Exact Algorithm for Operational Management of Station-Based Ecar Sharing Systems

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Operations Research Group

Motivation

- European Project e4-share - Models for Ecological, Economical, Efficient, Electric Car-Sharing

e4-share

Project Consortium

Project Partners

- University of Vienna (UV), Austria (Coordinator)
- Austrian Institute of Technology (AIT), Austria
- Université Libre de Bruxelles (ULB), Belgium
- University of Bologna (UB), Italy
- iC consulenten Ziviltechniker (iC), Austria

Associated Car-sharing Companies (LOIs)

- TPER, Bologna, Italy
- DB Rent GmbH, Berlin, Germany
- ZenCar, Brussels, Belgium

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Plan

1. Station-Based Electric Car Sharing Systems
2. Mathematical Model
3. Test Results
4. Future Work

Plan

Electric Car Sharing Systems

- Plug-in Electric Vehicle (Battery only or hybrid)
- Free-floating vs Station-based
- Charging stations (Parking spots)
- Two-way (roundtrip) vs One-way
- User-Based (UB) vs Operator-Based (OB) relocation

Optimization Problems

Type	Problem
Strategic	Infrastructure Positioning
	Size of the fleet (# of EV)
	Size of the relocator team (# of Relocators)
Operational	Assign Trips to Cars
	Re-balance the System
	Guarantee Enough Battery is left

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	Re-balance the System
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Literature review

- Forthcoming review on e-car sharing in:

G. Brandstätter, C. Gambella, M. Leitner, E. Malaguti, F. Masini, J. Puchinger, M. Ruthmair, D. Vigo.

"Overview of optimization problems in electric car-sharing system design and management".

To appear in K. Doerner, G. Feichtinger (ed.s) *Dynamic Perspectives on Managerial Decision Making*, Springer, Berlin.

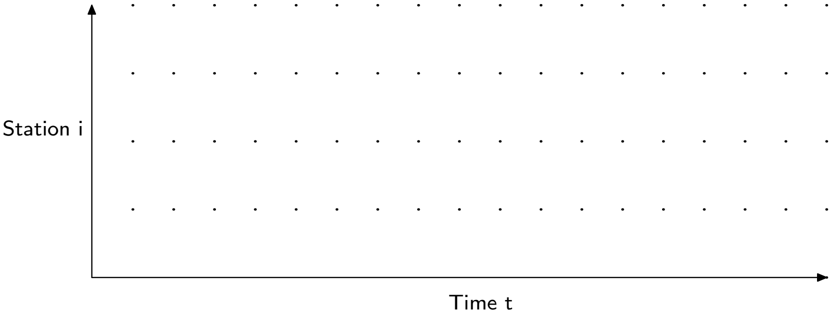
Reference	Strategy	Objective	methodology
[7]	UB	min. relocation costs	Simulation
[16]	UB	max. revenue and max. user's benefit	Simulation
[34, 35]	OB	min. relocation cost and rejected demand	Exact/Heuristic/Simulation
[45]	OB	min. relocation costs	Exact
[37]	OB	min. relocation distance	Simulation
[33]	OB	max. profit	Exact/Simulation
[9]	OB	max. number of relocations served	Exact
[8]	OB	max. revenue and max. user's benefit	Exact

Plan

Relocation in ECar-Sharing

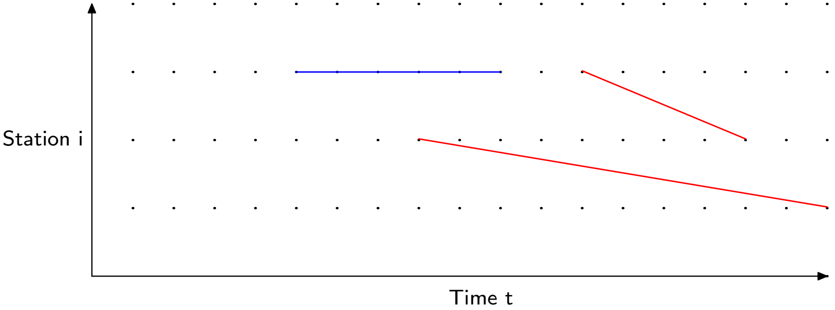
- Station-based one-way system
- Limited number of parking spots per station
- Operator-Based relocation
- Relocating personnel (may also travel as passenger and move autonomously)

