Improvements in Large Neighborhood Search for the Electric Autonomous Dial-A-Ride Problem*

Maria Bresich [1] Günther R. Raidl [1] Steffen Limmer [2]

[1]Institute of Logic and Computation, TU Wien, Austria,
mbresich, raidl@ac.tuwien.ac.at

[2]Honda Research Institute Europe, Germany,
steffen.limmer@honda-ri.de

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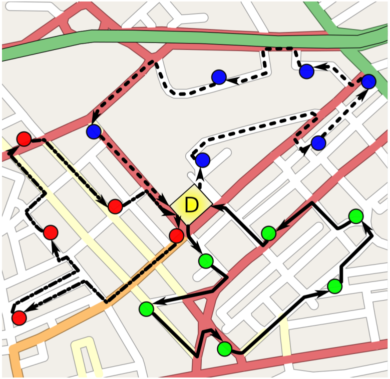
Motivation Ho et al. (2018)

Transportation services:

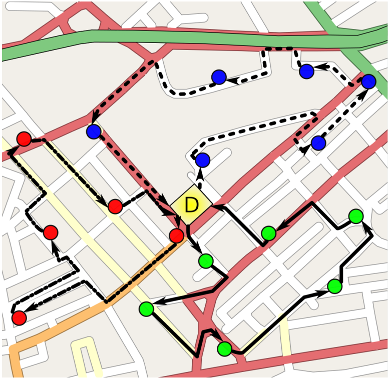
- Classic public transit services (bus, train)
  - + Many passengers, cost efficient
  - – Fixed routes, scheduled times, unavailability
- Taxi services
  - + Door-to-door service
  - – High cost
- On-demand public transit services = Dial-A-Ride (DAR)
  - + Cost efficient, environment-friendlier, customizable service
  - – Ride-sharing, detours

- Combinatorial optimization problem
- NP-hard
- Generalization of:
    - Vehicle Routing Problem
    - Pickup and Delivery Problem



Dial-A-Ride Problem (DARP) Cordeau and Laporte (2003)

- Combinatorial optimization problem
- NP-hard
- Generalization of:
  - Vehicle Routing Problem
  - Pickup and Delivery Problem



Definition (Standard DIAL-A-RIDE PROBLEM)

Given: n users with transportation requests from a pickup to a drop-off location, a fleet of m vehicles

Task: Design m vehicle routes serving all requests, s.t. the total routing cost is minimized and certain constraints are satisfied.

DARP Constraints Cordeau and Laporte (2003)

- Start and end at the depot

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- Service starts within time window, vehicles leave and return to depot within planning horizon
- User ride time $\leq$ maximum ride time
  $\rightarrow$ consideration of user inconvenience

Electric Autonomous DARP (E-ADARP)

Bongiovanni et al. (2019)

Definition (Static Electric Autonomous DARP)

Given: n users with transportation requests from a pickup to a drop-off location, a fleet of m electric autonomous vehicles
Task: Design m vehicle routes serving all requests, s.t. the total travel time and excess ride time of all users are minimized and certain constraints are satisfied.

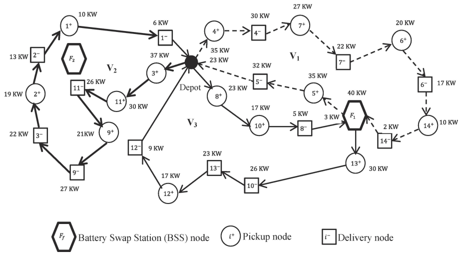

Figure: Example of E-DARP taken from Masmoudi et al. (2018).

E-ADARP Constraints I Bongiovanni et al. (2019)

- Start and end at ~~the depot~~ → a depot
- Pickup and drop-off of request in same route
- ~~Total route duration ≤ maximum route duration~~
- Service starts within time window, vehicles leave and return to depot within planning horizon
- User ride time ≤ maximum ride time
  → consideration of user inconvenience

E-ADARP Constraints II Bongiovanni et al. (2019)

New constraints: battery management

- Minimal battery levels at destination depots required
- Only empty vehicles can charge
- At most one visit per charging station over all vehicles

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Simplifying assumptions:

- Constant battery consumption independent from load, speed, and state-of-charge (SOC)
- Linear increase of SOC with time considering a recharge rate

Related Work

Static E-ADARP:

- Mixed integer linear programming (MILP) formulations and branch-and-cut algorithm by Bongiovanni et al. (2019)
  - 2-index formulation e-ADARP2
- Deterministic annealing (DA) algorithm by Su et al. (2023)
  - Linear-time exact route evaluation scheme
  - Battery-restricted fragments
- Bilevel large neighborhood search (BI-LNS) by Limmer (2023)
  - Outer level: charging stops
  - Inner level: requests

Definition (Battery-restricted fragment)

A *battery-restricted fragment* $\mathcal{F} = (i_1, i_2, \dots, i_k)$ is a subsequence of a feasible route that consists only of pickup and drop-off nodes, where the vehicle arrives empty at i_1 and leaves empty at i_k and has passenger(s) on board at all other nodes.

