)	z_8, z_1, z_5 (1,9), (2,9), (1,6), (1,7), (1,13)
F-Myopic	Operating Stations Paths Covered	z_8 (1,9), (2,9)	z_8, z_{10} (1,9), (2,9), (1,12)	z_8, z_{10}, z_3 (1,9), (2,9), (1,12), (1,5)

Solution Value		Assessment Criterion	
MP-NC FRLM	10.0	VMPS	11.11 %
Static Counterpart	9.0	VMPP	11.11 %
F-Myopic	9.0		

Table 13: Operating stations and covered paths of the numerical experiment in figure 25