Online-Appendix zu

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

Alexander Böhle

Karlsruher Institut für Technologie

Junior Management Science 6(4) (2021) 790-825

A Appendix

A.1 Model Formulations

MP-NC FRLM incl. Minimal Flow Coverage Constraint

$$\max \sum_{t \,\in\, T} \sum_{q \,\in\, Q} y_q^t \tag{A.1}$$

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

$$\sum_{q \,\in\, Q} f_q^t\, p\, r_{iq}\, g_{iq}\, x_{iq}^t \leq c_i\, z_i^t \qquad \forall\, i \,\in\, N,\ t \,\in\, T \tag{A.3}$$

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

$$\sum_{i \,\in\, N} x_{iq}^t = y_q^t\, l_q \qquad \forall\, q \,\in\, Q,\ t \,\in\, T \tag{A.5}$$

$$x_{iq}^t \leq z_i^t \qquad \forall\, i \,\in\, N,\ q \,\in\, Q,\ t\ in\ T \tag{A.6}$$

$$z_i^t \leq z_i^{t+1} \qquad \forall\, i \,\in\, N,\ t \,\in\, T \backslash \{n\} \tag{A.7}$$

$$z_i^t \;-\; z_i^{t-1} \leq k_i^t \qquad \forall\, i \,\in\, N,\ t \,\in\, T \backslash \{1\} \tag{A.8}$$

$$z_i^1 \leq k_i^1 \qquad \forall\, i \,\in\, N \tag{A.9}$$

$$\sum_{i \,\in\, N} o\, k_i^t \leq b_t \qquad \forall\, t \,\in\, T \tag{A.10}$$

$$\frac{\sum_{q \,\in\, Q} y_q^t\, f_q^t}{\sum_{q \,\in\, Q} f_q^t} \geq y_q^t, \qquad \forall\, q \,\in\, Q \tag{A.11}$$

$$\sum_{t \,\in\, T} k_i^t \leq 1 \qquad \forall\, i \,\in\, N \tag{A.12}$$

$$z_i^t,\ k_i^t \,\in \{0, 1\} \qquad \forall\, i \,\in\, N,\ t \,\in\, T \tag{A.13}$$

$$0 \;\leq\; x_{iq}^t \;\leq 1 \qquad \forall\, i \,\in\, N,\ q \,\in\, Q,\ t \,\in\, T \tag{A.14}$$

$$0 \;\leq\; y_q^t \;\leq 1 \qquad \forall\, q \,\in\, Q,\ t \,\in\, T \tag{A.15}$$

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
$K^q_{j,k}$	Set of all potential station locations, that can refuel the directional arc $a_{j,k} \in A_q$
Variables	
z^t_i	Binary Variable that equals to one, if a refuelling facility is open at node i in time period t
k^t_i	Binary Variable that equals to one, if a refuelling facility is constructed at node i in time period t
x^t_{iq}	Semi-Continuous Variable that indicates the proportion of vehicles on path q that are refuelled at node i in time period t
y^t_q	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^t_q	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

$$\max \sum_{t \in T} \sum_{q \in Q} f_q^t \, y_q^t \tag{A.16}$$

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

$$\sum_{q \in Q} f_q^t \, p \, r_{iq} \, g_{iq} \, x_{iq}^t \leq c_i \, z_i^t \qquad \forall\, i \in N,\ t \in T \tag{A.18}$$

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

$$\sum_{i \in N} x_{iq}^t = y_q^t \, l_q \qquad \forall\, q \in Q,\ t \in T \tag{A.20}$$

$$x_{iq}^t \leq z_i^t \qquad \forall\, i \in N,\ q \in Q,\ t\ in\ T \tag{A.21}$$

$$z_i^t \leq z_i^{t+1} \qquad \forall\, i \in N,\ t \in T \backslash \{n\} \tag{A.22}$$

$$z_i^t - z_i^{t-1} \leq k_i^t \qquad \forall\, i \in N,\ t \in T \backslash \{1\} \tag{A.23}$$