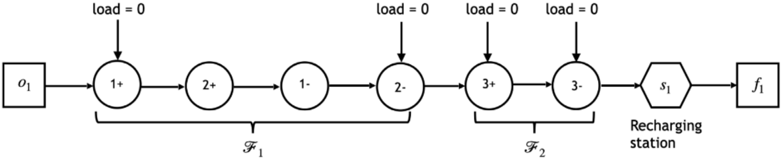

Figure: Route with battery-restricted fragments, taken from Su et al. (2023).

- Minimum user excess ride time $t_{\min}^{\text{excess}}(\mathcal{F})$: calculated exactly with a linear program (LP)

Efficient route cost computation:

- Minimum user excess ride time of a feasible route r with fragments $\mathcal{F}_1, \mathcal{F}_2, \ldots, \mathcal{F}_n$: $t^{\text{excess}}_{\min}(r) = \sum_{i=1}^{n} t^{\text{excess}}_{\min}(\mathcal{F}_i)$

Su et al. (2023):

- Enumerate and evaluate all feasible fragments during preprocessing
  $\rightarrow$ can be inefficient, time-consuming, memory demanding

Our approach:

- Evaluate fragments on first encounter
  $\rightarrow$ better scalability
- Improve charging stop insertion

Large Neighborhood Search (LNS)

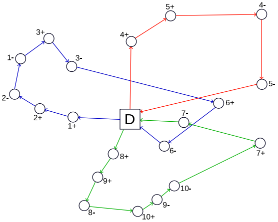

Figure: Initial solution.

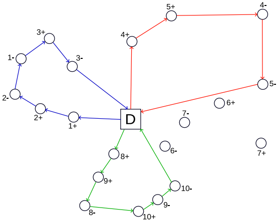

Figure: Destroyed solution.

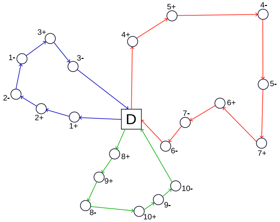

Figure: Repaired solution.

Destroy operator: random removal (Ropke and Pisinger (2006))

- Remove randomly selected requests

Large Neighborhood Search (LNS)

Repair Operators

Greedy heuristic: (Ropke and Pisinger (2006))

- Cheapest insertion over all unserved requests and routes

Time window order based heuristic:

- Consider unserved requests in non-decreasing order of the start of the pickup time windows
- Cheapest insertion over all routes

Random order based heuristic:

- Consider unserved requests in random order
- Cheapest insertion over all routes

Large Neighborhood Search (LNS)

Route Evaluation With On-The-Fly Charging Stop Insertion

- LNS does not deal with charging stops
- Route evaluation procedure:
  - Checks feasibility
  - Inserts charging stops as needed
  - Determines charging durations

Allows consideration of:

- Individual charging speeds at charging stations

On-The-Fly (OTF) Charging Stop Insertion

Mixed Integer Linear Program (MILP)

Goals:

- Determine insertion positions and charging durations satisfying battery-related constraints
- Minimize total detour length caused by new charging stops

Benefit:

- Optimal: charging stations, insertion positions

Drawbacks:

- Computationally expensive
- Slow

On-The-Fly Charging Stop Insertion

Time-Efficient Heuristic I

Workflow:

- Remove charging stops from route
- Determine remaining route R: fragments and depots
- Forward pass:
  - Earliest service start times t^{early} and waiting durations d^{wait}
  - Battery levels of vehicle
  - Latest stop i^{ch} before which charging is necessary
- Backward pass:
  - Latest service start times t^{late} and backward-waiting durations $d^{\mathrm{wait\_back}}$

On-The-Fly Charging Stop Insertion

Time-Efficient Heuristic I

Workflow (continued):

- Charging not necessary: terminate → feasible route
- Charging necessary:
  - Go backwards from i^{ch}
  - Check each possible position and charging station
- No feasible insertion: terminate → infeasible route
- Feasible insertions: select and insert stop
  - If available: feasible tour and minimum detour length
  - Otherwise: most energy charged
- Update all affected service and waiting times and battery levels
- Repeat

On-The-Fly Charging Stop Insertion

Time-Efficient Heuristic II

- Feasibility with 1 charging stop possible:
  - Optimal insertion
  - Linear run time: $O(|R|)$
- Multiple charging stops necessary:
  - Best insertion heuristic
  - Run time: $O(|R| \cdot n_{\text{charging}})$
  - n_{charging} ... number of inserted charging stations

Computational Study

Setup

- Implementation in `Julia 1.10.0`
- `Gurobi 10.0.3` (single-threaded) via `JuMP`
- Runs per instance: 30
- Time limit: 300 s
- Memory limit: 20 GB
- Intel Xeon E5-2640 v4 with 2.4 GHz

Computational Study

Benchmark Instances

- 2 data sets:
  - 14 Cordeau instances[a]: 2–5 vehicles, 16–50 requests
  - 10 Ropke instances[b]: 5–8 vehicles, 48–96 requests

  → enhanced with E-ADARP features[c]
- 2 modes for charging station visits:
  - 1 visit per station: $n_\mathrm{s} = 1$
  - Unlimited visits per station: $n_\mathrm{s} = \infty$
- 3 minimum battery level ratios: $\gamma \in \{0.1, 0.4, 0.7\}$

[a] DARP instances by Cordeau (2006)
[b] DARP instances by Ropke et al. (2007)
[c] cf. Bongiovanni et al. (2019)