Time Space Network
Arc Parameters



- Profit (cost), p_a
- Battery consumption/charging c_a
- Demand d_a

Time Space Network
Arc Types



- Wait Arcs $A_w\colon\ p_a = 0, c_a \geq 0$
- Travel (EV + Customer) $A_c\colon\ p_a > 0, c_a < 0, d_a \geq 1$
- Relocation (EV + Relocator) $A_r\colon\ p_a \leq 0, c_a < 0$
- Transfer (Relocator only) $A_t\colon\ p_a = 0, c_a = 0$

Parameters

Stations	$i \in S$
Station capacity	C_i
EVs	$h \in H$
Initial battery level	z_h^o
Relocators	$q \in Q$
Available travels	A_c
Vehicle capacity (relocators)	B
Time Steps	$t \in \{0, \ldots, T_{\max}\}$

Mathematical Formulation

- x_a^h Vehicle h travels on arc a
- y_a^q Relocator q travels on arc a

$$\max \sum_{h \in H} \sum_{a \in A_c \cup A_r} p_a x_a^h + \sum_{q \in Q} \sum_{a \in A_t \cup A_r} p_a y_a^q \tag{1}$$

$$\sum_{h \in H} x_a^h \leq d_a \qquad a \in A_c \tag{2}$$

$$\sum_{a=(i_t, i_{t+1}) \in A_w} \sum_{h \in H} x_a^h \leq C_i \qquad 1 \leq t < T_{\max}, i \in S \tag{3}$$

Mathematical Formulation
Flow Conservation

$$\sum_{a=(i_{\mathbf{0}},j_t)\cap(A_c\cup A_w\cup A_r)} x_a^h = 1 \qquad h \in H \tag{4}$$

$$\sum_{a\in(\delta^+(i_t))\cap(A_c\cup A_w\cup A_r)} x_a^h = \sum_{a\in(\delta^-(i_t))\cap(A_c\cup A_w\cup A_r)} x_a^h \qquad h \in H,\ 1 < t < T_{\mathsf{max}} \tag{5}$$

$$\sum_{a=(i_{\mathbf{0}},j_t)\cap(A_r\cup A_t\cup A_w)} y_a^q = 1 \qquad q \in Q \tag{6}$$

$$\sum_{a\in(\delta^+(i_t))\cap(A_r\cup A_t\cup A_w)} y_a^q = \sum_{a\in(\delta^-(i_t))\cap(A_r\cup A_t\cup A_w)} y_a^q \qquad q \in Q,\ 1 < t < T_{\mathsf{max}} \tag{7}$$

Mathematical Formulation
Link EV and relocators paths

$$\sum_{h \in H} x_a^h \leq \sum_{q \in Q} y_a^q \qquad a \in A_r \tag{8}$$

$$\sum_{q \in Q} y_a^q \leq B \sum_{h \in H} x_a^h \qquad a \in A_r \tag{9}$$

$$x_a^h \in \{0,1\} \qquad h \in H,\ a \in A_c \cup A_w \cup A_r \tag{10}$$

$$y_a^q \in \{0,1\} \qquad q \in Q,\ a \in A_r \cup A_w \cup A_t \tag{11}$$

Mathematical Formulation
Battery constraints

- z_h^t Battery of Vehicle h at Time t

$$0 \leq \underbrace{z_h^0 + \sum_{a=(i_\theta, j_\tau)\in A_c \cup A_w \cup A_r:\ \theta < \tau \leq t} c_a x_a^h}_{z_h^t} \leq Z_{max} \quad h \in H, t \in \{1, \ldots, T_{\mathrm{max}}\} \quad (12)$$

Solution Method
CPLEX 12.6

- Warm Start
  - Elimination of Relocation arcs
  - Quickly finds a "good" Solution
- Symmetry Constraints
  - From literature (see Bruglieri et al. [1])

$$\sum_{a=(i_t,j_{t'})\cap(A_c\cup A_r)} p_a x_a^h \geq \sum_{a=(i_t,j_{t'})\cap(A_c\cup A_r)} p_a x_a^{h'} \qquad h \in 2,\dots H_{max},\ h' < h$$

$$\sum_{a=(i_t,j_{t'})\cap A_r} p_a y_a^q \geq \sum_{a=(i_t,j_{t'})\cap A_r} p_a y_a^{q'} \qquad q \in 2,\dots Q_{max},\ q' < q$$