$$z_i^1 \leq k_i^1 \qquad \forall\, i \in N \tag{A.24}$$

$$\sum_{i \in N} o \, k_i^t \leq b_t \qquad \forall\, t \in T \tag{A.25}$$

$$\sum_{t \in T} k_i^t \leq 1 \qquad \forall\, i \in N \tag{A.26}$$

$$z_i^t,\ k_i^t \in \{0, 1\} \qquad \forall\, i \in N,\ t \in T \tag{A.27}$$

$$0 \leq x_{iq}^t \leq 1 \qquad \forall\, i \in N,\ q \in Q,\ t \in T \tag{A.28}$$

$$0 \leq y_q^t \leq 1 \qquad \forall\, q \in Q,\ t \in T \tag{A.29}$$

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b_t	Available budget in period t
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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

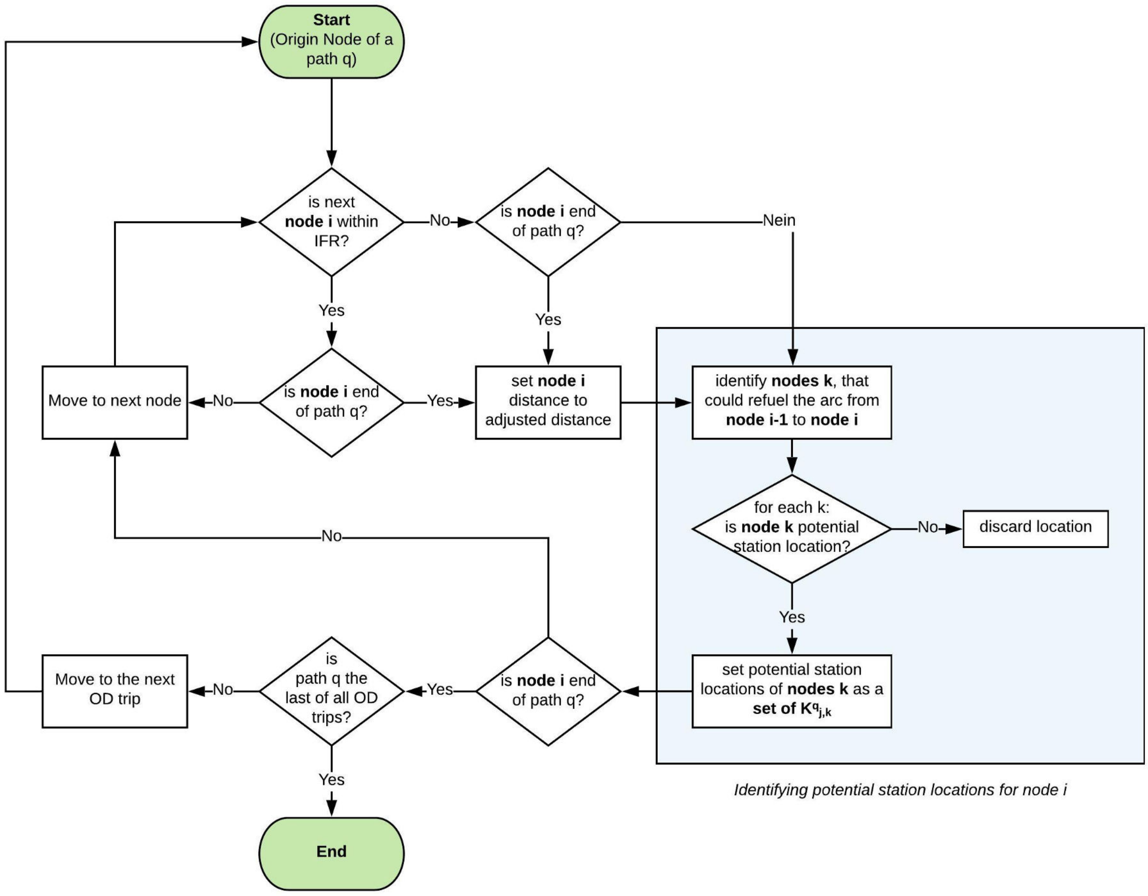

Figure 22: Flowchart to determine the Set $K^q_{j,k}$ in the NC-FRLM.