Results

Cordeau instances with $\gamma = 0.1$

Instance	e-ADARP2		DA			BI-LNS		OTF MILP		OTF Heuristic	
	RT [min]	Obj	RT mean [min]	Obj min	Obj mean	Obj min	Obj mean	Obj min	Obj mean	Obj min	Obj mean
$n_s = 1$											
a2-16	0.02	**237.38**	0.65	**237.38**	**237.38**	238.20	238.20	**237.38**	**237.38**	**237.38**	**237.38**
a2-20	0.07	**279.08**	1.23	**279.08**	**279.08**	281.00	281.00	**279.08**	**279.08**	**279.08**	**279.08**
a2-24	0.15	**346.21**	2.68	**346.21**	**346.21**	**346.21**	346.59	**346.21**	346.66	**346.21**	**346.21**
a3-18	0.08	236.82	0.42	236.82	236.82	238.73	238.75	**236.81**	**236.81**	**236.81**	**236.81**
a3-24	0.23	**274.80**	0.97	**274.80**	**274.80**	275.18	275.18	**274.80**	275.50	**274.80**	**274.80**
a3-30	1.70	**413.27**	0.90	**413.27**	**413.27**	414.88	414.88	**413.27**	414.33	**413.27**	**413.27**
a3-36	1.78	**481.17**	2.54	**481.17**	**481.17**	483.86	484.05	481.38	486.09	**481.17**	482.18
a4-16	0.06	**222.49**	0.32	**222.49**	**222.49**	**222.49**	**222.49**	**222.49**	222.61	**222.49**	**222.49**
a4-24	0.52	**310.84**	0.49	**310.84**	**310.84**	311.48	311.48	**310.84**	310.95	**310.84**	**310.84**
a4-32	10.20	393.96	0.87	393.96	395.12	394.66	394.79	**393.95**	394.89	**393.95**	**393.95**
a4-40	8.62	**453.84**	1.53	**453.84**	459.42	456.93	457.08	**453.84**	462.55	**453.84**	**454.46**
a4-48	120.00	**554.54**	2.36	555.93	561.26	557.24	557.94	556.36	560.02	**554.54**	**555.38**
a5-40	19.03	414.51	1.08	414.80	420.35	415.62	415.65	415.80	422.04	**414.50**	**414.99**
a5-50	120.00	**559.17**	2.29	561.41	570.58	560.07	**560.66**	563.50	571.47	**559.17**	562.18
$n_s = \infty$											
a2-16						238.20	238.20	**237.38**	**237.38**	**237.38**	**237.38**
a2-20						281.00	281.00	**279.08**	**279.08**	**279.08**	**279.08**
a2-24						**346.21**	346.22	**346.21**	346.39	**346.21**	**346.21**
a3-18						238.73	238.73	**236.81**	**236.81**	**236.81**	**236.81**
a3-24						275.18	275.18	**274.80**	275.60	**274.80**	**274.80**
a3-30						414.88	414.88	**413.27**	414.92	**413.27**	**413.27**
a3-36						483.86	483.86	**481.17**	486.63	**481.17**	**482.26**
a4-16						**222.49**	**222.49**	**222.49**	222.78	**222.49**	**222.49**
a4-24						311.48	311.48	**310.84**	310.96	**310.84**	**310.84**
a4-32						394.66	394.79	**393.95**	394.64	**393.95**	**393.95**
a4-40						456.93	457.37	455.26	462.06	**453.84**	**453.84**
a4-48						557.25	557.82	555.70	560.01	**554.54**	**555.43**
a5-40						415.62	415.62	416.45	422.27	**414.50**	**415.13**
a5-50						560.07	**560.95**	563.87	571.30	**559.17**	561.81