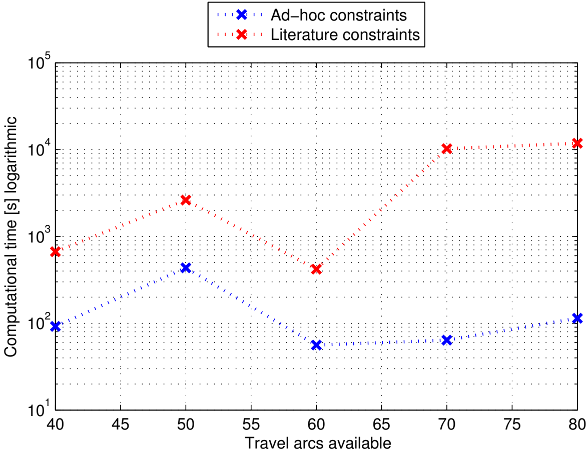
  - Ad-Hoc

$$\sum_{a=(i_\mathbf{0},j_t)\cap(A_c\cup A_w)} i x_a^h \geq \sum_{a=(i_\mathbf{0},j_t)\cap(A_c\cup A_w)} i x_a^{h'} \qquad h \in 2,\dots H_{max},\ h' < h$$

$$\sum_{a=(i_\mathbf{0},j_t)\cap(A_c\cup A_w)} i y_a^q > \sum_{a=(i_\mathbf{0},j_t)\cap(A_c\cup A_w)} i y_a^{q'} \qquad q \in 2,\dots Q_{max},\ q' < q$$

Symmetry Constraints

Test Results



Plan

DATA

- Used in Nair and Miller-Hooks [5], Kek et al. [4], Kek et al. [3]
- 14 Stations with different capacity
- Distance between stations
- 53 Vehicles
- Available travels A_c

PROBLEMS

- The cars were hybrid Honda
- Some of the travels are too long for EVs and are deleted

- The elimination of long travels (duration $> 6h$) reduces the number of A_c

ORIGINAL		DURATION<6h		DURATION<6h;8.00-18.00	
Rank	# A_c	Rank	# A_c	Rank	# A_c
1	98	1	60	1	50
2	97	2	56	2	50
3	96	3	54	3	47
4	96	4	53	4	45
5	95	5	52	5	45
6	95	6	52	6	44
7	95	7	52	7	44
Dataset Total	45570	Dataset Total	23212	Dataset Total	19633

Table: Number of customer travels; 7 days with highest demand

ICVS Singapore
Available Trips

- Since the demand is reduced, the resources (EV) are be reduced as well
- The filtering of long travels makes the instances too easy
- More challenging instances are obtained by randomly picking travels from the dataset

ICVS Singapore
Parameters

- 40 EV
- 40 Time steps (10 hours, 15 min each)
- 2 Relocators
- Look for Optimal Solution
- Since the difficulty of the instance may vary depending on which travel arcs are picked from the dataset, the following results are obtained as average of several runs with instances of the same size

- $\# A_c$: Available travels (instance size)
- $\# A_c$ NO REL : Trips served when relocation is not performed
- $\# A_c$ REL : Trips served with relocation

$\# A_c$	$\# A_c$ NO REL	$\# A_c$ REL	$\# A_r$ CHOSEN	TIME [s]
50	48	48.75	0.75	63.5
60	59.75	59.75	0	40.25
70	66.67	69.67	2.67	147
80	73.75	78.75	4.25	213.25
90	80.25	87.25	6.00	1002.25
100	92.33	97	6.33	558.33

Table: 40 EV results

- The number of relocations is too small
- In order to stress the model and increase relocations, it is possible to reduce the number of resources (EV)

# A_c	# A_c NO REL	# A_c REL	# A_r CHOSEN	TIME [s]
50	48	48.75	0.75	63.5
60	59.75	59.75	0	40.25
70	66.67	69.67	2.67	147
80	73.75	78.75	4.25	213.25
90	80.25	87.25	6.00	1002.25
100	92.33	97	6.33	558.33

Table: 40 EV results

ICVS Singapore
Few EV

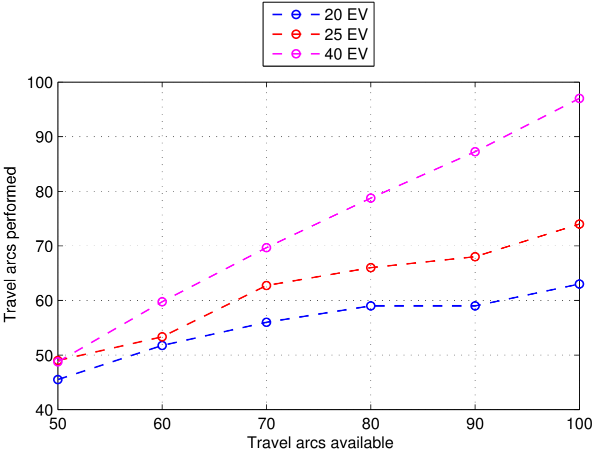
# A_c	# A_c NO REL	# A_c REL	# A_r CHOSEN	TIME [s]
50	47	49	3	65.25
60	50.33	53.33	4	142
70	59	62.75	4.5	213.25
80	62	66	7	259
90	63.33	68	6.33	163.67
100	64.75	74	8.75	147.25