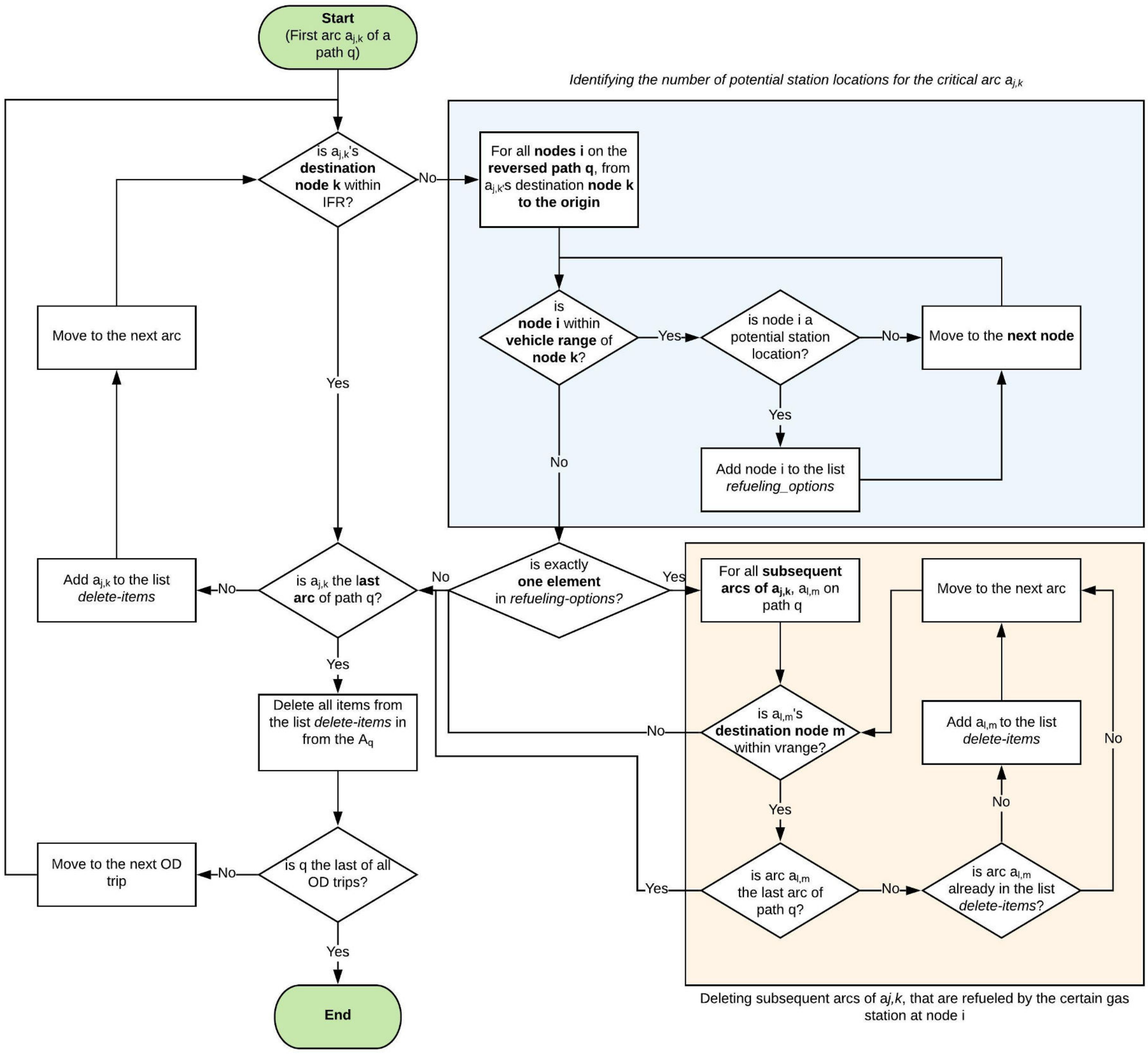

Figure 23: Flowchart to remove the non-critical arcs from A_q in the MP-NC FRLM.