Results

Cordeau instances with $\gamma = 0.7$

Instance	e-ADARP2 RT [min]	e-ADARP2 Obj	DA RT mean [min]	DA Obj min	DA Obj mean	BI-LNS Obj min	BI-LNS Obj mean	OTF MILP Obj min	OTF MILP Obj mean	OTF Heuristic Obj min	OTF Heuristic Obj mean
$n_s = 1$											
a2-16	0.09	**240.66**	1.60	**240.66**	**240.66**	242.83	245.50	**240.66**	240.84	**240.66**	**240.66**
a2-20	120.00	NA	2.88	**293.27**	294.11	NA	NA	**293.27**	294.98	**293.27**	**293.27**
a2-24	16.02	358.21	3.44	**353.18**	NA	356.99	363.04	**353.18**	353.45	**353.18**	**353.18**
a3-18	0.80	**240.58**	0.97	**240.58**	**240.58**	242.49	246.13	**240.58**	240.98	**240.58**	**240.58**
a3-24	2.54	277.72	2.06	**275.97**	277.43	277.52	277.52	**275.97**	277.46	**275.97**	**275.97**
a3-30	120.00	NA	1.30	**424.93**	436.20	432.27	436.56	**424.93**	430.32	**424.93**	**426.12**
a3-36	120.00	**494.04**	2.09	**494.04**	502.27	496.75	500.84	**494.04**	502.35	**494.04**	**497.18**
a4-16	1.12	**223.13**	0.52	**223.13**	**223.13**	**223.13**	223.95	**223.13**	223.37	**223.13**	**223.13**
a4-24	30.58	318.21	0.90	**316.65**	318.31	319.37	321.10	**316.65**	319.17	**316.65**	**316.65**
a4-32	120.00	430.07	1.19	**397.87**	405.85	401.97	402.59	**397.87**	399.98	**397.87**	**397.87**
a4-40	120.00	NA	1.91	479.02	NA	471.72	478.93	471.78	487.42	**467.72**	**474.47**
a4-48	120.00	NA	2.74	582.22	NA	579.71	588.48	580.49	591.36	**575.62**	**579.63**
a5-40	120.00	447.63	1.63	424.26	436.94	420.20	423.88	425.93	433.02	**418.75**	**421.16**
a5-50	120.00	NA	2.64	603.24	NA	593.71	602.30	596.54	612.00	**589.61**	**596.09**
$n_s = \infty$											
a2-16			1.99	**240.66**	**240.66**	242.44	242.44	**240.66**	**240.66**	**240.66**	**240.66**
a2-20			5.27	286.32	288.89	290.33	291.23	**285.86**	285.95	**285.86**	**285.86**
a2-24			5.96	354.38	374.68	354.53	356.89	**350.32**	350.33	**350.32**	**350.32**
a3-18			1.10	**238.82**	**238.82**	241.95	242.46	**238.82**	239.55	240.03	240.03
a3-24			2.50	**275.20**	**275.20**	277.52	278.02	**275.20**	276.05	**275.20**	**275.20**
a3-30			2.85	415.71	417.07	419.16	426.30	**413.45**	415.85	**413.45**	**414.08**
a3-36			5.72	484.85	487.91	490.26	492.79	**483.08**	490.60	484.49	**486.98**
a4-16			0.52	**222.49**	**222.49**	**222.49**	223.57	**222.49**	223.09	**222.49**	**222.49**
a4-24			1.18	315.98	317.99	316.51	318.38	**315.40**	316.00	315.98	**315.98**
a4-32			2.06	**394.94**	401.82	396.64	397.98	**394.94**	395.84	**394.94**	**394.94**
a4-40			3.77	458.52	467.60	461.16	461.91	**457.76**	465.13	457.88	**458.67**
a4-48			6.72	568.08	575.96	568.01	570.80	**561.15**	565.94	561.38	**564.54**
a5-40			2.50	419.33	425.29	418.79	421.06	**415.88**	425.07	**415.88**	**416.43**
a5-50			5.88	579.15	588.98	571.37	575.49	573.37	586.47	**567.61**	**571.48**

Results

Ropke instances with $\gamma = 0.1$

Instance	DA			OTF MILP			OTF Heuristic		
	RT mean [min]	Obj min	Obj mean	Obj min	Obj mean	Feas	Obj min	Obj mean	Feas
$n_s = 1$									
a5-60	2.97	691.83	706.20	689.73	697.36	30/30	**683.87**	**687.42**	30/30
a6-48	3.82	506.72	512.69	507.51	515.37	30/30	**506.45**	**506.77**	30/30
a6-60	2.12	692.00	700.15	695.27	705.03	30/30	**690.29**	**693.54**	30/30
a6-72	3.47	777.44	794.69	780.66	793.95	30/30	**762.16**	**770.69**	30/30
a7-56	1.47	613.10	624.51	616.18	629.56	30/30	**612.53**	**614.70**	30/30
a7-70	3.50	760.90	778.84	763.73	779.19	30/30	**756.27**	**761.16**	30/30
a7-84	5.38	889.38	904.88	900.10	914.76	30/30	**874.57**	**883.45**	30/30
a8-64	10.20	641.99	652.59	647.01	660.08	30/30	**632.21**	**637.93**	30/30
a8-80	5.96	803.52	828.67	810.67	828.02	30/30	**793.64**	**802.86**	30/30
a8-96	6.06	1053.11	1080.80	1055.38	1077.99	30/30	**1032.76**	**1041.59**	30/30
$n_s = \infty$									
a5-60	2.86	687.68	705.59	686.47	698.19	30/30	**683.81**	**686.03**	30/30
a6-48	4.03	506.91	514.15	508.63	517.20	30/30	**506.45**	**506.91**	30/30
a6-60	2.14	691.07	702.09	694.85	703.87	30/30	**689.86**	**692.31**	30/30
a6-72	3.51	777.46	795.14	776.58	793.20	30/30	**763.39**	**771.62**	30/30
a7-56	1.46	614.18	622.69	618.99	628.00	30/30	**612.01**	**615.23**	30/30
a7-70	3.37	760.10	777.10	763.75	779.40	30/30	**756.81**	**760.44**	30/30
a7-84	5.00	885.89	905.13	893.10	910.68	30/30	**874.69**	**884.33**	30/30
a8-64	10.80	640.24	653.81	646.60	658.10	30/30	**634.04**	**639.14**	30/30
a8-80	6.20	804.02	826.92	813.97	827.17	30/30	**792.92**	**802.74**	30/30
a8-96	6.11	1049.98	1077.21	1056.50	1080.17	30/30	**1031.01**	**1040.36**	30/30