Table: 25 EV results

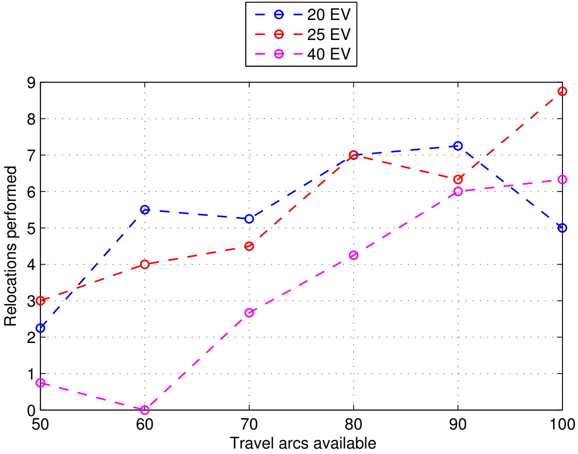
# A_c	# A_c NO REL	# A_c REL	# A_r CHOSEN	TIME [s]
50	43	45.5	2.25	72.25
60	47	51.75	5.5	88.75
70	50.75	56	5.25	162.75
80	46.33	59	7	151
90	55.25	59	7.25	122
100	61.5	63	5	257.75

Table: 20 EV results

ICVS Singapore
Few EV Comparison, Travels Served



ICVS Singapore
Few EV Comparison, Relocations Performed

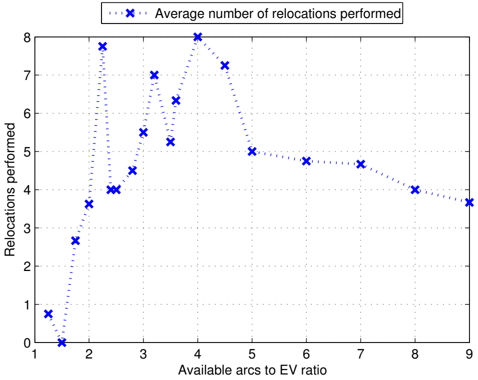


ICVS Singapore

- The number of relocations increases as the number of resources (EV) decreases
- If the ratio A_c/EV is too low, no relocation is needed, because there are a lot of EV
- However, when the ratio A_c/EV is too high, no relocation is performed, because there are a lot of available A_c and the EV can stay in a station and wait for other travel in that station
- Therefore, reducing the number of EV is not the proper way to stress the model

ICVS Singapore

- The ratio A_c/EV has an impact on the number of relocations performed

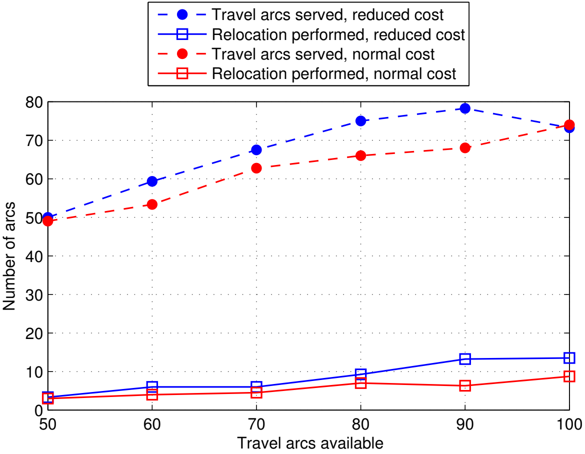


ICVS Singapore
Stress Instances: Low Relocation Cost (25 EV)

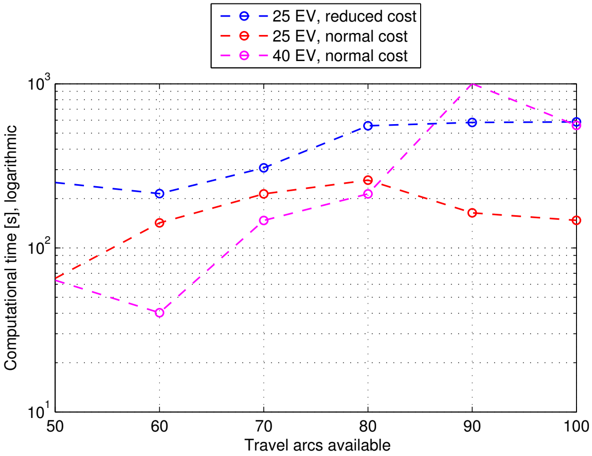
- The relocation cost was reduced, so that relocations are performed whenever is possible