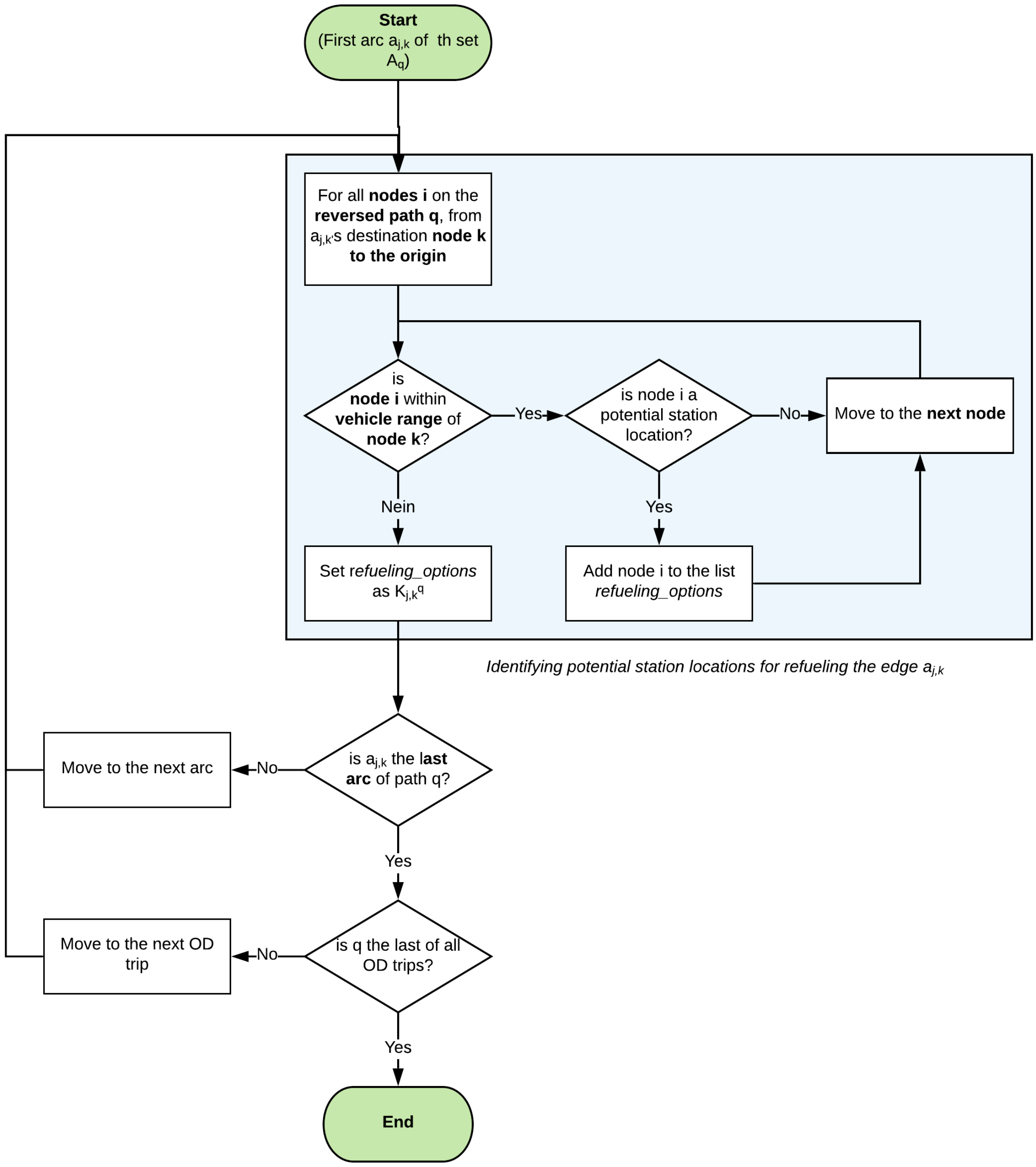

Figure 24: Flowchart to determine the Set $K_{j,k}^q$ in the MP-NC FRLM.