Results

Ropke instances with $\gamma = 0.7$

Instance	DA			BI-LNS			OTF MILP			OTF Heuristic		
	RT mean [min]	Obj min	Obj mean	Obj min	Obj mean	Feas	Obj min	Obj mean	Feas	Obj min	Obj mean	Feas
$n_s = 1$												
a5-60	8.46	NA	NA	NA	NA	0/10	NA	NA	0/30	NA	NA	0/30
a6-48	8.37	NA	NA	519.55	522.50	10/10	523.49	537.45	30/30	**517.12**	**521.62**	30/30
a6-60	5.45	NA	NA	733.45	742.02	9/10	736.52	750.14	10/30	**714.16**	**731.45**	30/30
a6-72	9.84	NA	NA	NA	NA	0/10	NA	NA	0/30	NA	NA	0/30
a7-56	3.69	NA	NA	649.11	669.71	10/10	656.86	675.48	23/30	**636.56**	**649.37**	30/30
a7-70	8.51	NA	NA	NA	NA	0/10	NA	NA	0/30	**816.64**	**840.59**	30/30
a7-84	13.18	NA	NA	NA	NA	0/10	NA	NA	0/30	NA	NA	0/30
a8-64	20.12	NA	NA	646.82	652.38	10/10	652.65	674.25	30/30	**639.06**	**651.33**	30/30
a8-80	14.47	NA	NA	854.85	863.74	10/10	869.19	888.37	8/30	**837.79**	**862.75**	30/30
a8-96	14.35	NA	NA	NA	NA	0/10	NA	NA	0/30	NA	NA	0/30
$n_s = \infty$												
a5-60	8.21	708.54	723.73	697.87	709.11	10/10	695.81	704.15	30/30	**686.36**	**692.75**	30/30
a6-48	8.07	509.76	525.10	511.04	514.53	10/10	509.87	519.44	30/30	**508.10**	**509.46**	30/30
a6-60	4.83	697.57	711.52	699.70	705.56	10/10	699.25	708.04	30/30	**689.95**	**695.13**	30/30
a6-72	9.57	796.19	826.48	788.34	801.80	10/10	782.32	799.84	30/30	**769.12**	**779.49**	30/30
a7-56	3.53	625.91	641.82	627.34	633.38	10/10	623.45	632.08	30/30	**617.12**	**621.51**	30/30
a7-70	8.00	781.56	800.35	777.69	785.49	10/10	769.84	783.03	30/30	**757.66**	**765.36**	30/30
a7-84	11.75	915.61	938.49	900.98	916.93	10/10	900.77	920.03	30/30	**888.40**	**897.33**	30/30
a8-64	21.50	649.93	668.48	645.62	648.60	10/10	654.75	663.89	30/30	**632.95**	**641.17**	30/30
a8-80	12.41	843.26	865.90	815.06	825.74	10/10	821.29	837.30	30/30	**801.08**	**814.87**	30/30
a8-96	13.45	1097.76	1136.43	1072.77	1091.06	10/10	1074.02	1091.18	30/30	**1048.87**	**1060.22**	30/30

Conclusion & Outlook

Conclusions:

- Charging stops more important for higher γ and larger instances
- OTF heuristic better than OTF MILP approach
  $\rightarrow$ especially on larger instances
- OTF heuristic overall best approach finding for almost all instances:
  - best mean objective values
  - best known or new best objective values

Conclusion & Outlook

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- Charging stops more important for higher γ and larger instances
- OTF heuristic better than OTF MILP approach
  $\rightarrow$ especially on larger instances
- OTF heuristic overall best approach finding for almost all instances:
  - best mean objective values
  - best known or new best objective values

Future Work:

- Very large-scale instances with different LNS operators
- Machine learning-based operator selection
- Dynamic E-ADARP

Thank you!

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Typical DARP Features Ho et al. (2018)

- **Request:** transportation from a pickup to a drop-off location
- **Time window:** earliest and latest times of pickup/drop-off
- **Route:** a vehicle's tour
- **Depot(s):** starting and ending location(s) of a route
- **Vehicle capacity:** maximum number of users in a vehicle at once
- **Load:** number of users in a vehicle
- **(Maximum) Ride time:** (maximum) time a user spends in a vehicle
- **(Maximum) Route duration:** (maximum) travel time of a vehicle for one tour

Routing and Scheduling in E-ADARP

Cordeau and Laporte (2007); Bongiovanni et al. (2019)

Routing:

- Sequence of pickup and drop-off locations
- Visits to charging stations

Scheduling:

- Departure time from the depot
- Service start time at each location
- Time for (partial) recharging

Goals:

- Satisfy constraints
- Minimize route duration and user excess ride time

Preprocessing

Goal: reduce the size of problem instances

Time Window Tightening: Su et al. (2023)

- Tighten known time windows
- Determine missing time windows

Arc Elimination: Goeke (2019); Dumas et al. (1991); Cordeau (2006)

- Remove infeasible arcs based on constraints
- Identify incompatible user pairs
  $\rightarrow$ forbid assignment to the same vehicle

Large Neighborhood Search (LNS)

Shaw (1998); Pisinger and Ropke (2010)

- Local search metaheuristics
- Large neighborhoods with complex move operators
  - Destroy operator
  - Repair operator

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Algorithm 1: Large Neighborhood Search

Input: feasible solution x
Output: best found solution x^b

$x^b \leftarrow x$;
repeat
    $x^t \leftarrow r(d(x))$;
    if accept(x^t, x) **then**
        $x \leftarrow x^t$;
    if $c(x^t) < c(x^b)$ **then**
        $x^b \leftarrow x^t$;
until stop criterion is met;
return x^b;

Large Neighborhood Search (LNS)