# A_c	# A_c NO REL	# A_c REL	# A_r CHOSEN	TIME [s]
50	46.67	50	3.33	250
60	54	59.33	6	214
70	63.25	67.5	6	307.25
80	66	75	9.25	554.5
90	67.75	78.25	13.25	581
100	67	73.25	13.5	585.25

ICVS Singapore
Relocation Cost Comparison (25 EV)



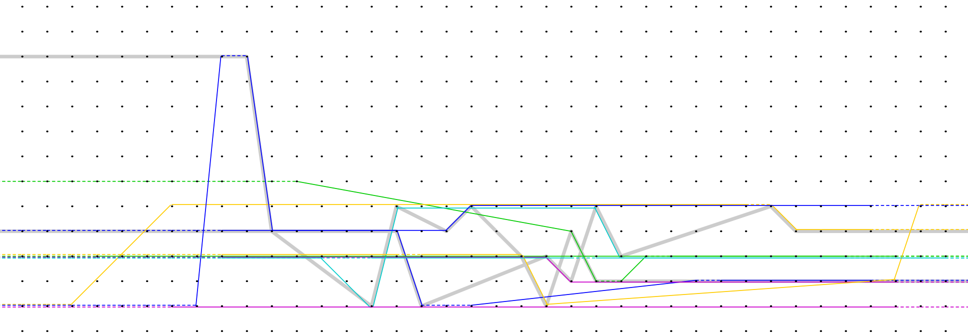
ICVS Singapore
Computational Time, Intel Xeon E3-1220 (3.10 GHz)



Solution Example

- A graphical tool has been developed in order to display the paths of EV and relocators
- The following graph represents a small instance (10 EV and 55 A_c)
- Relocators are the thick gray lines
- The EV paths have different colors; when an EV waits at a station, the line is dotted. Notice that some travel arcs are two-way

Solution Example



Plan

Future Work
Extensions and Heuristics

- Integrated Location/relocation model (based on CG)
- Extension of the models to free-floating
- Reducing relocation density (see Carlier et al. [2])
- Rolling horizon approach to solve large instances
  - Relaxation of integrality constraints
  - Inclusion of relocation arcs

Rolling Horizon Example
First time interval

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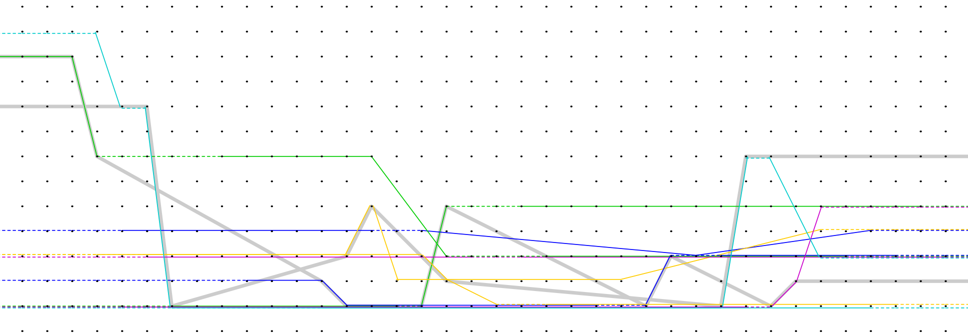
Rolling Horizon Example

Second time interval



Thank you for your attention

Bibliography

[1] M. Bruglieri, A. Colorni, and A. Luè. The vehicle relocation problem for the one-way electric vehicle sharing: An application to the milan case. *Procedia - Social and Behavioral Sciences*, 111:18–27, Feb. 2014.

[2] A. Carlier, A. Munier-Kordon, and W. Klaudel. Mathematical model for the study of relocation strategies in one-way carsharing systems. *Transportation Research Procedia*, 10:374 – 383, 2015. 18th Euro Working Group on Transportation, {EWGT} 2015, 14-16 July 2015, Delft, The Netherlands.

[3] A. G. Kek, R. L. Cheu, and M. Chor. Relocation simulation model for multiple-station shared-use vehicle systems. *Transportation Research Record*, 1986(1):81–88, Jan. 2006.

[4] A. G. Kek, R. L. Cheu, Q. Meng, and C. H. Fung. A decision support system for vehicle relocation operations in carsharing systems. *Transportation Research Part E: Logistics and Transportation Review*, 45(1):149–158, Jan. 2009.

[5] R. Nair and E. Miller-Hooks. Fleet management for vehicle sharing operations. *Transportation Science*, 45(4):524–540, Nov. 2011.