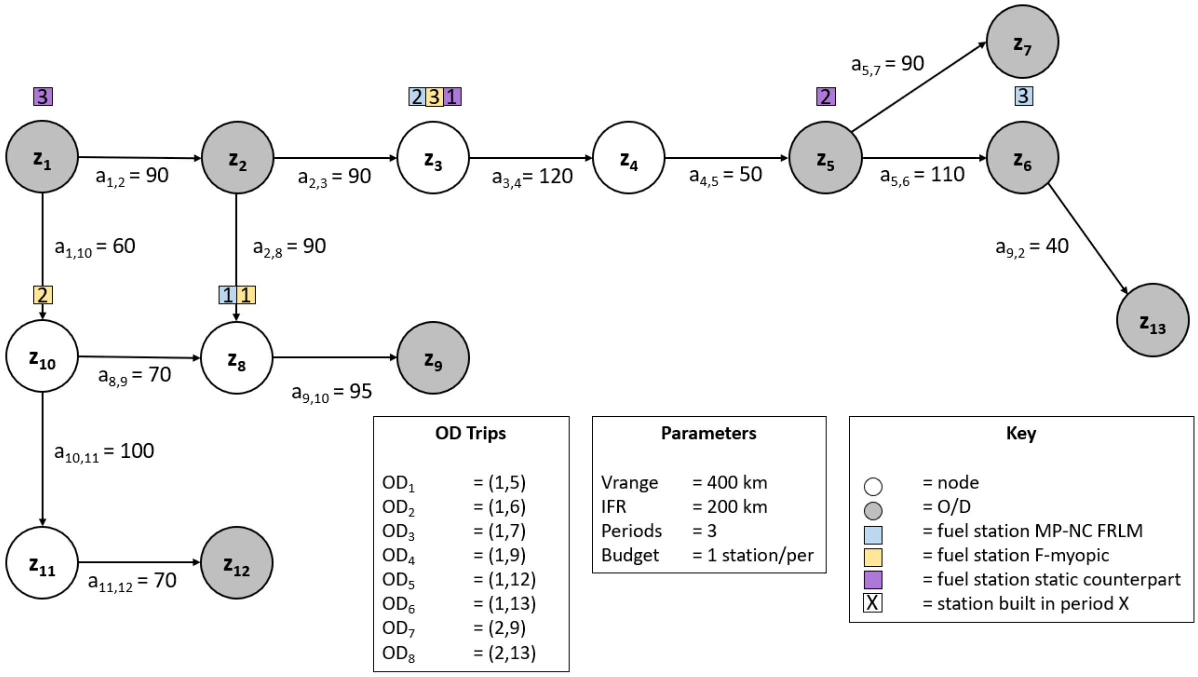

Figure 25: Exemplary problem in the numerical experiment with both VMPP > 0 and VMPS > 0

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**	z_8	$z_8,\ z_3$	$z_8,\ z_3,\ z_6$
	Paths Covered	(1,9), (2,9)	(1,9), (2,9), (1,5)	(1,9), (2,9), (1,5), (1,6), (2,13)
Static Counterpart	**Operating Stations**	z_8	$z_8,\ z_1$	$z_8,\ z_1,\ z_5$
	Paths Covered	(1,9), (2,9)	(1,9), (2,9)	(1,9), (2,9), (1,6), (1,7), (1,13)
F-Myopic	**Operating Stations**	z_8	$z_8,\ z_{10}$	$z_8,\ z_{10},\ z_3$
	Paths Covered	(1,9), (2,9)	(1,9), (2,9), (1,12)	(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