Shaw (1998); Pisinger and Ropke (2010)

- Local search metaheuristics
- Large neighborhoods with complex move operators
    - Destroy operator
    - Repair operator

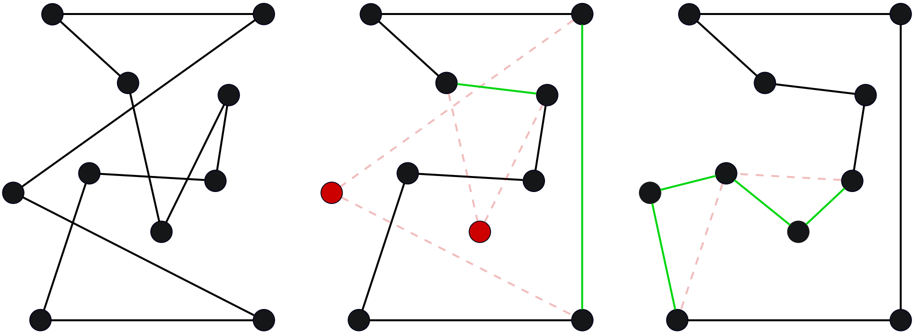

Figure: Initial solution.

Figure: After destroy operation.

Figure: After repair operation.

Large Neighborhood Search (LNS)

Initial Solution Construction

Step 1:

- Initialize an empty route for each vehicle
  - Start = predefined origin depot
  - End = nearest unvisited destination depot

Step 2: insert requests

- Time window order based repair operator

Result: valid solution satisfying all constraints

- Unserved requests possible

On-The-Fly Charging Stop Insertion

MILP I

Inputs:

- d_i = service duration at location at index i (i-th stop)
- $t_{i,j}$ = travel time from i-th to j-th stop
- $[w_i^{\mathrm{start}}, w_i^{\mathrm{stop}}]$ = time window of i-th stop
- b_i = battery consumption of i-th stop
- Q = battery capacity of vehicle
- α_s = charging rate of station s
- $\beta_{i,j}$ = battery consumption of arc between i-th and j-th stop

Decision variables:

- $x_{i,s}$ = 1 if charging station s is visited directly before i-th stop, 0 otherwise
- $d_{i,s}^{\mathrm{ch}}$ = charging duration at station s before i-th stop
- t_i^{serv} = service start time at i-th stop
- B_i = battery level on arrival at the i-th stop
- B_i^{ch} = battery level on arrival at charging station before i-th stop

MILP II

$$\min \quad \sum_{i=2}^{|R|} \sum_{s \in S} (t_{i-1,s} + t_{s,i} - t_{i-1,i}) \cdot x_{i,s} \tag{1}$$

$$\text{s.t.} \quad \sum_{s \in S} x_{i,s} \leq 1 \qquad i = 2, \dots, |R| \tag{2}$$

$$t_i^{\text{serv}} \geq t_{i-1}^{\text{serv}} + d_{i-1} + t_{i-1,i} + \sum_{s \in S} \left((t_{i-1,s} + t_{s,i} - t_{i-1,i}) \cdot x_{i,s} + d_{i,s}^{\text{ch}} \right) \qquad i = 2, \dots, |R| \tag{3}$$

$$B_i^{\text{ch}} = B_{i-1} - \sum_{s \in S} \beta_{i-1,s} x_{i,s} \qquad i = 2, \dots, |R| \tag{4}$$

$$B_i^{\text{ch}} + \sum_{s \in S} \alpha_s d_{i,s}^{\text{ch}} \leq Q \qquad i = 2, \dots, |R| \tag{5}$$

$$B_i = B_i^{\text{ch}} + \sum_{s \in S} \alpha_s d_{i,s}^{\text{ch}} - \beta_{i-1,i} - \sum_{s \in S} (\beta_{s,i} - \beta_{i-1,i}) \cdot x_{i,s} - b_i \qquad i = 2, \dots, |R| \tag{6}$$

On-The-Fly Charging Stop Insertion
MILP III

$$d_{i,s}^{\mathrm{ch}} \leq \frac{Q}{\alpha_s} x_{i,s} \qquad i = 2, \dots, |R|,\ s \in S \qquad (7)$$

$$x_{i,s} \in \{0, 1\} \qquad i = 2, \dots, |R|,\ s \in S \qquad (8)$$

$$d_{i,s}^{\mathrm{ch}} \geq 0 \qquad i = 2, \dots, |R|,\ s \in S \qquad (9)$$

$$0 \leq B_i \leq Q \qquad i = 2, \dots, |R| \qquad (10)$$

$$0 \leq B_i^{\mathrm{ch}} \leq Q \qquad i = 2, \dots, |R| \qquad (11)$$

$$w_i^{\mathrm{start}} \leq t_i^{\mathrm{serv}} \leq w_i^{\mathrm{stop}} \qquad i = 1, \dots, |R| \qquad (12)$$

On-The-Fly Charging Stop Insertion

Time-Efficient Heuristic

Algorithm 2: OTF charging stop insertion and evaluation.

Input: route r
Output: feasibility status of r

$r \leftarrow$ remove_charging_stops(r);
$R \leftarrow$ get_fragments_and_depots(r);
if contains_infeasible_fragment(R) **then**
  return false;
$i^{\mathrm{ch}} \leftarrow none,\ S' \leftarrow$ available_stations(S);
$t^{\mathrm{early}},\ d^{\mathrm{wait}},\ B,\ i^{\mathrm{ch}} \leftarrow$ forward_pass(R);
$t^{\mathrm{late}},\ d^{\mathrm{wait\_back}} \leftarrow$ backward_pass(R);
if violates_time_windows(t^{early}) **or** violates_time_windows(t^{late}) **then**
  return false;
while $i^{\mathrm{ch}} \neq none$ **do**
  $min\_detour \leftarrow \infty,\ max\_energy \leftarrow 0,\ \hat{i} \leftarrow none$;
  for i in $i^{\mathrm{ch}}, \ldots, 2,\ s \in S'$ **do**
    $feasible,\ detour,\ energy \leftarrow$ check_stop(R, i, s);
    if $feasible$ **and** better_stop($detour, energy, min\_detour, max\_energy$) **then**
      $min\_detour \leftarrow detour,\ max\_energy \leftarrow energy$;
      $\hat{i} \leftarrow i,\ \hat{s} \leftarrow s$;
  if $\hat{i} = none$ **then**
    return false;
  insert_charging_stop($r, R, \hat{i}, \hat{s}$);
  update($t^{\mathrm{early}}, d^{\mathrm{wait}}, t^{\mathrm{late}}, d^{\mathrm{wait\_back}}, B, i^{\mathrm{ch}}, S'$);
return true;

Results

Cordeau instances with $\gamma = 0.4$

Instance	e-ADARP2		DA			BI-LNS			OTF MILP				OTF Heuristic			
	RT [min]	Obj	RT mean [min]	Obj min	Obj mean	Obj min	Obj mean	Feas	Obj min	Obj mean	Obj sd	Feas	Obj min	Obj mean	Obj sd	Feas
$n_s = 1$																
a2-16	0.03	**237.38**	0.88	**237.38**	**237.38**	238.20	238.20	10/10	**237.38**	**237.38**	0.00	30/30	**237.38**	**237.38**	0.00	30/30
a2-20	0.83	**280.70**	2.35	**280.70**	**280.70**	282.90	283.24	10/10	**280.70**	**280.70**	0.00	30/30	**280.70**	**280.70**	0.00	30/30
a2-24	0.42	348.04	3.85	**347.04**	**347.04**	**347.04**	349.67	10/10	**347.04**	348.14	1.12	30/30	349.20	349.20	0.00	30/30
a3-18	0.07	236.82	0.44	236.82	236.82	238.73	238.73	10/10	**236.81**	236.94	0.43	30/30	**236.81**	**236.81**	0.00	30/30
a3-24	0.28	**274.80**	1.13	**274.80**	**274.80**	275.58	275.58	10/10	**274.80**	276.42	1.34	30/30	**274.80**	**274.80**	0.00	30/30
a3-30	1.65	413.37	1.48	**413.34**	**413.34**	415.51	415.75	10/10	**413.34**	415.36	2.46	30/30	413.37	413.37	0.00	30/30
a3-36	5.11	484.14	2.63	**483.06**	**483.86**	485.98	487.42	10/10	**483.06**	490.65	5.00	30/30	**483.06**	485.92	2.78	30/30
a4-16	0.09	**222.49**	0.32	**222.49**	**222.49**	**222.49**	**222.49**	10/10	**222.49**	222.91	0.46	30/30	**222.49**	**222.49**	0.00	30/30
a4-24	0.66	**311.03**	0.53	**311.03**	311.65	311.48	311.48	10/10	**311.03**	311.35	0.30	30/30	**311.03**	**311.03**	0.00	30/30
a4-32	11.36	**394.26**	1.05	**394.26**	397.21	394.96	395.45	10/10	**394.26**	395.12	1.10	30/30	**394.26**	**394.26**	0.00	30/30
a4-40	6.96	**453.84**	1.94	**453.84**	459.46	457.01	457.39	10/10	**453.84**	462.97	4.77	30/30	**453.84**	**454.84**	1.87	30/30
a4-48	120.00	**554.60**	2.96	558.11	563.47	557.56	560.09	10/10	556.83	563.07	2.89	30/30	**554.60**	**556.98**	1.49	30/30
a5-40	20.35	414.51	1.21	416.25	420.32	415.63	415.63	10/10	415.79	421.75	3.91	30/30	**414.50**	**415.12**	1.05	30/30
a5-50	120.00	560.50	2.71	567.54	574.56	560.41	**562.55**	10/10	566.50	576.18	4.69	30/30	**559.51**	564.41	3.44	30/30
$n_s = \infty$																
a2-16			0.84	**237.38**	**237.38**	238.20	238.20	10/10	**237.38**	**237.38**	0.00	30/30	**237.38**	**237.38**	0.00	30/30
a2-20			2.42	280.70	280.70	282.62	283.10	10/10	**280.58**	**280.58**	0.21	30/30	280.70	280.70	0.00	30/30
a2-24			4.43	**346.28**	**346.28**	347.93	349.07	10/10	**346.28**	346.56	0.05	30/30	348.92	348.92	0.00	30/30
a3-18			0.42	236.82	236.82	238.73	238.73	10/10	**236.81**	236.91	0.76	30/30	**236.81**	**236.81**	0.00	30/30
a3-24			1.11	**274.80**	**274.80**	275.18	275.46	10/10	**274.80**	275.49	0.96	30/30	**274.80**	**274.80**	0.00	30/30
a3-30			1.73	413.34	**413.34**	415.51	415.81	10/10	**413.28**	414.51	1.87	30/30	413.37	413.37	0.00	30/30
a3-36			4.15	**481.17**	**481.17**	484.07	485.37	10/10	**481.17**	487.67	3.64	30/30	**481.17**	482.68	2.26	30/30
a4-16			0.30	**222.49**	**222.49**	**222.49**	**222.49**	10/10	**222.49**	223.14	0.54	30/30	**222.49**	**222.49**	0.00	30/30
a4-24			0.49	**311.03**	311.65	311.48	311.48	10/10	**311.03**	311.28	0.47	30/30	**311.03**	**311.03**	0.00	30/30
a4-32			1.03	**394.26**	397.27	394.96	395.15	10/10	**394.26**	395.58	1.19	30/30	**394.26**	**394.26**	0.00	30/30
a4-40			2.02	**453.84**	458.74	456.93	457.50	10/10	455.22	463.28	3.85	30/30	**453.84**	**454.53**	1.84	30/30
a4-48			3.86	558.96	564.86	557.63	559.63	10/10	556.09	561.83	3.26	30/30	**555.25**	**556.40**	1.24	30/30
a5-40			1.18	415.79	419.82	415.62	415.62	10/10	416.98	423.21	3.79	30/30	**414.50**	**414.91**	0.82	30/30
a5-50			3.07	567.13	574.28	560.41	**562.64**	10/10	562.56	574.19	7.02	30/30	**559.48**	562.81	2.78	30/30

Results

Ropke instances with $\gamma = 0.4$

Instance	DA			BI-LNS			OTF MILP				OTF Heuristic			
	RT mean [min]	Obj min	Obj mean	Obj min	Obj mean	Feas	Obj min	Obj mean	Obj sd	Feas	Obj min	Obj mean	Obj sd	Feas
							$n_s = 1$							
a5-60	4.89	697.97	718.44	688.16	693.43	10/10	691.49	703.42	5.68	30/30	**685.51**	**690.63**	2.94	30/30
a6-48	4.29	506.91	514.46	506.85	507.43	10/10	508.70	515.80	4.66	30/30	**506.45**	**506.84**	0.30	30/30
a6-60	2.89	694.78	706.07	692.69	695.13	10/10	698.53	705.90	5.77	30/30	**690.29**	**693.16**	2.31	30/30
a6-72	5.83	799.60	821.17	771.97	778.30	10/10	783.18	795.86	8.00	30/30	**765.64**	**776.00**	4.47	30/30
a7-56	1.67	613.66	624.40	614.58	616.02	10/10	618.27	628.57	5.52	30/30	**612.78**	**615.27**	2.51	30/30
a7-70	4.56	766.05	784.54	761.62	765.71	10/10	763.06	778.86	8.93	30/30	**756.46**	**760.21**	2.03	30/30
a7-84	9.74	932.12	NA	886.19	891.04	10/10	893.14	914.92	11.51	30/30	**878.99**	**890.18**	7.23	30/30
a8-64	10.69	638.36	652.30	637.95	640.41	10/10	646.28	655.15	5.41	30/30	**632.95**	**639.02**	3.05	30/30
a8-80	7.47	811.19	833.05	**793.17**	**798.41**	10/10	811.62	823.98	7.00	30/30	794.04	800.85	5.13	30/30
a8-96	10.29	NA	NA	1048.72	1057.47	10/10	1055.03	1080.91	10.41	30/30	**1036.22**	**1047.47**	5.62	30/30
							$n_s = \infty$							
a5-60	4.75	691.72	709.78	685.68	689.42	10/10	691.64	698.91	4.29	30/30	**683.85**	**686.91**	2.53	30/30
a6-48	4.26	507.25	514.64	506.85	507.30	10/10	507.82	518.25	5.12	30/30	**506.45**	**506.87**	0.22	30/30
a6-60	2.90	692.83	701.86	692.25	**693.68**	10/10	698.82	705.81	4.47	30/30	**690.40**	693.72	2.62	30/30
a6-72	5.71	781.22	801.86	774.38	778.84	10/10	784.50	797.62	9.52	30/30	**762.05**	**772.91**	4.45	30/30
a7-56	1.65	615.74	623.51	614.58	615.40	10/10	619.52	629.99	4.88	30/30	**612.53**	**614.78**	2.15	30/30
a7-70	4.56	761.58	778.04	762.78	764.51	10/10	767.89	784.46	9.43	30/30	**757.01**	**760.15**	2.23	30/30
a7-84	7.61	896.91	916.23	884.94	890.81	10/10	901.72	916.28	11.20	30/30	**877.98**	**886.22**	5.82	30/30
a8-64	11.99	637.84	652.17	637.95	640.30	10/10	649.89	662.91	8.31	29/29	**632.21**	**639.48**	3.15	30/30
a8-80	7.52	813.16	829.92	794.38	**797.08**	10/10	825.43	835.17	6.71	29/29	**793.39**	802.36	5.25	30/30
a8-96	9.41	1058.41	1090.04	1048.45	1053.35	10/10	1068.79	1082.10	8.35	29/29	**1034.17**	**1043.42**	6.12	30/30